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Essays on heterogeneity and uncertainty in climate policy and development

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Abstract

This thesis consists of four papers focusing on the role of heterogeneity and uncertainty in the context of climate change policy and agricultural development. By using intra-household data, the first paper illustrates differences in spouses' perception of climatic risks and its effect on household's adoption of climate change adaptation in sub-Saharan Africa. In Kenya, female spouses' perception of climatic risks increases the household's likelihood of adopting climate adaptation strategies, whereas males' perception has no statistically significant effects. The adoption of livestock-based strategies for climate change adaptation is positively associated with both female and male spouses' perceptions of climatic risks in Uganda, whereas it has a negative relationship with females' perception in Tanzania. Moreover, both male and female spouses' perceptions of climatic risks have positive associations with households' likelihood of adopting crop-based strategies for climate change adaptation in Uganda and Tanzania. The second paper assesses how the impacts of climate change vary across crops and across agro-ecosystems in Ethiopia using the household-level panel data. The empirical results show that climate change will induce an increase in coffee and teff yields at high altitudes while it will decrease coffee yield at low altitudes, and barley, maize, and wheat yield at high altitudes by the years 2041-2060. The third paper provides a systematic review of literature that uses a real-options approach for the analysis of investment in climate adaptation and mitigation actions. The review shows the need of future research incorporating climate uncertainty, risk preferences, and decisions-makers' strategic interactions. The fourth paper models farmers' opportunity to relocate coffee farms to higher altitudes in Ethiopia as climate adaptation strategy. The results illustrate how the uncertainty in net returns and high establishment costs may induce farmers to postpone their adaptation actions. The findings of papers presented in this thesis point to the need to take into account the differences in individual behaviours, vulnerabilities and uncertainties in designing climate and development policies.

Keywords: Climate adaptation, Climate mitigation, Gender, Sustainable agriculture

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Dedication

To my mother Soreeti Kajawa.

To the memory of my father Ginbo Gatiso.

To the memory of late Professor Emeritus Yves Surry.

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Tsegaye Ginbo* and Helena Hansson. Intra-household risk perceptions and climate change adaptation in sub-Saharan Africa (The manuscript submitted to Agricultural Economics).

II. Tsegaye Ginbo* and Yves Surry. Heterogeneous impacts of climate change on crop yields across altitudes in Ethiopia (The manuscript submitted to Climatic Change).

III. Tsegaye Ginbo*, Luca Di Corato and Ruben Hoffmann (2021). Investing in climate change adaptation and mitigation: A methodological review of real-options studies. Ambio, 50(1), 229–241.

IV. Luca Di Corato* and Tsegaye Ginbo. Climate change and coffee farm relocation in Ethiopia: a real-options approach (The manuscript submitted to Climate Change Economics).

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The contribution of Tsegaye Ginbo Gatiso to the papers included in this thesis was as follows:

I. Developed problem formulation, hypothesis (research questions) and study design jointly with the co-author, undertook all data curation, preparation and empirical analysis, prepared the initial draft of the paper, and wrote the final paper under supervision and guidance of the co-author.

II. Developed problem formulation, hypothesis and study design jointly with the co-author, undertook all data curation, preparation and empirical analysis, prepared the initial draft of the paper, and wrote the final paper under supervision and guidance of the co-author.

III. Developed problem formulation, hypothesis and study design jointly with the co-authors, undertook all literature search, selection, information extraction, analysis and synthesis, prepared the initial draft of the paper, and wrote the final paper jointly with the co-authors.

IV. Developed problem formulation, hypothesis and study design jointly with the co-author, undertook all data curation and preparation, undertook empirical analysis jointly with the co-author, prepared the initial draft of the paper, and wrote the final paper jointly with the co-author.

Abbreviations

CRRA	Constant Relative Risk Aversion
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FDRE	Federal Democratic Republic of Ethiopia
FGLS	Feasible Generalized Least Squares
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
IPCC	Intergovernmental Panel on Climate Change
IV	Instrumental Variables
LSMS-ISA	Living Standards Measurement Study - Integrated Survey on Agriculture
NDCs	Nationally Determined Contributions
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
SDGs	Sustainable Development Goals
UNDP	United Nations Development Program
UNFCCC	United Nations Framework Convention on Climate Change

1. Introduction

Combating climate change is crucial to realize global Sustainable Development Goals (SDGs). The SDGs, including goals to end poverty, improve health and education, reduce inequality, ensure clean water and sanitation, and spur economic growth, go hand-in-hand with tackling climate change and preserving nature. In recognition of its importance, climate policy[1] initiatives and agreements commenced at global level to mitigate climate change and to adapt to it. For example, endorsed in 2015, the Paris Agreement aims at limiting global warming to well below 2°C compared to pre-industrial levels, enhancing the ability to adapt to climate change and ensuring finance for climate-resilient and green development (see UNFCCC, 2015). The effectiveness of the initiative hinges on climate change mitigation and adaptation activities of countries, regions, institutions and individuals with diverse interests and behaviours under uncertainty. Consequently, as highlighted by IPCC (2014d) and Chan et al. (2018), main challenges of climate policy include addressing the diversity of the actors' perceptions of the costs and benefits of climate policy actions, as well as uncertainty and heterogeneity in the impacts of climate change. The IPCC's synthesis report for policy makers also highlights that how individuals and organizations perceive climatic risks and how they take into account uncertainties[2] influence the design of climate policy (see IPCC, 2014d; IPCC, 2014e).

In this regard, formulation of effective climate policy requires due consideration of risks and uncertainties pertaining to climate change. This is because these two aspects influence decision-makers' actions in response to climate change (IPCC, 2014e). Moreover, there are often divergence between people's perceptions and experts' judgments about climatic risks.

[1] Climate policy encompasses strategies for climate change mitigation, i.e. interventions to reduce the sources or enhance the sinks of GHGs emissions, and/or adaptation, i.e. actions to eliminate the harmful effects or make use of the potential opportunities associated with climate change (IPCC, 2014a, 2014d).

[2] Uncertainties about climate change emanate from the lack of information about future climate change and its impacts, the ways societies will react to it as well as the imperfect forecasting of the future lifestyles and gains from climate change adaptation and mitigation investment (Heal & Millner, 2014; Quiggin, 2008).

For example, residents may choose not to contribute to measures to alleviate future flood risks if the perceived probability of flood damage is lower than that of the experts' judgment (IPCC, 2014d).

Another key aspect in climate policy is the need to consider the heterogeneities in the vulnerability of climate change across spatial locations or agro-ecologies as well as social groups including gender (see e.g. IPCC, 2014a). Specifically, gender dimensions of the heterogeneity is more prevalent in the context of developing countries where women are more vulnerable to climate change than men. These differences emanate from the existing gender inequality where women have lower access to productive resources and higher dependence on climate-sensitive societal roles and livelihoods (FAO, 2017; IPCC, 2014a, 2014b; Meyiwa et al., 2014). In addition, recent evidences show that climate change generally increases existing gender inequalities in poor countries (see e.g. Eastin, 2018). As a result, tackling climate change and enhancing livelihood resilience can reduce the gender inequality in developing countries. Furthermore, spatial differences in the impacts of climate change are due to variations in agro-ecological, latitudinal and altitudinal factors that characterize differences not only in the initial conditions of temperature, precipitation and other climatic factors but also in the rate of change in climate. This is because the impacts of global warming are a function of initial climatic conditions and can differ in cooler areas compared to warmer areas (Kolstad & Moore, 2019). For example, low altitude areas are more vulnerable to increasing temperature than high altitude areas in Ethiopia (Moat et al., 2017).

