Extreme Climate Shock and Locust Infestation Impacts in Ethiopia: Farm-level Agent-based Simulation of Adaptation and Policy Options

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This thesis is dedicated to

My late Mother Tejitu Midheksa and brother Turi Tolemariam

Summary

Extreme climate shocks have been a daunting problem for smallholder farmers in Ethiopia for a decade. In recent years, locust invasions in many parts of the country have become another livelihood challenge to the subsistence farming population who already lives in dire livelihood situations. These two compounding shocks can lead to total crop failure at the early crop development stage or any crop growth stage. They are creating a massive economic upheaval in rainfed-dependent countries particularly affecting the well-being of resource-poor subsistence farmers. To reduce the effect of recurring shocks, especially climate risks, farmers have been implementing different risk management strategies. In addition to farmer autonomous adaptation practices, the government has been supporting farmer climate adaptation efforts by designing different policy interventions. In locust-hit areas, government and non-governmental organizations have designed and implemented different locust relief programs aimed at reducing associated welfare losses. Whether farmers can adapt to the effects of climate shocks or not by autonomous adaptation and/or with policy support is an empirical policy question. Moreover, as there are no studies of locust impacts and locust relief programs evaluation, the degree of locust livelihood devastation and the roles of locust relief policy interventions in minimizing the effect of locust shock are policy concerns.

To address these important and key empirical questions, this thesis applied a farm-level agent-based simulation model. MPMAS, a modeling framework developed at the University of Hohenheim for agent-based simulations, was applied to capture inseparable production and consumption decisions of subsistence farming households in the Central Rift Valley of Ethiopia. The modeling framework uses a whole-farm mathematical programming modeling approach to represent complex dynamics of farm household decisions where a set of constraints and their complex relationships are considered. This simulation model enables scenario-based policy analysis by comparing different climate, locust, and policy scenarios which is hardly possible using statistical and other reduced forms of econometrics models. Through establishing scenarios, the model helps to disentangle the pathways through which external shocks may affect the well-being of smallholder farmers.

MPMAS has been extensively applied for policy simulations in different countries including Ethiopia. This thesis extends previous MPMAS applications in Ethiopia by including new features

for Central Rift Valley (MPMAS_CRV). MPMAS_CRV was parameterized from the CIMMYT household survey augmented with CSA datasets and own field research. Smallholder farmers *ex-ante* considerations of risk management strategies for possible climate shock are explicitly captured in MPMAS_CRV to assess their role in climate adaptation and welfare improvements. As part of enhancing the adaptive capacity of farm households to recurring climate shocks, the effect of policy interventions such as better access to credit services and improved agricultural technology are quantified by establishing climate and policy scenarios. Similarly, the thesis quantified the impact of locust invasions on household welfare outcomes and their response to locust relief interventions including food or cash transfers complemented with inputs and livestock provisions. Locust simulation is one of the novelties of this research as it is the first study to explicitly capture the welfare effects of the desert locust and assess the roles of locust relief programs through the application of MPMAS.

To enable climate and locust shock effects quantification and associated policy interventions, different simulation experiments were designed comprised of climate and locust shock frequencies and policy scenarios. The simulation experiments and analysis were performed using the computational resources of *bwForCluster* within the *bwHPC* infrastructure in the state of Baden-Württemberg, Germany.

Before using MPMAS_CRV for policy simulations, its reliability was validated using land use, livestock holding, and amount of crop sales by comparing simulated against observed survey values. The validation results suggest that MPMAS_CRV can represent and reflect real-world conditions so that it is reliable to use for impact quantification and policy simulations. In addition to empirical validation, the thesis conducted a global uncertainty analysis to check the robustness of the simulation results under different parameter variations and combinations to minimize erroneous policy formulations. Uncertainty analysis results show that the model converges rapidly at 50 repetitions which implies that these model repetitions are enough to cover the model uncertainty space.

In terms of extreme climate impacts and adaptations, the simulation results suggest that climate shocks affect the welfare of agents adversely to the extent that they face temporary food shortages, loss of discretionary income, and depletion of livestock assets. The welfare losses are similar for both with and without *ex-ante* measure scenarios which indicates that farm agents cannot adapt to extreme shocks by employing autonomous adaptations. After the shocks are over, the simulation results reveal that agents cannot recover income and livestock losses immediately even when they consider *ex-ante* measures in the planning for possible risks. This suggests that for resource-poor farm agents, income and assets recovery takes a longer period after perturbation which can lead to a long-term livelihood crisis and a poverty trap. But, according to the simulation results in this thesis, agents can recover from food shortage immediately after the shocks are over, as meeting minimum food requirements are an absolute priority for agents (which is also true with real-world subsistence smallholder farmers) over other competing goals.

Credit and technology policy simulation analysis further depict that welfare losses are partly compensated compared to without policies. Welfare losses of agents are better compensated when credit and technology are used jointly than when they are implemented separately. Similarly, technology policy intervention is better in compensating welfare losses compared to credit policy. Though policy interventions have compensational effects in minimizing the losses, they cannot completely offset the negative effects of extreme climate shocks even when implemented jointly. Disaggregation of simulation results by resource endowments suggests that agents with higher baseline income (without policy) and farm size appeared to be relatively less affected by shocks, and benefit from policy interventions the most.

Locust simulation results also suggest that locust shock leads to agent livelihood crisis and makes slower recovery of income and livestock assets rebuild without any relief intervention programs. Simulation of different locust relief policy interventions reveals that combined relief policy interventions appear to be superior in compensating welfare losses compared to individual relief interventions. When food or cash transfer is combined with inputs and assets the welfare losses are considerably reduced compared to the individual policy intervention. When asset recuperation is combined with other relief programs, livestock losses are substantially reduced which signifies the importance of asset support in building an asset base which has long-term benefits. Strengthening early warning systems by including seasonal weather forecasting has paramount importance to prevent the crisis of desert locust plague.

Zusammenfassung

Extreme Klimaschocks sind für Kleinbauern in Äthiopien seit einem Jahrzehnt ein beängstigendes Problem. In den letzten Jahren sind Heuschreckeninvasionen in vielen Teilen des Landes zu einer weiteren Herausforderung für die Existenzgrundlage der ohnehin schon unter schwierigen Bedingungen lebenden Subsistenzbauern geworden. Diese beiden sich gegenseitig verstärkenden Schocks können zu totalen Ernteausfällen in der frühen Entwicklungsphase der Ernte oder in jeder Wachstumsphase führen. Sie führen zu massiven wirtschaftlichen Umwälzungen in Ländern, die vom Regen abhängig sind, und beeinträchtigen insbesondere das Wohlergehen der ressourcenarmen Subsistenzbauern. Um die Auswirkungen wiederkehrender Schocks, insbesondere von Klimarisiken, zu verringern, haben die Landwirte verschiedene Risikomanagementstrategien eingeführt. Zusätzlich zu den autonomen Anpassungspraktiken der Landwirte hat die Regierung die Bemühungen der Landwirte zur Klimaanpassung durch verschiedene politische Maßnahmen unterstützt. In Gebieten, die von Heuschrecken heimgesucht wurden, haben Regierung und Nichtregierungsorganisationen verschiedene Programme zur Bekämpfung der Heuschrecken entwickelt und umgesetzt, um die damit verbundenen Wohlfahrtsverluste zu verringern. Ob sich Landwirte durch autonome Anpassung und/oder mit politischer Unterstützung an die Auswirkungen von Klimaschocks anpassen können oder nicht, ist eine empirische politische Frage. Da es keine Studien über die Auswirkungen von Heuschrecken und die Bewertung von Heuschreckenhilfsprogrammen gibt, sind das Ausmaß der Zerstörung der Lebensgrundlagen durch Heuschrecken und die Rolle der Heuschreckenhilfsmaßnahmen bei der Minimierung der Auswirkungen des Heuschreckenschocks von politischem Interesse.

Um diese wichtigen und zentralen empirischen Fragen zu beantworten, wurde in dieser Arbeit ein agentenbasiertes Simulationsmodell auf Betriebsebene eingesetzt. MPMAS, ein an der Universität Hohenheim entwickelter Modellierungsrahmen für agentenbasierte Simulationen, wurde angewandt, um die untrennbaren Produktions- und Verbrauchsentscheidungen von Subsistenzbauernhaushalten im zentralen Rift Valley in Äthiopien zu erfassen. Der Modellierungsrahmen verwendet einen mathematischen Programmierungsansatz für den gesamten Betrieb, um die komplexe Dynamik der Entscheidungen der bäuerlichen Haushalte darzustellen, wobei eine Reihe von Beschränkungen und deren komplexe Beziehungen berücksichtigt werden. Dieses Simulationsmodell ermöglicht eine szenariobasierte Politikanalyse durch den Vergleich

verschiedener Klima-, Heuschrecken- und Politikszenarien, was mit statistischen und anderen reduzierten Formen ökonometrischer Modelle kaum möglich ist. Durch die Erstellung von Szenarien hilft das Modell, die Wege zu entschlüsseln, über die sich externe Schocks auf das Wohlergehen von Kleinbauern auswirken können.

MPMAS wurde in verschiedenen Ländern, darunter auch in Äthiopien, ausgiebig für Politiksimulationen eingesetzt. Diese Arbeit erweitert frühere MPMAS-Anwendungen in Äthiopien durch neue Funktionen für das zentrale Rift Valley (MPMAS_CRV). MPMAS_CRV wurde anhand der CIMMYT-Haushaltsbefragung parametrisiert und mit CSA-Datensätzen und eigener Feldforschung ergänzt. Ex-ante-Überlegungen von Kleinbauern zu Risikomanagementstrategien für mögliche Klimaschocks werden in MPMAS_CRV explizit erfasst, um ihre Rolle bei der Klimaanpassung und der Verbesserung des Wohlstands zu bewerten. Um die Anpassungsfähigkeit der landwirtschaftlichen Haushalte an wiederkehrende Klimaschocks zu verbessern, werden die Auswirkungen politischer Maßnahmen, wie z. B. ein besserer Zugang zu Krediten und verbesserter landwirtschaftlicher Technologie, durch die Erstellung von Klima- und Politikszenarien quantifiziert. In ähnlicher Weise wurden in dieser Arbeit die Auswirkungen von Heuschreckeninvasionen auf das Wohlergehen der Haushalte und ihre Reaktion auf Heuschreckenhilfsmaßnahmen wie Nahrungsmittel- oder Geldtransfers, ergänzt durch Betriebsmittel und Viehhaltung, quantifiziert. Die Heuschrecken-Simulation ist eine der Neuerungen dieser Studie, da sie die erste ist, die explizit die Auswirkungen der Wüstenheuschrecken auf das Wohlergehen der Haushalte erfasst und die Rolle von Heuschrecken-Hilfsprogrammen durch die Anwendung von MPMAS bewertet.

Um die Auswirkungen von Klima- und Heuschreckenschocks zu quantifizieren und damit verbundene politische Interventionen zu ermöglichen, wurden verschiedene Simulationsexperimente entworfen, die Klima- und Heuschreckenschockhäufigkeiten und politische Szenarien umfassen. Die Simulationsexperimente und Analysen wurden mit den Rechenressourcen des bwForCluster innerhalb der bwHPC-Infrastruktur des Landes Baden-Württemberg durchgeführt.

Vor der Verwendung von MPMAS_CRV für Politiksimulationen wurde seine Zuverlässigkeit anhand der Landnutzung, des Viehbestands und des Umfangs der Ernteverkäufe durch Vergleich der simulierten mit den beobachteten Erhebungswerten validiert. Die Validierungsergebnisse deuten darauf hin, dass MPMAS_CRV reale Bedingungen darstellen und widerspiegeln kann, so dass es zuverlässig für die Quantifizierung von Auswirkungen und für Politiksimulationen verwendet werden kann. Zusätzlich zur empirischen Validierung wurde in dieser Arbeit eine globale Unsicherheitsanalyse durchgeführt, um die Robustheit der Simulationsergebnisse unter verschiedenen Parametervariationen und -kombinationen zu überprüfen und fehlerhafte Politikformulierungen zu minimieren. Die Ergebnisse der Unsicherheitsanalyse zeigen, dass das Modell bei 50 Wiederholungen schnell konvergiert, was bedeutet, dass diese Modellwiederholungen ausreichen, um den Raum der Modellunsicherheit abzudecken.

In Bezug auf extreme Klimaauswirkungen und Anpassungen deuten die Simulationsergebnisse darauf hin, dass Klimaschocks das Wohlergehen der Landwirte insofern beeinträchtigen, als sie mit vorübergehender Nahrungsmittelknappheit, dem Verlust von verfügbarem Einkommen und der Erschöpfung des Viehbestands konfrontiert sind. Die Wohlfahrtsverluste sind sowohl für Szenarien mit als auch ohne Ex-ante-Maßnahmen ähnlich, was darauf hindeutet, dass sich die landwirtschaftlichen Akteure nicht durch autonome Anpassungen an extreme Schocks anpassen können. Nach den Schocks zeigen die Simulationsergebnisse, dass die Landwirte die Einkommens- und Viehbestandsverluste nicht sofort ausgleichen können, selbst wenn sie bei der Planung möglicher Risiken Ex-ante-Maßnahmen berücksichtigen. Dies deutet darauf hin, dass es bei ressourcenarmen Landwirten länger dauert, bis sich Einkommen und Vermögen nach einer Störung erholen, was zu einer langfristigen Existenzkrise und einer Armutsfalle führen kann. Den Simulationsergebnissen in dieser Arbeit zufolge können sich die Agenten jedoch unmittelbar nach dem Ende der Schocks von der Nahrungsmittelknappheit erholen, da die Deckung des Mindestbedarfs an Nahrungsmitteln für die Agenten absolute Priorität vor anderen konkurrierenden Zielen hat (was auch für Subsistenz-Kleinbauern in der realen Welt gilt).

Die Simulationsanalyse der Kredit- und Technologiepolitik zeigt außerdem, dass Wohlfahrtsverluste im Vergleich zu einer Politik ohne sie teilweise kompensiert werden. Die Wohlfahrtsverluste der Akteure werden besser ausgeglichen, wenn Kredit und Technologie gemeinsam eingesetzt werden, als wenn sie getrennt eingesetzt werden. In ähnlicher Weise kompensiert die Technologiepolitik Wohlfahrtsverluste besser als die Kreditpolitik. Obwohl politische Interventionen kompensatorische Effekte haben, indem sie die Verluste minimieren, können sie die negativen Auswirkungen extremer Klimaschocks nicht vollständig ausgleichen, selbst wenn sie gemeinsam eingesetzt werden. Eine Disaggregation der Simulationsergebnisse nach Ressourcenausstattung legt nahe, dass Agenten mit einem höheren Grundeinkommen (ohne Politik) und einer höheren Betriebsgröße relativ weniger von Schocks betroffen zu sein scheinen und am meisten von politischen Maßnahmen profitieren.

Die Ergebnisse der Heuschrecken-Simulationen deuten auch darauf hin, dass der Heuschreckenschock zu einer Existenzkrise führt und eine langsamere Erholung des Einkommens und des Viehbestands ohne jegliche Hilfsprogramme bewirkt. Die Simulation verschiedener Heuschreckenhilfsmaßnahmen zeigt, dass kombinierte Hilfsmaßnahmen im Vergleich zu einzelnen Hilfsmaßnahmen die Wohlfahrtsverluste besser auszugleichen scheinen. Wenn Nahrungsmittel- oder Geldtransfers mit Betriebsmitteln und Vermögenswerten kombiniert werden, sind die Wohlfahrtsverluste im Vergleich zu den einzelnen Maßnahmen erheblich geringer. Wenn die Rückgewinnung von Vermögenswerten mit anderen Hilfsprogrammen kombiniert wird, werden die Verluste beim Viehbestand erheblich reduziert, was auf die Bedeutung der Unterstützung von Vermögenswerten für den Aufbau einer Vermögensbasis hinweist, die langfristig von Nutzen ist. Die Stärkung der Frühwarnsysteme durch Einbeziehung saisonaler Wettervorhersagen ist von größter Bedeutung, um die Krise der Wüstenheuschreckenplage zu verhindern.

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List of acronyms

ABM	Agent-based Model
CIMMYT	Centro Internacional de Mejoramiento de Maíz y Trigo
CRV	Central Rift Valley
CGIAR	Consultative Group for International Agricultural Research
CRGE	Climate Resilient Green Economy strategy of Ethiopia
CSA	Central Statistical Agency
DTMA	Drought Tolerant Maize for Africa
ERHS	Ethiopian Rural Household Survey
FAO	Food and Agriculture Organization
FGD	Focus Group Discussion
GDP	Gross Domestic Product
ICARDA	International Center for Agricultural Research in the Dry Areas
IPCC	Intergovernmental Panel on Climate Change
MFIs	Micro-finance Institutions
MNL	Multinomial Logit
MPMAS	Mathematical Programming-based Multi-Agent Systems
NAPA	National Adaptation Program of Action
SCC	Share of Correctly Classified
SIMLESA	Sustainable Intensification for Maize-Legume Cropping Systems for Food Security in Eastern and Southern Africa
SSA	Sub-Saharan Africa
TLU	Tropical Livestock Unit
UA	Uncertainty Analysis
UN	United Nations
USDA	United States Department of Agriculture

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Chapter 1: General background

Over the past years, Ethiopia has been facing various compounding crises. Extreme climate risks and the recent desert locust outbreak are the two major external factors threatening household welfare status. Climate variability and change negatively affect the welfare of smallholder households by negatively affecting production and productivity, livestock endowments, and other income-earning opportunities. This is mainly due to heavy reliance of their livelihood on agricultural production which is rainfed with limited irrigation practices (Di Falco et al., 2012). Increased climatic variations induce recurrent extreme climate events like drought risk which have adverse effects on agricultural production and subsequently affect smallholder farmers welfare and assets.

Apart from climate variability-induced shocks, the recent desert locust upsurge in the country has become an additional challenge that has brought up a livelihood crisis, which makes subsistence and smallholder farmers dominated agriculture more even vulnerable and exacerbates the already dire food security conditions. Though locust outbreak is not new to Ethiopia, the country has experienced the worst invasions in over 25 years in recent years (FAO, 2020a). The first wave of severe and recurrent locust invasions started in 2019. It's believed that climate change is partly responsible for the desert locust outbreak and widespread. Salih et al. (2020) argue that increased temperature and rainfall over the lowland areas of Red Sea coastlines and strong winds make conducive conditions for desert locust breeding and widespread not only in Ethiopia but also in other horn African countries.

1.1. Linkage between economic performance and extreme shocks in Ethiopia

Sub-Saharan African countries face many challenges that increase their vulnerability to economic shocks mainly arising from external drivers (Lewis, 2017; Thomas and Zuberi, 2012). Because of relatively better policies to boost major economic drivers like agriculture in recent periods, many SSA countries, including Ethiopia, have shown significant economic progress in terms of GDP growth.

A study by Ketema and Diriba (2021) shows that in Ethiopia between 2010 and 2019, real GDP growth and real GDP per capita growth averaged 9.27% and 6.54%, respectively compared to the 2000-2009 period which stands at 7.51% and 4.7%. According to NBE (2020) report between 2016 and 2020 the country registered an average economic growth rate of 8.2% per year, which was considered one of the fastest-growing economies in the region. Decomposing economic growth into sectoral contributions, recently agriculture has become the second most important sector contributor to economic growth next to the service sector. The agriculture sector used to lead the economic growth of the country until 2015 which has been overtaken by the service sector (Ketema and Diriba, 2021). In the year 2000, the share of the agricultural sector to GDP was 54% while the service sector contributed 35% with the industrial sector share of only 11%. In 2019/20, the service sector contribution increased to 40% of GDP while the agricultural sector contribution declined to about 33% (NBE, 2020). The share of the fast-growing industrial sector was 27% (Ketema and Diriba, 2021). By further decomposing the agriculture sector into its components the share of crop production to agricultural GDP was 65% on average followed by livestock farming which was 26% (NBE, 2020).

It is evidenced that the remarkable economic progress due to continuous economic policy reforms over the past 20 years contributed to reduced poverty rates and improved food security. During the period 2010/2011–2015/2016, the proportion of the population living below the national poverty line decreased by 6 percentage points - from 30% in 2011 to 24% (World Bank Group, 2020). The same report shows that between 2004/05 and 2015/16 the country saw a 7 percentage points decline in the extreme poverty rate, confirming a virtuous trend since the early 2000s mainly due to positive contributions from progressive economic policy reforms. Despite this impressive economic growth and poverty rate reductions, the country is still one of the world's poorest countries with a per capita income of $850 (World Bank Group, 2020). One important issue in this regard due to low level of the manufacturing industry and the dependence of agriculture on rainfall conditions.

The agricultural sector in Ethiopia is characterized by subsistence farming heavily reliant on rain-fed systems with irrigation agriculture covering only 1% of its cultivated areas (Di Falco et al., 2012). Smallholder households cultivate on average less than a hectare of land and are endowed with limited resources or assets that undermine viable investment options (Di Falco et al., 2011; Giller, 2020; Ouedraogo et al., 2006). The share of agricultural outputs produced by smallholder farmers in Ethiopia is about 95% out of which 75–80% of the annual output is consumed at the household level (World Bank, 2006). Part of the harvest is also sold to meet their immediate cash consumption requirements.

Low resource endowments to smallholder farmers and the reliance of the agricultural sector on rainfall amount and distribution determine the contribution of the agriculture sector to the national economy (World Bank, 2006). The share of the agricultural sector to national income is largely determined by the amount and distribution of rainfall. Erratic rainfall during the crop growing stages causes yield variability and crop yield production uncertainties (Kassie et al., 2014b). Rainfall-dependent agricultural production increases the exposure of subsistence farm households to the negative effect of shocks as there are low or non-existence agricultural insurance schemes in Ethiopia that further increase their vulnerability (Gebrehiwot and van der Veen, 2020). Rapid population growth and the recent desert locust invasion are other factors threatening the performance sector and hence household welfare.

1.2. Rapid population growth, climate shocks and household food security

Persistent and prevalent extreme poverty rates are the main causes of food security and malnutrition. Under different scenarios, it is projected that in 2030, the extreme poverty rate and prevalence of undernourishment in SSA would still be greater and show slight reductions (Molotoks et al., 2021; World Bank Group, 2018). Consequently, SDG1's target goal of zero hunger – to end hunger and ensure food access by all people by 2030 will probably not be achieved (FAO, IFAD, UNICEF, 2020). Like many other African countries, smallholder farm households in Ethiopia face various production and market-related risks which are often interlinked with their food security status.

Food security, which is a key dimension of poverty, can result from multiple factors that can be generalized under food supply and consumption categories (Moreland and Smith, 2013). These factors are determinants of food demand and supply which involve increased food prices, access to limited resources to produce and buy necessary food requirements, inadequate food distributions due to remoteness and lack of road networks, policy-related interventions such as land use policy, climate change-induced shocks, and rapid population growth (Lewis, 2017; Molotoks et al., 2021;

Moreland and Smith, 2013; Thomas and Zuberi, 2012). Among many of these, two of them - high population growth rate, and climate change are arguably the main drivers of food security, poverty prevalence and malnutrition. These drivers are very prominent in poorer countries like Ethiopia where social services like access to health care are limited and farm households have low adaptation capacity to withstand the effects of changing climate. In addition to the commonly known factors, in recent years, desert locust upsurge has become an important driver of food security in most countries in the horn of Africa including Ethiopia.

Ethiopia is among the populous countries with the highest population growth rates. UN (2019) report shows that the total population of the country is projected to be over 112 million with an annual growth rate of 2.6%. Among the age structures of the population, the share of the population between 25 and 64 years of age was 35 % which is the highest of all age groups. Similarly, evidence from the UN (2019) report shows that the total population of SSA was 1.07 billion in 2019. This size is close to the combined population size of Europe and the Northern American continents, which was 1.11 billion. Likewise, the future total population size projection (2020 – 2100) shows that the SSA population will be fourfold while the population of Europe and North America will remain the same (UN, 2019).

Increased current and projected population size and growth rates can result in farmland fragmentation and environmental degradation in poorer countries like Ethiopia (Giller, 2020; Shiferaw et al., 2014b). In Ethiopia land has been highly fragmented due to rapid population growth. The land fragmentation is expected to continue mediated by increased population growth rate which further leads to the cultivation of marginal and sloping areas which have never been suitable for crop production. Given lack of technological innovations that can potentially boost food production, pervasive macroeconomic problems such as lack of employment opportunities and weak resource bases, population growth will continue to aggravate the existing farmland fragmentation which leads to environmental damage and poses a significant challenge to meeting food and nutrition security (Giller, 2020; Molotoks et al., 2021; Shiferaw et al., 2014b).

In addition to the increased human population, climate-induced shocks such as extreme drought and crop disease risks caused by global warming have continued to threaten smallholder welfare by affecting food production and thereby income, food, and nutrition security, and overall livelihood

(Lewis, 2017; Shiferaw et al., 2014b). In moisture stress areas of Ethiopia and similar countries in SSA, climate-induced shocks are responsible for yield reduction and yield variability (Kassie et al., 2014a; Tadesse et al., 2019). This is mainly due to long dry spells during the sensitive crop growth stage, the late start of the rain, and early rainfall cessation through which climate variability manifest itself. Severe and recurring shocks can damage crop yield in the range of 61-100 %, depending on the crop varieties grown (Mideksa et al., 2018). Given the low, stagnant agricultural productivity and low profitability of many crops under smallholder crop management practices, climate-related risks are worsening the livelihood crisis (Giller, 2020).

The production-related effects of climate shocks lead to rising in food prices due to aggregate supply shortages. Many scholars argue that climate change and variability alter food prices indirectly by affecting food production and aggravating food supply (Berger et al., 2017; Carauta et al., 2021a; Hertel et al., 2010; Wossen et al., 2017b, 2014; Wossen and Berger, 2015). When food crop prices raises in the local markets, it would be difficult for low-income farmers to afford which further increases their vulnerability to climate-induced price shocks.

Extreme climate-induced shocks are also responsible for the loss of household livestock endowments. Livestock rearing is part of the mixed production systems for subsistence farmers in Ethiopia. To counter the adverse effect of recurring climate-induced events on food production, farmers usually sell livestock assets for consumption smoothing which gradually depletes their asset bases that are accumulated over years. They are forced to sell livestock often at lower prices due to poor livestock physical conditions as climate variability also affects livestock feed and water availability.

The overall production and subsequent prices and asset effects of extreme climate shocks have negative repercussions on household food security status, asset accumulation, and income (Berger et al., 2017; Di Falco, 2014; Mahoo et al., 2013; Wossen et al., 2014). When it occurs over extended periods, the recovery period elongates and is expected to inflict greater damage to household well-being (Smithers and Smit, 1997).

The future climate projections for Ethiopia show that the mean annual temperature will increase in the range of 0.9 -1.1 °C by 2030 in the range of 1.7-2.1 °C by 2050 and in the range of 2.7-3.4 °C by 2080 under mid-range scenario compared to 1991-1990 as the baseline scenario (Zerga and Gebeyehu, 2016). This projection is expected to pose a sustained threat to the overall economy of the country, particularly to the agricultural sector which will continue to be affected severely unless effective climate adaptation and mitigation measures are in place. Similarly in SSA, compared to the current emissions trajectory (i.e. RCP 8.5), future climate projection is expected to be higher in the region than in other places, with a temperature increase of 1.7 °C by the 2030s, 2.7 °C by the 2050s, and 4.5 °C by the 2080s (Girvetz et al., 2019). Climate models show that climate change will continue to adversely affect crop yields in the future (Molotoks et al., 2021). For example, maize crop yield is projected to decrease up to 35 percent by 2030 due to climate change and variability in most SSA (Bailey, 2011). Regions and countries which are already suffering from low agricultural productivity, little investment, and limited ability to cope and adapt to future shocks could have consequential harmful effects on food security and poverty levels (Wossen et al., 2015).

1.3. Risk exposure, climate adaptation and farm heterogeneity

Climate variability and change manifest themselves through variations of temperature and precipitation both in the short-run and long-run and increased frequencies of extreme climate events such as drought, disease outbreak, and floods (Kassie et al., 2013; Zerga and Gebeyehu, 2016). Over several years in Ethiopia, rainfall and temperature trends exhibit significant variations in different regions which increases the vulnerability of smallholder farmers (NMA, 2001). Vulnerability is also exacerbated by low resource endowments which limit the adaptation capacity of farm households. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system or community is exposed, sensitive, and capacity to adapt to the climate crisis (IPCC, 2007). The study by Maplecroft (2015) shows that Ethiopia is among the ten most at-risk countries out of the 193 rated by their climate change vulnerability and climate change index. Among vulnerability factors, low adaptive responses to climate change and variability are largely responsible for greater climate risk vulnerability.

Climate adaptation is defined as "*the actions of adjusting practices, processes, and capital in response to the actuality or threat of climate change as well as changes in the decision environment, such as social and institutional structures, and altered technical options that can affect the potential or capacity for these actions to be realized*" (IPCC, 2007). It is a non-stop process that is part of risk management measures[1], forward-looking, and directed toward long-term livelihood security (Asfaw et al., 2018; Gebrehiwot et al., 2021; Howden et al., 2007).

Climate adaptation is believed to minimize the harmful effects of climate shocks and hence reduce household vulnerability. Adaptation to climate change and variability is important to protect the livelihood and build the resilience of resource-poor households against risk exposures. It can significantly reduce the risk exposure of farm households to the current and anticipated climate risks by making adjustments to farm practices which potentially minimize the damage and livelihood crisis when shock actually occurs (Asfaw et al., 2018; Bryan et al., 2009). By implementing adaptation strategies at production decisions (usually at the outset of the season), households can better prepare for possible future climate shocks to avoid or minimize exposure to risks (Asfaw et al., 2018).