Consequently, a clear understanding of subjective perceptions of climatic risks, heterogeneities in the impacts of climatic changes as well as the role of uncertainty in decision-makers' responses to climate change can help to provide useful inputs for designing effective climate policy instruments. Existing household-level studies usually consider risk perceptions of household heads (see e.g. Alpizar et al., 2011; Hasibuan et al., 2020; Jianjun et al., 2015; Sullivan-Wiley & Short Gianotti, 2017; Teklewold & Köhlin, 2011; Wossen et al., 2015), yet evidences of gender roles from intra-household studies of decisions about climate adaptation or mitigation are missing. In addition, literature investigating the impacts of climate change emphasize nationally or regionally aggregated effects on crop yields (e.g. Burke & Emerick, 2016; Butler & Huybers, 2013; Chen et al., 2016; Schlenker & Roberts, 2008; Zhang et al., 2017), and its variability (e.g.

Carew, 2017; Carew et al., 2009; Chen et al., 2004; Isik & Devadoss, 2006; McCarl et al., 2008; Poudel & Kotani, 2013). Yet there are evidences for crop- and location-differentiated impacts of climate change on agriculture, which calls for analysis of heterogeneities in key dimensions (see e.g. Jones & Thornton, 2003; Moat et al., 2017; Ray et al., 2019). Furthermore, the vast majority of existing micro-level studies on climate actions do not incorporate climate-induced uncertainties, i.e. volatility in climate conditions and gains from adaptation and mitigation investments, although there are some macro-level simulations (see e.g. Webster et al., 2012) and climatic scenarios analysis (see Ginbo et al. (2021) for a review of literature).

To fill these research gaps, this thesis provides insights into why and how climate and development policies should consider heterogeneities in perceptions and vulnerability as well as how uncertainty in the impacts and potential gains of climate change influence adaptation and mitigation decisions. It includes papers that study how gender-differentiated perceptions of climatic risks affect households' decisions for climate change adaptation, how the impacts of climate change vary across different contexts within a country and how uncertainty influence investments in mitigation and adaptation actions. More specifically, Paper I examines how climatic risk perception varies among spouses within households in Kenya, Tanzania and Uganda and how it affects their decisions for the adoption of climate change adaptation strategies. Paper II estimates the heterogeneity of the impact of climate change on production yields across different crops and altitudes in Ethiopia. Paper III provides a systematic review of the literature regarding the incorporation of climate uncertainty and decision-makers' risk aversion and strategic interactions into the real-options analysis of investment in climate adaptation and mitigation by individuals and organizations. Finally, Paper IV investigate how climate-induced uncertainty in yield differential and farm establishment costs affect coffee farmers' decision to migrate a strategy for climate change adaptation in Ethiopia.

The insights reflected in this thesis have particular importance in supporting sustainable development in the global south. In the context of developing countries, a successful implementation of SDGs requires the alignment of its targets with effective climate policy instruments. This is because there are substantial inter-linkages between limiting the effects of climate change and eradicating poverty to achieve sustainable development (IPCC, 2014a, 2014e). Aligning SDGs with climate policy can help poor countries to exploit the benefits from strengthening the linkages as well as to lower trade-offs and costs of implementing the two policies. For example, integrating the Paris Agreement within the SDGs and strengthening the implementation thereof is a cost-efficient and convenient approach to economic development in developing regions including Sub-Saharan Africa (Gomez-Echeverri, 2018; Leimbach et al., 2018). In this regard, policy-oriented researches can help to facilitate the effective integration and implementation of the policies. It is with this spirit that this thesis conducted to provide inputs for climate and sustainable development policies taking into account context heterogeneity and uncertain environments.

2. Theoretical and empirical frameworks

This doctoral thesis uses a combination of theoretical and empirical approaches to study climate and development policies under heterogeneity and uncertainty. The subsequent sub-sections highlight the main theoretical and empirical frameworks employed in the papers appended in the thesis.

2.1 Collective household models

Unlike the unitary household model, the collective household model considers a household as collection of different individuals. It takes into account the characteristics of female spouses, male spouses and grown-up children in a household since their preferences and cognitive behaviors may not be uniform (Vermeulen, 2002). The collective household model is further grouped into cooperative and non-cooperative model. In non-cooperative model, one household member maximizes her/his utility by taking others' utility given and this model does not necessarily result in Pareto efficient allocations within a household (Basu, 2006; Vermeulen, 2002). On the other hand, cooperative model entails that a household reach an agreement to allocate the gains of living together that lead to a Pareto efficient allocation of welfare (Vermeulen, 2002). In the collective model, household's decision-making, including the adoption of climate change adaptation, involves intra-household bargaining processes.

However, existing literature commonly consider a farm household as unitary entity and emphasize the effects of household head characteristics on decisions for climate adaptation and sustainable farming practices (see e.g. Bedeke et al., 2019; Bryan et al., 2013; Deressa et al., 2009; Di Falco, 2014; Di Falco et al., 2020; Wossen et al., 2015). Nevertheless, household's adoption of strategies for climate change adaptation is a composite decision involving multiple actors, including female and male spouses as well as grown-up children. In addition, climatic risk perceptions, vulnerability and adaptive capacity can differ among members of a household. Therefore, considering the effects of the characteristics and the behaviors of grown-up members, in addition to the household head, on the adaptation decision can provide a more complete picture of climate adaptation decision process.

In this regard, there has been increasing, but scanty, applications of collective household models in the research areas of intra-household resource allocations, gender gap and technology adoption (see e.g. Flinn et al., 2018; Mohapatra & Simon, 2017; Ngigi et al., 2017). Even though it is interesting to consider the role of grown-up children, most of the applications assume for simplicity only two individuals in a household, particularly male and female spouses. This thesis, in Paper I, contributes to this line of literature by applying a collective household model to assess how climatic risk perceptions of female and male spouses affect household's decisions for climate change adaptation. Considering the preferences and behavioral characteristics of each actor within a single decision-making unit, i.e. a household or a firm, can be useful in order to understand practical mechanisms to promote the effective implementation of climate policy involving both adaptation and mitigation.

2.2 Cross-sectional and non-linear panel data models

Following the pioneering study of the Ricardian approach by Mendelsohn et al. (1994), the cross-sectional approach has become popular to estimate farm-level impact of climate change on agriculture. The cross-sectional approach uses variations of climate conditions to measure the sensitivity to climate change and hence it compares the outcome across space (Kolstad & Moore, 2019; Mendelsohn, 2007). Specifically, as highlighted by Kolstad and Moore (2019), the cross-sectional approach spatially compares outcomes using hotter places with the current climate as equivalents in the future for currently colder places under climate change. In this approach, farm outcome, such as farm revenues or profits, are regressed on climatic or weather variables by controlling for socioeconomic factors. The main advantage of using cross-sectional approach to estimate impacts on climate change is that it captures the effects of adaptation because it measures people's response to adjust to conditions at place where they live (Carter et al., 2018; Kolstad & Moore, 2019; Mendelsohn, 2007). However, the cross-sectional approach is subject to bias from omitted variables which causes endogeneity problem (Carter et al., 2018; Kolstad & Moore, 2019). Several studies use the IV approach to control for endogeneity problems arising from the unobserved farm characteristics such as soil quality (see e.g. Di Falco et al., 2012; Elum et al., 2018; Tibesigwa et al., 2015). However, the success of disentangling the effects of climate change on farm outcomes depends on the strength of the instruments used and it is empirically challenging to obtain strong instruments to control for the endogeneity (Abrevaya, 2006). In addition to weak casual identification, the difficulty to study impacts of climate change at a specific crop level is another common problem when using the Ricardian approach (Carter et al., 2018).

Consequently, there are recently increasing number of studies using panel data approach, instead of cross-sectional approach, to examine impacts of climate change on agriculture. Panel data models use plausibly random year-to-year variations in weather to investigate the impacts of climate change on agricultural profits or crop yields within fixed effects estimation approach. In this regard, it helps to control for unobservable time-invariant factors or omitted variables (Carter et al., 2018). Moreover, non-linear panel models capture the effects of climatic changes on outcome variables, such as crop yields, farm revenues and food security indicators, by including linear as well as quadratic terms. The inclusion of both linear and quadratic terms helps to capture the effects of both linear and extreme trends in weather and climate conditions. In this case, the coefficient on the higher-order term uses both variation from within units as well as across units. Econometric identification arises from both within-unit time series variation and cross-sectional variation across units, and this allow for plausibly causal estimates that incorporate adaptation (Auffhammer, 2018; Carter et al., 2018; Kolstad & Moore, 2019).

Another issue about the identification of the impacts of climate change on agricultural production is the use of weather fluctuations rather than climate, which entails the critics about the failure of this approach to capture long-term aspects, particularly the effects of adaptation. However, the recent study by Deryugina and Hsiang (2017) showed that the marginal effect of weather variables on output is the same as the marginal effect of corresponding climate indicators on output. This indicates that for relatively small changes in climate, using weather variation rather than climate variation, can predict the response to climate. For this condition to hold true, however, the outcome variable in regression models should be the crop revenue or profit that farmers aim to maximize instead of the simple yields (Carter et al., 2018).

Based on the reviewed literature, this thesis, in Paper II, uses non-linear panel data model to estimate the heterogeneity of the impact of climate change on crop yields across altitudes. It calibrates the impacts of climate change on crop yields, by using the estimated coefficients of weather variables, namely temperature and precipitation, and the data for changes in both climatic variables over the past and future 30 years. It is worth noting that the estimates presented in Paper II may not capture the long-term adaptation effect since it uses crop yields instead on profits, the reason highlighted in the above paragraph, but it plausibly identifies the impacts of climate change since it controls for location- and time-fixed effects within a non-linear panel data framework.

2.3 Modelling climate uncertainty using real-options analysis

It is suitable to use the real-options analysis to investigate the timing and value of investment in climate policy actions under uncertainty (Guthrie, 2019). In the real-options analysis, uncertain variables such as input and output prices are modelled using Geometric or Arithmetic Brownian motion, Mean-Reverting process and Poisson process (see Amram & Kulatilaka, 1998; Black & Scholes, 1973). The underlying investment problem is then solved algebraically or resorting to numerical approaches namely binomial tree, multinomial models, as well as Monte-Carlo and Least Squares Monte-Carlo simulations (see Boyle, 1977; Longstaff & Schwartz, 2001; Schiel et al., 2018). In addition to capturing the uncertainty, the real options-analysis stresses the role of managerial flexibility when undertaking irreversible investments. There are two main categories of irreversibility in relation to climate policy. The first one is environmental irreversibility that refers to irreversible accumulation of greenhouse gases in the atmosphere (Sims & Finnoff, 2016) and irreversible environmental damages due to the development investments on conserved nature (Fisher & Krutilla, 1974). The second type of irreversibility deals with the irrecoverability of investment costs and uncertainty in investment returns due to uncertain climatic or market conditions. The real-options-analysis is useful when analyzing investment under the second type of irreversibility in that it allows considering whether it makes sense investing later or adjust the investment scale (Trigeorgis & Reuer, 2017; Wesseler & Zhao, 2019).

Despite its relevance to capture uncertainty and flexibility, as documented in Paper III, there is a limited application of real-options analysis in climate change adaptation and mitigation in agriculture. Paper III also presents important research gaps related to the applications in the context of investments in climate change adaptation and mitigation in developing countries. To fill the research gap in studying climate adaptation investment under uncertainty in the context of developing countries, Paper IV included in this thesis analyzes the timing and value of farmers' decision to relocate their coffee farms to resilient areas, in response to the climate change, in Ethiopia. It provides useful insights about how governments may support the farmers' decision to invest in climate adaptation.

3. Data

The empirical analyses presented in the papers included in this thesis are based on the several datasets. The main datasets used in this thesis include the CGIAR's intra-household survey data collected from Kenya, Tanzania and Uganda, the Ethiopian Socioeconomic Survey (ESS) data, which is a part of the World Bank's LSMS-ISA datasets, and the Ethiopian Agricultural Sample Survey (AgSS) data.

Paper I utilizes the intra-household data obtained from the two separate surveys in sub-Saharan Africa collected by the CGIAR centers, namely the Research Program on Climate Change Agriculture and Food Security (CCAFS) and the International Center for Tropical Agriculture (CIAT). The first survey is undertaken in 2013 in Kenya and Uganda by the CCAFS[3]. It covers three sites, namely the Nyando and Wote in Kenya, and the Rakai in Uganda. The sample selection involves two stages, the first stage being the identification of 20 villages and classifying them into strata of different farming systems. At the second stage, 10 households per village were randomly selected from a list of farm households that gives the total sample of 200 households per each of the three sites. The data from the second survey are collected from 585 households in 2014 in Uganda and 608 households in 2015 in Tanzania by the CIAT in collaboration with the International Institute of Tropical Agriculture (IITA)[4]. In Tanzania, the sample of households were selected randomly from 19 villages in the districts of Mbarali and Kilolo. The selection of sample in the four sub-counties in the Nwoya district unloved two stages, namely the probability-proportional-to-size to determine the size of sample, and random sampling

[3] The survey documentations and data are publicly available for use at the Harvard dataverse: https://dataverse.harvard.edu/dataverse/IFPRI?q=%22IFPRI-CCAFS+Gender+and+Climate+Change+Survey+Data%22. See Bryan et al. (2018) for more details about the survey instruments.