There have been contentious debates among scholars on whether resource-poor farm households sufficiently respond to short-term climate variability or long-term climate changes by implementing adaptation options to reduce their vulnerability to the adverse effects of climate risks. Some scholars (Cooper et al., 2008; Dercon, 2002; Howden et al., 2007; Kassie et al., 2014b; Shiferaw et al., 2014a) argue that current adaptation decisions or coping measures to short-term climate variability can facilitate adaptation to long-term climate change. A study by Bryan et al.(2009) in Ethiopia and South Africa found that farmer decisions regarding farming system adjustment to perceived climate variability were not merely based on long-term climate change. This implies that subsistence farmers employ different combinations of risk management options to reduce the effects of climate risks in the short run which might also help to reduce the long-term effects of climate impacts through capital/assets accumulation or through shortening the recovery periods after the occurrence of the shocks. Other scholars argue that short-term adaptive responses can further increase farmer vulnerability to long-term and recurrent climate changes as it deteriorates the asset base and depletes resources (Smithers and Smit, 1997).

Based on past and current experiences, and future anticipations of climate shocks, smallholder farmers usually make certain adjustments in their choice of production, consumption, and technology decisions (Cooper et al., 2008). The adjustments are risk management options to counter

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[1] In this thesis risk management strategies encompass both *ex-ante* adaptation and *ex-post* coping measures. Hence risk management strategies is used interchangeably for both *ex-ante* adaptation and *ex-post* coping measures

current and anticipated climate risks. These farm-level risk management strategies can be broadly categorized as *ex-ante* and *ex-post* coping measures to minimize the effect of anticipated and current climate shocks respectively. Cooper et al. (2008) further identified additional categories by including in-season adjustment of cropping activities and management options in response to climate shocks when they often evolve. Such adaptation options could consist of switching to new crop varieties from varieties that were originally planned to grow.

As *ex-ante* measures, farm household often adjusts farm production practices to minimize possible adverse outcomes of climate shocks. These measures are meant to mitigate the adverse effects of possible shocks that could undermine the positive opportunities they can gain in average or normal years (Cooper et al., 2008). By operating in a safer mode, smallholder farmers usually try to minimize anticipated risks (Pandey and Bhandari, 2009). The measures can also include the choice of different production options with low returns but potentially reduce household risk exposure. Given the multiple goals of smallholder farmers including possible risk reductions and complex constraints in which they operate these kinds of choices could be optimal. Choices of production options in the face of climate risks can compromise income gains as the yield from such options could be lower than high-yielding activities prone to shocks (Shiferaw et al., 2014b). However, in the face of actual shocks, such choices can reduce income fluctuations (Pandey and Bhandari, 2009).

Some of the most common *ex-ante* climate risk management strategies of smallholder farmers in Ethiopia and in most SSA countries include the choice of drought/tolerant varieties, switching planting dates, adjustment of farm-level crop management, early planting using the first raindrops, switching crop species, *in-situ* farmland management including soil and water management, taking out short term production credit, livelihood diversification (like mixed crop-livestock farming), changing cropping pattern like double or inter-cropping (Bryan et al., 2009; Cooper et al., 2008; Deaton, 1991; Fisher et al., 2015; Gebreegziabher et al., 2020; Gebrehiwot and Van Der Veen, 2013).

Farmers also respond to existing climate shocks through various *ex-post* coping measures which help them to reduce livelihood vulnerability. These measures include reducing meal consumption (both frequency and portion), selling productive assets like livestock, buying food from the market, engaging in off-farm employment opportunities, borrowing, and seeking aid (Cooper et al., 2008; Pandey et al., 2007).

Whether farm households implement a set (s) of adaptation measures or not to sufficiently withstand and offset the adverse effects of climate shocks entirely depends on many conditions. Farm households choices of *ex-ante* or *ex-post* coping measures both in the short and long run substantially differ due to differences in biophysical resources, crop management, agroecology, and farm-level socioeconomic factors (Lobell et al., 2008; Schreinemachers and Berger, 2011). These factors determine the types of adaptation option(s) a given farm household implements to minimize climate risk. In Ethiopia, there is considerable heterogeneity in agroecology and farming systems even in smaller administrative units like *kebeles*[2] (Di Falco et al., 2012) which contributes to differences in the use of adaptation options. Farming systems diversity reflects differences in climate, soil, altitude, land use type, and resource bases (Giller, 2020). In a single location, there could be a huge diversity in household food security and welfare status due to farm household heterogeneity in terms of resource endowments, consumption preferences, innovativeness, access to technological options, and communications networks (Giller, 2020; Schreinemachers and Berger, 2011; Tulman, 2014).

1.4. Desert locust invasions and household welfare

In recent years, smallholder farmers in Ethiopia have been facing additional compounding external factors - locust invasions on top of recurring climate shocks. It has become an important shock event which devastates the livelihood of many smallholder farmers in the Horn of African countries. Though desert locust occurrence is not uncommon in Ethiopia the recent outbreak has been recurring and very intense in terms of its devastation. It is believed that climate change is partly responsible for the desert locust outbreak and widespread. Salih et al. (2020) indicate that increases in temperature and rainfall over the lowland areas of Red Sea coastlines and strong winds make conducive conditions for locust breeding and widespread not only in Ethiopia but also in other horn African countries.

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[2] It’s the lowest administrative unit in Ethiopia

Locust swarm has caused devastation to crop production and livestock pasture resources which further threatens the livelihood of smallholder farmers who don’t have little or no options to counteract such extreme shock events. Locust invasions have been immense when crops get mature and ready for harvest, which exacerbates crop damage levels. Locust occurrence has posed unprecedented challenges to the already alarming livelihood and food security situations by causing damage to crops and pasture. FAO (2020a) report shows that in 2020 alone, over 200,000 hectares of cropland were devastated in Ethiopia despite government and international organizations efforts to curb locust widespread through surveillance and aerial spraying. UN March 2021 report even takes the crop damage level close to 365,015 hectares of cropland across multiple regions in the country (UN,2021)[3].

Whenever locust outbreak overlaps with extreme climate shock events, they become compounding and increase the vulnerability of farm households. This shock further negatively affects household welfare conditions that already live in precarious situations. To cope with the negative welfare effects of this shock, households might be forced to look for remittances from their family elsewhere and opt for migration in search of earning additional income to buy food for the family. However, this kind of shock could affect a wide range of geographical areas as the locust swarm moves fast and in masses. When it covers a wide range it becomes a covariate risk which makes the entire risk-sharing network ineffective as there is no one in the community to be better off to help others (Wossen et al., 2016). Government and non-governmental organizations also provide humanitarian support in the form of locust relief programs for locust-affected households as a response to minimizing the adverse effects.

The two compounding external factors –climate shocks and locust invasions have the potential to significantly hamper the economic performance of Ethiopia and negatively affect the livelihood of smallholder farmers who entirely depend on agricultural production for food consumption and income earnings. The livelihood crisis from two compounding shocks is also being exacerbated by the COVID-19 pandemic, which is creating massive economic upheaval in the country. A study by Beyene et al. (2020) in Ethiopia shows that due to COVID-pandemic, losses of household welfare at the national level would be 1.9% and 10.7% in the mild and severe scenarios compared to the no-COVID-19 conditions respectively.

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[3] *https://dailypost.ng/2021/03/06/ethiopia-un-raises-concern-over-desert-locust-invasion/*

1.5. Role of credit and technology policies in reducing climate risk effects

Besides farmer autonomous adaptation strategies, planned adaptations through government support are also common in Ethiopia and elsewhere in developing countries to improve farm household resilience against extreme climate shocks. Policy interventions aim to reduce smallholder farm households vulnerability to the impacts of climate shocks by building their adaptive capacity and resilience. Among policy interventions, improving credit and technology access has been emphasized in the National Adaptation Program of Action (NAPA) which has been adopted by the government of Ethiopia. The purpose of the program was to support farmer climate adaptation endeavors to address climate change effects by focusing on the sectors that are most vulnerable to the impacts of climate change such as agriculture. By building on NAPA's experiences, the government has initiated the Climate-Resilient Green Economic (CRGE) initiative to protect the country from the adverse effects of climate change and variability. It also aims at building green economy that helps to realize the country’s ambition of the country to reach middle-income status before 2025.

1.5.1. Role of credit service in reducing climate crisis

Lack of access to adequate rural finance is one of the key challenges for poor farm households in Ethiopia. Limited access to adequate credit hampers economic progress by slowing the investments meant to boost agricultural production. In Ethiopia where the capital shortage is pervasive and agricultural production dominates the livelihood options, access to credit plays a crucial role in reducing poverty. Better access to credit services can unleash liquidity constraints and enhance new technology adoption and can potentially build the resilience of subsistence smallholder farmers who usually have meager resources (Asfaw and Lipper, 2016; Di Falco et al., 2011, 2007).

Use of climate adaptation strategies, like the use of new technologies, often involves additional cash that has to be covered by smallholder farmers. But they often don’t have sufficient cash to cover the cost of adaptation strategies that include improved technologies. Use of improved technology in turn can reduce the vulnerability of subsistence farm households to recurring climate risks and increases the resilience of agricultural production to extreme effects of climate shocks, thereby contributing to long-term food security and better farm income (Tulman, 2014). In the absence of credit access, it would largely difficult for smallholder farmers to afford new technologies even if they know their economic benefits.

Despite its importance in reducing livelihood crises by increasing farm household resilience, smallholder farmers in Ethiopia face acute access to credit market. One fundamental problem in accessing credit to smallholder farmers is supply-side constraints. Smallholder farmers access to credit is affected mainly by market imperfections, including lack of credit facilities (Gurmessa, 2017; Holden and Shiferaw, 2004). Conventional formal financial institutions like commercial banks are often located in urban centers and prefer to serve clients with significant loan demand and possess reliable collateral security like immovable property. Smallholder farmers are perceived as those who don't have the required collateral assets for extending the loan funds. Moreover, they usually engage in agricultural production, which is vulnerable to climate-related risks. Smallholder agriculture reliant on rainfall often faces unexpected climate-related shocks like unreliable rainfall distribution and amount which subsequently lower their income and threaten loan repayment capacity. This makes them to be considered as high-risk borrowers which involve high default risk. Due to this, conventional banks prefer to allocate the loan funds to less risky ventures with some big commercial agriculture which discriminate or exclude smallholder farmers from accessing credit schemes (Gurmessa, 2017; Mukasa et al., 2017). The other critical problem for smallholder farmers in accessing credit is high transaction costs. Farmers usually live dispersedly in rural centers where financial institutions are rarely available. Distance from the financial institutions usually makes high transaction costs associated with poor infrastructures making the disbursement, monitoring, and collection cumbersome. Besides this, communication and transportation infrastructures are extremely poor in these centers making accessing credit costly.

Households access to credit facilities doesn’t necessarily ensure their utilization. They can access credit from any sources if they can borrow from a particular source. They may choose not to borrow even if there is access to loans due to various reasons related to credit demand. The availability of credit sources largely influences the credit demand of farmers, amount of interest rate, credit limits, expected rate of return, and farm characteristics. Even if credit supply like the credit facilities is ensured, there could be low participation in the credit market by some smallholder farmers due to fear of high risk of losing collateral security associated with the inability to repay loans (Mukasa et al., 2017). Moreover, farm households may have limited awareness and experience on loan availability from lenders how to use loan funds, loan access criteria, and modalities due to a lack of training and education which leads to information asymmetry.

Micro-finance institutions (MFIs) in Ethiopia were established in 1996 to fill smallholder farmers credit demand by alleviating conventional bank bureaucracies and systematic exclusionary policy (Zwedu, 2014). The expansion of MFIs across the country has helped to reach out a considerable rural population which was not possible through formal financial institutions. The primary purpose of establishing MFIs was to improve credit availability and outreach to poor farmers in rural areas thereby contributing to poverty reduction and improving food security. Since then, the coverage and client membership of MFIs are growing though still many poor people are not served as intended. Ejigu (2009) reveals that MFIs in Ethiopia have been serving only a small proportion of the potential demand of the rural people. MFIs provide short-term credit mainly for farm inputs purchase for less than 12 months. Some of the bottlenecks that contribute to not fulfilling households credit demand are the availability of limited loan capital, extensive default at times of crisis, and limited institutional capacity. Besides this, similar to conventional banks, MFIs are often located mainly in urban centers, making them inaccessible to many smallholder farmers. Borrowers who are well-informed and live close to MFIs are highly likely to access the loans than those who live in remote areas.

The other issue for low outreach of MFIs is related to lending approaches. MFIs, often use a group lending approach as collateral security to extend credit services. This is meant to avoid fixed assets requirements for collateral security by the banks. Every group member is responsible when one of them cannot repay the loan obligations with loan interest rates at the end of the year. This loan disbursement and collection arrangement have two adverse effects on household short-term credit market participation. On the one hand, if one of the group members fails to pay their own debt, the other remaining group members are liable to pay extra loans in addition to their obligations. On the other hand, b, if the group members fail to pay back the debt of the whole group, they face the risk of exclusion from future credit schemes.

Overall credit access to smallholder farmers in Ethiopia is influenced by supply and demand-side factors determining credit access conditions. Even if there are actual and potential demands for credit, formal institutions like MFIs serve only a small proportion of households demand. Evidence shows that the overall share of formal credit to agriculture in the country is less than 10% (Mukasa et al., 2017; Zwedu, 2014). These have a significant implication on production and consumption decisions and other investment opportunities for resource-poor households who are operating under pronounced capital constraints.

Cognizant of the impediments to accessing credit market and its potential in boosting agricultural production that can be transformed into better income and food availability, the government of Ethiopia has recently revised a new credit policy reform. This policy is known as the movable property security rights proclamation, which allows a movable property to be used as collateral to secure credit from conventional banks. To regulate and execute the new policy implementation, movable collateral registry office has been established in the National Bank of Ethiopia. A movable collateral registry policy wasn't in place with formal banking systems that help them to use movable assets to extend credit. This scheme is part of the newly homegrown economic reform initiative to promote financial inclusion by granting movable assets as collateral security to conventional banks. The reform aims to improve access to credit services for small-scale business schemes, including smallholder farmers from commercial and other conventional banks. With the current policy reform, smallholder farmers are expected to access credit by pledging movable assets like livestock, land-use certificates, perennials, and forestry as security collateral assets. The new policy reform requires banks to dedicate at least 5% of their credit disbursement to business loan portfolios toward the agricultural sector, including individual households, cooperatives, unions, and enterprises using the movable property as collateral. The new policy reform is expected to improve smallholder farmers credit access and contribute to reducing the adverse effects of climate-related shocks.

1.5.2. Role of improved technology access in minimizing household vulnerability

Like credit access, the use of new technology is also considered an important adaptation strategy that is part of policy responses to reduce the vulnerability of smallholder households against the negative impacts of climate variability and change (Adams et al., 1999). It is part of adjusting the farming practices by using new crop varieties which potentially minimize the effect of climate shocks. Adaptation through the use of new technologies can buffer the effect of climate-related risks and play an important role in reducing food insecurity and improving the income of farm households (Di Falco and Veronesi, 2013).

Development, testing, and popularization of viable technological options have been vital components of farm-level adaptation measures to address climate risk effects in Ethiopia. In this regard, different organizations have been developing various technological options which are believed to withstand the effects of climate shocks and are expected to improve smallholder farmers welfare. Particularly wheat and maize crops have been given due attention because of their large contribution to household food security. For example, at the national level in Ethiopia, 88% of maize production is meant for local human consumption (Abate et al., 2015). Due to increased variation in climate variables like temperature and rainfall, the main focus of the research agenda is to minimize the current or expected adverse effects of climate-induced drought/disease by generating and popularizing drought/disease-tolerant maize and wheat varieties in climate-induced prone countries like Ethiopia. Drought-tolerant maize for Africa (DTMA) and the promotion of rust-tolerant wheat variety projects in Ethiopia and other similar African countries are some initiatives meant to develop and popularize maize and wheat innovations that can be used as adaptation strategies to different shock stresses. Such initiatives can serve as risk-mitigating technology interventions in the absence of formal insurance and safety-net mechanisms (Fisher et al., 2015; Gebrehiwot and van der Veen, 2020; La Rovere et al., 2014). Different studies confirm that these initiatives have contributed to productivity gains and improved the welfare of maize and wheat growers in the intervention areas (Fisher et al., 2015; Simtowe et al., 2019; Wossen et al., 2017a).

Despite the continued efforts of technology developments and popularization, the genetic potential of existing improved technologies is continuously breaking down. This is mainly due to an increased frequency and severity of drought risks, aggressive and devastating crop diseases like wheat yellow rust races prevalence, and the recent emergence of epidemics of Ug99 stem rust (Tadesse et al., 2019). Stem and yellow rust have caused significant yield losses ranging up to 100 % in the wheat-growing areas due to the collapse of dominant wheat varieties such as *Kubsa* and *Galema* (Badebo and Hundie, 2016). New emerging crop disease like fall armyworm has become very common in Eastern African countries which mainly affect maize production.

When drought shock becomes severe and new crop diseases emerge over time, the existing innovation becomes highly susceptible, necessitating the development of innovation including new varieties to counter the new production challenges. For instance, during the field research, farmers witnessed that the current wheat and maize varieties are completely different from what they used to grow 5 and 10 years back. The old improved varieties have been kicked out from the formal seed systems and the new varieties that are believed to be shock tolerant varieties are being used. This shows the dynamism of technology turnover in response to external shocks. Due to the emergence of new production risks, new crop variety development and popularization have been an ongoing research agenda in countries like Ethiopia where emergency of new crop disease is common and other climate-related risks are pervasive. The research agenda is meant to generate new crop varieties with superior resilient traits that can provide better yield and reduce the downside risk in the face of actual or expected severe drought shocks or emerging new races of crop diseases.

With the collaboration of national agricultural research systems, CGIAR centers like CIMMYT and ICARDA are spearheading the maize and wheat breeding program to generate, test, and popularize new varieties that are expected to withstand biotic and abiotic stress in the face of changing climate (Tadesse et al., 2019). These varieties often have traits like early maturing, better yielding, and stress-tolerant varieties that can potentially increase productivity and reduce the probability of crop failure in the face of climate risks. Such innovations can improve crop production under extreme heat and drought conditions (Hertel and Lobell, 2014). Improving productivity and reducing downside risks under climate variability are the defining features of stress-tolerant crop varieties (Simtowe et al., 2019). The aim is not merely to develop innovations and increase crop productivity but also to support maize and wheat growers to build their resilience by helping them adapt/use so that food insecurity prevalence would be reduced.

Adoption of new agricultural innovations is instrumental in the process of adaptation to climate change and variability. However, under smallholder farmer conditions, access to such improved technologies doesn't necessarily ensure their adoption. This is because the majority of smallholder farmers have a meager resource base including a shortage of capital, operate under political and environmental uncertainties, missing credit and insurance market, and poor communication networks which influence adaptation responses or farmers choices (Bryan et al., 2009; Jaleta et al., 2018; Ringler et al., 2011). In addition to these factors, adoption decisions are likely to be influenced by unobservable characteristics (like perception and managerial skills) and cultural perspectives (Teklewold et al., 2017). Moreover, as they are often risk-averse and sensitive to additional costs associated with innovations, farmers often examine the new technologies before they decide to use them as climate adaptation alternatives. When they anticipate risk, they may prefer low-risk and low-return technological options to higher payoff options (Wossen et al., 2017a).

Understanding the potential role of technological interventions under the increased frequency and intensity of climate-induced shocks is crucial in designing appropriate policy responses. The magnitude of the impacts of any technology intervention on household well-being is always an empirical question. Empirical evidence on quantifying the role of new technological innovation as adaptation strategies over longer periods is a dearth in Ethiopia which requires greater scientific insights that can be used as input for designing and implementing policies.

1.6. Motivation

Successfully addressing the adverse effects of external factors require understanding existing local-level adaptation and coping strategies and how smallholder respond to different policy interventions. Understanding the role of farm-level adaptation and coping options is an essential first step toward adapting to future climate changes and variability (Cooper et al., 2008; Dercon, 2002). Incorporating farm household local knowledge and practices in response to climate change and variability is essential to shaping current and future adaptation policies (Bewket, 2012; Kassie et al., 2014a). Lobell et al. (2008) also argue that since climate variability impacts substantially vary across regions, local hot spot challenges, and the existing adaptive response need to be considered. Adaptation of new farm practices such as the use of technological innovation is often successful when they fit to the local conditions. Moreover, assessment of the effectiveness of policy interventions (such as credit, technological innovations, and locust relief programs) is paramount important for policy targeting and scaling up/out the effective policy options in the face of recurring external shocks. Policymakers need to know which policy options work better to customize and prioritize policy interventions. It helps farmers and policy-makers to make informed decisions from short-term tactical decisions to long-term strategies (Howden et al., 2007).

In developing countries including Ethiopia studies on external factors (climate and locust) impacts, household vulnerability, farmer adaptive responses and assessment of policy interventions in reducing shock effects are scanty both at aggregated and local levels (Cooper et al., 2008; Gebreegziabher et al., 2020; IPCC, 2007). Particularly local-level climate-related studies are often limited, which augment local-level adaptation decisions as climate variations, impacts and climate adaptations are often location-specific. Moreover, due to the expected increase in the trend of climate risk frequencies and severity in the future, adaptation options and coping measures are likely to change over time and space which requires a new scientific knowledge base.

There are studies in Ethiopia on climate change impacts on agricultural production and farmers adaptation and coping using crop growth and statistical models. However, as recurring and extreme locust shock is relatively a new phenomenon in the country, so far, there are no studies on locust impacts and assess the roles of relief policy interventions meant to minimize welfare losses. Some studies evaluated the impacts of climate change and variability on crop yields (Kassie et al., 2014a), adaptation options, and vulnerabilities (Kassie et al., 2014a; Tesfaye et al., 2018), determinants of adaptation decisions (Bryan et al., 2009; Deressa et al., 2009; Kassie et al., 2014a) economic impacts of climate change and variability on agriculture (Arndt et al., 2011; Deressa et al., 2009; Di Falco et al., 2012; Gebreegziabher et al., 2020; Robinson et al., 2013).

Most of these past studies explain the current situations using past data which provide little information on the impacts of external dynamics like markets, policy, and changes in resource bases. Moreover, many of these studies on climate variability and change often provide relevant information at the aggregate level, which often overlooks local climate shock variations and effects. Evidence produced at aggravate or national level would have less relevance for local policy design and response to address local-level problems (Deressa et al., 2009). Most of these studies have focused on crop farming by overlooking other important farm components like livestock subsystem, which are equally important to address the climate change impacts by serving as essential adaptation and coping measures for smallholder subsistence farmers (Gebreegziabher et al., 2020). On top of this, the studies often capture specific farming aspects without analyzing the whole-farm system. Capturing a whole-farm system can represent the reality at the farm household level where individual components in the system are interlinked in terms of the decision-making process and sharing limited farm-level resources.

To address the limitations in the existing studies of external shock impacts on agriculture in Ethiopia, a farm-level simulation model is a suitable approach to disentangle the pathways through which external shocks may affect the welfare of smallholder farmers. This model is appropriate to assess farmer adaptive capacity and identify effective policy options which considerably contribute to reducing household vulnerability to various recurring shocks.

Quantification analysis with farm-level simulation helps to assess the degree of effects of external factors on farmers livelihood and test qualitative inquiries (Adams, 1989). Quantification of the impacts of climate variability and disentangling its adverse effects on agricultural production, food security, and household income from other confounding factors have paramount importance to design appropriate climate adaptation policies, strategies, and prioritizing policy interventions (Berger et al., 2017). Similarly, quantifying and understanding the pathways through which desert locust shock may affect households livelihoods are crucial in designing appropriate and effective risk management strategies.

To the best of my knowledge, only Berger et al. (2017) quantified livelihood impacts of climate variability, farmer adaptive capacity, and assessed the role of policy interventions using a farm-level simulation modeling approach in Ethiopia. This thesis seeks to extend the study of Berger et al. (2017) on climate variability impacts and policy assessment in four aspects. First, the previous study was based on nationally collected data from Ethiopian Rural Household Survey (ERHS) and the Nile Basin survey, but this study used relatively new datasets from Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) household survey complemented with data from Central Statistical Agency (CSA). Second, it focuses on a specific study area in Ethiopia where a mixed crop-livestock production system dominates and climate-induced risks are rampant. Capturing local-specific household characteristics, adaptation and coping options help policy targeting to address local hot spot challenges (Berger and Troost, 2014; Lobell et al., 2008). Third, this thesis implements and evaluates farm-level risk management strategies which are commonly practiced by many farm households as part of the preparation for future possible shocks – it explicitly captures ex-*ante* measures such as storage activities for possible shocks in the future. It also assesses the effectiveness of short-term production credit access and the use of new technological innovation in reducing vulnerability and enhancing smallholder farmers adaptive capacity. Fourth, on top of extreme climate shocks impact and adaptive capacity assessment, the thesis also captures the welfare effects of desert locust invasions and assesses the effectiveness of locust relief policy interventions which have never been studied.

1.7. Objectives of the study

The objective of the study is to assess the impacts of external factors of climate-induced shocks and desert locust invasions on the livelihood of smallholder farmers in Ethiopia. It also aims to identify effective policy options which are designed and implemented to reduce the adverse livelihood effects of climate and locust shocks.

1.8. Research questions

The following research questions are designed in line with the objectives stated above.

What are the likely impacts of extreme climate shocks on the well-being of smallholder farm households?

The occurrence of extreme climate shock events is common in most parts of Ethiopia. Specifically, extreme climate events have been recurrent and intense in the moisture-stressed lowland area which adversely affects smallholder farmers welfare. Climate-related extreme events are among the main drivers of food insecurity, reduced household income, and asset depletion both in the short and long run.

Increased incidence of extreme climate shocks reduces incentives to invest in agricultural production technologies, potentially offsetting the positive impacts of increasing food price trends (Porter et al., 2015). Food production is an important aspect of food security and source of income for smallholder farmers. The evidence that climate change and variability affect food production implies that it would have a negative effect on household food security and income by limiting food availability and subsequently rising food prices. Whenever food and income are not sufficiently available for household consumption, farmers employ selling livestock resources to cover food and basic non-food expenditures. This implies that climate shocks indirectly affect livestock endowments by forcing households to deplete livestock to generate cash which in turn is used to buy food and other amenities. Quantifying the adverse effects of extreme climate shocks on smallholder farmers welfare including livestock assets provides valuable insights for policy designing and targeting at various levels aiming at reducing household vulnerability to the negative effects of extreme climate events.

How do farmers respond to the effects of extreme climate-induced shocks?

Subsistence or semi-subsistence farm households implement different risk management strategies to reduce vulnerability to climate risk. *Ex-ante* adaptation strategies are part of risk management measures implemented in expectation of possible climate shocks in the future whereas *ex-post* coping measures are implemented once the shocks occur as an immediate response. It is paramount important to understand the mix of *ex-ante* adaptation and *ex-post* coping measures that smallholder farmers are using to mitigate the negative effects of climate-induced shocks. This helps to assess and understand whether farmer autonomous risk management measures can sufficiently reduce the effect of recurring extreme climate shocks or not.

Which policy interventions are effective in reducing farm household vulnerability to extreme climate shocks?

Apart from farmer autonomous risk management strategies, various policy interventions are promoted by the government to combat the climate crisis. Among many policy interventions, access to technological innovations and credit services are the main options widely implemented in Ethiopia and beyond where farming is dominated by resource-poor farm households. Since farm households differ in terms of income, resource endowments, and climate risk adaptation capacity, not all policy interventions are equally important and effective in combating climate shock effects due to heterogeneous responses of households (Wossen et al., 2014). Thus, identifying policy options that are effective in compensating for welfare loss from climate shock is paramount important.

What are the welfare effects of desert locust invasions?

On top of recurring climate shocks, in recent years, desert locusts outbreak has become common and recurrent in most areas in Ethiopia. Even if there have been locust control and surveillance efforts to limit locust swarm expansion across the country, it has devastated crop harvest in major crop-producing areas and livestock feed production in pastoral areas. Locust outbreaks aggravate the likelihood of welfare deterioration for smallholder farmers who are already in dire conditions. This creates huge implications for smallholder farmers food production and income-earning opportunities which need to be investigated and quantified. Quantification of welfare effects of locust invasion would inform policy-makers to design appropriate mechanisms through which the adverse effects are reduced.

Which locust relief policy interventions are effective in minimizing the adverse effects of locust invasions?

As an immediate response to the outbreak of desert locust over the years, different locust relief policy program interventions are designed and implemented by government and non-governmental organizations in the locust-hit areas. These relief policy interventions are humanitarian support aimed at reducing locust outbreaks. Thus, this thesis seeks to quantify and identify effective locust relief programs and their combinations in reducing the adverse effect of recurring locust invasions.