[4] The second survey documentation and data are publicly available for use at the Harvard dataverse: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/0ZEXKC. See Mwungu et al. (2017) for more details about the survey instruments.

procedure to select the final sample of households. Both surveys interviewed female and male spouses independently and gathered the gender-disaggregated data about intra-household decision-making processes, personal values, access to agricultural services, climate risk perceptions, and adoption of climate adaptation strategies. In addition to the survey data, Paper I uses rainfall and temperature shocks, calculated by using village-level rainfall and temperature data extract from Worldclim, and provided by the Climatic Research Unit of the University of East Anglia, as instruments to control for the endogeneity of the risk perception variable.

The data used in Paper II comes from the first three rounds of the ESS collected in 2011-2012, 2013-2014, and 2015-2016. It is a nationally representative panel data for rural households in Ethiopia organized by the World Bank and the Ethiopian Central Statistical Agency (CSA) as a part of the LSMS-ISA[5]. The ESS covers 3,776 rural households in the first round while it increases to 5,262 in the second round to include households living in urban areas. The ESS survey employs the two-stage clustered sampling technique to select the sample of households. At the first stage, it uses simple random sampling to select the sample of primary sampling units known as Enumeration Areas (EAs). At the second stage, the sample of households was randomly selected from the sample EAs. The selected households were visited three times during the production season. The first and the third visit involved the collection of detailed data about farm inputs and agricultural production at the field and parcel level in addition to the socioeconomic characteristics of the households. The second visit, on the other hand, involved the collection of data about livestock production. We combine the ESS data about households' background and agricultural activities with the information about village-level weather and climate data. Agricultural activities include crop-farming activities, use of inputs, farm management practices, and crop harvest. We extract village-level weather and climate data from the Copernicus Climate Change Service[6], as well as the historical

[5] The documentation of the ESS data is available at http://surveys.worldbank.org/lsms/programs/integrated-surveys-agriculture-ISA/ethiopia.

[6] The data is provided by the European Centre for Medium-Range Weather Forecasts and available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/ecv-for-climate-change.

climate data for the past 30 years (1988-2018) and the future 40 years (2021-2060) provided by Climatic Research Unit of the University of East Anglia[7].

Paper III in this thesis relies on the information gathered through a systematic literature review procedure. The literature search was undertaken using the Scopus, Google Scholar, Web of Sciences and EconLit databases. The final set of 67 relevant peer-reviewed papers, published during the 1973 - 2018 period and that specifically applied real-options analysis were selected for the review. After the selection of papers based on the search criteria, the careful extraction and analysis of information were undertaken to address the research questions of Paper III.

Furthermore, Paper IV uses the time series data constructed from the AgSS data for the 2003 – 2017 period. The AgSS is a countrywide farm-level survey of the main crops produced in Ethiopia collected by the Central Statistical Agency (CSA) of Ethiopia. It includes household-level information about crop planting and harvest area, production, land and other input uses, farm management and crop utilization. In addition to the AgSS, Paper IV uses data on coffee yields obtained from the FAOSTAT[8]. Moreover, the paper use the estimates of the farmers' costs of coffee production in Western Ethiopia gathered by the Ethiopian Institute of Agricultural Research (see Diro et al., 2019).

[7] Both historical and future climate data available at https://www.worldclim.org/data/index.html.

[8] The FAOSTAT data about coffee production and yield are available at http://www.fao.org/faostat/en/#data/QC

4. Summaries of appended papers

This section provides summaries of each of the four papers included in this doctoral thesis.

4.1 Paper I - Intra-household risk perceptions and climate change adaptation in sub-Saharan Africa

This paper aims to examine the effects of gender-differentiated perceptions of climatic risk on households' adaptation to climate change in Africa south of the Sahara. Specifically, it investigates how female and male spouses' perceptions about climatic risks affect *i)* household's adaptation to climate change and *ii)* female spouse's participation in the household's choices of climate adaptation strategies. For this purpose, the paper adopts a collective household model framework. It utilizes the cross-sectional data collected from the intra-household surveys of 400 households in Kenya, 608 households in Tanzania and 585 households in Uganda (see Bryan et al., 2018; Mwungu et al., 2017). Moreover, we use plausibly exogenous shocks in rainfall and temperature during the data collection and contemporaneous crop-growing months as instruments to control for the endogeneity of spouses' perceptions of climate risks. Perceptions of climatic risks defined as a composite variable derived from the combination of indices constructed by multiplying spouses' beliefs about the likelihood of climate change occurrence with the corresponding magnitude of associated damages.

Our results indicate differences in climatic risk perception of female and male spouses within a household and its effects on their decisions for climate adaptation. In Kenya, female spouses' perception of climatic risks has a positive impact on household's adoption of climate change adaptation strategies. The IV estimates show that households with female spouses' who perceive climatic changes as a more likely danger to their family and community have 3.8% and 10% higher probability to adopt climate change adaptation strategies as well as to implement soil & water conservation, respectively. In Tanzania and Uganda, the effects of spouses' perception about climatic risk are specific to the type of adaptation strategies. In Tanzania, for example, male spouses' perception of climate risk has a positive association with the household's probability of adopting crop-based adaptation strategies whereas it has a negative relationship with the adoption of soil and water conservation strategies. In Uganda, female spouses' perception of climate risk is positively associated with household's adoption of crop-and livestock-based adaptation strategies. These results are robust to whether we consider the female or the male spouse as the household head.

Furthermore, our results show that female spouse's perception of climatic risks increases the likelihood of their participation in making the final decision for adoption of crop-based strategies a well as soil and water conservation in Kenya. The IV estimates indicate that climatic risk perception of female spouses increase the probability of females' participation in decisions for climate adaptation as well as soil and water conservation by about 10% and 19%, respectively. In Tanzania, male spouses' perception of climatic risks has positive association with the probabilities of female spouses' participation in household's decision for the adoption of crop-based and livestock-based strategies. This implies that male spouses who have strong awareness about climatic risk encourage their female spouses to participate in decisions for climate adaptation.

Our findings have several implications. First, it points to the importance of considering gender-differentiated perceptions at household level for understanding the adoption of climate adaptation strategies, as compared to considering gender only in terms of the gender of the household head. Second, it suggests that policies targeting women empowerment in agricultural decision-making could enhance households' adoption of climate-smart agricultural practices. In this regard, it is important to understand the drivers of gender gaps or inequality in the access to resources and strengthening women's rights-based approaches to development.

4.2 Paper II - Heterogeneous impacts of climate change on crop yields across altitudes in Ethiopia

With this paper, we examine the heterogeneity of the impacts of climate change on crop yields across different crops and agro-ecologies in Ethiopia. The paper uses the household-level panel data from the LSMS-ISA as well as the historical and future climate data. It employs the stochastic production function approach, where climatic and weather variables affect crop yields as well as the production risk, i.e. the variability of crop yields, in line with the framework initially developed by Just and Pope (1978). We specify the non-linear panel data regression model, where the effect of weather variables on a crop yield is represented by two parameters, namely the coefficients of the linear and nonlinear terms of temperature and precipitation during the crop-growing season in a year at a household location. These are included to capture linear and extreme weather and climate, respectively. In addition, the coefficient on the higher-order term uses both within-unit time series variation as well as cross-sectional variation across units and this ensures the plausible estimates of the impacts of climate change that incorporate long-run adaptation (Auffhammer, 2018). Our specification allows us to obtain the plausibly causal estimates of the impacts of climatic variables on crop yields. This is because we exploit the random year-to-year exogenous variation in precipitation as well as temperature. The inclusion of a time-invariant zonal fixed effect and the year fixed effect in our regression model controls for unobserved regional heterogeneity in terms of soil quality and farming tradition, and for any exogenous shock including technological change across time, respectively. To find out whether the climatic variables have heterogeneous impacts on crop yields across altitudes, we categorize households in the sample into three or two groups based on the traditional agroecological zones in Ethiopia, namely *Kolla*, *Woinadega* and *Dega*. We estimate a separate regression model for each of the subgroups for each of the six crops using the FGLS procedure, given a heteroskedastic error term. Furthermore, we calibrate the impacts of climate change for medium and long-term periods based on the estimated coefficients as well as the past 30 and future 40 years' data for average temperature and precipitation.

Our empirical results show that the heterogeneity in the impacts of climate is mainly derived by the effect on temperature. At low altitudes, temperature has a U-shaped relationship with the mean yield of coffee, whereas its effect is an inverted U-shaped at high altitudes. Temperature also has an inverted U-shaped relationship with the mean yields of barley, maize, and wheat at high altitudes, whereas its effect is statistically insignificant at low altitudes. Precipitation also has an inverted U-shaped relationship with the mean yield of sorghum at low altitudes and teff at middle altitudes whilst its effect exhibits a U-shaped relationship with the mean yield of maize at high altitudes. We use the coefficients estimated from the econometric model to evaluate the effect of climate change on the crop yields. Compared to 1988-2018, climate change by the years 2041-2060, will induce an increase in coffee and teff yields by 31% and 8.3%, respectively at high altitudes, under a medium emissions scenario. Conversely, it will reduce coffee yield by 3% at low altitudes, and barley, maize, and wheat yield by 22.7%, 48% and 10%, respectively at high altitudes.

Our findings suggest that tailoring agricultural development programs and climate adaptation strategies to address location- and crop-specific sensitivity to climate change may help to build resilience and improve the livelihood of smallholder farmers. Specifically, identification of the locations that are becoming suitable and/or unsuitable for a specific crop is crucial to provide policy input regarding the comparative advantages for alternative crops and land uses. Agricultural policy programs in Ethiopia, such as cluster farming, would better map crop suitability by considering future climate change and develop agroecological clusters instead of those based on traditional crop-growing geography. For instance, building coffee and teff clusters or commercialization centers at high altitudes can enhance climate-resilience as these areas will become suitable for the two crops. Clustering farms can help not only to reduce the existing land fragmentation, but also to exploit synergies among climate adaptation practices and enhance farmers' food security. It is necessary to provide evidence-based guidance and support for farmers to switch to crops suitable for their respective agro-ecological settings. This requires designing the specialized training for extension workers and rural development experts about the climate sensitivity of each crop at different micro-climate and agro-ecological conditions in Ethiopia.

4.3 Paper III - Investing in climate change adaptation and mitigation: A methodological review of real-options studies

This paper provides an overview of the literature adopting a real option approach to analyze investments in climate change adaptation and mitigation. Specifically, it examines how previous literature model the uncertain impacts of climate change on the condition of the human environment, risk preferences, and strategic interactions among decisions-makers. For this purpose, the paper adopts a systematic review methodology in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The Scopus, Google Scholar, Web of Sciences and EconLit databases are used for the search of peer-reviewed articles, published between 1973 and 2018, and that applied a real-options analysis for the evaluation of investments in climate change adaptation or mitigation. This search procedure resulted in the final set of 67 articles considered in the review. Detailed information was extracted and analyzed about the selected articles concerning i) the context including climate policy strategy they focused, ii) the methodology including the unit of analysis, underlying assumptions, stochastic processes, types of uncertainties, consideration of strategic interactions, and solution methods and iii) the main results.

The review results highlight some key issues in the literature. First, the majority of reviewed papers focus on climate change mitigation, particularly investments in clean energy technologies, with limited focus on climate adaptation in agriculture. Second, the emphasis was given to land-use changes, particularly the shifts to bioenergy production and forestland from agriculture, as important strategies to mitigate and adapt to climate change. However, other on-farm measures, such as alternative farming practices, introducing new crops, alternative cropland management, a reduction in the use of chemical fertilizers, and the restoration of organic soils, could be considered by farmers aiming at adapting to or mitigating climate change.

Furthermore, the review revealed that uncertainties associated with climate change is only partially taken into account in modeling investment in climate change mitigation and adaptation actions. In addition, the analyses are usually limited to decisions taken by individual risk neutral profit maximizers. The results suggest the need for further research to fill the identified gaps and better inform climate policy, particularly when it comes to consider how climate uncertainty and risk attitudes affect investment in climate adaptation and mitigation in developing countries.

4.4 Paper IV - Climate change and coffee farm relocation in Ethiopia: a real-options approach

In order to secure climate resilience of the Ethiopian coffee production, it has been suggested to relocate coffee farms from low altitudes i.e. Eastern or South-eastern areas to high altitudes i.e. the South-western areas (see Moat et al., 2017). Due to the favorable combination of moderate temperature and sufficient rainfall at high altitude, Moat et al. (2017) project the relocation may lead to a fourfold increase in the coffee-growing area if compared with a no-migration scenario. Based on this background, this paper studies how sunk establishment costs, uncertain net returns, and policy-induced incentives may affect the optimal timing and profitability of a coffee farm relocation. It develops a real-options model taking into account the relevant drivers of the farmer's decision to relocate. The model assumes that establishment costs are constant while the yield differential between the two cultivation sites, i.e. the current and the new site, evolves over time following an Arithmetic Brownian motion. It also evaluates if the government subsidies covering a portion of the cost of establishing a new plantation can induce relocation earlier than privately optimal. To test the model empirically, the paper uses the data from the AgSS survey and other sources about yields and costs undertaken by an hypothetical coffee farm located in a coffee-growing area in Eastern, South-eastern and South-western Ethiopia.

The results show that relocation is a rather attractive opportunity even though the presence of volatile net returns and relatively high establishment costs may induce its postponement. The relocation may be faster if the yield differential between the two sites would evolve over time at a higher rate and with lower volatility with respect to what we estimate using empirical data. In contrast, it will be further postponed if the cost of establishing a new plantation increases and/or net returns from coffee production decrease. Studying the effect of risk-aversion, we find that risk aversion may drastically delay relocation. Last, as increasing the climate resilience of coffee production has become an issue to be urgently addressed at policy level, we show that incentivizing farmers by offering a subsidy covering a part of the establishment cost may be an effective measure for fostering the relocation process.

The paper concludes by highlighting four main issues worth considering in decision for coffee farm relocation. First, migrating away may have a cost associated with the loss of the established social networks, a cost difficult to monetize but likely relevant for the decision to relocate. Second, potential conflicts between farmers previously settled in climatically resilient areas and new comers must be seriously taken into account. Third, the conservation of natural forest may become problematic in the light of the need of clearing land for coffee production. The key implication of these challenges is that it may be worth considering policy support to strategies enhancing the resilience of coffee production at the existing farm locations. In this regard, the promotion of sustainable farm management practices, such as mulching, irrigation and shade-tree planting, and the development of climate resilient coffee varieties are some of the key policy directions for building a climate-resilient and sustainable coffee sector in Ethiopia.