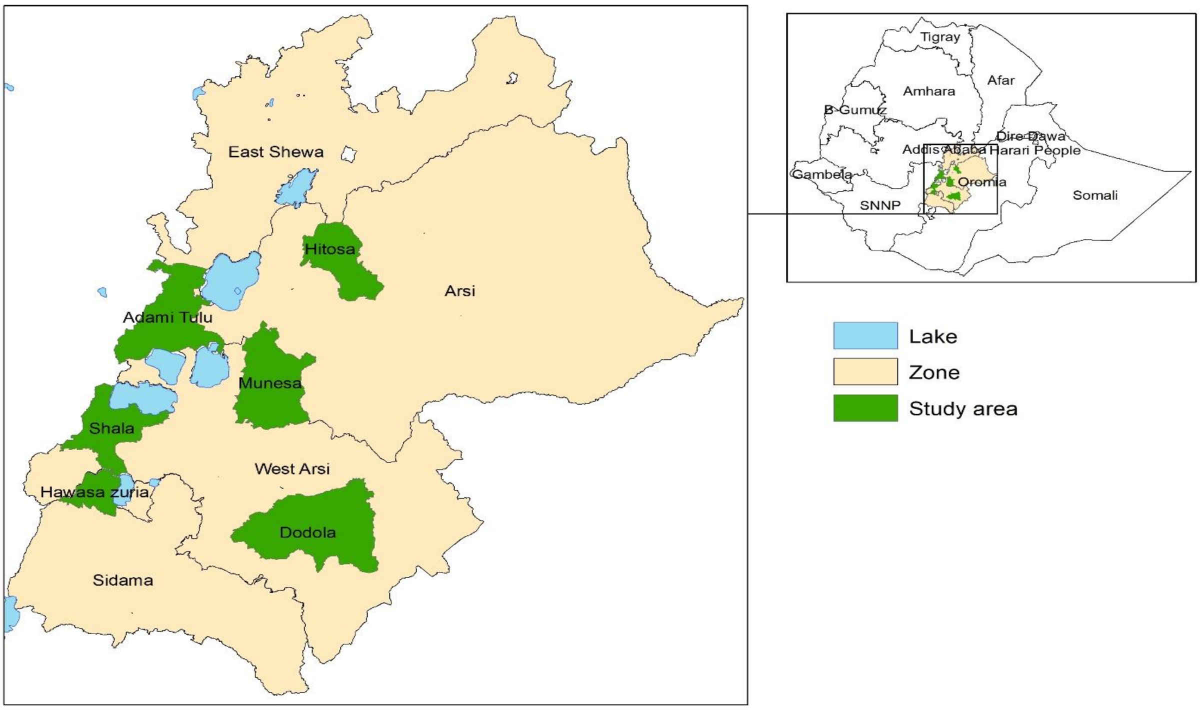
Chapter 2. General methods and data

2.1. Description of the study area

The study was conducted in the Central Rift Valley (CRV) of Ethiopia in six districts: Adami Tulu, Shalla, Hawassa Zuriya, Munesa, Dodola, and Hitosa (Figure 1). CRV is part of the great Eastern African Rift Valley system that dissects Ethiopia into two. It starts from the Awash River in the north and extends down to Lake Chamo in the south. The area is predominantly characterized by semi-arid and sub-humid climatic situations where erratic rainfall is not uncommon (Shimeles and Legesse, 2014).

The altitude of the CRV ranges from approximately 1600 to over 3000 meters above sea level (Hengsdijk, 2010). Due to altitudinal variations, rainfall distribution also varies across the districts. Bimodal rainfall distribution is common in the lowland districts like Hawassa Zuriya and Shalla. The bimodal rain distribution consists of short and long rainy seasons that allow the production of diverse crops. *Belg* rainy season is characterized by a short rainy season from March to May, whereas the long rainy season (*meher*) is from June and September (GETNET et al., 2016). The bimodal rainfall distribution in some districts allows for practicing crop intensification through double cropping. In the short rainy season, farm households usually grow *teff* and in the long rainy season, they cultivate the same plots and grow common beans. However, the *meher* rainy season is the dominant production season for many farmers in the study area.

Figure 1: Map of the study area



Source: own constructed map

The study area is endowed with diverse crop production activities. The area can be broadly classified into two production systems-maize and wheat-based systems that support millions of people's livelihoods. Cereal production dominates both systems, where maize and wheat occupy 26% and 24 % of the total cultivated areas, respectively (GETNET et al., 2016).

The maize-based system is characterized by a mixed crop-livestock production system in lower altitude areas. According to GETNET et al. (2016), the soil types of the area are characterized by Andosols and Fruvisols. Crops like maize, common bean, and *enset* dominate while farm households extensively raise livestock. In some districts of this system (like Adami Tulu), farm households usually keep higher heads of livestock partly due to better availability of common grazing land and water from various lakes. However, in some districts (like Hawassa and Shalla districts), livestock production is highly constrained by grazing land shortage due to small land area ownership and relatively higher human population density.

Wheat-based production system is characterized by relatively higher altitudes and suitable temperatures for wide varieties of crops and livestock. Luvisols mostly dominate the soil type, but there are considerable Nitosols and Vetisols in some areas (GETNET et al., 2016). Compared with the maize-based system, the area receives a relatively higher rainfall amount which is suitable for wheat and barley production. In addition to challenges imposed by changing climate, crop diseases, and frequent rust epidemic outbreak, have been a major threat to wheat and barley production.

In both production systems, rain-fed crop production is the most dominant practice. Even if some farmers have access to water sources (those who lives close to lakes), they don't have enough resources (capital and reasonable farm size) to invest in a small-scale irrigation system. Due to this, irrigated crop production practice is very rare.

2.2. Modelling farm household decisions and policy analysis

There are different modeling approaches in agriculture suitable to capture the impacts of external factors, adaptation options, and policy analysis. They constitute mainly three model approaches: standard crop growth models, economic models, and a combination of the two (bio-economic models).

According to Van Ittersum et al. (2013), crop growth models are capable of representing crop growth processes and interactions of soil-crop-management-climate components that determine crop growth and development. Such models enable an understanding of the impact of climate variability and change on crop yields (Van Ittersum et al., 2013; White et al., 2011). It also involves simulation analysis of cropping systems (like crop yield changes) between plausible climate change scenarios to analyze the impact of climate change and variability (Lobell et al., 2008).

Despite the potential of these models to quantify the impacts of climate change, they have many limitations. Crop simulation approaches usually focus on the bio-physical process involved in the plant system and are often criticized for not capturing socioeconomic drivers like the system resource dynamics. Moreover, these model types fail to capture farmers behavior, farm dynamism, and decision-making (Berger and Troost, 2014). Farmers are decision-makers or managers who can influence biophysical and socioeconomic drivers (Challinor et al., 2018). These models are also often calibrated for a single crop that might not give the whole-farm perspective in addressing climate change and variability impacts (Deressa, 2007; Sadiq et al., 2019). As a result, crop simulation models capture limited adaptation options and fail to encompass the broad spectrum of adaptation and coping strategies that smallholder farmers often employ to reduce current and anticipated climate-induced shocks (Challinor et al., 2018).

Another group modeling is economic models which are often applied to capture the impacts of climate variability and change and examine the effectiveness of climate adaptation options. These models include Computable General Equilibrium (CGE), Partial Equilibrium (PE), Ricardian approach, and econometric models (Arndt et al., 2011; Bryan et al., 2009; Deressa, 2007; Gebreegziabher et al., 2020; Kassie et al., 2014a; Robinson et al., 2013). CGE models are economy-wide policy assessment models capable of capturing the direct and indirect effects of climate variability and change on different economic sectors at global, national, and regional levels (Robinson et al., 2013). PE models analyze the impact of climate variability at sectoral levels. Both CGE and PE can analyze climate change adaptation and capture the complex effects of exogenous changes across economic sectors or regional levels.

Despite their usefulness in providing policy insights at aggregate levels, CGE and PE models barely provide insights at disaggregated levels that enable targeted policy formulations (Berger and Troost, 2014). They are often parameterized at aggregated levels which can obscure the local-level effects. The other drawbacks of these equilibrium models are the difficulties of parameter specification and functional form, the absence of statistical tests for model specifications, and calibration problems (Deressa, 2007).

Ricardian approach is among the economic models suitable to capture external shocks like climate shock impacts and local-level adaptation options at the farm or local levels (Deressa, 2007; Fernández and Blanco, 2015). These model groups are often used to address the limitations in crop growth models that failed to capture adaptation measures implemented by farmers, resulting in overestimating external shock impacts by providing biased estimates (Sadiq et al., 2019).

The Ricardian approach uses econometric estimation approaches to estimate the impact of climate change and variability on household welfare outcomes, such as land value and net farm revenues. It can also estimate the impact of climate adaptation options in reducing the adverse effects of climate change and variability. The model helps to analyze the contributions of environmental, climate parameters, and other farm characteristics towards farm performances using the value of land and net revenues as dependent variables (Darwin, 2017; Mendelsohn et al., 1994). Economic damages by climate shocks are considered reductions in net revenue or land value calculations.

Despite its strength in capturing climate variables and being cost-effective compared to other models, the Ricardian approach involves many drawbacks. One of the weaknesses of the approach is that it has a highly reduced nature, where it captures climatic factors as the main stimuli for farm responses. It also fails to fully capture the impact of other variables that can explain farm performance outcomes (Mano and Nhemachena, 2016). Furthermore, the model doesn't account for price effects as it assumes price is constant (Deressa, 2007; Mano and Nhemachena, 2016). But in practice, climate variability affects prices indirectly by reducing aggregate agricultural supply. Failing to take into account the price effects on farmer responses could also lead to estimation bias of household welfare (Cline, 1996). This approach and other statistical models have limitations in analyzing new climate-related policies with scenario analysis as model parameters are derived from past observations or sample data (Berger and Troost, 2014).

Another modeling approach is a hybrid of crop-growth and economic models. These are bio-economic household models which apply mathematical programming and are capable of integrating economic models with biophysical models to represent complex farm household decision-making (Berger, 2001; Berger et al., 2006; Holden and Shiferaw, 2004). Moreover, they are capable of assessing policy alternatives and technological innovations in specific farming systems (Holden et al., 2004; Janssen and van Ittersum, 2007). This model is dynamic, non-separable, and simultaneously integrates economic optimization in production and consumption with multi-period environmental feedback (Holden and Shiferaw, 2004). However, they are non-spatial and capture only little real-world heterogeneity in socioeconomic and environmental aspects, and they don’t allow interaction between households (Berger et al., 2006; Schreinemachers et al., 2007). As a result, farm households are represented as non-connected and non-spatial in bio-economic models (Berger et al., 2006).

Agent-based model (ABM) is a hybrid model similar to bio-economic models which are capable of integrating socio-economic and biophysical models and address many limitations of biophysical, statistical, and bio-economic household models. It addresses the limitations of biophysical models by considering farm households as decision-makers and capturing the whole farm approach than one crop. ABM has more structures to address limitations in statistical models and the Ricardian estimation approach by allowing detailed predictions or scenario analysis of farm household responses to external shocks like climate risks at local levels (Berger et al., 2006; Berger and Troost, 2014). In ABM, farm households are represented as computational agents and treated as autonomous decision-makers who interact, communicate and make decisions that can alter the environment (Berger et al., 2017, 2006; Schreinemachers et al., 2011).

ABM shares many characteristics of bio-economic farm models and addresses the limitations of these and other simulation models. It accounts for agent heterogeneity which emanates from resource availability, decision-making process, agroecology, market conditions, and investment opportunity environment (Berger et al., 2017, 2006; Schreinemachers et al., 2011). Spatially explicit and cell-based framework processes help to capture agent heterogeneity and their responses (Berger and Troost, 2014). Moreover, the model also allows for agent interactions with each other and the environment that aggregated models are unable to capture directly (Berger et al., 2006; Berger and Troost, 2014). Model agents can interact with one another for sharing resources such as land use, input use labor, and capital sharing. They also share information among themselves on new available technologies and weather conditions. Incorporating agent interactions and getting environmental feedback helps capture better management options for agricultural systems (Schreinemachers and Berger, 2011).

Overall agent-based bio-economic model overcomes traditional farm-based modeling by capturing a spatial landscape representation, agent heterogeneity, and agent interactions which is not possible in other models (Schreinemachers et al., 2010). When heterogeneity and interactions of agents and environments are important and policy responses cannot be aggregated linearly, ABM would be the preferred model (Berger et al., 2006).

Farm-level agent-based simulations are multi-period planning decision models which can flexibly capture a wide range of real-world farming systems opportunities and micro-level constraints to simulate real-world decision-making processes (Berger and Troost, 2014; Schreinemachers and Berger, 2006). It can also reproduce real-world conditions by empirical parameterization of agents, representing real-world farm households (Schreinemachers and Berger, 2006). Therefore, the model can be used as a descriptive analysis tool to represent farm-level decision-making processes over time (Schreinemachers and Berger, 2006) which can be empirically validated. Each real-world farmer is represented by a farm agent which allows a one-to-one correspondence with real-world and computational agents (Berger et al., 2006).

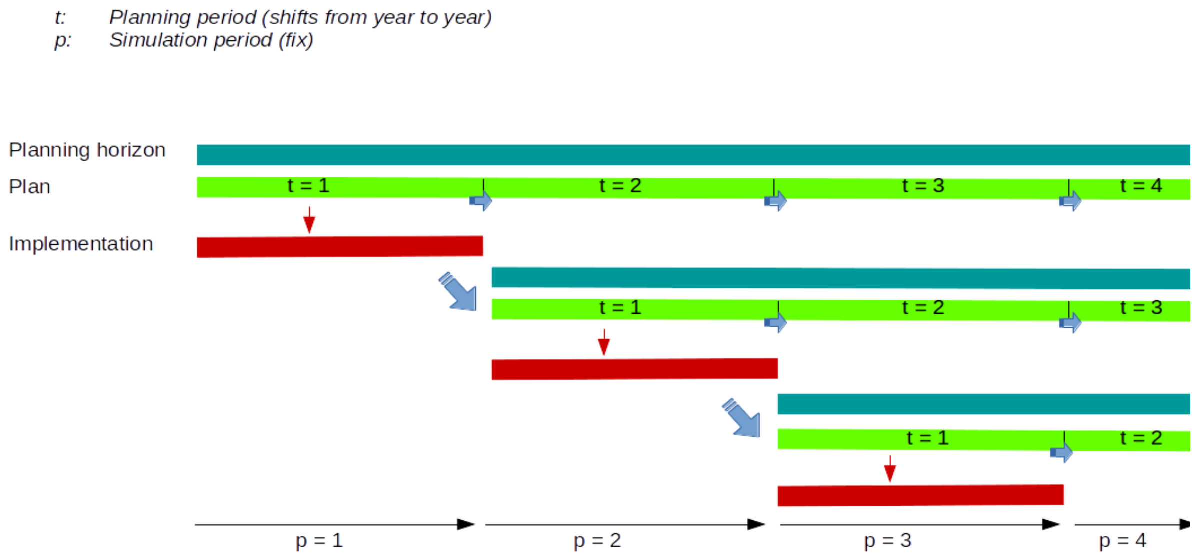
MPMAS (Mathematical Programming-based Multi-Agent Systems), which is the software of farm-level agent-based model, is used to capture inseparable production and consumption decisions with subsistence farming households. It uses a whole-farm mathematical programming modeling approach to represent the complex dynamics of farm household decisions where a set of constraints and their complex relationships are considered (Berger and Troost, 2014; Schreinemachers et al., 2010; Schreinemachers and Berger, 2011; Troost and Berger, 2015).

In MPMAS, mixed-integer linear programming (MILP) formulates agent production decisions at the beginning of the periods based on expected short-term prices and yields, resource availability, and allocating resources among competing farm activities. At the point of decisions, agents don't know the climate and price conditions exactly in advance which means the plan is made without perfect foresight about future weather conditions. These decisions are realized at the end of every planning period, usually at harvest time. In between, there could be unforeseen climate and price shocks that can potentially cause a divergence between original plans and actual realization. In this stage, actual household production and incomes are determined by climate and markets. In the subsequent production decisions, agents are assumed to adapt the plan based on feedback from past decisions, and available information on new and existing opportunities like new technologies, new credit schemes, new marketing, and policy opportunities not considered in the past.

This implies that over simulation periods the decisions are not independent of each other which creates recursiveness as the resource availabilities are updated over simulation years. Recursive-dynamic farm-level modeling with inter-temporal planning can best represent subsistence farm household production and consumption decisions that are not separable (Berger et al., 2017). Subsistence farm households are characterized by consuming a substantial share of crop and livestock yield with less participation in the output market (Schreinemachers and Berger, 2006). The inseparability of production and consumption implies that smallholder farmers make production and consumption decisions simultaneously not recursively (De Janvry et al., 1991). Farm production decisions like the adoption of new farm practices of new technology use, resource allocations between different choices, level of agent incomes, consumption patterns like purchase, and autonomous consumption of food are simultaneously determined (Berger and Troost, 2014).

Recursive–dynamic farm model also helps to capture short and long-term structural changes in the farm over many periods. Most importantly, the modeling approach is more suitable when inherent time lags, like in crop production where households make decisions and realize results after some time. Between crop production decisions and harvesting, surprises like unpredictable climate and price shocks may occur. Likewise, such a model is also a powerful tool to represent household risk management strategies and assess the impact of climate variability by disentangling different pathways through which climate variability may affect household welfare (Dillon et al., 2015). It has been widely applied to assess and simulate climate impacts, policy targeting, and *ex-ante* evaluation of potential technological innovations in agriculture in different countries with different farm contexts (Berger et al., 2017, 2006; Berger and Troost, 2014; Troost et al., 2012). It allows agents to have longer planning periods and implement the plan over the planning periods that would be adapted based on past experiences/ learning, current new policies, and market conditions.

Figure 2: Conceptualization of recursive dynamic simulations with multi-period planning



Source*:* MPMAS tutorial, 2019

According to Carauta et al. (2021b), MPMAS has recently been widely applied in 11 different countries for integrated assessment, quantification of climate change impacts, and policy analysis. These countries have different agroecological conditions, agricultural and market policies, and climate conditions. It was first developed at the University of Hohenheim by the research team and after that, it has been applied and got wider acceptance as a model in agriculture and policy analysis. One of the countries where MPMAS was built to simulate smallholder farmers adaptation measures and policy options is Ethiopia (Berger et al., 2017).

The team of researchers took up MPMAS_ERHS[4] developed for Ethiopia by Berger et al. (2017) and extend it by building a general model to serve simulation analysis in two parts of the country - CRV and northwestern which later was used for different but complementing research purposes. The research team comprises Christian Troost, Alemu T. Ejeta, Habtamu D. Yismaw and Thomas Berger extend the 2017 MPMAS_ERHS by building a general MPMAS for Ethiopia to represent smallholder decision-making and policy analysis. This general model was built by using new datasets. It has additional features like explicitly capturing *ex-ante* measures and storage activities. After setting up MPMAS with the new features for Ethiopia, I adapted the general MPMAS for CRV (MPMAS_CRV) and Habtamu (2021)[5] customized and used the model for the northwestern part of the country. In addition to the new features in the general model like considerations of *ex-ante* measures, MPMAS_CRV has also additional features for desert locust invasion simulations which have never been implemented and studied before. MPMAS_CRV was parametrized from the data collected from CRV which was used to simulate the impact of climate-induced shocks (drought and crop diseases), locust invasions, and the effectiveness of policy interventions including locust relief programs.

2.3. Representing multiple farm household objectives in MPMAS_CRV

When production and consumption decisions are inseparable, like in the case of subsistence farm households, markets are assumed to be imperfect and less competitive (Holden et al., 2004). Subsistence agriculture in developing countries like Ethiopia is characterized by nonprofit goals, operates under risk and uncertainties, and limited information flow that can be considered as a source of inefficiencies which further contributes to imperfect foresight in the optimizations (Schreinemachers and Berger, 2006). When markets are imperfect or high levels of risks involved in farm decision-making, market goods cannot fully substitute farm-produced goods which makes

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[4] MPMAS_ERHS (MPMAS_Ethiopia Rural Household Survey)

[5] Habtamu D.Yismaw. 2021. Smallholder adaptation through agroforestry: Agent-based simulation of climate and price variability in Ethiopia. PhD dissertation. University of Hohenheim, Germany.

farm households satisfy subsistence goals largely from their production (Schreinemachers and Berger, 2006). Due to prevalent market imperfection with smallholder farmers in the CRV, individual household agents were assumed to maximize expected utility rather than profit from different options subject to crop and livestock production options, technological and consumption preference constraints which are often complex. The utility function of individual household agents comprises multiple goals such as meeting minimum food and non-food expenditure consumption demand and maximizing expected discounted returns after fulfilling the minimum subsistence requirements.

When possible, individual agents aim to meet all these goals simultaneously. However, resources, technological availability, environment, and market conditions could potentially limit achieving them simultaneously. For instance, during unfavorable climatic conditions, crop yields become low, relative crop prices could rise, and the price of livestock can go downward partly due to higher supply to the local market or lower purchasing power. This in turn adversely affects agent incomes, consumption patterns, and overall welfare status. Likewise, resource constraints make individual goals compete with each other – satisfying one goal might lead to underachievement for the other goals which involve tradeoffs. Such conditions necessitate assigning weights to different goals which help to establish ranking to better reflect its importance and desirability in the model set up (Ragsdale, 2012).

Following Ragsdale (2012) suggestions on how to assign weights to different competing goals in the utility function, we (I and MPMAS model developers) defined weighted one-sided linear deviation functions (the penalties or disutility) to individual agent goals in the MPMAS_CRV. Weighted one-sided deviation means the amount by which each objective deviates from the target value (like meeting the minimum food consumption requirements). Underachieving the target values for objectives would be undesirable which carries penalties. But overachieving a particular target value may be considered desirable as long as other minimum targets are achieved.

The penalties also constitute weighting between the objectives to establish a clear preference order or relative importance. The preference order is implemented in MPMAS_CRV by assigning different weights to multiple and competing objectives of agents. Objectives with the highest penalty mean that deviating from the target carries the highest utility loss which is undesirable. In the model, the highest penalty is assigned to meeting the minimum food consumption requirements objective, followed by achieving minimum essential non-food expenditure before maximizing expected return objectives. Assigning a relatively higher penalty value to the minimum food consumption requirement show its precedence over all other agent objectives. Whenever there are competing objectives, agents first choose to satisfy minimum energy and protein requirements before meeting minimum essential non-food expenditures such as school fees and then maximize expected discounted returns. This implies ensuring food security is a priority for model agents, which is also true with real-world smallholder farmers.

But there are cases when farm household agents are unable to meet the minimum targets for objectives due to various reasons. For instance, agents may be unable to satisfy minimum consumption requirements due to extreme climate-induced risks (like drought and disease that may lead to severe crop harvest failure) or when the locust outbreak is intense which leads to serious production loss and worsen the existing food insecurity problem. Severe resource limitations (deprivation) can also prevent agents not to cover minimum consumption requirements. In such worst cases, agents may choose the last resort options like defaulting on credit and running into temporary food and non-food expenditure deficits involuntarily (Berger et al., 2017). In such cases, MPMAS_CRV would be infeasible. To ensure that agent decision problems have feasible solutions and allow agents to go below the targets (below minimum consumption requirements) in emergency cases, separate relaxing activities (foregone activities) are defined in the model. Foregone activities depict how much agent utility declines with every unit below the minimum targets. This prevents agents not to operate below the minimum targets voluntarily. Overall discreet implementation of multiple agent objectives in the model on how agents react during normal and emergency cases and prioritization of competing objectives help to represent and approximate real subsistence farmer decision-making and prioritizations.

Computational agents choose the optimal combinations from the different options subjected to resources, technological, risk considerations, and consumption preferences. In the farm household decision model set-up, individual agents have crop production, livestock rearing, off-farm employment opportunity, and access to short-term credit options to choose to meet their objectives. In the subsequent subsections, important model features are described as implemented in

MPMAS_CRV, which are used throughout all thesis chapters. The sources of data and how they were used in the MPMAS_CRV parametrization are also described in detail.

2.4. Parameterization of MPMAS_CRV

MPMAS_CRV was parametrized from different data sources. The main data source used for the construction of the MPMAS_CRV input files was the CIMMYT household survey which was collected in 2013 nationally in maize and wheat-dominated production systems. Moreover, the CSA survey of the same year was also used to complement and crosscheck information on some variables such as cropping activities, livestock holding, and prices. Own field research conducted in 2018 using focused group discussion, key informants, and expert interviews in selected villages in CRV was also used to augment data on household production mixes, landholding, consumption patterns, and livestock endowments. Among others, trends, frequency of shock events, perceptions of climate-induced shocks, farm household consumption rules, and risk management strategies were collected during field research.

A household survey of CIMMYT was collected in 2013 which covers a wide range of wheat and maize-based production systems (Jaleta et al., 2019, 2018) in CRV. Surveyed households were sampled using stratified random sampling. Among the sampled districts in maize and wheat production systems, six of them belonging to CRV were chosen for this thesis. From these districts, 54 households were chosen where maize and wheat are predominately grown. Household selection for modeling purposes is based on resource bases, particularly land size, household size, and livestock ownership which was used as a proxy for their wealth status and resource heterogeneity. These households were represented as computational agents in MPMAS_CRV by including their resource ownership in the initial asset endowments and representing their decisions. This help to create the agent population in the model with similar characteristics to real-world farm households like household composition, household member types, asset ownership (such as land and livestock, and initial liquidity).

Household food consumption

In CIMMYT and CSA household surveys, annual household crop utilization was collected. But food energy and protein requirements for individual household members were missing. To fill the gap, the thesis used FAO database to estimate individual household minimum food energy and protein requirements by their ages. Food consumption requirements depend on household composition and age, and it changes if the household size changes. In addition to this, the household energy and protein supply of each food item was computed from the USDA database. The estimated food energy and protein requirements for each labor group of agents and food supply from individual food items were then fed to the input files in the MPMAS_CRV.

Annual crop farming

Crop production is the main agricultural activity in Ethiopia. It is the main livelihood strategy that covers large land-use shares. Cereal production covers about 82% of the cultivated area, followed by pulses covering 12% (NBE, 2020).

Crop production is one of the alternatives for individual farm agents to achieve their objectives. The crop production decision problems involve which crops to grow and how many land areas to allocate given limitations on resources, perceived risks, and technology options. Over years, resource availability, asset endowments, market opportunity, and technology access changed where agents adopt long-term production planning recursively on annual basis.

In the parameterization of MPMAS_CRV, seven major crops were included from which the individual agents choose at the point of production decisions. These are maize, wheat, barley, common bean, faba bean, *teff*[6], and potato, commonly grown in the study areas. Due to variations in agroecologies across the study areas, not all cropping options are available to all agents. Crop yield is set to zero in areas where a particular crop activity is not commonly grown. Individual crop yields are determined by soil type, input choices, input use level, and other crop management options. In the model, various cropping activities were implemented as alternatives varied by different crop management options over soil types that determine yield levels. Crop management options were included in the input files, which range from growing crops with local varieties to existing crop innovations. The use of different crop varieties was then combined with the use of mineral fertilizer application. These management options were identified for each crop and soil type, which form various cropping activities. For individual cropping activities, input types, input use intensity, and associated production costs were estimated from CIMMYT household survey data

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[6] *teff* is an endemic cereal crop, looks like grass on the stand and fine-grained which is widely grown in Ethiopia

and own field research which was then used in MPMAS_CRV as input files. In the model, agents have alternatives to buy production inputs from the local market at the prevailing market prices.

Similarly, per-hectare labor requirements for land preparation, weeding, harvesting, and other cropping activities were also estimated from CIMMYT household survey data and own field research used for the parametrization of MPMAS_CRV. Labor periods were separated into bimonthly bases to allow labor availability for multiple and overlapping cropping activities as labor demand is affected by seasonality. Household labor types were further disaggregated into different labor use types. Land preparation was assumed to be performed by male household members only. Crop harvesting was performed by male and female household members, whereas crop weeding activity was performed by all household member types, including children.

Most cropping activities have often provided two types of yields - grain and crop residues. Part of the crop resides are usually used as livestock feed. Thus, the amount of crop residue from specific cropping activities was estimated following Meshesha et al. (2019) with grain-biomass yield ratio calculations.

Livestock farming

Livestock farming is an integral component of agricultural activities in Ethiopia. Despite the large livestock population in the country, its contribution to the economy is low, partly due to its low production performance. Livestock production is predominantly traditional based on low inputs, less integration with market services, poor feeding, and low investment under subsistence farming conditions (Asresie and Zemedu, 2015; Bezabih et al., 2014).

In CRV as well, livestock is one of the crucial components of a farming system. Mixed crop-livestock system dominates livelihood strategies in the area. Farm households usually keep different animal species ranging from poultry to large animals (like cows and bulls) for multiple functions. Households often make savings in the form of productive assets by keeping many heads of livestock with diverse livestock herds (Asresie and Zemedu, 2015; Bezabih et al., 2014) though feeding them is a challenge due to resource limitations particularly grazing lands. This allows them to decide on the number and types of livestock sales during hardship. Besides this, the livestock subsector complements crop farming by providing draught power and manure supply which enhances production and productivity.

Livestock assets also contribute to household food security through food supply and generating income that can be exchanged for food at times of severe shocks which lead to consumption risks (Doti, 2010). Due to prevailing imperfect credit and insurance markets, livestock assets are often regarded as a hedge against household climate risks for smallholder farmers. They use livestock keeping as a precautionary strategy to dis-invest at any time for consumption smoothing at times of hardship. Even during normal average years cash generated from livestock and its byproducts relax household liquidity constraints to finance upfront production inputs or cover other consumption requirements (Mahoo et al., 2013; Megersa et al., 2014).

In MPMAS_CRV, multiple roles of livestock farming were captured and implemented. Different livestock species are usually kept by smallholder farmers such as cattle, sheep, goats, and chicken which are represented in the MILP decision module. Livestock herd management was captured by incorporating herd size evolution and aging at each decision stage. At the start of the simulation, farm agents were assigned with initial livestock asset endowments to capture initial agent heterogeneity in terms of livestock holding. Farm agents can then decide whether to maintain, buy additional stock, or sell the animals over the simulation horizon, which is mainly dictated by the cash demand/reserve of agents or the severity of any hardships. The decision of agents whether to keep, sell or buy livestock is determined by the profitability in a ‘normal’ year given the costs associated with each species and the availability of feed sources. Variable costs associated with raising livestock are r defined and assigned to individual livestock types in the model. This cost is assumed to include any price other than investment in livestock or acquisition cost, including tablet purchases for deworming, veterinary services, and supplementary feed purchases. Oxen hiring is also defined in the model as it gives options for agents to choose from by comparing the relative profitability between keeping or hiring a pair of oxen for ploughing purposes.