5. Implications for future research and policy

The results of analyses presented in this thesis have several implications for future studies and policies. One of the implications is the need to consider the preferences and behaviours of various actors in a household, in an organization or in a country. The intra-household analysis presented in Paper I revealed differences in climatic risk perception and choices of adaptation strategies, even within a household, between female and male spouses. This calls for future research to further investigate how individuals, other than household heads, can influence climate change adaptation or mitigation strategies adopted by farm households in developing countries contexts. In this respect, future analysis of gender-differentiated decision-making in adaptation and mitigation of climate change are crucial to support resilient livelihoods. Furthermore, the behaviors of grown-up children should not be overlooked in policies promoting actions for sustainable agricultural development. This is because, we believe, younger generations can play an important role in both creating awareness about environmental concerns as well as contributing to the successful implementation of climate policy. Existing data sets, including the ones used in this thesis, do not allow the analysis of the role of grown-up children in household decisions. Therefore, future household surveys should design tools to gather information about the detailed characteristics of children and their role in climate adaptation and mitigation decision. Furthermore, there can also be heterogeneities in the behaviours and objectives of decision-makers at an organization and or country levels. In this regard, it is worth considering the effect of behaviors on the climate policy orientation of individual organizations or political parties.

Moreover, future research could create better understanding about how the adoption of climate-smart practices affect the vulnerable groups. For example, investigating how the adoption of climate adaptation strategies affect women and children welfare is one of the interesting areas for future research. Specifically, interesting research questions, such as how climate resilient strategies affect gender gap, what is the relationship between the adoption of climate adaptation strategies and child labor, child nutrition and child schooling outcomes, remain unanswered yet. Addressing these questions is crucial to provide inputs to policies to address the issue that women and children are more vulnerable to climate change as compared to other groups in developing countries. As highlighted in Paper I, differences in the vulnerability emanates from reliance of climate sensitive activities and roles, and gender inequality in the ownership of the productive assets. In this regard, it is interesting to study whether the adoption of climate change adaptation or mitigation are helping to close the existing disparities and enhancing the welfare of the vulnerable groups. Identifying policies and strategies to close the gender gap, as well as designing effective incentives to promote climate-smart strategies are also interesting policy challenge in the context of developing regions in general and in sub-Saharan Africa in particular.

Another implication from the results of analysis in this thesis is that climate policy need to internalize and address heterogeneities in the impacts of climate change across different agroecological locations. As indicated in Paper-II, changes in temperature have different impacts on crops, e.g. coffee production, in high altitudes compared to low altitudes. In this regard, there is a need to devise climate adaptation strategies that suits different contexts and agro-ecological settings. Moreover, there can be disparities in the impacts of climate change on different social groups, such as gender, age or income groups given the pre-existing socioeconomic conditions and inequalities (see Eastin, 2018; IPCC, 2014a, 2014c, 2014e). Consequently, the analysis of policy instruments to address variations in climate sensitivity among different social groups can provide useful inputs for designing strategies to achieve sustainable development goals.

Furthermore, the disparities in climatic and environmental changes across places may induce relocation and migration of people across the globe. These can have several socioeconomic and environmental impacts, particularly, on the recipient places. As pointed out in Paper-IV, one of the solutions for these issues is to devise effective tools and policy strategies so as to building resilience to climate change in the original locations and maintain people who wish to relocate or migrate. In this regard, for example, the development of crop varieties or livestock breeds that can better cope up with the changing climate is helpful to build resilient and sustainable agriculture. It is also interesting to study drivers and barriers to farmers' decisions to switch to high-yield and drought-resistant crops. These can also have some implications for food systems. For instance, farmers' shifting from food crops production to non-food (cash) crops production can hamper the availability of food. This implies that it is important to consider multiple factors in a systemic approach to understand decisions for crop switching. In this regard, policy-oriented research can support in understanding synergies and tradeoffs among the alternative strategies for climate change adaptation.

References

Abrevaya, J. (2006). Estimating the effect of smoking on birth outcomes using a matched panel data approach. *Journal of Applied Econometrics*, *21*(4), 489-519. https://doi.org/10.1002/jae.851

Alpizar, F., Carlsson, F., & Naranjo, M. A. (2011). The effect of ambiguous risk, and coordination on farmers' adaptation to climate change — A framed field experiment. *Ecological Economics*, *70*(12), 2317-2326. https://doi.org/10.1016/j.ecolecon.2011.07.004

Amram, M., & Kulatilaka, N. (1998). *Real Options: Managing Strategic Investment in an Uncertain World*. Oxford University Press. https://EconPapers.repec.org/RePEc:oxp:obooks:9780875848457

Auffhammer, M. (2018). Quantifying Economic Damages from Climate Change. *Journal of Economic Perspectives*, *32*(4), 33-52. https://doi.org/https://10.1257/jep.32.4.33

Basu, K. (2006). Gender and Say: A Model of Household Behaviour with Endogenously Determined Balance of Power. *The Economic Journal*, *116*(511), 558-580. https://doi.org/10.1111/j.1468-0297.2006.01092.x

Bedeke, S., Vanhove, W., Gezahegn, M., Natarajan, K., & Van Damme, P. (2019). Adoption of climate change adaptation strategies by maize-dependent smallholders in Ethiopia. *NJAS - Wageningen Journal of Life Sciences*, *88*, 96-104. https://doi.org/10.1016/j.njas.2018.09.001

Black, F., & Scholes, M. (1973). The Pricing of Options and Corporate Liabilities. *Journal of Political Economy*, *81*(3), 637-654. http://www.jstor.org/stable/1831029

Boyle, P. P. (1977). Options: A Monte Carlo approach. *Journal of Financial Economics*, *4*(3), 323-338. https://doi.org/https://doi.org/10.1016/0304-405X(77)90005-8

Bryan, E., Bernier, Q., & Ringler, C. (2018). *A User Guide to the CCAFS Gender and Climate Change Survey Data*. https://www.ifpri.org/publication/user-guide-ccafs-gender-and-climate-change-survey-data

Bryan, E., Ringler, C., Okoba, B., Roncoli, C., Silvestri, S., & Herrero, M. (2013). Adapting agriculture to climate change in Kenya: Household strategies and determinants. *Journal of Environmental Management*, *114*, 26-35. https://doi.org/10.1016/j.jenvman.2012.10.036

Burke, M., & Emerick, K. (2016). Adaptation to Climate Change: Evidence from US Agriculture. *American Economic Journal: Economic Policy*, *8*(3), 106-140. https://doi.org/https://10.1257/pol.20130025

Butler, E. E., & Huybers, P. (2013). Adaptation of US maize to temperature variations. *Nature Climate Change*, *3*(1), 68-72. https://doi.org/https://10.1038/nclimate1585

Carew, R. (2017). Climate change impacts on hard red spring wheat yield and production risk: evidence from Manitoba, Canada. *Canadian journal of plant science*, *v. 98*(no. 3), pp. 782-795-2017 v.2098 no.2013. https://doi.org/https://10.1139/cjps-2017-0135

Carew, R., Smith, E. G., & Grant, C. (2009). Factors Influencing Wheat Yield and Variability: Evidence from Manitoba, Canada. *Journal of Agricultural and Applied Economics*, *41*(3), 625-639. https://doi.org/https://10.1017/S1074070800003114

Carter, C., Cui, X., Ghanem, D., & Mérel, P. (2018). Identifying the Economic Impacts of Climate Change on Agriculture. *Annual Review of Resource Economics*, *10*(1), 361-380. https://doi.org/https://10.1146/annurev-resource-100517-022938

Chan, G., Stavins, R., & Ji, Z. (2018). International Climate Change Policy. *Annual Review of Resource Economics*, *10*(1), 335-360. https://doi.org/10.1146/annurev-resource-100517-023321

Chen, C.-C., McCarl, B. A., & Schimmelpfennig, D. E. (2004). Yield Variability as Influenced by Climate: A Statistical Investigation. *Climatic Change*, *66*(1), 239-261. https://doi.org/https://10.1023/B:CLIM.0000043159.33816.e5

Chen, S., Chen, X., & Xu, J. (2016). Impacts of climate change on agriculture: Evidence from China. *Journal of Environmental Economics and Management*, *76*, 105-124. https://doi.org/https://doi.org/10.1016/j.jeem.2015.01.005

Deressa, T. T., Hassan, R. M., Ringler, C., Alemu, T., & Yesuf, M. (2009). Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. *Global Environmental Change*, *19*(2), 248-255. https://doi.org/10.1016/j.gloenvcha.2009.01.002

Deryugina, T., & Hsiang, S. (2017). The Marginal Product of Climate. *National Bureau of Economic Research Working Paper Series*, *No. 24072*. https://doi.org/10.3386/w24072

Di Falco, S. (2014). Adaptation to climate change in Sub-Saharan agriculture: assessing the evidence and rethinking the drivers. *European Review of Agricultural Economics*, *41*(3), 405-430. https://doi.org/10.1093/erae/jbu014

Di Falco, S., Doku, A., & Mahajan, A. (2020). Peer effects and the choice of adaptation strategies. *Agricultural Economics*, *51*(1), 17-30. https://doi.org/https://doi.org/10.1111/agec.12538

Di Falco, S., Yesuf, M., Kohlin, G., & Ringler, C. (2012). Estimating the Impact of Climate Change on Agriculture in Low-Income Countries: Household Level Evidence from the Nile Basin, Ethiopia [journal article]. *Environmental and Resource Economics*, *52*(4), 457-478. https://doi.org/10.1007/s10640-011-9538-y

Diro, S., Erko, B., & Yami, M. (2019). Cost of Production of Coffee in Jimma Zone, Southwest Ethiopia. *Ethiopian Journal of Agricultural Sciences*, *29*, 13-28.

Eastin, J. (2018). Climate change and gender equality in developing states. *World Development*, *107*, 289-305. https://doi.org/10.1016/j.worlddev.2018.02.021
Elum, Z. A., Nhamo, G., & Antwi, M. A. (2018). Effects of climate variability and insurance adoption on crop production in select provinces of South Africa. *Journal of Water and Climate Change*, *9*(3), 500-511. https://doi.org/10.2166/wcc.2018.020
FAO. (2017). *Climate Smart Agriculture Sourcebook: The role of gender in Climate-Smart Agriculture* (Enabling Frameworks, Issue. http://www.fao.org/climate-smart-agriculture-sourcebook/enabling-frameworks/module-c6-gender/chapter-c7-2/en/
Fisher, A. C., & Krutilla, J. V. (1974). Valuing long run ecological consequences and irreversibilities. *Journal of Environmental Economics and Management*, *1*(2), 96-108. https://doi.org/https://doi.org/10.1016/0095-0696(74)90007-2
Flinn, C. J., Todd, P. E., & Zhang, W. (2018). Personality traits, intra-household allocation and the gender wage gap. *European Economic Review*, *109*, 191-220. https://doi.org/https://doi.org/10.1016/j.euroecorev.2017.11.003
Ginbo, T., Di Corato, L., & Hoffmann, R. (2021). Investing in climate change adaptation and mitigation: A methodological review of real-options studies. *Ambio*, *50*(1), 229-241. https://doi.org/10.1007/s13280-020-01342-8
Gomez-Echeverri, L. (2018). Climate and development: enhancing impact through stronger linkages in the implementation of the Paris Agreement and the Sustainable Development Goals (SDGs). *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2119), 20160444. https://doi.org/doi:10.1098/rsta.2016.0444
Guthrie, G. (2019). Real options analysis of climate-change adaptation: investment flexibility and extreme weather events. *Climatic Change*, *156*(1), 231-253. https://doi.org/10.1007/s10584-019-02529-z
Hasibuan, A. M., Gregg, D., & Stringer, R. (2020). Accounting for diverse risk attitudes in measures of risk perceptions: A case study of climate change risk for small-scale citrus farmers in Indonesia. *Land Use Policy*, *95*, 104252. https://doi.org/10.1016/j.landusepol.2019.104252
Heal, G., & Millner, A. (2014). *Reflections: Uncertainty and Decision Making in Climate Change Economics* (Vol. 8). https://doi.org/10.1093/reep/ret023
IPCC. (2014a). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects* (Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Issue. C. U. Press.
IPCC. (2014b). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.* (Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Issue. http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-PartA_FINAL.pdf
IPCC. (2014c). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects* (Contribution of Working Group II to the Fifth Assessment

Report of the Intergovernmental Panel on Climate Change Issue. C. U. Press. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartB_FINAL.pdf

IPCC. (2014d). *Climate Change 2014: Mitigation of Climate Change* (Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Issue. C. U. Press.

IPCC. (2014e). *Climate Change 2014: Synthesis Report* (Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Issue. IPCC. https://www.ipcc.ch/report/ar5/syr/

Isik, M., & Devadoss, S. (2006). An analysis of the impact of climate change on crop yields and yield variability. *Applied Economics*, *38*(7), 835-844. https://doi.org/https://10.1080/00036840500193682

Jianjun, J., Yiwei, G., Xiaomin, W., & Nam, P. K. (2015). Farmers' risk preferences and their climate change adaptation strategies in the Yongqiao District, China. *Land Use Policy*, *47*, 365-372. https://doi.org/10.1016/j.landusepol.2015.04.028

Jones, P. G., & Thornton, P. K. (2003). The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change*, *13*(1), 51-59. https://doi.org/https://doi.org/10.1016/S0959-3780(02)00090-0

Just, R. E., & Pope, R. D. (1978). Stochastic specification of production functions and economic implications. *Journal of Econometrics*, *7*(1), 67-86. https://doi.org/https://doi.org/10.1016/0304-4076(78)90006-4