While implementing and testing the MPMAS_CRV multiperiod model for livestock activities there were some workarounds and considerations to ensure that the model realistically represents the livestock production dynamics of real farmers. It is assumed and defined that agents were allowed to buy different species of animals only at the age they have the highest price and sell them after a specific age (after 2 years) except chicken. This means there is no incentive for agents to buy livestock for only selling purposes after a year, but only if they want to keep it for breeding and then sell it afterward. This restricts agents not to simply buy a specific livestock species and sell after a year. Real farmers usually keep livestock not only for one year but beyond a year for various purposes (breeding, ploughing, dairy, etc.).

Climate-induced risks adversely affect household livestock resources. It potentially affects livestock resources directly or indirectly (Andersson et al., 2011). It directly affects the growth immunity and physiological performance of livestock by affecting the availability of pasture and crop biomass which has a subsequent negative effect on livestock (Adams et al., 1999). This effect makes livestock assets in poor conditions and often leads to their die-offs in extreme moisture stress areas like in the pastoral farming communities and low land areas of CRV. This direct effect was also implemented in MPMAS_CRV by capturing shock effects on crop biomass production as a byproduct of crop production.

Shocks also indirectly affect livestock resources by reducing crop yield for subsistence farm households. Whenever there are recurring shocks, which leads to substantial production loss, smallholder farm households often use livestock resource as a hedge against risks to smooth food and income consumption. At times of shocks, they usually sell more animals often at lower prices because drought shock is usually covariate by its nature it affects wider areas and many households which forces many households to sell livestock for income-earning which further increases local livestock supply compared to normal years (Berger et al., 2017; Pandey et al., 2007). In MPMAS_CRV parameterization livestock is also included as an important resource where agents decide to keep them to sell for consumption smoothing in case of any unforeseen production and market-related shocks. This indirect effect on livestock prices is also implemented in MPMAS_ CRV through livestock prices. In addition to this, agents can either sell or buy livestock products like eggs, dairy, and dairy products. They can sell live animals but not meat and milk since this is not common in the rural part of the study area. Moreover, model agents can slaughter and consume beef and mutton from their herd.

For individual livestock species, agents assign housing space for staying overnight. Corral capacities and space requirements for different livestock species were assigned to individual species. For various livestock species, different space requirements and space limits are assumed in

MPMAS_CRV. Labor requirement for livestock keeping was implemented in MPMAS_CRV based on the expert opinion. Accordingly, a person can keep 30 cattle (large ruminants) as he/ she can keep many livestock types together. Moreover, labor requirement was differentiated and assigned to large and small ruminants separately in MPMAS_CRV. Household and hiring labor for herding were alternatives for agents to choose from. Furthermore, it was assumed that any household member could be assigned to herding activities.

Livestock feed activities and feed requirements

In MPMAS_CRV, farm agents have three main sources to feed livestock. These natural pastures by allocating part of the total owned land area, crop residues from crop production, and communal grazing. Livestock stocking rates for each source of livestock feed are missing in both household surveys of CIMMYT and CSA. The problem was addressed by following different empirical sources to calculate the feed supply from each feed source that can support heads of different species of livestock (Amsalu and Addisu, 2014; FAO, 2018; Meshesha et al., 2019). Feed supply from crop residue was estimated based on grain-biomass yield conversion factors from each crop type and converted to dry matter. The dry matter demand was calculated for each livestock head based on daily livestock feed requirements, which were later converted to annual values (which is 2.28 tons/TLU/year). The stocking rate was calculated for common grazing land following Meshesha et al. (2019), which was set to 5.4 TLU/ha and implemented in the MPMAS_CRV. Similarly, livestock stocking rate on pasture land was calculated based on the study of Amsalu and Addisu (2014), which was conducted in a mixed crop-livestock farming system context similar to the study area. Following their studies, a hectare of pastureland can supply an average stocking rate of 10 TLU/ha. Based on this approach, a maximum of 10 TLU was assumed as a capacity to be fed on pasture land.

Credit services

Limited availability of liquidity can substantially affect smallholder farmers livelihood. It can limit the adoption of modern technologies such as improved seed and fertilizer and can impede investments like buying livestock assets that can have long-term benefits. Access to adequate capital enhances new technology uptake by relaxing liquidity constraints that could further the negative effects of shocks. In MPMAS_CRV, agents have two alternative credit sources from which they access credit to ease their liquidity constraints. These are micro-finance institutions and moneylenders, where farm agents can choose if they decide to take loans at the time of decision-making. Based on the CIMMYT household survey and different MFIs reports, the loan interest rate for microfinance institutions is 20% p.a. Since moneylenders usually set a higher interest rate, 40% loan interest was assumed in the model.

At the end of the year, agents may decide to default on credit taken for many reasons, mainly when the harvest fails due to exogenous factors like climate-induced shocks. In the MPMAS_CRV strict repayment rules were implemented for credit and repayment activities by assigning penalties for not to choose credit default. Dis-utility values were assigned to the objective functions higher than the maximum amount of credit the agents get with loan interest rates to prevent defaulting on credit voluntarily. It was implemented in the model in such a way that agents face utility loss if they choose to default on credit taken voluntarily. These rules prevent agents from voluntarily choosing to default on credit unless they are forced by unforeseen circumstances. The utility loss was assigned as credit dis-utility to show its ranking and preference order in relation to food consumption requirements and non-food expenditure objectives. Whenever they choose to default on the loans, agents are penalized and are blocked from the subsequent years credit schemes for five years. This is also true with many formal financial institutions including MFIs which have strict loan repayment rules that dictate that households are not allowed to access credit services unless they or collateral group as loan security pay loans received in the preceding year. There are circumstances where agents cannot repay the loan obligations even though they know that defaulting on credit has negative consequences on future credit access. In such situations, they wouldn't have the capacity to repay loans and prefer to default on credit involuntarily as they may not have sufficient funds. This was also implemented in the current MPMAS_CRV which makes the model feasible in case agents choose to default on credit.

Improved technology - related to cropping activities

Smallholder farm households adopt new technology or innovations if the expected utility from adoption is greater than the expected utility when they didn't adopt (Jaleta et al., 2013). This implies that accessibility of improved technology may not necessarily enhance technology adoption. Adoption of new technology is subject to various farm resources, characteristics, institutional, environmental, and cultural factors. Moreover, new technology options often come up with additional input requirements, which further determine whether to use technology or not. Thus, to enhance the adoption of technologies that can be used as climate adaptation options for the resource-poor farming population, it needs to be higher in productivity gains and more profitable than the existing technologies.

After farm households are convinced and decide to use new technologies, different factors may force them to dis-adopt the new technologies over time. Severe external shocks such as prolonged shocks could be one of the potential factors that force resource-poor farmers to abandon the use of new technologies even if they remain profitable and proven to be resilient in the face of climate variability. This is associated with the effect of recent past shocks which affect the liquidity of farmers, and other endowments which may indirectly affect input decisions and technology choices (Holden and Quiggin, 2017). Extreme climate risks like recurrent drought can result in considerable income reduction by affecting the volume of production which in turn limits the capacity to buy yield-enhancing technologies. Even when farmer access to short-term production credit is guaranteed but climate risk becomes stronger, farmers may still dis-adopt as they may choose to default as a coping measure than buy new improved seed for the subsequent production season.

In MPMAS_CRV, apart from the existing improved technologies explained earlier, the newest cropping activities and associated inputs use intensity were defined for new and high-yielding maize and wheat technologies that model agents were allowed to choose as potential climate adaptation options. Due to their importance to enhance household food security and income maize and wheat new varieties were captured and tested in the MPMAS_CRV.

Empirical studies like La Rovere et al. (2014) assumed 15% optimistic maize yield gains to analyze the *ex-ante* assessment of DTMA projects in some African countries. Productivity gains assessment from DTMA projects of CIMMYT in some African countries also shows that under random drought risk, productivity gain from maize technologies ranges from 26-47% compared to the existing improved technology (Fisher et al., 2015). Besides this in Ethiopia maize productivity is superior to wheat and other cereal grains. Mupangwa et al.(2022) study shows 20% of wheat productivity gains from different improved agronomics practices. Following these studies, it is assumed and implemented that the expected productivity gains from the newest drought/disease tolerant maize and wheat varieties would be 25% for maize and 20% for wheat cropping activities. In addition to the productivity gains, under changing climate, maize and wheat technology options are assumed to have the potential of reducing downside risk by 15%.

Resource constraints

Decisions of agents are constrained by different resource availability. The type and amount of resources available could vary over the simulation years captured in MPMAS_CRV. Labor availability is another constraining resource that is determined by household compositions (member type, age). Labor availability for individual agents was implemented in MPMAS_CRV by defining household labor compositions. Labor types and compositions (sex and age), labor provision, minimum non-food expenditure, and food requirements have been defined such that agents consistently update their labor supply at each decision stage by accounting for household demography (household member aging and unexpected death).

The seasonal nature of cropping activities dictates the seasonal labor requirements of agents in MPMAS_CRV. Higher labor is required for farm operations in the peak season, whereas in the off-season, lower labor quantities are demanded. In case the seasonality of resource uses such as labor use is erroneously ignored in the MPMAS_CRV implementation, it would make unrealistic results as some activities require more resources in some periods than available and lead to resource idle in other periods (Hazell and Norton, 1986). Labor balances were disaggregated into half-monthly bases over the periods to allow labor availability for multiple and overlapping cropping activities to account for the seasonality of labor requirements. Whenever there is a labor shortage to perform different cropping activities, agents have the option to hire labor to relax labor constraints.

Cash is also another essential resource requirement that determines agent decisions. In MPMAS_CRV, agents got initial liquidity first simulation period where there are no standing crops for harvest. It serves as financial cash available at the initialization of the simulation to meet agent financial requirements. In the subsequent simulation periods except for the first simulation period, individual agent cash balances comprise cash revenues generated from sales, cash transfer activities from the previous period, cash earned from off-farm employment, interest earned from short-term deposits, and borrowing in the current year subtracted from cash expenses, loan interest payment for short term credit.

2.5. Agent expectation formation

Farm household heterogeneity can arise from observable household characteristics–most importantly differences in resource endowments (Troost and Berger, 2015). In MPMAS_CRV, observable heterogeneity is incorporated by assigning different assets and resources available to different agents. The behavior of real-world households could also differ due to unobservable characteristics, which might be difficult to capture. Agent future price and yield expectations are unobservable but can be proxied by following different expectation formation theories in experimental economics. Such agent-specific characteristics can also make variations in the behavior of agents. Agent expectation formation is often based on agent learning experiences and exposures over time. Eisele et al. (2021) suggest that it is possible to incorporate behavioral heterogeneity of agents which arises from expectation formation into the farm household decision-making problem.

There are different forms of expectations, e.g., näive/constant, adaptive, and rational. Implementation of one of these expectations depends on research and target household exposure to communication outlets (Berger, 2001). In CRV in particular and in Ethiopia in general real-world farmers operate in conditions where communication infrastructures are poor, and crop production involves possible future shocks that adversely affect yield and price when the risks occur. This implies that future yield and price are not known at the time of decision-making as no one can predict future events perfectly (Berger and Schreinemachers, 2006). Consequently, farm agent decisions at the beginning of the simulation are based on the short-term expectation of yield and prices. Under such conditions, farm agents make production decisions without perfect foresight about weather and prices. Actual yield and prices are realized almost after a year for subsistence farmers who mainly produce annual crops. Between the production plan and realization, there could surprise like shock events which often lead to divergence of farm plans and farm outcomes *ex-post* (Berger et al., 2017). The inability to perfectly predict the future crop yield and price deter not to fully exploit the available opportunities and reduce possible future risk (Berger et al., 2017).

In the current MPMAS_CRV implementation, it was assumed that farm agent decisions are made without perfect foresight about future weather and prices which can result in variations between plans and outcomes. Agent yield and price expectations are assumed to be constant under ‘normal’ conditions. Since *ex-ante* shock mitigation measures are defined in the model, agent price and yield expectations for various shocks are also assumed constant. Crop yield and price information implemented in the model was available from CIMMYT - SIMLESA survey. Prices for all commodities are not available in the CIMMYT survey which was complemented by data from CSA.

2.6. Smallholder household decision-making under recurring shocks

Subsistence smallholder households have been facing various compounding factors which threaten their food security status and make their income unstable from year to year (Hazell and Norton, 1986). To counteract the effect of the extreme shocks, farm households often employ a combination of different adaptation options as precautionary measures to reduce exposure to risks. Failing to consider risks and risk management strategies in representing farm households decision-making in the farm-level simulations would bias simulation results. This implies that simulation results reflect little reality of the actual decisions of farmers which highly reduces its credibility and replicability (Hazell and Norton, 1986).

In representing farm household decision-making in MPMAS_CRV, considerations of *ex-ante* measures were explicitly captured by including different risk management options that agents can implement in production decisions. As shock occurrence is unpredictable, agents are uncertain about future yield and price. As a result, they need to take precautionary measures to minimize the effects of possible shocks. When model agents anticipate risks at times of production decisions, they plan and implement measures that help to reduce the adverse effect by choosing various *ex-ante* measures. Such measures include choosing drought/disease tolerant crop varieties from cropping activities which can provide better yield under worst-case condition compared to crop varieties that are susceptible to climate-related shocks and carries substantial yield penalty.

2.7. Accounting for inflation in MPMAS_CRV implementation

Prices in Ethiopia are affected by inflation both for farming inputs and outputs. The purchasing power of cash decreases over time due to high inflation, which further alters household decisions. In MPMAS_CRV, inflation is dealt with by factoring it out. Real or constant prices were used everywhere in the model and correspondingly also real interest rates for deposits and loans. However, a special situation arises if the inflation rate is higher than typical deposit rates available to households (when bank accounts are available at all). In Ethiopia, the general annual inflation rate in 2012/13 was 13.5 % and the deposit bank interest rate was 7%, which negatively affects savings (NBE, 2020). However, a negative interest rate on deposits is not enough since agents would keep the money in cash. This cash also loses value due to inflation. This was captured in MPMAS_CRV as cash transfers were devaluated by the assumed inflation factor, which was 15%. Due to this, not all amounts of cash are transferred from one period to another but only the inflation corrected factor of cash as the remaining cash value is lost due to inflation.

2.8. Working definition of outcome indicators in the MPMAS_CRV

External factors such as recurring climate shocks and locust invasions usually cause severe production loss which has a direct impact on household food security and income. Apart from this, it adversely affects the livestock assets of smallholder farmers who often sell them for consumption smoothing during hardships. Therefore, this thesis used three outcome indicators to measure the welfare status of agents: (1) discretionary income, (2) food security status, and (3) equity in the form of livestock assets.

1) To measure agent income status, discretionary income was used. Discretionary income is defined as the amount of income left after meeting minimum food and essential non-food expenses. This is the amount of agent incomes available for spending on any non-essential expenses which are not required for the farm operations which may include investments or long-term savings. Discretionary income depletes first when any external shocks severely affect agent incomes. When discretionary income happens to be negative, it implies that agents cannot cover the minimum essential non-food expenditure. When discretionary income is positive it implies that agents achieved basic necessities like food and essential non-food expenditures and possess surplus income.

2) The agent food security status refers to whether individual household agents can meet the minimum food nutrition requirements or not. Food nutrition is divided into calorie and protein intake at the agent levels. Minimum food nutrition demand was implemented in MPMAS_CRV for individual household labor groups as food protein and energy requirements are household size-specific depending on gender and household composition. At times of extreme climate-induced shocks like drought and crop disease events, food

availability and access could be severely hampered due to production losses or reductions resulting in a temporary food shortage or deficit. Once shock occurs, the effects may last for more than one production season which becomes recurring. Increased climate variability aggravates existing household food shortages for smallholder households and leads to seasonal food insecurity (Angassa and Oba, 2007).

3) Livestock assets are also another policy variable that needs to be measured against external shocks. Livestock assets are important farm endowments for smallholder farmers that are often employed *as ex-post* coping measures to counteract external shock impacts. Recurrent and severe shocks have the potential to erode the productive assets mainly livestock resources of smallholder farmers which cannot be easily restocked within short periods.

Overall MPMAS_CRV of Ethiopia was parameterized for heterogeneous agents over 15 years of planning. In each MILP there are 25,741 columns, 17,282 rows, and 14,369 integers to simulate individual household decisions in MPMAS_CRV. Input files conversions were run on a local computer with high processing capacity. For running simulations, *bwForCluster* computational resource was used which is funded by the Ministry of Science, Research and the Arts and the Universities of the State of Baden-Württemberg, Germany, within their *bwHPC* program.

Chapter 3: Farm household perceptions on climate-induced shocks and risk management strategies: Evidence from exploratory field research in Central Rift Valley of Ethiopia

3.1. Introduction

Smallholder farmers in sub-Saharan African countries have been operating in risky environments mainly emanating from climate change and variability. Their livelihood depends on agriculture with a small area of land which is mainly rain-fed. Over several years, farmers have developed different risk mitigation strategies from their long-term experience and subjective risk assessment (Kassie et al., 2013). Understanding local and indigenous risk management (adaptation/coping) strategies to address climate-induced risks helps to improve recommendations on sets of adaptation strategies (Kassie et al., 2013). Government policy interventions that take into account the integration of local adaptation practices and scientific innovations would also have a higher probability of bringing positive livelihood impacts than implementing exogenously generated technical innovations alone.

Assessment of farmer perceptions about the trend of climate variability and the severity of associated climate shocks helps to incorporate local-level adaptation strategies in MPMAS_CRV and assess their roles in reducing the effects of climate shocks. Moreover, understanding local knowledge and farmer perceptions helps to design appropriate policy interventions to reduce the effects of climate shocks. Di Falco (2014) argues that farmer perceptions about climate variability are an important component of the policy targeting process.

To explore farmer behavior and perceptions of the impacts of climate shocks, extensive exploratory field research was conducted in CRV in 2018 in selected villages from the districts already implemented in the MPMAS_CRV. Focused group discussions (FGD) were conducted in 5 villages (3 in maize-growing and 2 in wheat-dominated areas). Before organizing each FGD in these villages, field guides were oriented on the purpose of the study and criteria for choosing and inviting farm households from the community. Accordingly, FGD participants were invited from different social and economic strata (poor, better off, and male, female, young, and old) to get diverse perceptions. Agricultural experts working closely with farmers in the villages were also asked separately to understand expert views. In each FGD, 10-15 discussants participated in the meeting. Each FGD was guided by a checklist prepared before field research. Leading questions such as climate risk profiles, perceptions of risk, risk occurrence trends, and local risk management strategies were part of the checklist. Discussants were asked about their observations and experiences in the patterns of temperature and rainfall over the past years, their perception of climate-induced shocks like drought events, and their perceived impacts on crop production and livelihood.

3.2. Results from exploratory field research

3.2.1. Farm household perceptions on climate variability and change

During the field research, farmers and experts were asked how they perceive climate variability, its impacts, and coping measures. They unanimously explained that over time they are experiencing considerable rainfall variability. It was reported that due to unpredictable rainfall distributions and amounts, crop planting and harvesting season has shifted considerably. In the past, they used to plant cereals like maize in March/April as soon as the rain started, with a long growing period often extends until September/October. Over time, however, the rainy season onset has become late and short, even pushing maize planting towards May/June.

According to farmer perceptions, dry spells have become frequent and prevalent during crop growth stages due to rainfall variability. Rainfall variability causes extended dry spells at different crop growth stages that significantly affect grain filling and subsequently affect crop harvest. They perceive extended dry spells as an indicator of drought conditions. Farmers experience with dry spells and their effects are also confirmed by scientific research conducted by Mamo et al. (2016) in CRV which shows that the probability of dry spells is higher during the early parts of the growing season, with a declining trend until the peak of the rainy season and slopping up towards the end of the rainy season. They found out that in-season dry spells with varying lengths either during the early or later parts of the crop growing season can adversely affect crop growth performance and yield particularly if it occurs at any of the sensitive crop growth stages like flowering.

Farmers perceive drought shock as a natural disaster caused by a shortage or complete failure of rains during the crop growing season. They perceive that rainfall variability is also considered as the main cause of crop diseases such as rust epidemic in wheat-growing areas. Due to early cessation of rain, crop diseases have become more common resulting in yield variability and substantial crop yield losses. Many farmers and experts explained that drought events and rust epidemics have become very common in recent years. They reported that 15 and 20 years ago, the shock frequency was like once in 10 years. But currently, they occur 2 to 3 times in five years. Drought has become very frequent, especially in semi-arid areas of CRV where moisture stress is very prevalent. Perceived risk factors, their temporal properties, and their effects are summarized in Table 1.

Table 1: Perceived production and market risks, frequency and their effects

Risk factor	Frequency and intensity	Perceived adverse effects
Drought	frequent, low intensity	harvest failure, food supply shortage, increased output price, reduced income, loss of livestock
Flooding	less frequent, high intensity	total yield loss, land degradation
Crop diseases	frequent, high intensity	yield reduction, income losses
Market price volatility	frequent	reduce household income

Source: own exploratory survey, 2018

3.2.2. Farm household experiences on climate adaptation and coping mechanisms

During the field research, farmers were asked how they respond to the risk factors identified in Table 1. According to their responses, adaptation and coping options greatly vary across the study areas and production systems. The main adaptation strategies used by farmers to climate-induced shocks are using different crop varieties which are promoted by the government as drought and disease-resistant, early maturing, and high yielding. Moreover, changing cropping and planting dates, migration, searching for off-farm employment, food storage, selling livestock, and borrowing money from relatives are some of the risk management strategies farmers employ to minimize climate shock effects (see Table 2). To reduce the adverse effects of the rust epidemic incidence, farm households spray chemicals multiple times. Due to increased shock frequency and intensity, old crop variety said to be shock-resistant has become susceptible which results in low production.

Consequently, farmers keep on replacing crop varieties, especially in wheat-dominated areas. In both wheat and maize production systems, farmers and experts agreed that the current wheat and maize varieties are completely different from what they used to grow 5 to 10 years back as the old varieties become susceptible to crop diseases and droughts. Crop variety replacement is also partly driven by the continuous generation and promotion of new crop varieties by the government which are believed to withstand drought and disease shock effects. In some districts like Shalla and Hawassa, farmers practice double-cropping using a short rainy season within one production calendar. In the short rainy season, they grow teff and subsequently beans on the same plot in the main rainy season.

Table 2: Common farm-level risk management strategies

Risk management strategies	***Ex-ante/ex-post***
Engage in off-farm employment activity	*Ex-post*
Precautionary cash reserve	*Ex-ante*
Dis-saving	*Ex-post*
Taking out micro-credit	*Ex-ante/ex-post*
Mutual assistance (in-kind support)	*Ex-post*
Temporary migration	*Ex-post*
Temporary renting out land	*Ex-post*
Sell livestock, including oxen	*Ex-post*
Store food	*Ex-ante*
Growing drought-tolerant crop varieties	*Ex-ante*
Adopting short-maturing crop varieties	*Ex-ante*
Application of pesticides (for rust epidemics)	*Ex-post*
Crop diversification (double cropping)	*Ex-ante*

Source: Own exploratory survey, 2018

Chapter 4: Empirical model validation and uncertainty analysis

4.1. Empirical model validation

4.1.1. Introduction

Due to increasing number of farm-level and agent-based models in explaining or predicting farm household behaviors, the interest in empirical model validation has been growing. Empirical modelers need to check whether their application for a specific area or region and research question reproduces the reality on the ground before using the simulation results for policy analysis and recommendations. To be useful, simulation models must be able to exhibit the key properties of the real-world system which they are supposed to represent (Wossen et al., 2014; Wossen and Berger, 2015). Likewise, reviewers and stakeholders are also interested to know the goodness-of-fit of the simulation model to build trust in the results. This approach further ensures transparency and consistent communication about the model result credibility (Troost and Berger, 2020).

There has been a long debate among ABM modelers on the types of methodological approaches to conducting formal empirical validation (Troost and Berger, 2020). As ABM applications are in diverse disciplines and contexts, there has not been a consensus among the modelers on the choice of empirical model validation methods (Troost et al., 2023). Consequently, ABM modelers employ a large variety of validation methods as a “one *size fits all*" approach cannot be easily materialized and is undesirable as it limits flexibility (Troost and Berger, 2020). Troost et al., (2023) argued that model validity is to ensure the adequacy of simulation analysis for the intended purpose. It implies that choices of methods for empirical validation entirely depend on research types in different fields of studies, availability and adequacy of datasets about the system being modeled, and research questions to be answered (Troost et al., 2023).

As there is no single standard and agreed approach in all studies, the application of combinations of different empirical validation approaches, which would augment each other, would increase the model results credibility and replicability. Bert et al. (2014) suggested that empirical model validation approaches for farm-level modeling including ABM can take two complementary ways. The first approach is micro face validation, where the mechanisms and properties of the simulation models are compared against the actual observed properties. The approach involves different conceptual validity methods, including local experts and other stakeholders who know the context in which the model is being built. It allows for checking some of the model results with the local experts and farm households and then verifying the underlying assumptions considered while building a model.

The second approach is an application of empirical data to validate model outcome indicators. This approach compares how well the simulation model results match the actual observation: simulated-observed comparison approach by using different outcome measures both in observation and simulation. A model is considered good when it fits the observed data better - with higher expected predictive powers (Troost and Berger, 2020).

For empirical model validation, finding a good comparison is often challenging. One key issue is the limited availability of detailed and up-to-date datasets in terms of dimensionality, representativeness, and variance to well parameterize the model and use it for comparison in empirical model validation (Troost and Berger, 2020). Likewise, due to its higher resource demand, time-series data are largely missing at the farm and plot level (Berger and Troost, 2012). Historical cross-sectional observation data are often available for modelers for empirical model validation even if it involves systematic errors in reflecting the actual conditions. Ciaian et al. (2013) argue that historical data are used to validate model results which are often less accurate and involve many systematic errors. Despite its limitations, historical data collected through household surveys have been extensively applied in different farm contexts to check the reliability of model results with different outcome indicators and comparison methods.

Many empirical research approaches used historical data to demonstrate empirical model validation with the application of MPMAS before using the simulation results for policy analysis or any kind of prediction. To examine the extent to which the model was able to capture farmer decisions Berger and Schreinemachers (2006) suggested comparing simulated to observed land uses at an individual and aggregate level using goodness-of-fit. Schreinemachers and Berger (2011) also compared observed with simulated land uses as an indicator for model validation. Similarly, Berger et al. (2017) employ per-adult food expenditure and area of land cultivated as indicators for model validation over full model repetitions. Regression analysis was also used as an approach to validate MPMAS results by regressing simulated characteristics of agents on observed household characteristics (Wossen et al., 2014; Wossen and Berger, 2015). Troost and Berger (2015) extend this validation approach and introduce model efficiencies based on standardized absolute errors.

4.1.2. Methods

After MPMAS parameterization with farm-level data, the simulation results were validated by employing different complementary approaches at various model building, testing, and analysis stages to test that the model is capable of replicating reality. Such approaches help to develop confidence in model results and check if simulation results reproduce real-world observations (Wossen et al., 2014). This can also improve the applicability of model results for wider policy analysis (Bert et al., 2014). Two model validation approaches were employed in this thesis to check the reliability of model results.

The first approach employed to check MPMAS_CRV was face validation for model test results. At this stage, the aim was not to conduct full model validation as the parametrized MPMAS_CRV results were being tested whether they realistically reflect what real farmers are actually doing. Rather the purpose was to verify and get feed back on parameter values implemented in the model and validate whether the test results were plausible. Following Berger and Troost (2012) approach, field research was organized and conducted in five selected villages of the study areas in 2018 to discuss with farmers and experts on the appropriateness of parameters and their respective values used in the MPMAS_CRV as input files. The key assumption in the model setup was checked for variables like household consumption, technological options, off-farm employment opportunities, input use types, and intensities with farmers and experts. This was made through discussions with farm groups and experts in five villages of the study areas. In addition to this, some values of parameters computed from the CIMMYT household survey were cross-checked as survey data are often prone to errors. Triangulation was made with farmers about parameters values of yields, relative crop and livestock prices, land-use shares, livestock, and landholding, cropping patterns, and resource capacities to make the simulation results as realistic as possible. After getting feedback from farmers and experts, important model parameter values were adapted and assumptions on these variables like household consumption rules were revised that subsequently used to improve model results. Such verification and validation approaches are relevant to cross-checking simulation model results before getting a full-fledged result analysis and also enhance farm household participation at local levels (Berger and Troost, 2014). Furthermore, the approach provides an opportunity to adjust model parameter values, revise simulation model input files or consider additional constraints and decision variables that have never been considered in the model (Bert et al., 2014).

The second approach employed was the comparison of results of MPMAS_CRV results against observed household survey results as it has been done in many empirical studies which applied MPMAS. Results for relevant outcome indicators such as land use, livestock holding, and quantity of crop sales were computed from household surveys to compare with similar outcome indicators in MPMAS_CRV. Then, observed outcome variables from the CIMMYT household survey were compared to simulated outcome indicators in the first simulation year of MPMAS_CRV. The main purpose of the comparison was not to compare real-world farm household outcome variables against individual model agent outcome decisions but to establish consistency of observed outcomes pattern between simulation and observation over the agent population or cluster of agents (Wossen et al., 2015). This approach was illustrated by plotting distribution graphs (kernel density and scatterplots) that depict how well simulated and observed outcomes were fitted. This also shows whether the simulated outcomes are over or under-fitted compared to outcome indicators in observation data.

Fitting regression model was also employed for empirical model validation as an alternative approach meant to establish systematic relationships between outcome variables and farm and household characteristics. Multinomial logistic regression (MNL) was employed to establish the systematic relationship between explanatory variables in the observation and simulation. Relevant explanatory variables used in the model are: observed household and farm characteristics, agroecological zones, household endowments, and institutional factors like access to credit services which were computed from the household survey of CIMMYT and used in fitting MNL (Table 3). The purpose of fitting MNL was not to get the full-fledged results of classical regression but to observe the relationships between important explanatory variables and decision outcomes. It is not to compare each agent to its observation counterpart but to make sure that the regression model captures the essential patterns in the empirical data. Once validation of the model outcomes against the best possible available data is conducted and a plausible pattern is established, then simulation experiments can be sequentially run to isolate the effects of parameter changes (Berger et al., 2006; Berger and Troost, 2012).

Table 3: Description of explanatory variables used in the MNL regression

Variables	Description of variables
Farm size	Total household farm size (hectare)
Family size	Total household size (number)
TLU	Total livestock holding (TLU)
Age	Age of household head (year)
Education	Education status of households head(1= literate, 0, otherwise)
Credit for fertilizer	Credit access for fertilizer purchase (1=yes, 0, otherwise)
Credit for seed	Credit access for improved seed purchase(1=yes, 0, otherwise)
Ext. Service	Access to extension service (1=yes, 0, otherwise)
Production system	Production system (1=wheat dominated, 0, otherwise)
Farm size*family size	Interaction between farm size and household size
Farm size*TLU	Interaction between farm size and livestock holding

4.1.3. Model validation results

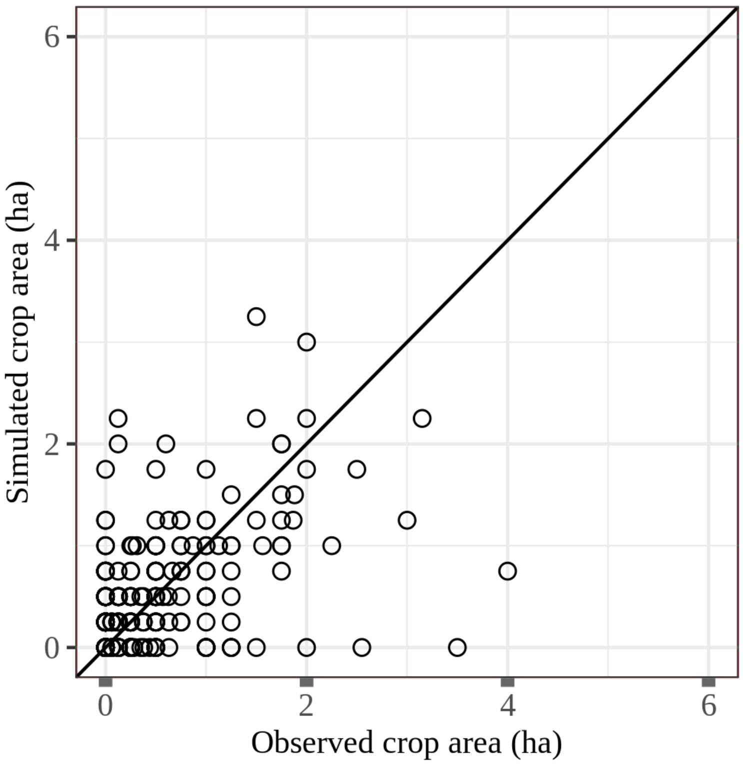
Household land use

Land ownership is a key resource for smallholder farm households. The size of the land is an important indicator of household welfare and wealth status in the community. Due to this farm household decisions to adopt improved technologies, livestock herd size, household food security, and income status are highly linked to land size.

To check whether MPMAS_CRV replicates the actual observations or not land use was computed for major crops (maize, wheat, barley, common bean, and faba bean) widely grown in the study area. CIMMYT household survey data was used to establish comparison crop areas for simulation model outcomes.

Figure 3 shows the comparison of simulated and observed land-use area distribution for major crops from the household survey and MPMAS_CRV results for all agents. The graph shows that many agents and farmers allocate about a hectare of land for growing the major crops. The graph further depicts that there is a slight underestimation of land use in higher crop areas.

Figure 3: Observed and simulated land-use area distribution for major crops

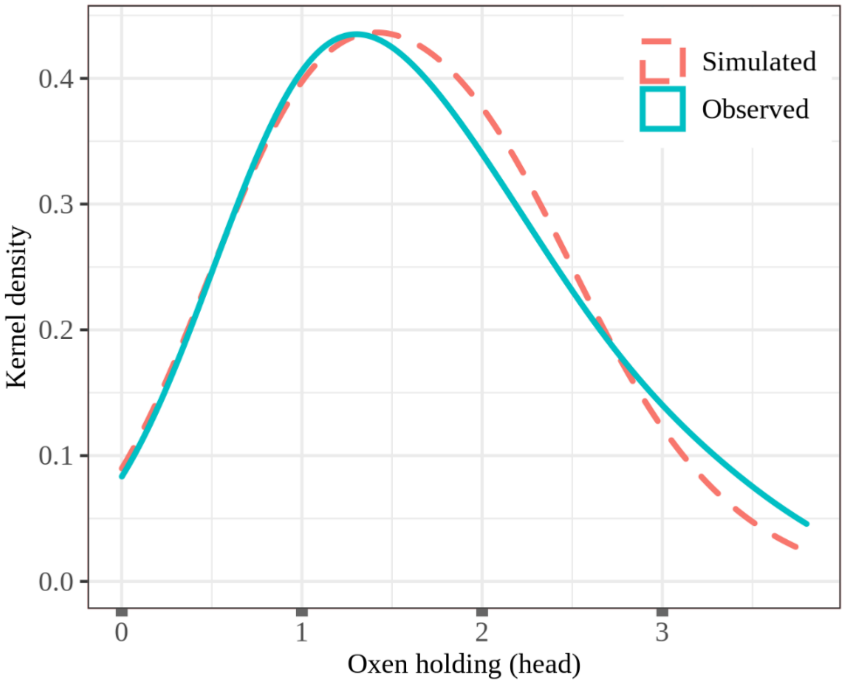


Household livestock holding

Mixed crop-livestock farming is the dominant livelihood strategy in the study area. Crop and livestock farming are highly integrated in terms of farm resource sharing and flows. Livestock provides draft power and manure for crop production, whereas crop residues are used for livestock feed. On the other hand, smallholder farmer sells livestock to satisfy household cash consumption requirements both during normal and bad years. This important asset was included in the farm-level simulation model as the model is capable of capturing the whole-farm system.

Figure 4 depicts the average oxen holding distribution for observed and simulated results over the agent population. The figure shows that many model agents own about two oxen in the simulated results which are also similar to real-farm households in the observed result. The average oxen holding was calculated from second-year simulation results and compared to the observation from the household survey. A closer visualization of the kernel density distribution graph shows the ABM model has a similar pattern to real observation with slight underestimation at higher oxen holding.

Figure 4: Observed and simulated oxen holding distribution



In addition to oxen holding, comparison is also made for all livestock species that the agents own. TLU[7] was calculated following Storck et al. (1991), which helps to convert different livestock species into the same unit. Figure 5 shows that many farmers and corresponding computational agents own about 3 livestock heads measured in TLU. It also shows that the maximum number of livestock heads is somewhat lower in the MPMA_CRV than in the observed data. The distribution graph further shows a similar pattern between simulated and observed livestock holding with slight underestimation at higher heads of livestock (Figure 5).

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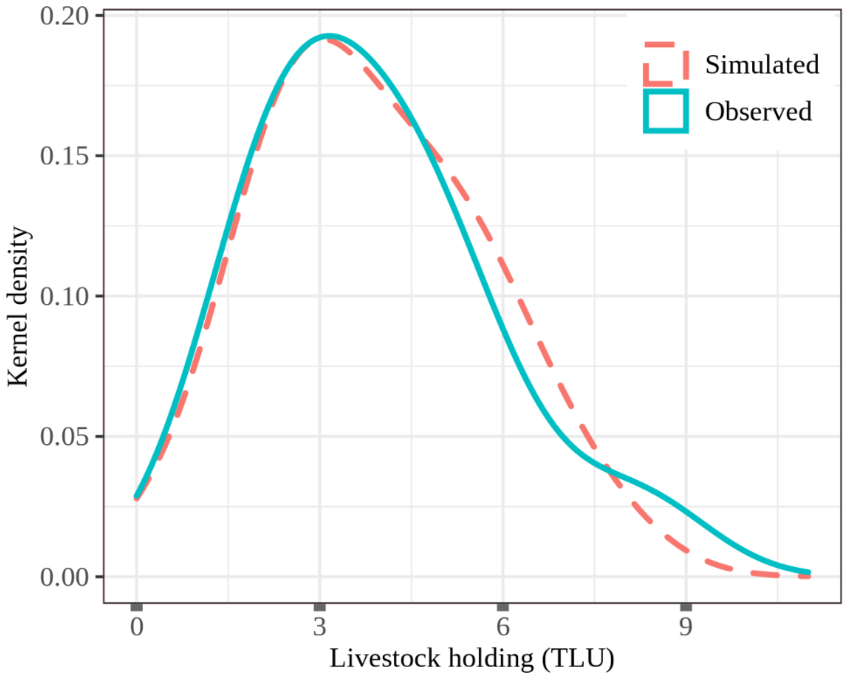
[7] Tropical Livestock Units 1 TLU = 250 kg live weight

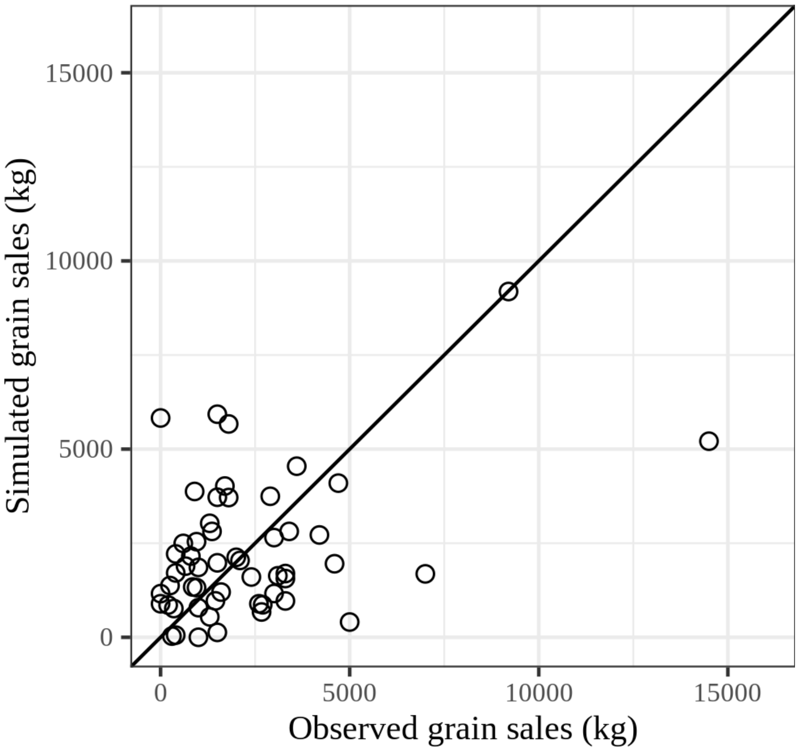
Figure 5: Observed and simulated livestock distribution (TLU)



Household grains sales

Grain sale is an essential component of crop harvest utilization that can indicate the status of household food- self-efficiency. Smallholder farm households often sell part of their produce to meet basic cash consumption requirements and cover upfront production input costs. The amount of sales is also determined by farmer market orientation behaviors and production volume in a given period (Gebremedhin and Tegegne, 2012). When there is a good harvest season due to better rainfall conditions, the grain yield volume increases which may increase the amount of grain taken to the market. Increased market participation may imply subsistence farming transition to (semi) commercialize agriculture by improving productivity through the application of higher modern inputs. It can also show a given households market position, whether it is a net buyer, a self-sufficient or a net seller. Figure 6 compares simulated grain sales to the observations from the household survey of the agent population. It can be visualized that there are similar patterns between simulated and observed results with slight overestimation at lower grain sales.

Figure 6: Observed and simulated grain sales distribution



Apart from illustrating model validation indicators with distribution graphs, the MNL model was additionally fitted to determine if systematic relationships exist in the datasets with land-use share indicators. MNL was fitted with observations for nine land use categories used as the dependent variables with relevant explanatory variables. Unlike other standard regression models, MNL doesn't provide the R^2 to measure the goodness-of-fit. Consequently, as a proxy to R^2 to illustrate the goodness of model fit, the share of correctly classified (SCC) plots was calculated. To check the existence of systematic relationships in the empirical data, MNL was fitted at different aggregation levels. First MNL was fitted for the whole study area (full sample) and then fitted separately to the maize and wheat-dominated system to check the goodness-of-fit of the model at different aggregation levels.

Table 4 shows the MNL results for the nine land use categories in the study areas. Potato land use is a base category in the model where other land use coefficients are interpreted against the base. From MNL, land use is influenced by household endowments like farm size, household size, and agroecological zones. Maize and pasture land use shares are significantly influenced by total farm size and agroecological zone predictors. Maize and pasture land use share increase as households own higher total land areas (Tables 4 and 5). Moreover, maize land use share is lower in wheat-dominated production systems, whereas pasture land use is higher in the same agroecological zone (Table 6). Similarly, common bean land use share is lower in wheat-dominated areas, whereas faba bean land use share is higher in both systems. The SCC values of correct classification are 0.64, 0.52, and 0.68 for all samples, maize-dominated and wheat-dominated systems respectively, which are used to measure the goodness of fit of the MNL model. Overall, 64 %, 52 %, and 68 % of the variation are explained by fitted MNL in all samples, maize, and wheat-dominated systems respectively (Tables 4 to 6).

Table 4: Multinomial regression results of land use determinants (full sample)

Land use category	farm size	Family size	TLU	Age	education	credit fertilizer	credit for seed	ext. service	production system	farm size *farm size	farm size *TLU
Faba bean	0.256 (0.277)	-0.156 (0.132)	0.100* (0.065)	-0.011 (0.013)	-0.545 (0.442)	-0.517 (0.465)	-0.740* (0.508)	0.764 (0.544)	0.625* (0.451)	-0.004 (0.031)	-0.018* (0.013)
Barley	0.232 (0.210)	-0.060 (0.097)	0.056 (0.048)	-0.032*** (0.010)	-0.848*** (0.350)	0.150 (0.335)	-0.212*** (0.356)	1.308 (0.422)	0.107 (0.313)	-0.014 (0.022)	-0.008 (0.009)
Maize	0.736*** (0.231	0.138* (0.096)	0.057 (0.047)	-0.025 (0.010)	-0.799*** (0.337)	0.320 (0.324)	-0.643** (0.341)	0.765** (0.358)	-3.564*** (0.317)	-0.093*** (0.025)	-0.008 (0.010)
Teff	0.117 (0.256)	-0.109 (0.114)	0.103** (0.051)	0.003 (0.012)	0.013 (0.406)	-0.489 (0.385)	0.307*** (0.406)	1.607 (0.572)	-1.514 (0.361)	0.000*** (0.027)	-0.011 (0.010)
Wheat	0.216 (0.194)	-0.042 (0.091)	0.118*** (0.045)	-0.026*** (0.010)	-0.856*** (0.338)	0.209 (0.320)	-0.347 (0.341)	0.421 (0.363)	0.967*** (0.306)	-0.009 (0.020)	-0.010 (0.009)
Pasture	0.667*** (0.217)	-0.068 (0.109)	0.186*** (0.053)	-0.042*** (0.011)	-1.271*** (0.379)	-0.119 (0.373)	-0.267 (0.401)	-0.628 (0.399)	7.986*** (0.543)	-0.021 (0.024)	-0.025*** (0.010)
Fallow	0.295 (0.387)	0.073 (0.200)	-0.057 (0.121)	-0.067*** (0.028)	0.006 (1.176)	0.480 (0.658)	-5.370 (0.025)	5.501 (0.736)	4.553*** (0.795)	-0.008 (0.042)	0.000 (0.023)
Common bean	0.181 (0.291)	0.144* (0.107)	0.078* (0.053)	-0.001 (0.011)	-0.809*** (0.363)	1.097*** (0.362)	-0.770** (0.369)	0.183 (0.382)	-8.812*** (0.013)	-0.093*** (0.033)	-0.001 (0.013)

Potato land use is a base category in the MNL model
Standard errors values are in parentheses

** Significance at 10 percent level. ** Significance at 5 percent level. *** Significance at 1 percent level*

the overall share of correctly specified (SCC) plots for the study area is 0.64

Table 5: Multinomial regression results of land use determinants (maize-dominated system)

Land use category	farm size	family size	TLU	age	education	credit for fertilizer	credit for seed	ext. service	farm size*family size	farm size*TLU
Faba bean	3.302***	0.613*	-0.116	-0.080**	4.533***	-0.588	-1.615*	7.081***	-0.500**	0.159**
	(1.155)	(0.449)	(0.217)	(0.039)	(0.880)	(1.102)	(1.134)	(0.836)	(0.194)	(0.088)
Barley	1.480**	0.445**	-0.270**	-0.076***	-1.383**	1.119**	-0.233	2.529***	-0.233***	0.164***
	(0.721)	(0.199)	(0.152)	(0.020)	(0.634)	(0.627)	(0.605)	(0.691)	(0.068)	(0.062)
Maize	2.030***	0.564***	-0.262**	-0.060***	-0.843*	0.451	-1.170**	1.506***	-0.309***	0.184***
	(0.674)	(0.184)	(0.145)	(0.018)	(0.596)	(0.555)	(0.539)	(0.553)	(0.063)	(0.060)
Teff	1.037*	0.240	-0.234*	-0.027	0.116	-1.224**	-0.348	2.402***	-0.177**	0.194***
	(0.757)	(0.215)	(0.151)	(0.021)	(0.686)	(0.621)	(0.609)	(0.760)	(0.071)	(0.061)
Wheat	1.194*	0.274*	-0.210*	-0.068***	-0.854*	-0.225	-0.889*	1.198**	-0.197**	0.192***
	(0.726)	(0.203)	(0.149)	(0.021)	(0.658)	(0.610)	(0.600)	(0.622)	(0.068)	(0.061)
Pasture	0.622**	0.261	-0.302	-0.029	-0.738**	0.349	-0.924	1.058	-0.182	0.211
	(0.310)	(3.147)	(2.085)	(0.335)	(0.393)	(0.158)	(0.091)	(0.058)	(0.691)	(0.553)
Fallow	1.979	0.363	-0.261	-0.085	-0.528	0.385	-0.782	0.928	-0.292	0.194
	(5.013)	(3.095)	(1.852)	(0.464)	(2.524)	(1.501)	(1.486)	(2.017)	(0.933)	(0.554)
Common bean	1.369**	0.558***	-0.250**	-0.036**	-0.877*	1.197**	-1.262**	0.960**	-0.302	0.194***
	(0.690)	(0.188)	(0.146)	(0.019)	(0.606)	(0.575)	(0.555)	(0.563)	(0.066)	(0.061)

Standard errors values are in parentheses

** Significance at 10 percent level, ** Significance at 5 percent level, *** Significance at 1 percent level*

The overall share of correctly specified (SCC) plots for the maize-dominated system is 0.52

Table 6: Multinomial regression results of land use determinants (wheat-dominated system)

Land use category	farm size	family size	TLU	Age	education	credit for fertilizer	credit for seed	ext. service	farm size*family size	farm size*TLU
Faba bean	0.006	0.092	-0.057	0.046***	0.212	-0.285	-0.246	0.154	-0.013	0.001
	(0.303)	(0.16)	(0.074)	(0.016)	(0.535)	(0.578)	(0.634)	(0.688)	(0.034)	(0.013)
Barley	0.092	-0.099	0.037	0.016	0.328	0.168	-0.412	0.974	0.013	-0.014
	(0.243)	(0.137)	(0.064)	(0.014)	(0.481)	(0.489)	(0.533)	(0.631)	(0.028)	(0.011)
Maize	-0.240	0.231*	-0.084	0.022	-0.035	0.001	-0.374	0.059	-0.047	0.019*
	(0.370)	(0.179)	(0.072)	(0.018)	(0.570)	(0.590)	(0.656)	(0.744)	(0.043)	(0.012)
Teff	-0.100	0.148	-0.144*	0.057***	1.165*	0.608	0.328	21.414	-0.052	0.021*
	(0.430)	(0.204)	(0.085)	(0.018)	(0.615)	(0.590)	(0.626)	(0.801)	(0.053)	(0.015)
Wheat	0.024	0.123	-0.011	0.024**	0.077	0.383	-0.058	0.337	-0.015	0.003
	(0.227)	(0.127)	(0.057)	(0.013)	(0.448)	(0.458)	(0.494)	(0.560)	(0.025)	(0.009)
Pasture	0.466**	0.061	0.073	0.005	-0.350	0.007	-0.088	-0.792	-0.022	-0.013*
	(0.243)	(0.138)	(0.061)	(0.014)	(0.471)	(0.489)	(0.528)	(0.560)	(0.027)	(0.010)
Fallow	0.106	0.201	-0.170	-0.021	0.906	0.598	-23.581	19.828	-0.010	0.011
	(0.406)	(0.219)	(0.126)	(0.030)	(1.209)	(0.736)	(0.001)	(1.195)	(0.045)	(0.024)
Common bean	-0.275	-0.208*	-0.566***	0.124	4.151***	-2.319***	-3.494	-8.154	-0.016	0.048
	(0.231)	(0.128)	(0.167)	(0.264)	(0.025)	(0.001)	0.001	(0.001)	(1.484)	(0.571)

Standard error values are in parentheses

** Significance at 10 percent level, ** Significance at 5 percent level, *** Significance at 1 percent level*

The overall share of correctly specified (SCC) plots for the wheat-dominated system is 0.68

From the above three tables of MNL results for all samples, maize, and wheat-dominated systems, it can be concluded that more than 50% of the variations are explained by the explanatory variables fitted in MNL. This shows that there is a systematic relationship between land use share and explanatory variables like farm size in the empirical data from which MPMAS_CRV was parameterized.

4.2. Uncertainty analysis with MPMAS

Disaggregated farm-level simulation models involve considerable model uncertainty (Troost and Berger, 2015). Failing to capture and analyze such embedded model uncertainty might lead to erroneous policy formulations. The modelers require to check the robustness of the simulation results under different parameter variations and combinations to minimize bias. For a better understanding of how these uncertain model parameters affect the results, model uncertainty needs to be documented in a transparent manner. Troost and Berger (2015) suggest reporting the global distributions over the uncertain parameter space is more important rather than analyzing and reporting simulation outcomes as point estimates. This approach would sufficiently capture potential parameter combinations and model parameter uncertainty.

Model uncertainty emanates from unknown values of parameters or process representation in the parameterized model which may not be fully eliminated but can be minimized (Berger and Troost, 2014). The global uncertainty analysis (UA) approach refers to the determination of the uncertainties in model outcome analysis (Helton et al., 2006). Among various types of uncertainties, epistemic is common and arises from incomplete knowledge of the appropriate value to use for the quantity that is fixed in a given analysis (Berger and Troost, 2014; Helton et al., 2006). These values are associated with uncertainty in the model structures and parameters. Such problems can be minimized by using quality input data, choosing well-tested modules, and validating model results with different methodological approaches like carrying out UA (Berger and Troost, 2014). Finding quality input data is often quite challenging as many available datasets are historical which might not fully reflect the current situation of farm households. In such cases, carrying out UA will be important because it helps to vary the values of parameters and allows for their combinations.

MPMAS is well-suited for creating computer simulation experiments for uncertainty analysis. It helps the modelers to identify model input parameters (model parameters and exogenous variables), allows them to create input parameter combinations, and generates several ranges of values for parameter combinations. This virtual experiment helps to analyze how far the results/conclusions of simulation outcomes are robust under different ranges of uncertain parameters. Accounting for any unknown values of model inputs helps to evaluate the model results under different parameter combinations. Moreover, it enables to identify robust policy interventions including adaptation measures in the face of severe external shocks (Berger and Troost, 2014). Uncertainty experiments allow for combinations of all UA model parameters implemented in the model that gives full factorial design. However, this has a curse of dimensionality and requires considerable computational resources which poses an additional challenge if high-performance computing is not employed (Troost and Berger, 2015). Sampling-based UA is necessary especially when there are many parameter combinations with wide ranges.

In MPMAS_CRV, a Sobol' sequence was employed with uniform distribution for sampling from full factorial combinations of identified model inputs following the approach first developed by Berger et al. (2017). The Sobol' sequence is a quasi-random sampling technique that covers the parameter space more evenly and converges faster (Tarantola et al., 2012). Compared to other sampling techniques such as Monte Carlo and space-filling designs like Latin-hypercube, Sobol' design has many comparative advantages. Sobol’ sequence produces a more representative sample of combinations with a lower number of model runs and, therefore, the estimates converge more rapidly compared to other techniques. Other sampling techniques like Monte Carlo make the sampling less efficient as the sampling is made entirely random, and there could be a space. Due to these comparative advantages, Sobol' design has been applied widely in many practical cases (Berger et al., 2017; Tarantola et al., 2012).

Empirical studies (Berger et al., 2017; Berger and Troost, 2014; Troost and Berger, 2015) employed statistical procedures to analyze MPMAS parameter uncertainties in farm-level simulation analysis. This was done by implementing and including possible ranges of parameter values used in the model inputs parameterization and evaluating the model results under different parameter combinations. Following the empirical approach, this thesis identified 38 main model parameter uncertainty which helps to generate different parameter combinations and create model repetitions over scenarios. Table 7 shows the description of uncertain model parameters, their distribution type and minimum and maximum values.

Table 7. Description of model parameter uncertainty as implemented in MPMAS_CRV

Variable	Description	Distribution sample	Minimum value*	Maximum value*
Wheat price	Variation factor	Uniform	0.5	1.5
Maize price	Variation factor	Uniform	0.5	1.5
Potato price	Variation factor	Uniform	0.5	1.5
Teff price	Variation factor	Uniform	0.5	1.5
Barley price	Variation factor	Uniform	0.5	1.5
Common bean price	Variation factor	Uniform	0.5	1.5
Faba bean price	Variation factor	Uniform	0.5	1.5
Cow price	Variation factor	Uniform	0.5	1.5
Bull price	Variation factor	Uniform	0.5	1.5
Doe price	Variation factor	Uniform	0.5	1.5
Buck price	Variation factor	Uniform	0.5	1.5
Ewe price	Variation factor	Uniform	0.5	1.5
Ram price	Variation factor	Uniform	0.5	1.5
Chicken price	Variation factor	Uniform	0.5	1.5
Urea price	Variation factor	Uniform	0.5	1.5
DAP price	Variation factor	Uniform	0.5	1.5
Pesticide price	Variation factor	Uniform	0.5	1.5
Herbicide price	Variation factor	Uniform	0.5	1.5
Barley seed price	Variation factor	Uniform	0.5	1.5
Common bean seed price	Variation factor	Uniform	0.5	1.5
Faba bean seed price	Variation factor	Uniform	0.5	1.5
Medium maturing maize seed price	Variation factor	Uniform	0.5	1.5
Short-maturing maize seed price	Variation factor	Uniform	0.5	1.5
Susceptible wheat seed price	Variation factor	Uniform	0.5	1.5
Resistant wheat seed price	Variation factor	Uniform	0.5	1.5
Potato seed price	Variation factor	Uniform	0.5	1.5
Teff seed price	Variation factor	Uniform	0.5	1.5
Discount rate	Variation factor	Uniform	0.1	1.1
Deposit interest rate	Variation factor	Uniform	0.1	1.1
Loan interest rate micro-finance	Variation factor	Uniform	0.1	1.1
Loan interest rates from money lenders	Variation factor	Uniform	0.1	1.1

Variable	Description	Distribution sample	Minimum value*	Maximum value*
Wheat yield	Variation factor	Uniform	0.5	1.5
Maize yield	Variation factor	Uniform	0.5	1.5
Barley yield	Variation factor	Uniform	0.5	1.5
Potato yield	Variation factor	Uniform	0.5	1.5
Common bean yield	Variation factor	Uniform	0.5	1.5
Faba bean yield	Variation factor	Uniform	0.5	1.5
Teff yield	Variation factor	Uniform	0.5	1.5

**Minimum and maximum values are in standardized percentage change*

Parameter level variations were made over scenarios that create separate simulation runs. Among these repetitions, the first 50 model repetitions were used to check model convergence using the baseline scenario, which is the same across all simulation experiments. The convergence check is helpful to determine whether enough repetitions are done or not for a given scenario for model agents. The model outcome variables used for uncertainty model tests are agent discretionary incomes and livestock holding to check how quickly the model converges over given repetitions.

4.2.1. Results from uncertainty analysis

Figures 7 and 8 show the test for model convergence indicates the mean, 5th, and 95th percentile of the baseline scenario for income and livestock endowments outcomes. The results show that the model rapidly converges to stable values with 50 repetitions. This implies that these repetitions are enough to cover the model uncertainty space.