Kolstad, C. D., & Moore, F. C. (2019). *Estimating the Economic Impacts of Climate Change Using Weather Observations. National Bureau of Economic Research, Working Paper No. 25537*. http://www.nber.org/papers/w25537

Leimbach, M., Roming, N., Schultes, A., & Schwerhoff, G. (2018). Long-Term Development Perspectives of Sub-Saharan Africa under Climate Policies. *Ecological Economics*, *144*, 148-159. https://doi.org/https://doi.org/10.1016/j.ecolecon.2017.07.033

Longstaff, F. A., & Schwartz, E. S. (2001). Valuing American Options by Simulation: A Simple Least-Squares Approach. *The Review of Financial Studies*, *14*(1), 113-147. https://doi.org/https://10.1093/rfs/14.1.113

McCarl, B. A., Villavicencio, X., & Wu, X. (2008). Climate Change and Future Analysis: Is Stationarity Dying? *American Journal of Agricultural Economics*, *90*(5), 1241-1247. https://doi.org/https://10.1111/j.1467-8276.2008.01211.x

Mendelsohn, R. (2007). Measuring Climate Impacts With Cross-Sectional Analysis. *Climatic Change*, *81*(1), 1-7. https://doi.org/10.1007/s10584-005-9007-0

Mendelsohn, R., Nordhaus, W. D., & Shaw, D. (1994). The Impact of Global Warming on Agriculture: A Ricardian Analysis. *The American Economic Review*, *84*(4), 753-771. http://www.jstor.org/stable/2118029

Meyiwa, T., Maseti, T., Ngubane, S., Letsekha, T., & Rozani, C. (2014). Women in selected rural municipalities: Resilience and agency against vulnerabilities to climate change. *Agenda*, *28*(3), 102-114. https://doi.org/10.1080/10130950.2014.955686

Moat, J., Williams, J., Baena, S., Wilkinson, T., Gole, T. W., Challa, Z. K., Demissew, S., & Davis, A. P. (2017). Resilience potential of the Ethiopian coffee sector under climate change [Article]. *Nature Plants*, *3*, 17081. https://doi.org/https://10.1038/nplants.2017.81

Mohapatra, S., & Simon, L. (2017). Intra-household bargaining over household technology adoption. *Review of Economics of the Household*, *15*(4), 1263-1290. https://doi.org/10.1007/s11150-015-9318-5

Mwungu, C. M., Mwongera, C., Shikuku, K. M., N. Nyakundi, F., Twyman, J., Winowiecki, L. A., L. Ampaire, E., Acosta, M., & Läderach, P. (2017). Survey data of intra-household decision making and smallholder agricultural production in Northern Uganda and Southern Tanzania. *Data in Brief*, *14*, 302-306. https://doi.org/https://doi.org/10.1016/j.dib.2017.07.040

Ngigi, M. W., Mueller, U., & Birner, R. (2017). Gender Differences in Climate Change Adaptation Strategies and Participation in Group-based Approaches: An Intra-household Analysis From Rural Kenya. *Ecological Economics*, *138*, 99-108. https://doi.org/10.1016/j.ecolecon.2017.03.019

Poudel, S., & Kotani, K. (2013). Climatic impacts on crop yield and its variability in Nepal: do they vary across seasons and altitudes? *Climatic Change*, *116*(2), 327-355. https://doi.org/https://10.1007/s10584-012-0491-8

Quiggin, J. (2008). Uncertainty and Climate Change Policy. *Economic Analysis and Policy*, *38*(2), 203-210. https://doi.org/https://doi.org/10.1016/S0313-5926(08)50017-8

Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V., & Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLoS One*, *14*(5), e0217148. https://doi.org/https://10.1371/journal.pone.0217148

Schiel, C., Glöser-Chahoud, S., & Schultmann, F. (2018). A real option application for emission control measures. *Journal of Business Economics*. https://doi.org/10.1007/s11573-018-0913-9

Schlenker, W., & Roberts, M. J. (2008). Estimating the Impact of Climate Change on Crop Yields: The Importance of Nonlinear Temperature Effects. *National Bureau of Economic Research Working Paper Series*, *No.13799*. http://www.nber.org/papers/w13799

Sims, C., & Finnoff, D. (2016). Opposing Irreversibilities and Tipping Point Uncertainty. *Journal of the Association of Environmental and Resource Economists*, *3*(4), 985-1022. https://doi.org/10.1086/688499

Sullivan-Wiley, K. A., & Short Gianotti, A. G. (2017). Risk Perception in a Multi-Hazard Environment. *World Development*, *97*, 138-152. https://doi.org/10.1016/j.worlddev.2017.04.002

Teklewold, H., & Köhlin, G. (2011). Risk preferences as determinants of soil conservation decisions in Ethiopia. *Journal of Soil and Water Conservation*, *66*(2), 87-96. https://doi.org/10.2489/jswc.66.2.87

Tibesigwa, B., Visser, M., & Turpie, J. (2015). The impact of climate change on net revenue and food adequacy of subsistence farming households in South Africa.

Environment and Development Economics, *20*(3), 327-353. https://doi.org/10.1017/S1355770X14000540

Trigeorgis, L., & Reuer, J. J. (2017). Real options theory in strategic management. *Strategic Management Journal*, *38*(1), 42-63. https://doi.org/https://doi.org/10.1002/smj.2593

UNFCCC. (2015). *The Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Vermeulen, F. (2002). Collective Household Models: Principles and Main Results. *Journal of Economic Surveys*, *16*(4), 533-564. https://doi.org/10.1111/1467-6419.00177

Webster, M., Sokolov, A. P., Reilly, J. M., Forest, C. E., Paltsev, S., Schlosser, A., Wang, C., Kicklighter, D., Sarofim, M., Melillo, J., Prinn, R. G., & Jacoby, H. D. (2012). Analysis of climate policy targets under uncertainty. *Climatic Change*, *112*(3), 569-583. https://doi.org/10.1007/s10584-011-0260-0

Wesseler, J., & Zhao, J. (2019). Real Options and Environmental Policies: The Good, the Bad, and the Ugly. *Annual Review of Resource Economics*, *11*(1), 43-58. https://doi.org/10.1146/annurev-resource-100518-094140

Wossen, T., Berger, T., & Di Falco, S. (2015). Social capital, risk preference and adoption of improved farm land management practices in Ethiopia. *Agricultural Economics*, *46*(1), 81-97. https://doi.org/https://doi.org/10.1111/agec.12142

Zhang, P., Zhang, J., & Chen, M. (2017). Economic impacts of climate change on agriculture: The importance of additional climatic variables other than temperature and precipitation. *Journal of Environmental Economics and Management*, *83*, 8-31. https://doi.org/https://doi.org/10.1016/j.jeem.2016.12.001

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This thesis studies how heterogeneity and uncertainty affect climate policy and agricultural development. Paper I investigates the effects of spouses' perception of climatic risks on household's adoption of climate adaptation. Paper II assesses how the impacts of climate change vary across crops and agroecosystems in Ethiopia. While Paper III provides a review of real-options literature on climate adaptation and mitigation investments, Paper IV illustrates how uncertainty in net returns and establishment costs influence farmers' decision to relocate as an adaptation strategy.

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