Figure 7: Model convergence test for 50 repetitions – discretionary income

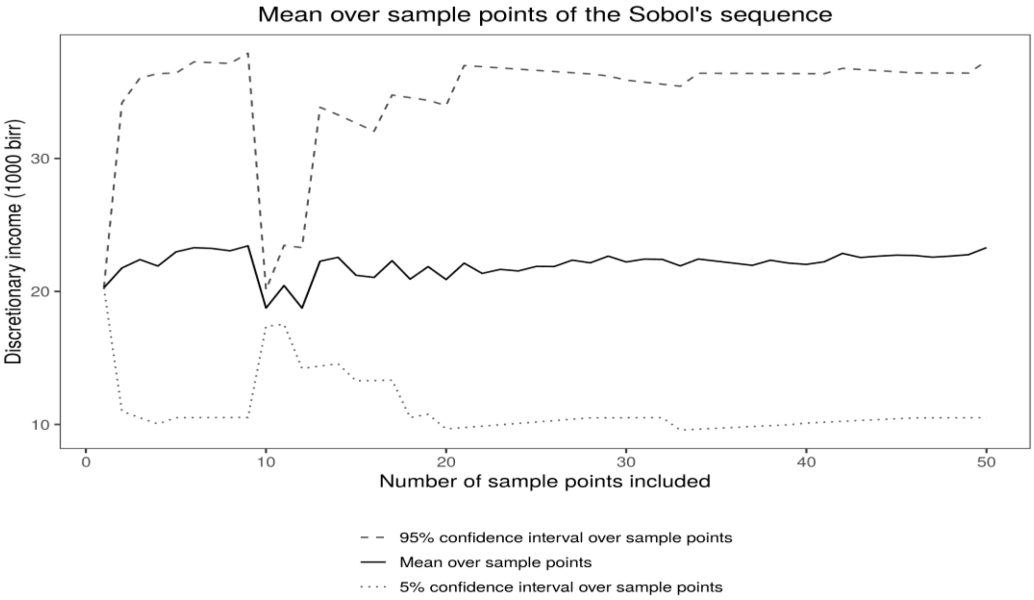
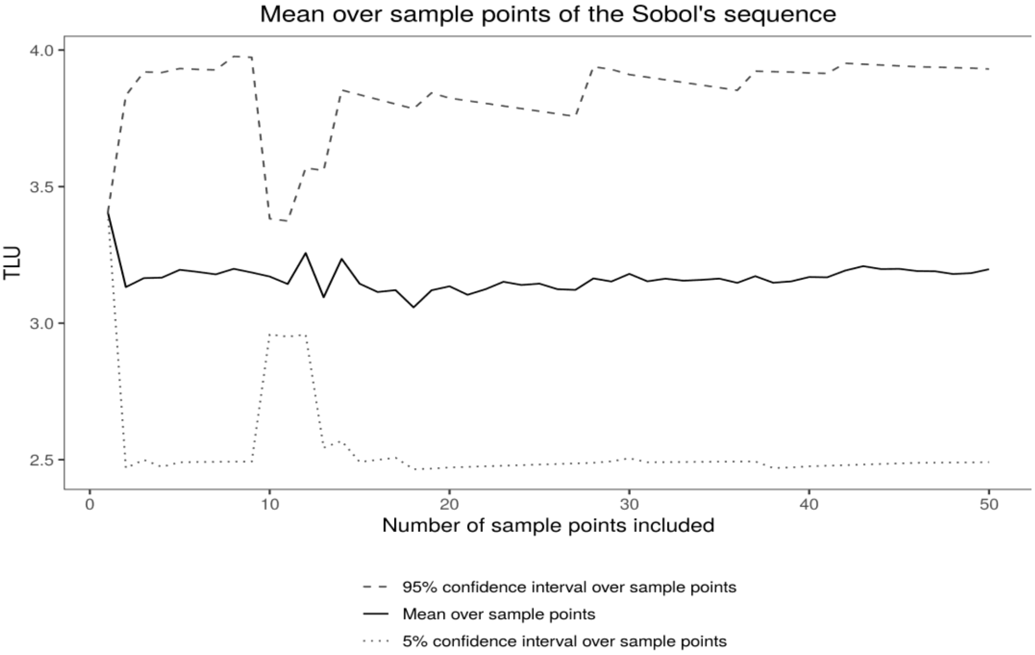


Figure 8: Model convergence tests for 50 repetitions – livestock endowments (TLU)



After checking the model convergence over repeated samples, simulations were then run for 50 repetitions over ten simulation periods per scenario to disentangle scenario effects on each agent from any variation in other parameters (Berger et al., 2017; Troost and Berger, 2015). Moreover, for each established scenario, long-term structural changes in yield and price levels were allowed to vary between simulation runs but constant within runs or simulation periods.

4.3. Conclusion

By following different model validation approaches, a benchmark was established against which the simulation model results are compared. Important model validation indicators like land use, grain sales, and livestock holding observed-simulated comparison distributions clearly show that MPMAS_CRV is capable of reproducing real-world observation patterns as the pattern of distributions is fairly similar. Moreover, by fitting MNL regression against the farm characteristics, household endowments, and agroecological zones, a systematic relationship was established between land use and the predictors in the empirical data from which MPMAS_CRV was parametrized. Furthermore, the model goodness of fit shows that the parameterized model can explain more than 50% variance in land use using relevant explanatory variables. This implies that MPMAS_CRV results fit well with observation data to establish a systematic relationship. Thus, since we found the systematic relationship in the observations, we can conclude that MPMAS_CRV can also capture the systematic relationship between simulated outcome decisions and other farm and household variables. The different validation approaches underline that the parameterized MPMAS_CRV of Ethiopia is reliable and can represent and describe real farm household decision processes.

Global uncertainty analysis using two simulation outcome variables underscores that the model converges rapidly at 50 repetitions. It implies that the number of repetitions is enough to cover the model uncertainty space. This further helps to net out the scenario effects on each outcome variable from any variation in other parameters.

Chapter 5. Impacts of extreme climate shocks, climate adaptation and roles of policy interventions: A farm-level modeling approach in Ethiopia

5.1. Introduction

Increased vulnerability of smallholder farmers to the negative impacts of extreme climate shocks arises from their low adaptive capacity and climate-sensitive livelihood base. During the exploratory field research in 2018, farmers and experts in CRV underlined that extreme climate events like drought and crop disease incidence have been increasing over the past years and the current frequency of shock is 2-3 in five years. This is confirmed by empirical research in Ethiopia by Fisher et al. (2015) which reveals that 60-90% of the survey households perceived drought occurred 4-6 times in the past ten years from 2003 to 2013.

To minimize the negative effects of climate shocks, farm households use different adaptation strategies which were captured and implemented in MPMAS_CRV. These are risk management strategies which include *ex-ante* adaptation and *ex-post* coping measures from which agents can choose. These options are existing crop management practices including use of existing improved crop varieties, keeping livestock, cash reserve, takeout loans, and buying additional food and food storage activities.

The inclusion of existing crop management options with different cropping activities enables agents to choose from various options subject to different constraints such as availability of capital, access to information and market, and farm sizes. Crop management options also include existing technologies which are disease and drought-tolerant crop varieties under different soil types and input application intensities that contribute to yield variations. In the model, farm agents have also options to store food from previous or current harvests to withstand the effects of possible shocks, which is also true with real smallholder farm households. They have also alternatives to take out short-term credit at the beginning of each production year to cover upfront production inputs costs, which eases liquidity constraints to enhance the adoption of improved technologies as the use of improved technologies often require additional cash. In addition to this, agents do have options to deposit cash in the bank or reserve part of the cash earned from previous period farm sales at home to buffer any anticipated risks that may occur until the subsequent harvest season. Simulation experiments were implemented in the MPMAS_CRV to simulate the effect of extreme climate shocks and assess the effectiveness of access to credit and improved agricultural technologies.

5.2. Simulation experiments

To isolate the effects of extreme climate shocks and assess the effectiveness of policy interventions establishing a benchmark or reference is important against which other scenarios are compared. In MPMAS_CRV, the thesis used without climate shocks and policy as a benchmark for different impact analyses. It is a hypothetical scenario run with constant average prices and yield (Table 8). Comparison of with and without climate shocks helps to quantify climate shocks impact on the welfare of agents.

Two climate shock frequencies were defined and implemented in MPMAS_CRV over simulation periods. The effect of these shock frequencies was analyzed by comparing them to a hypothetical case condition or reference scenario. Shock frequencies and their yield effects are implemented based on exploratory field research and empirical evidence in Ethiopia (Fisher et al., 2015; Mideksa et al., 2018). These two different shock frequencies were introduced in the model over ten simulation periods, which represent two different scenarios. One scenario consists of four shock years that occur in a row in ten years (4/10). The other scenario is five shock years in ten simulation years (5/10) but at different intervals – three shock occurrences in a row and two shock occurrences in a row at different simulation years.

To disentangle the effects of *ex-ante* considerations in the planning, without *ex-ante* measures scenario is compared to the hypothetical case scenario with *ex-ante* measures under different climate trajectories. In without ex-*ante* measures scenario, agents do not plan for risk and hence don’t choose and implement any kind of *ex-ante* strategies which was controlled in the scenario setup. In reality, however, households implement some kind of *ex-ante* measures for possible shocks. When agents consider risk in the planning, they are cautious about the possible risks and make necessary preparations during the production decisions.

Credit policy intervention was also established in the model to compare to a hypothetical case scenario (without climate shocks and policy) to isolate the effect of credit access in reducing welfare loss to climate shocks. In the current credit access condition, only 30% of model agents access credit from different sources. This is based on the study of Mukasa et al. (2017) and computations from the CIMMYT household survey. The empirical study by Mukasa et al. (2017) shows that in Ethiopia about 67% of the sampled households are credit constrained. Similarly, the results from the household survey of CIMMYT in CRV show that only 30% of the surveyed households have access to short-term production credit among the households who needed and applied for credit services. With the credit policy intervention scenario, all agents were allowed to access short-term production credit. Comparing with and without credit policy intervention under different climate trajectories help to assess and disentangle its potential impacts on farm household well-being.

Similar to credit policy intervention, the potential benefits of technology policy intervention (access to the newest maize and wheat technologies) are disentangled by comparing with and without technology policy intervention under different climate trajectories. In without climate shock and policy scenario, agents have access to only existing maize and wheat improved technologies and are not exposed to the newest maize and wheat technologies. Access to the newest maize and wheat technology was restricted in MPMAS_CRV by disallowing the needed inputs purchase for the cropping activities. Cropping activities which require those restricted inputs were blocked for the model agents without a technology policy scenario. However, with the technology policy scenario, model agents were exposed to the newest improved maize and wheat varieties. The necessary inputs needed for cropping activities with the newest maize and wheat varieties were not restricted by the technology policy scenario. The newest maize and wheat varieties are assumed to have superior traits over the existing improved varieties. These traits are drought/disease tolerant, high yielding, and reduce downside risks in the face of severe climate shocks. Running simulations with and without technology policy intervention helps to isolate the effects of technology policy in reducing farm household vulnerability to the negative impacts of climate shocks. The two policy interventions (credit and technology) are also combined to make up a scenario to assess their effects compared to individual credit and technology policy interventions.

Table 8 below summarizes the setup of simulation experiments for the climate, *ex-ante* consideration in planning and policy interventions as implemented in MPMAS_CRV.

Table 8: Climate and policy simulation experiments

Scenario	Prices	Yield	Shock frequency
Without shocks – with *ex-ante* measures	Constant	Constant	
With four shock years (4/10) – with *ex-ante* measures	Variable	Variable	1,2,3,4
With four shock years (4/10) – without *ex-ante* measures	Variable	Variable	1,2,3,4
With five shock years (5/10) – with *ex-ante* measures	Variable	Variable	1,2,3,7,8
With five shock years (5/10) – without *ex-ante* measures	Variable	Variable	1,2,3,7,8
With credit policy-four shock years (4/10)	Variable	Variable	1,2,3,4
With credit policy-five shock years (5/10)	Variable	Variable	1,2,3,7,8
With technology policy-four shock years (4/10)	Variable	Variable	1,2,3,4
With technology policy-five shock years (5/10)	Variable	Variable	1,2,3,7,8
With credit & technology policy-four shock years (4/10)	Variable	Variable	1,2,3,4
With credit & technology policy-five shock years (5/10)	Variable	Variable	1,2,3,7,8

5.3. Simulation results

Under this topic, the thesis presents detailed simulation results from climate and policy simulation runs by comparing different scenarios. Scenarios are compared to measure the welfare effects of climate shocks and how well the farmer autonomous and policy interventions are effective in reducing the vulnerability of agents. Simulation results are presented in six sections: (i) climate shock impacts and considerations of *ex-ante* measures (ii) heterogeneous effects of extreme climate shocks (iii) roles of credit and technology policy options (iv) heterogeneous effects of credit and technology policy interventions (v) role of joint policy interventions (vi) heterogeneous effects of joint policy interventions.

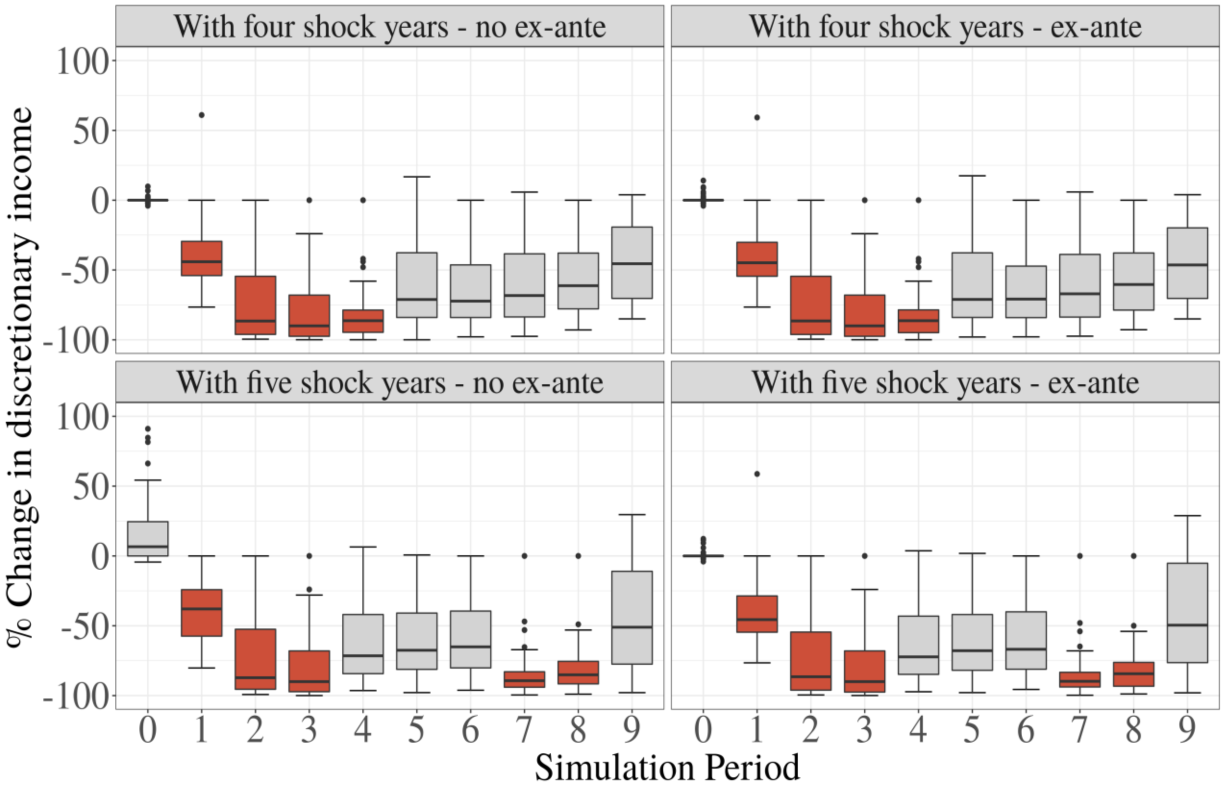
5.3.1. Extreme climate shocks impact and the role of *ex-ante* measure considerations

Income effect of extreme climate shocks

Income change was compared between with and without *ex-ante* measures considerations under two climate shock frequencies (Figure 9). The figure shows the distribution of income change over 50 repetitions for all agents in all simulation periods. Not surprisingly, simulation results show that extreme climate shocks have severe negative effects on agent incomes under both four (4/10) and five (5/10) climate shock frequencies. A closer investigation at the results in each year shows that income effect is also pronounced in the actual shock years which leads, for some agents, up to 100% discretionary income loss. Simulation results also show that considerations of *ex-ante* measures in the planning have minimal income effects. Between the two scenarios (with and without *ex-ante* measures) there is no or minimal difference in terms of income loss.

Compared to the benchmark (without climate shocks and policy), agent discretionary income declines by 53% and 56% on average over periods with four (4/10) and five (5/10) shock years under both with and without considerations of *ex-ante* measures respectively. As expected, five shock years tend to have more adverse income effects compared to four shock years. In the post-shock years, the income loss is still large under different shock scenarios but the degree of the income loss gradually declines over the years. These results reveal two things. First, it underscores the long-term negative effect of extreme climate shocks beyond the actual year of shock incidence as resource re-accumulation usually needs quite some time for resource-poor agents. Second, severe shock makes it difficult for model agents to immediately recover from shock devastation immediately in the post-shock years. This is due to the effect of the preceding year shock events as it limits the capacity of farm agents to recover by eroding the previously accumulated assets and capital. Severe and frequent climate shocks have usually adverse accrued effects over the normal successive periods after their occurrence in the preceding years.

Figure 9: Income change with and without *ex-ante* considerations under shock frequencies



Note: Change of agent discretionary incomes averaged over repetitions in all simulation periods

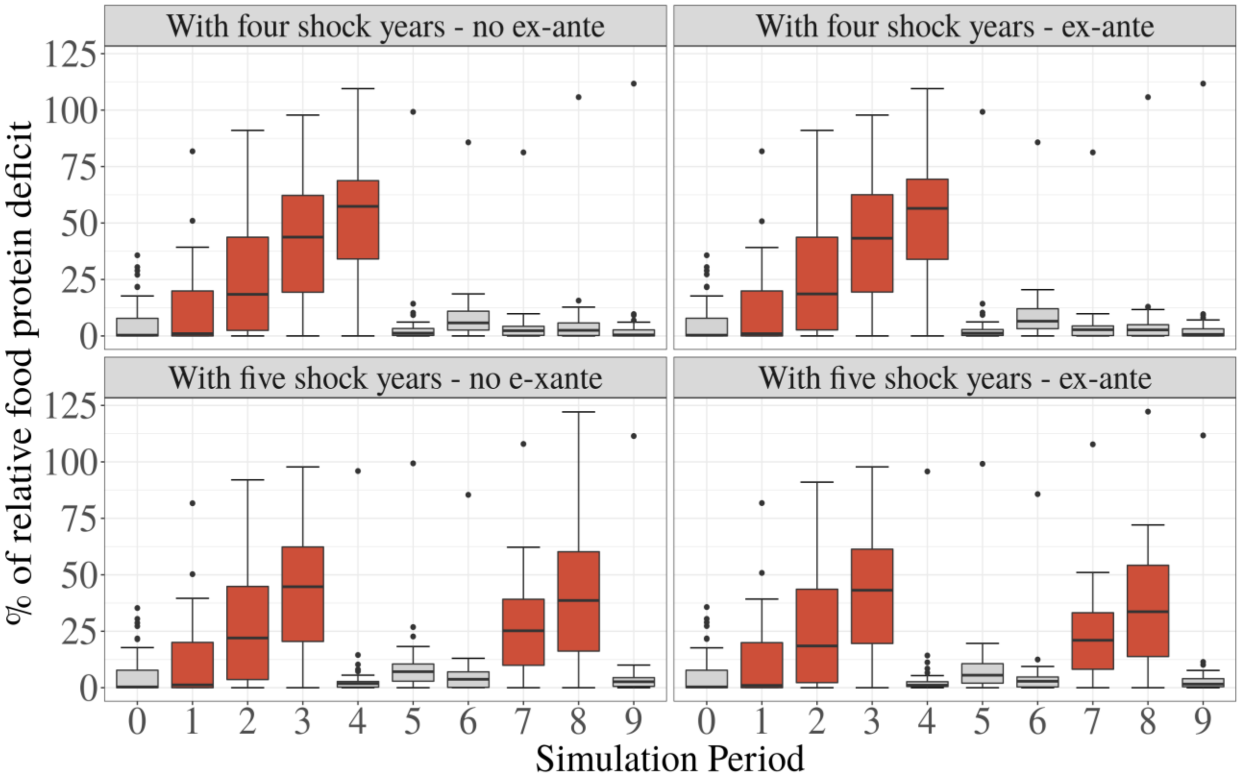
Food security effect of extreme climate shocks

Household food security is simulated and analyzed to quantify whether model agents can meet minimum food nutrition requirements or not under severe climate shocks. The percentage of relative food protein and energy deficit are used as outcome measures and computed by dividing the simulated quantity of protein and energy deficits with agent food protein and energy requirements. This helps to compute the starvation rate (how much agent food nutrition requirement is not fulfilled) and the proportion of agents who fails to meet the minimum food nutrition requirements due to climate shocks.

Figure 10 shows the distribution of the relative percentage of food protein consumption deficit of agents over 50 repetitions in all simulation periods. Simulation results suggest that the food protein consumption deficit is stronger in the years of incidence of recurrent climate shocks. In normal years after recurring climate shocks are over, except for some agents, many agents immediately recover from temporary food protein deficits.

On average over periods, with four shock years (4/10) with considerations of *ex-ante* measures, the relative percentage of food protein deficit (food protein starvation rate) is about 16% which is also similar without *ex-ante* measures. But with five shock years (5/10) without *ex-ante* measures, the average relative percentage of food protein deficit is 18%. Under similar climate shock frequency (5/10) with *ex-ante* measures, the percentage of relative food protein consumption deficit decline to 16%. The results show that even if agents consider *ex-ante* measures for possible risks, temporary food protein shortage prevails in the shock years.

Figure 10: Relative food protein deficit with and without *ex-ante* considerations

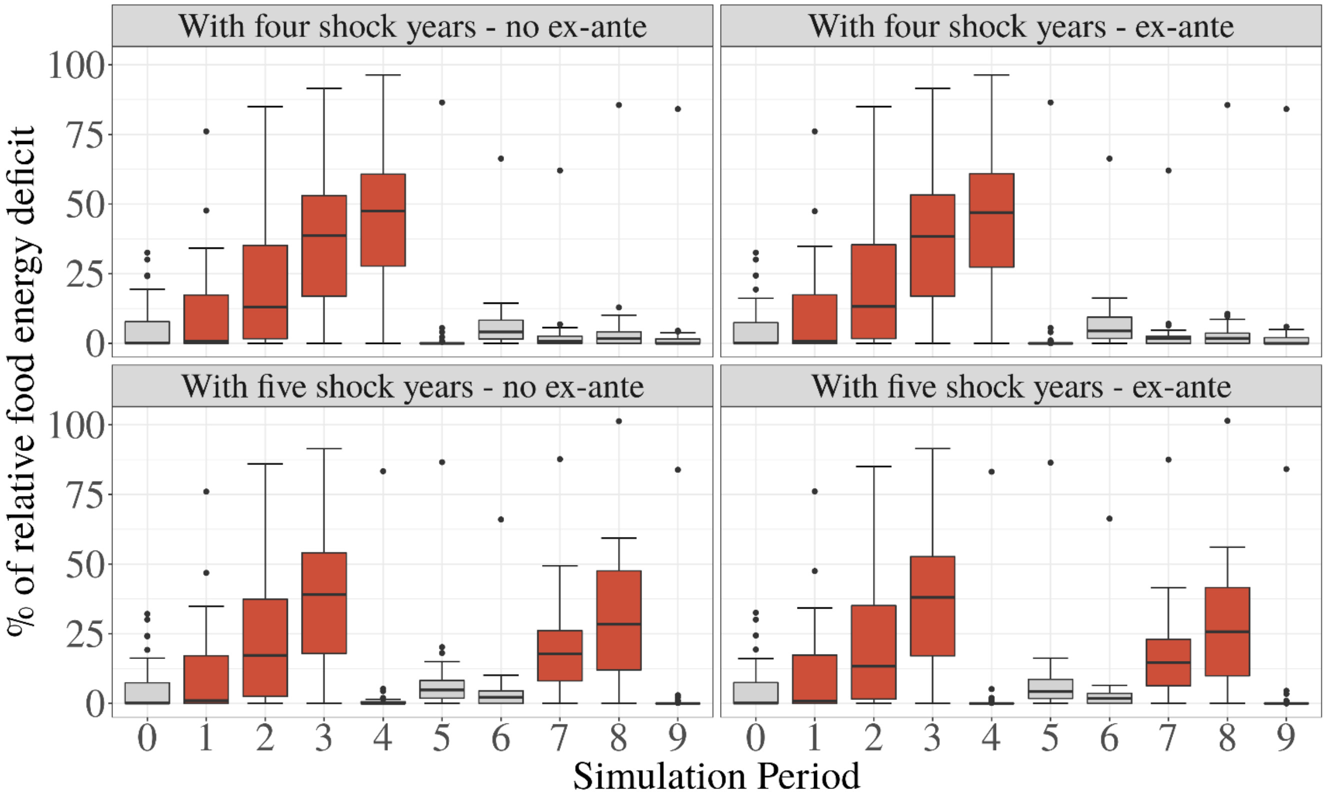


Note: Percentage of relative food protein deficit averaged over repetitions in all simulation periods

Figure 11 also shows the distributional effects of extended climate shocks on food energy consumption under different scenarios. On average over periods, the relative percentage of food energy consumption deficit is 13% with four shock years (4/10) under both with and without *ex-ante* measures. In five shock years (5/10) without *ex-ante* measures, the average food energy starvation rate is 14%. Under similar climate shock frequencies with *ex-ante* measures (5/10), the percentage of relative food energy deficit declines to 13% on average.

Alike the discretionary income effect, *ex-ante* measures have no food security effect under four shock years (4/10) for both with and without *ex-ante* considerations. However, in five shock years (5/10), there is a slight positive contribution in reducing the starvation rate. This shows that under more frequent climate shocks, considerations of *ex-ante* measures play a minimal positive compensation role in reducing food consumption deprivation.

Figure 11: Relative food energy deficit with and without *ex-ante* considerations



Note: Percentage of relative food energy deficit averaged over repetitions for all simulation periods

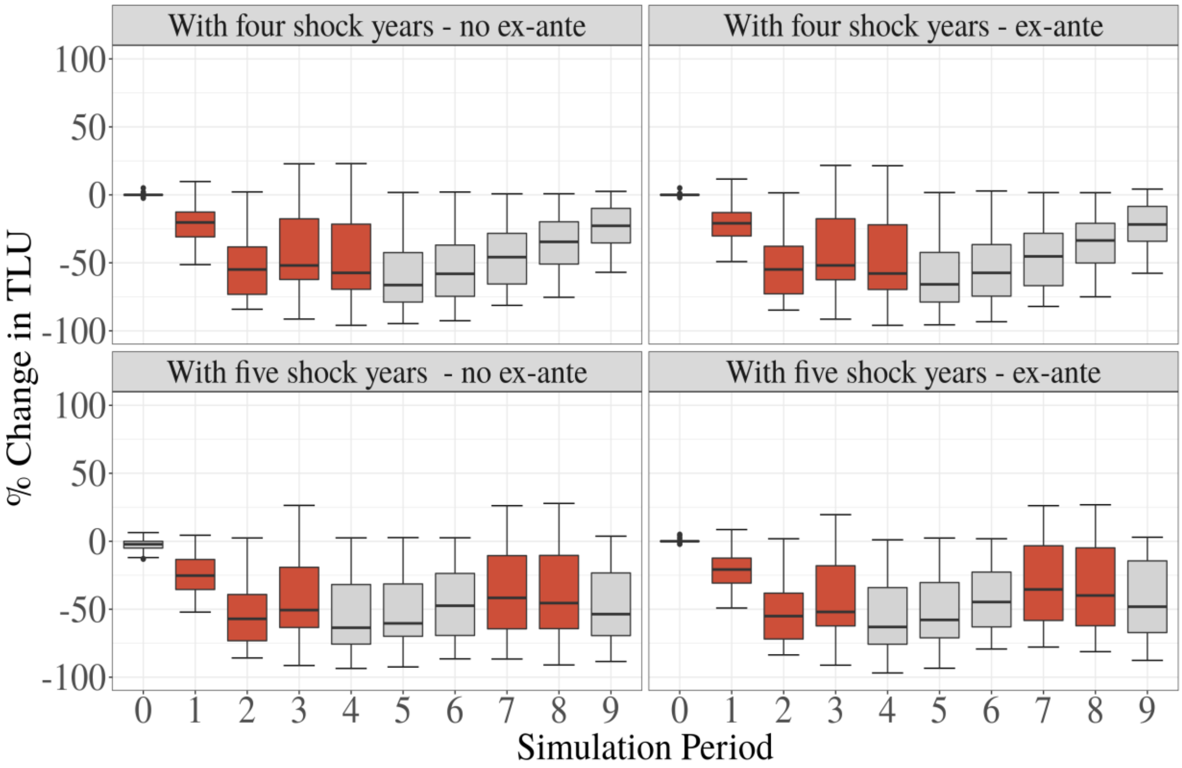
Simulation results for both food protein and energy nutrition deprivations suggest that many agents face food insecurity (or run into temporary food shortage) under recurrent climate shocks as they are not able to fulfill their minimum food protein and energy requirements even if they have options in the model to choose and implement *ex-ante* measures for possible shocks. Moreover, the results underscore that the severity of temporary food shortage is pronounced under five shock years (5/10) compared to four shock years (4/10).

Extreme climate shocks effect on household livestock assets

Simulations analysis was made to quantify the impact of extreme climate risks on agent livestock assets by comparing with and without climate shocks without any policy interventions. Figure 12 shows the distributional effects of recurring climate shocks on livestock assets over 50 repetitions for all agents in all periods under different climate shock frequencies. The results show that severe shocks lead to large livestock losses both in the shock and subsequent post-shock years. The immediate post shock years effect is even larger in some years than the actual shock years as agents keep on selling the remaining livestock assets due to the incidence of preceding shocks. After quite some time in the post shock years, agent livestock endowment improves gradually though it takes longer period to rebuild the asset base.

On average over periods, livestock asset loss is 37% under with and without *ex-ante* considerations for four shock years. Under five shock years (5/10), livestock holdings of agents decline by 39% on average. The simulation results clearly show how severe and recurrent climate shock erodes livestock asset bases of agents that would lead to long-term livelihood crises.

Figure 12: Livestock heads change with and without *ex-ante* considerations



Note: Change of agent livestock holdings averaged over repetitions in all simulation periods

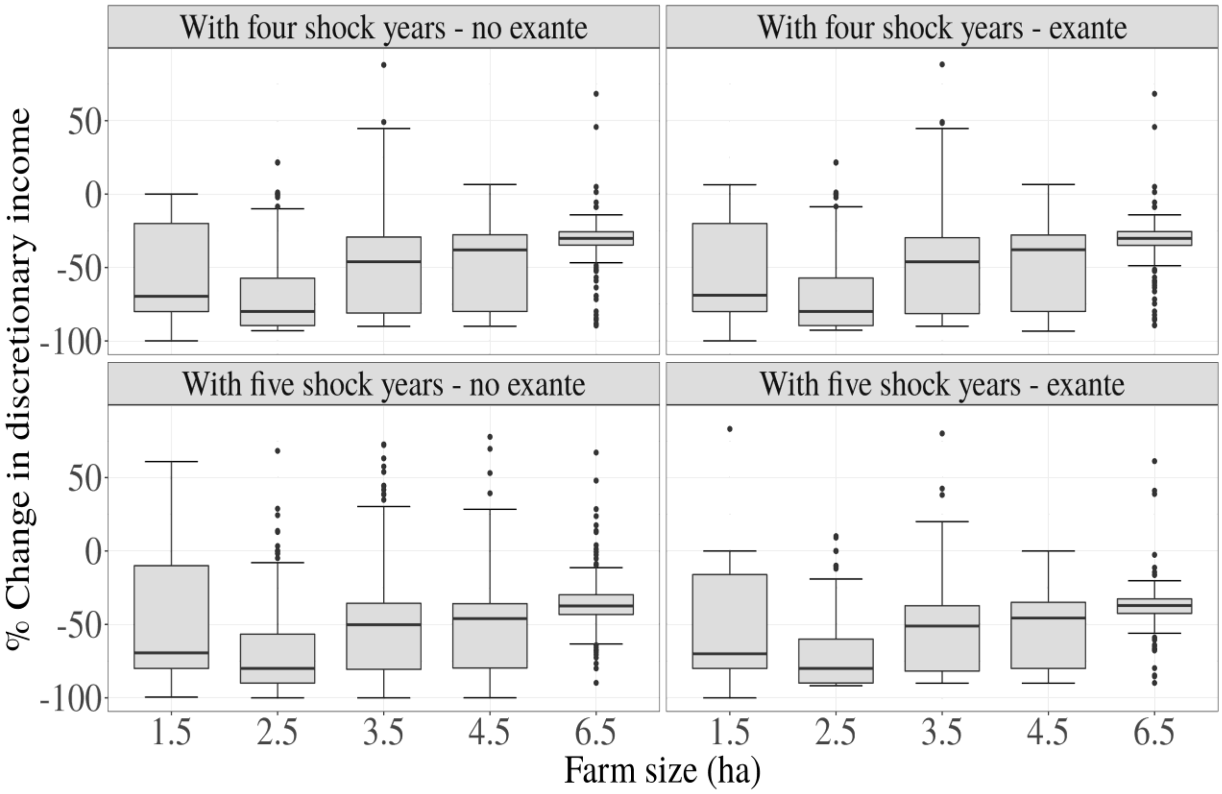
5.3.2. Heterogeneous effects of extreme climate shocks

The preceding simulation analysis shows the aggregated simulation results for all agents and repetitions. As MPMAS_CRV captures agent heterogeneity arising from spatial, biophysical, and socioeconomic endowments, it is extremely important to disaggregate simulation results to different agents according to their resources and agroecological heterogeneity.

Disaggregated analysis helps to know how recurrent shock incidence affects individual agents with heterogeneous resources. It helps to indicate the distributional outcome effects across different agent trajectories according to their location and initial resource endowments. The result provides insights on which agents are benefited or affected the most by recurrent climate shock incidences.

One important resource differential between model agents is farm size which also holds true for real-farmers. Farm size is an important farm endowment to analyze the heterogeneity effect of climate shocks. Figure 13 shows agent trajectories by farm size and respective income effect of recurring climate shocks.

Figure 13: Income change by farm size with and without *ex-ante* considerations

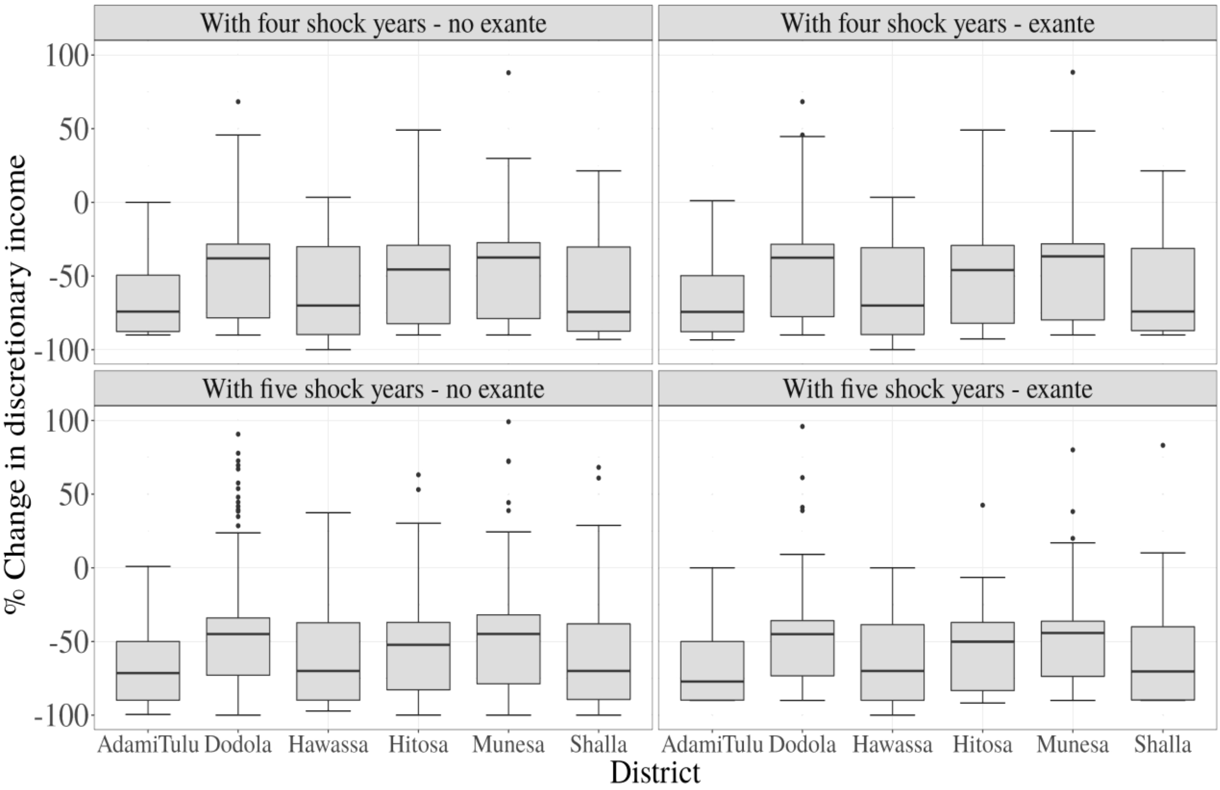


Note: Change of agent discretionary income averaged over periods by the size of landholding

The results suggest that agents with smaller farm sizes are affected severely by extreme climate shocks compared to higher farm sizes except for agents with 2.5 ha which are severely affected even more than agents holding lesser land area. Under different shock frequencies with and without *ex-ante* measures, the average income loss of agents reduces when farm size is more than 2.5 hectares.

Simulation results are further disaggregated to districts and household size as shown in Figures 14 and 15 respectively. Figure 14 shows the income loss to recurring shocks in each district. It presents that income loss is lower in wheat-dominated districts (Munesa, Hitsoa and Dodola) than in maize-dominated districts (Shalla, Adami Tulu, and Hawassa). The higher income loss is attributed to the severe moisture stress in the maize-growing areas of CRV compared to the wheat production system. Moreover, observed data from which MPMAS_CRV was parameterized, shows that most households in the wheat-growing areas own larger farm sizes compared to maize-growing districts. Better resource endowments can also allow them to better buffer adverse livelihood crises posed by extreme climate-induced shocks.

Figure 14: Income change by districts under with and without *ex-ante* considerations

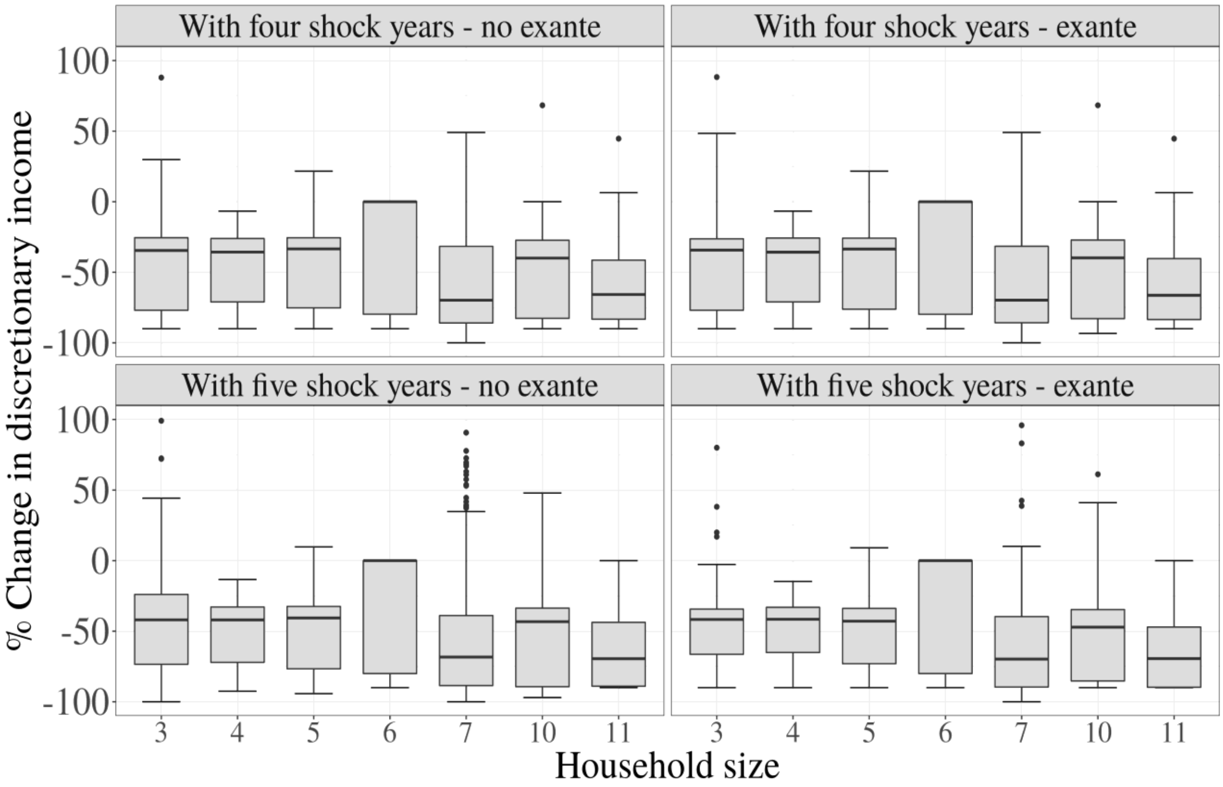


Note: Change of agent discretionary incomes averaged over periods for all districts

The distribution of the full income effects for different household sizes is shown in Figure 15 under different climate shocks. The results show that welfare loss in terms of change of discretionary income is relatively higher for agents with higher household sizes compared to agents with lower household sizes. This is mainly because agent non-food consumption expenditure and food consumption demand increase with higher household size as it was captured and implemented in MPMAS_CRV. At times of extreme shocks, model agents with relatively higher household sizes run into food and non-food expenditure deficits compared to agents with lower household sizes, hence discretionary income loss becomes higher.

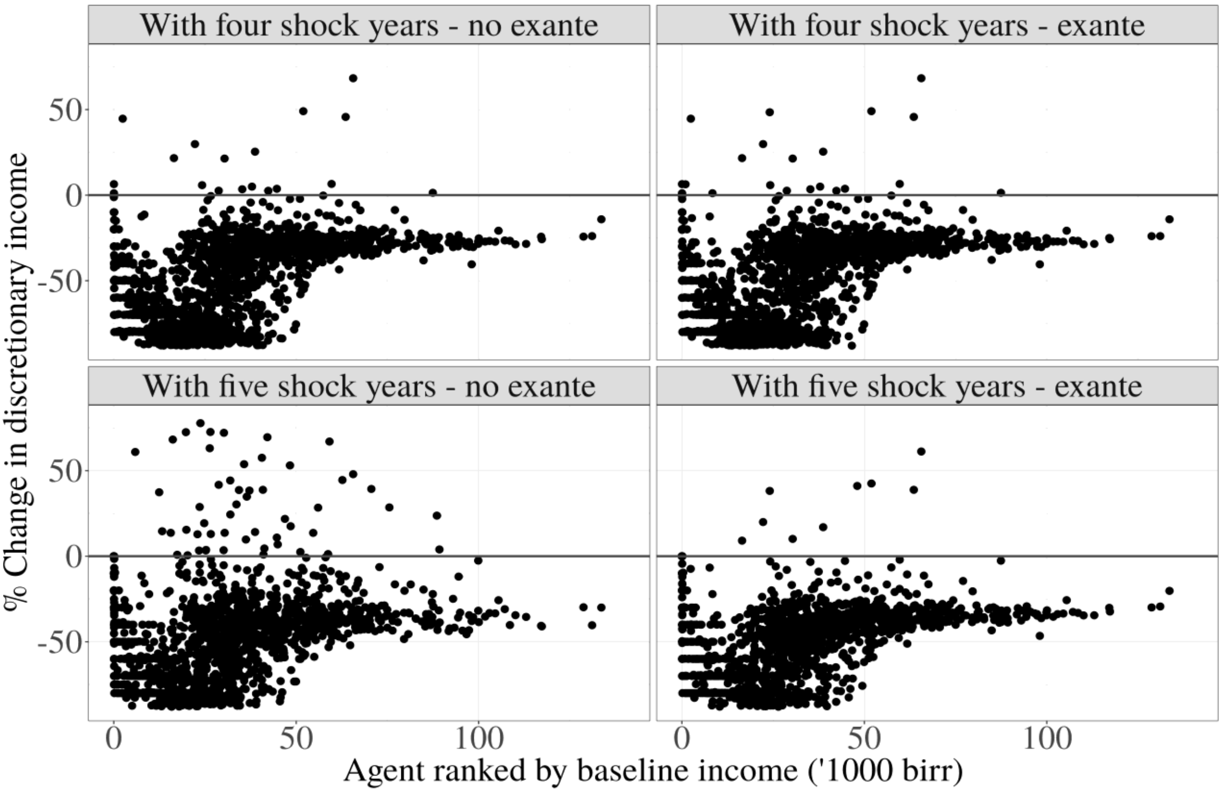
In addition to this, the scatterplot in Figure 16 shows the distribution of change of discretionary income disaggregated by agent baseline incomes (incomes of hypothetical case scenario) under different climate shocks. The simulation results suggest that almost all agents are affected by extreme climate shocks though the level of severity varies by agent baseline income status. Agents with lower baseline income are more severely affected than agents with higher baseline income under all shock frequencies with and without *ex-ante* measures scenarios. The poorest agents are disproportionally affected by severe climate shocks mainly due to limited resource endowments and associated low adaptive capacity.

Figure 15: Income change by household size under with and without *ex-ante* considerations



Note: Change of agent discretionary incomes averaged over periods by household size

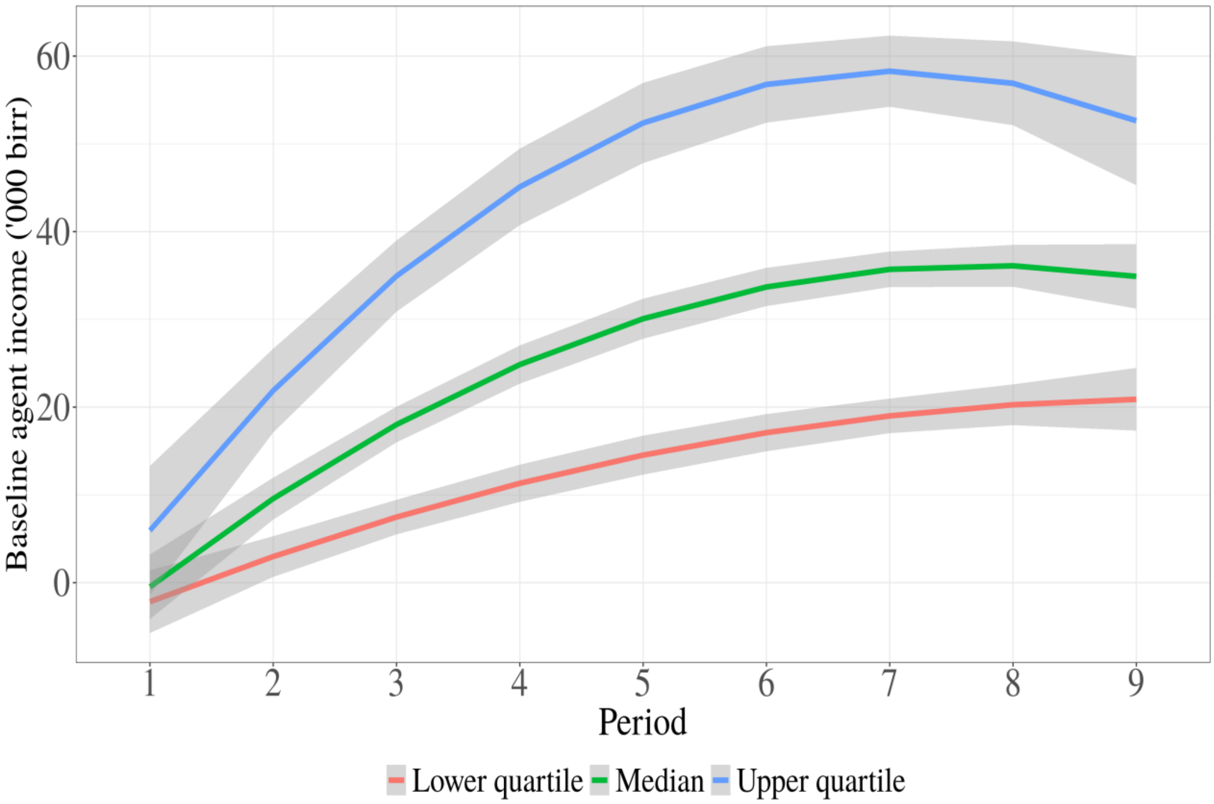
Figure 16: Income change by baseline income under with and without *ex-ante* considerations



Note: Change of individual agent incomes averaged over periods and ranked by agent hypothetical baseline income

In addition to Figure 16, which shows income change of agents by baseline income, the dynamics of agent income quartiles are depicted in Figure 17. The result shows that baseline income (income of without shocks and policy scenario) quartiles development over years and 50 repetitions. Overall agent income quartiles are increasing though the growth tends to be higher for upper quartiles with higher variations. Income increment at lower quartiles is modest but the variation is low compared to the higher quartiles.

Figure 17: Agent income quartiles development over periods



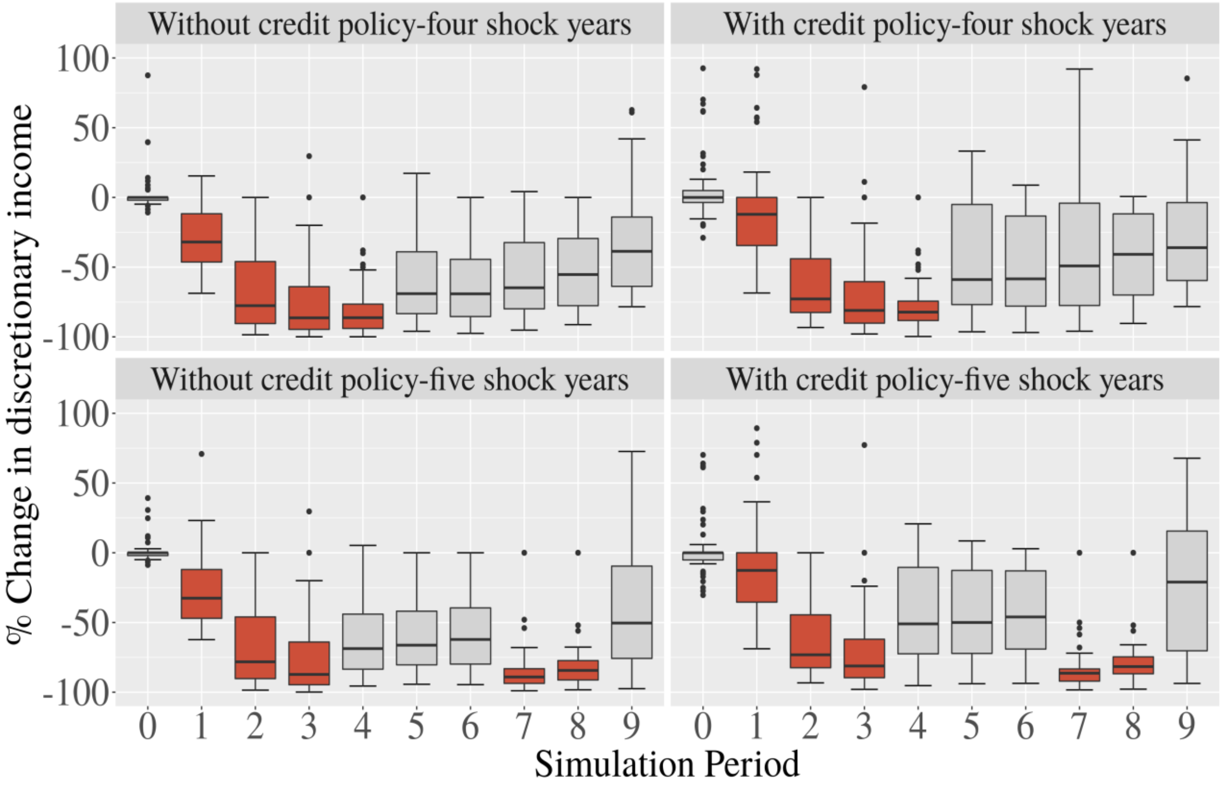
5.3.3. Roles of policy interventions in reducing household vulnerability

Under this topic, the thesis presents two simulation analysis results - the role of individual credit and technology policy under different climate trajectories.

Impacts of credit and technology policy interventions on household income

The distributional agent incomes change with and without individual credit and technology policy are presented in Figures 18 and 19. The graphs help to visualize and compare the extent to which policy interventions compensate for income loss to extreme climate shocks. Under both four and five shock years without policy interventions, income loss is stronger and recovery takes longer years. In the 'normal' years after shocks, income loss relatively declines as the income deviation slowly reduces. Individual credit and technology policies have modest effects in compensating income loss to extreme climate shocks.

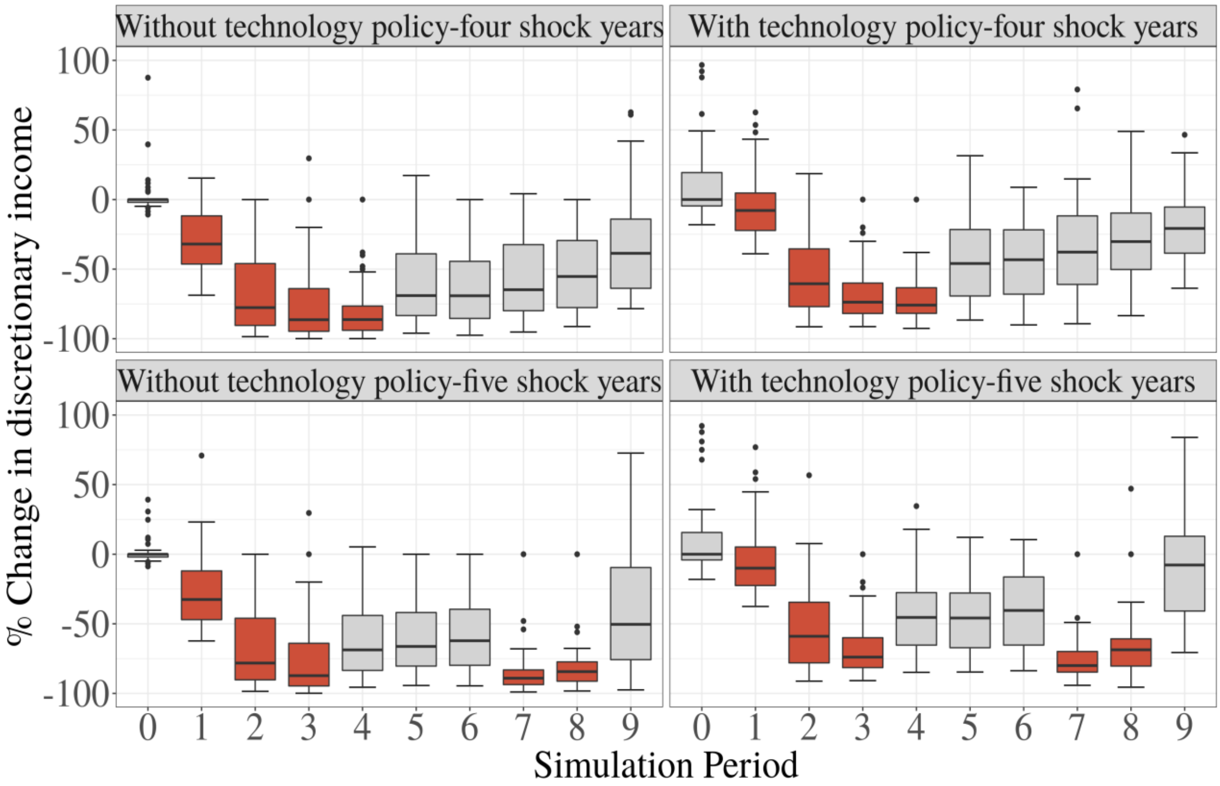
Figure 18: Income change with credit policy compared to without shock and policy



Note: Change of agent discretionary incomes averaged over repetitions in all simulation periods

Under extreme climate shocks without policy, agent discretionary income loss is 53% and 56%, on average over periods, under four and five shock years respectively. With credit and technology policy intervention, the average income loss is 45% and 41% under four shock years (4/10) respectively. Likewise, under five shock years (5/10) with credit and technology policy intervention, agent income declines by 48% and 44% respectively compared to without shock and policy. Due to credit and technology policy intervention, income loss reduces by 8 and 12 percentage points respectively under both four and five shock years. The use of these policies as a climate adaptation measure tends to better compensate for the adverse effect under four shock years compared to five shock years. Moreover, compared to credit, technology policy has relatively better compensational effects in reducing agent income loss to extreme climate shocks.

Figure 19: Income change with technology policy compared to without shock and policy



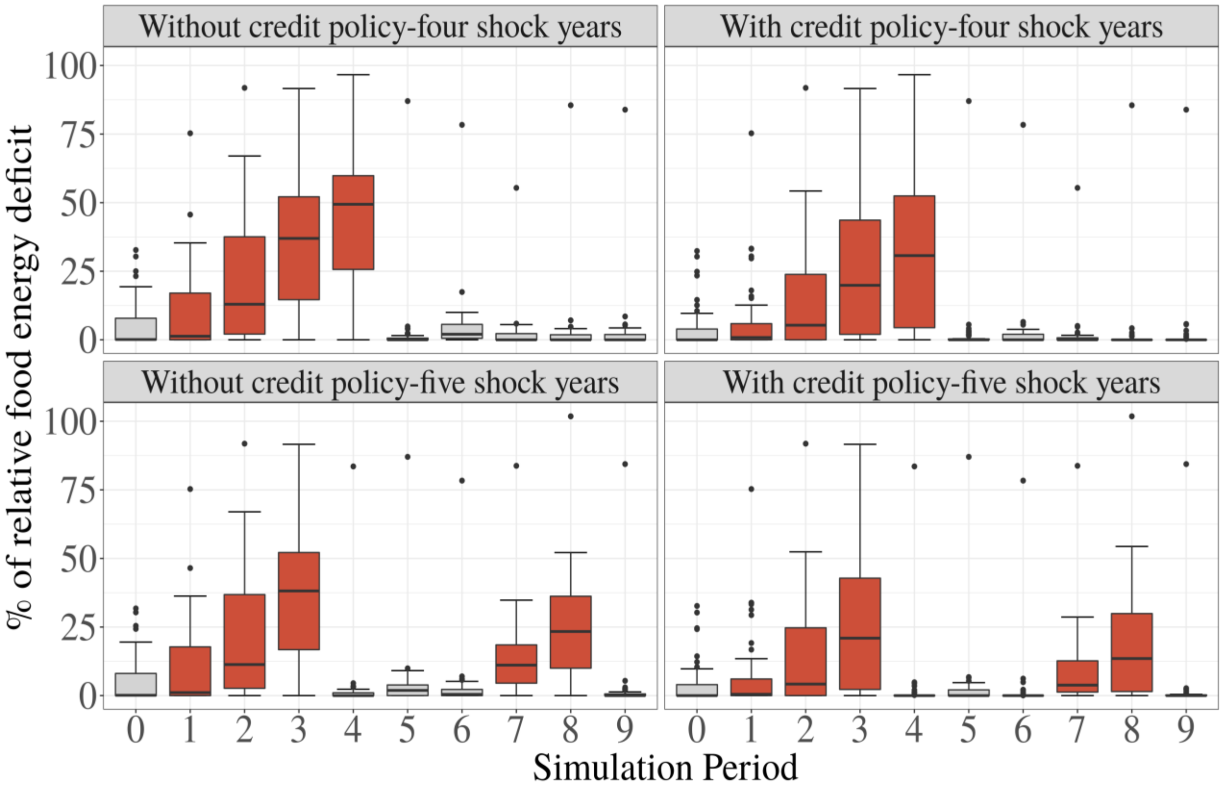
***Note**:* Change of agent discretionary incomes averaged over repetitions in all simulation periods

Food security effect of credit and technology policy interventions

Recurring climate shocks affect household food security by affecting production thereby income meant to buy food and non-food items. Figures 20 to 23 show the distribution of relative food energy and protein consumption deficits (how much of agent food consumption demand is unmet) over 50 repetitions with and without credit and technology policy interventions. The simulation results underline that many agents are unable to meet minimum food energy and protein requirements in the severe shock years in all scenarios. With policy interventions as well the starvation rate is still prominent in shock years but the degree of starvation rate relatively declines compared to without policy. In 'normal' years in 10 simulation periods under with and without individual policy interventions, agents immediately start to recover and meet minimum food energy and protein consumption requirements. After climate shock is over, agents can fulfill their minimum food consumption requirements as this objective is an absolute priority over other targets.

On average over periods, the starvation rate of food energy and protein is 13% and 16% without policy under both four and five shock years respectively. But with individual credit and technology policy, the relative food energy consumption deficit is 8% and 9% on average under four (4/10) shock years respectively. Likewise, with credit and technology policy food energy consumption deficit is 9% on average for five (5/10) shock years. This shows that due to individual credit and technology interventions, the relative food energy starvation rate declines by 5 and 4 percentage points under four shock years respectively.

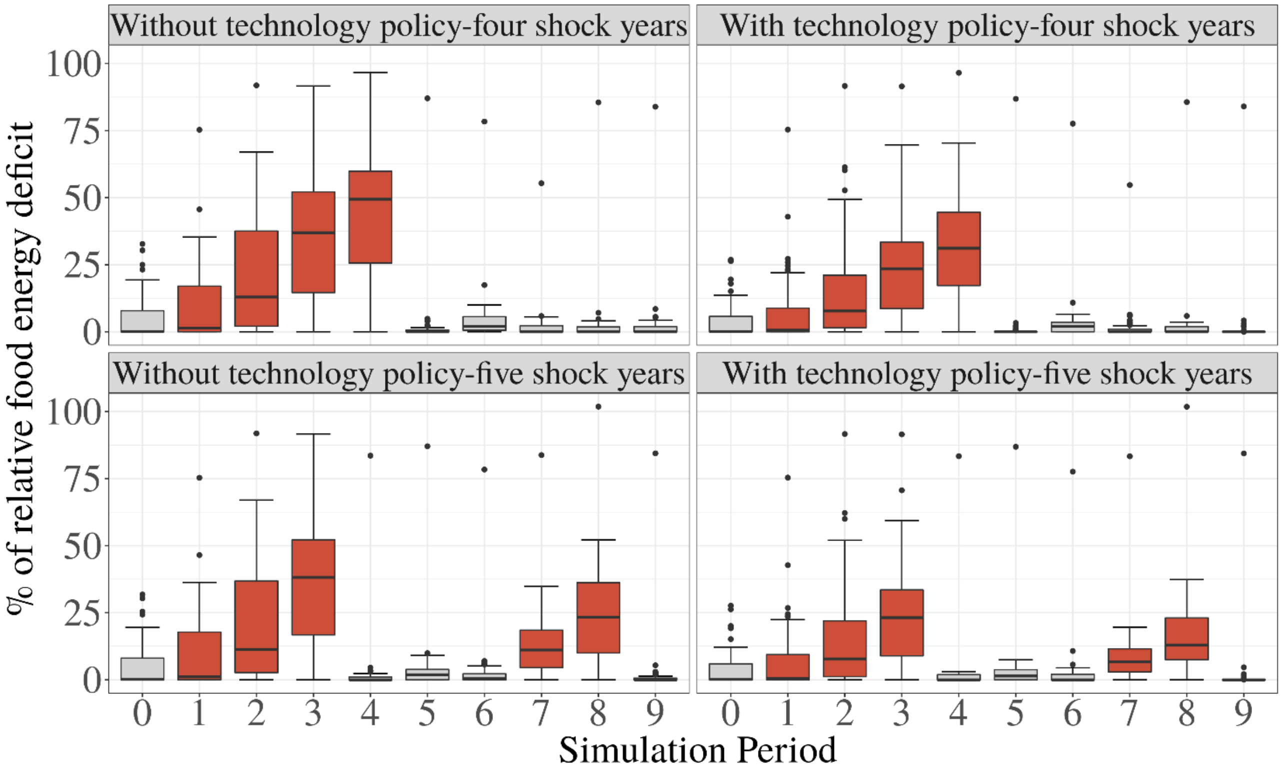
Figure 20: Relative food energy deficit with credit policy compared to without shock and policy



***Note**:* Percentage of relative food energy deficit averaged over repetitions in all simulation periods

By further analyzing the proportion of agents who run into food consumption deficit, the result suggests that 23% and 24% of the agent population cannot meet the minimum food energy consumption requirement without policy under four and five climate shocks respectively. With credit policy, 16% and 17% of the agent population is exposed to food energy consumption deficit under four and five shock years respectively. Similarly, with technology policy, 17% of the agent population is unable to meet minimum food energy consumption requirements under both four and five shock years (Table 9). With joint policies, however, only 11% of the agent population is unable to meet their minimum energy requirements. Policy simulation experiments suggest that compared to joint policies, individual polices have modest positive contributions in lifting agents from food insecurity status under both climate shock frequencies as many agents are still unable to meet minimum food consumption requirements.

Figure 21: Relative food energy deficit with technology policy compared to without shock and policy



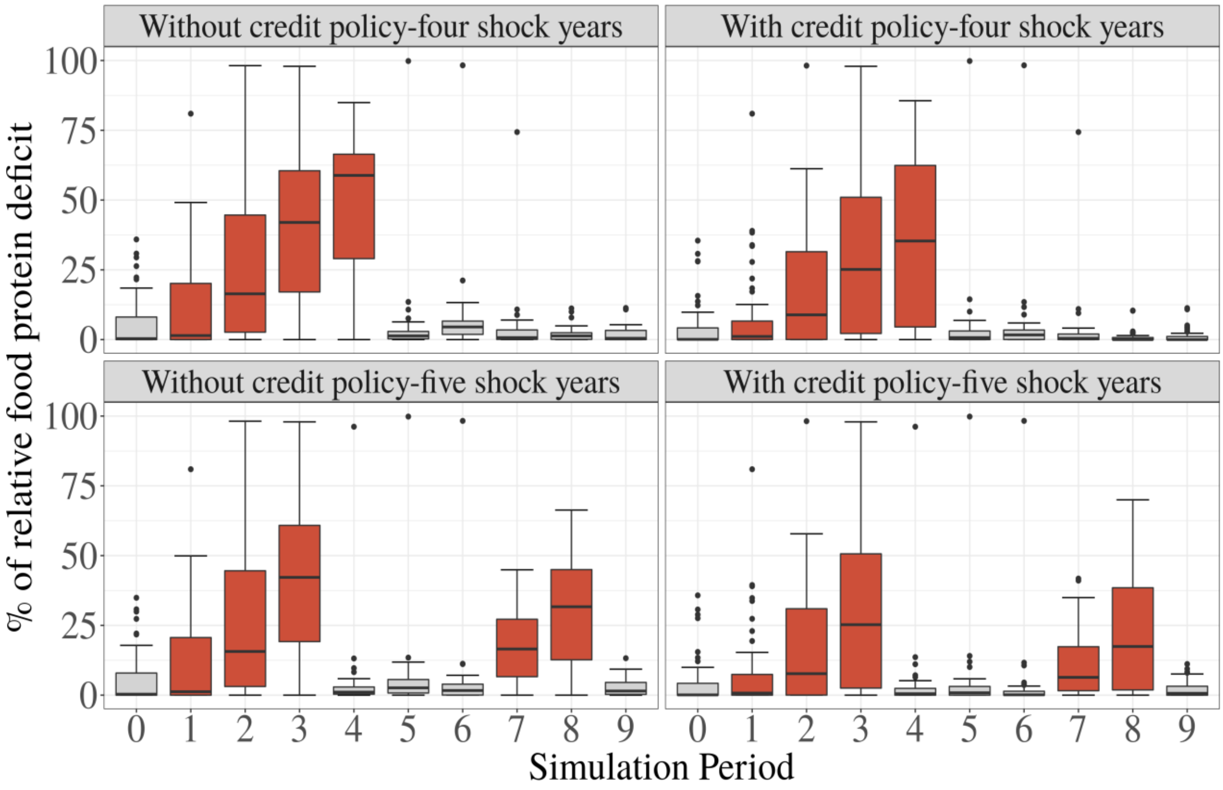
Note: Percentage of relative food energy deficit averaged over repetitions in all simulation periods

With regards to fulfilling the minimum food protein requirements, without policy, 29% and 31% of the agent population cannot meet the minimum food protein consumption requirement under both four and five shock years respectively. However, with credit policy, 22% and 23% of agents are unable to meet the minimum food protein requirements with four and five shock years respectively. With technology policy, 22% of the agents are not able to meet minimum protein under both climate shock frequencies (Table 9). Similar to the food energy effect, individual credit and technology policies modestly compensate for temporary food protein shortages. When the two policy interventions are jointly used, agents facing food protein deficit considerably reduce to 15%.

Table 9: Proportion of agents by nutritional deprivation status under different scenarios

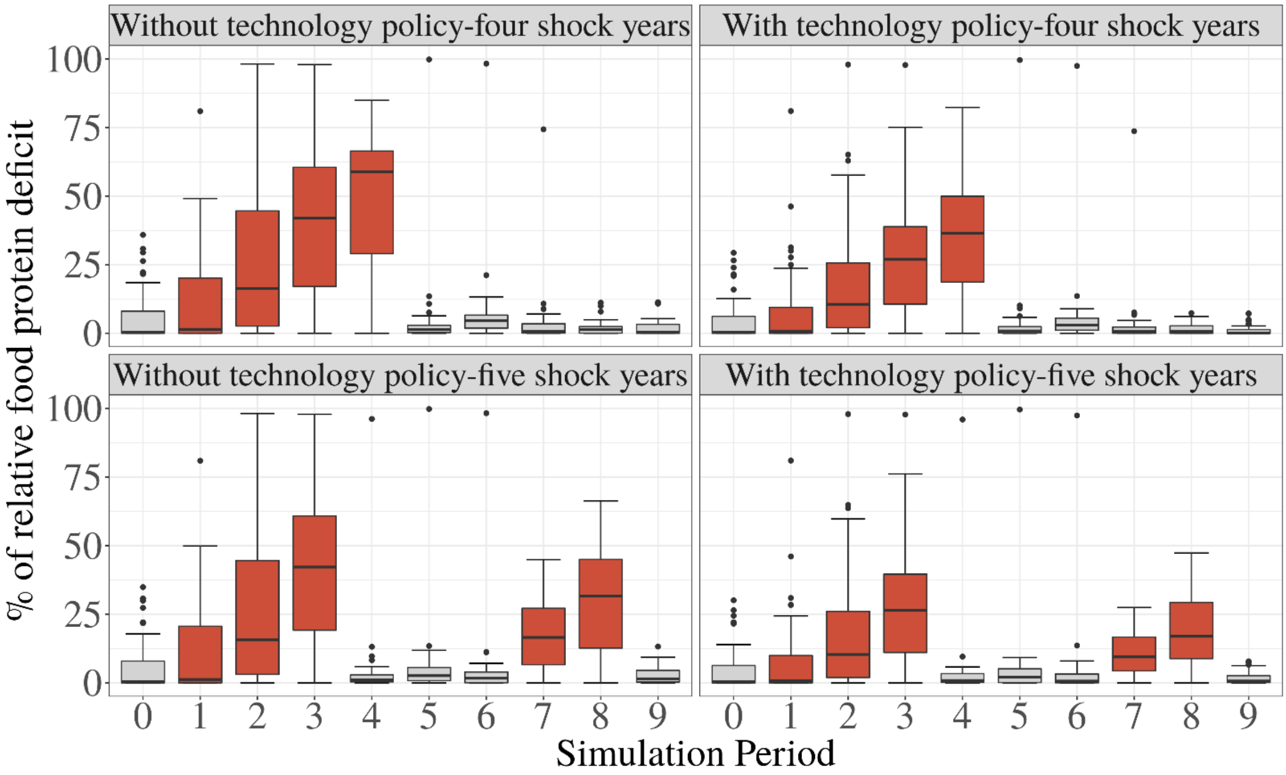
	Food energy (%)		Food protein (%)	
Scenario	**Deficit**	**Fulfilled**	**Deficit**	**Fulfilled**
Without policy-four shock years (4/10)	23	77	29	71
Without policy-five shock years (5/10)	24	76	31	69
Credit policy-four shock years (4/10)	16	83	22	78
Credit policy-five shock years (5/10)	17	84	23	77
Technology policy-four shock years (4/10)	17	83	22	78
Technology policy-five shock years (5/10)	17	83	22	78
Joint policies-four shock years (4/10)	11	89	15	85
Joint policies-five shock years (5/10)	11	89	15	85

Figure 22: Relative food protein deficit with credit policy compared to without shock and policy



Note: Percentage of relative food protein deficit averaged over repetitions in all simulation periods

Figure 23: Relative food protein deficit with technology policy compared to without shocks and policy



Note: Percentage of relative food protein deficit averaged over repetitions in all simulation periods

In addition to analyzing the adaptation role of improved credit access in reducing the vulnerability of agents to climate shocks, loan default rates were also analyzed over different climate and credit policy scenarios. Without shock and policy, among agents who take out loans, 14% of them get defaulted (Table 10). With the credit policy when all agents were allowed to access short-term credit, 71% and 70% of the agent population take credit under four and five shock years respectively. Among these agents, 43% and 45% of them are unable to pay loans taken under four and five shock years respectively. As expected, the results show that due to the increased incidence of climate shocks, the loan default rate increase as agents who took credit couldn't afford to repay the loans. This has a huge cost implication for the government or creditors and has profound economic consequences at large that compromise alternative public investment potentials. It also has greater repercussions on the future credit access of individual agents as they are blocked from the credit scheme when they choose to default.

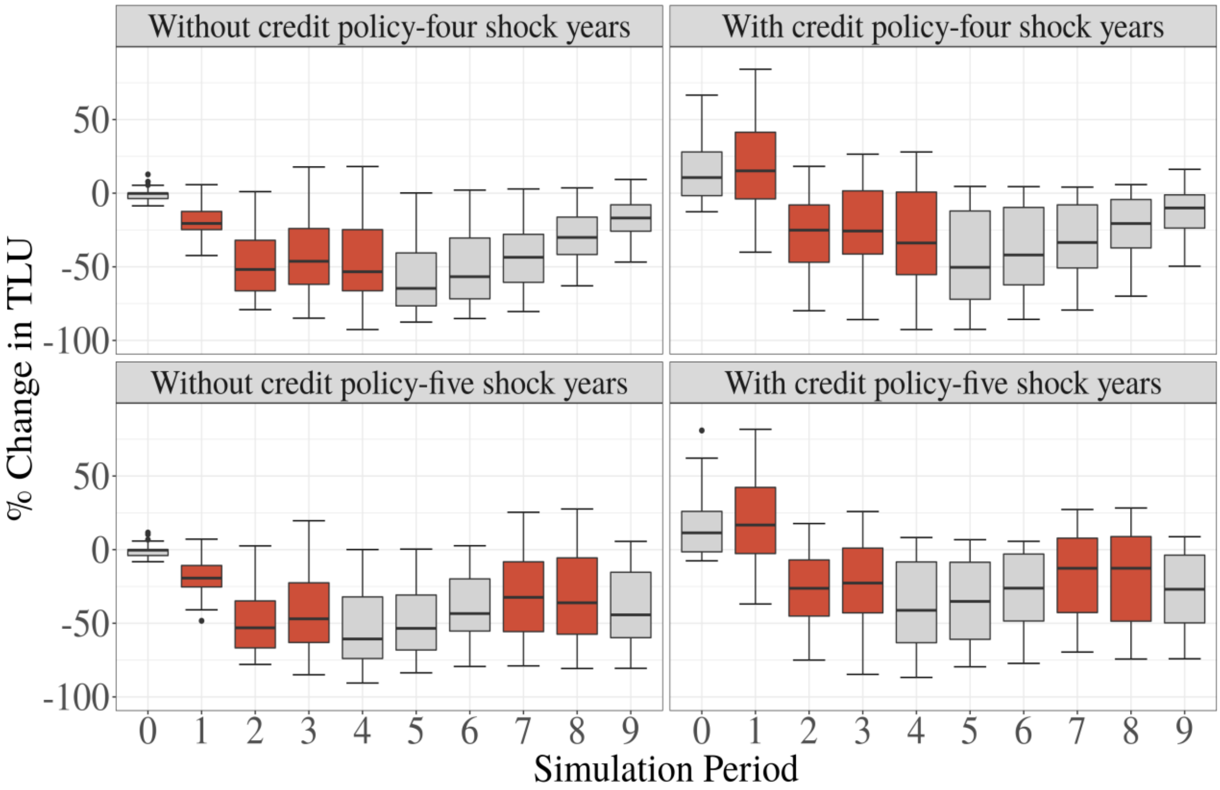
Table 10*:* Proportion of agents by repayment status

Scenario	Credit taken (%)		Credit repaid (%)	
	Yes	No	Yes	No
Without credit policy & climate shocks	17	83	86	14
Credit policy-four shock years (4/10)	71	29	57	43
Credit policy-five shock years (5/10)	70	30	55	45

Role of credit and technology policy on livestock assets

Policy interventions can have a direct effect on boosting food production and household income for smallholder farmers. This, in turn, is expected to contribute to protect household livestock assets by providing necessary food and cash for households. Figures 24 and 25 show the effect of climate shocks on livestock assets with and without policy interventions over 50 repetitions. The simulation results indicate that without policy, extreme climate shocks have a pronounced effect on livestock holdings under both four and five shock years. This is because when there are shock incidences, agents use livestock assets as coping measures to smooth consumption which is also true with real-world subsistence farmers. However, with credit and technology policy under climate variability, the livestock asset loss reduces substantially. Credit and technology policy can compensate for livestock loss by providing additional income for consumption requirements which otherwise is filled from distressed livestock sales.

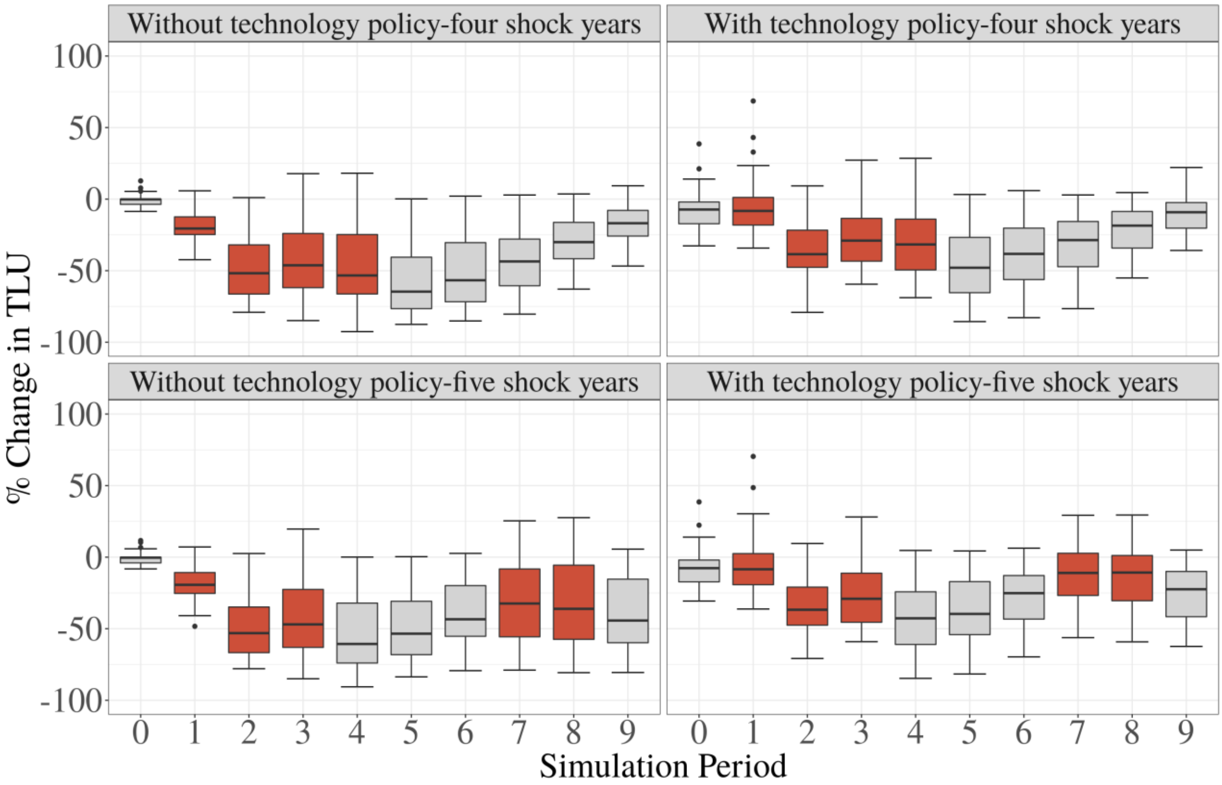
Figure 24: Livestock changes with credit policy compared to without shock and policy



***Note**:* Change of agent livestock holdings averaged over repetitions in all simulation periods

On average over periods for all scenarios and all agents, livestock holdings reduce by 37% and 39% under four and five shock years without credit policy respectively. Under four shock years, livestock holdings decline to 29% and 26%, on average through credit and technology policy intervention respectively. With five shock years, average livestock loss declines to 28% and 24% for credit and technology policy respectively. Simulation results suggest that credit and technology policy interventions have positive contributions in reducing livestock losses in the face of climate shocks though the losses are still substantial with policy interventions. Credit access compensates livestock loss by 8 and 11 percentage points under four and five shock years respectively. Similarly, due to technological intervention, livestock loss reduces by 11 and 15 percentage points under four and five shock years respectively.

Figure 25: Livestock changes with technology policy compared to without shock and policy

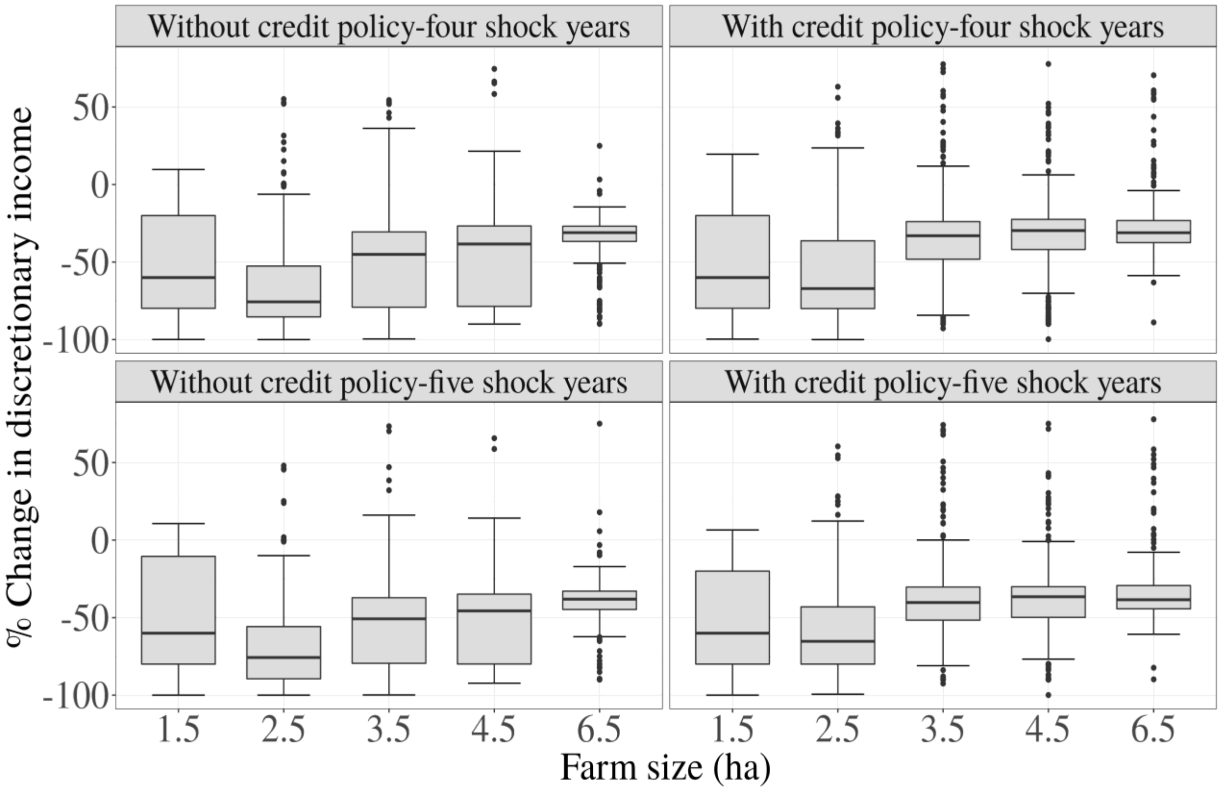


***Note**:* Change of agent livestock holdings averaged over repetitions in all simulation periods

5.3.4. Heterogeneous effects of credit and technology policy interventions

Household-specific characteristics can potentially determine farmer choices of climate adaptation strategies and policy responses (Berger et al., 2017, 2006). To understand agent trajectories in terms of resource endowments, simulation results are further disaggregated by farm size and baseline income (a hypothetical case scenario income) under climate and policy scenarios.

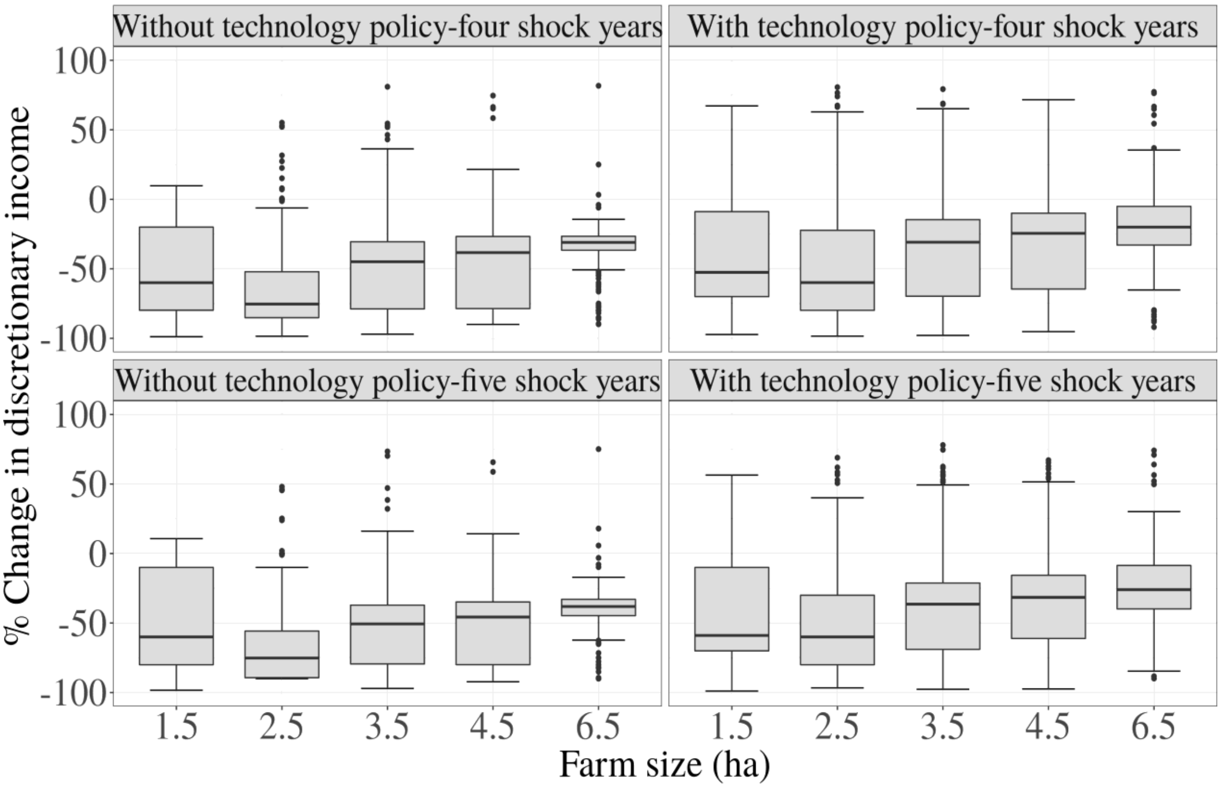
Figure 26*:* Income change by farm size with credit policy compared to without shocks and policy



Note*:* Change of agent discretionary incomes averaged over periods by the size of landholding

Figures 26 and 27 show the distribution of change in agent incomes over farm sizes for credit and technology policy intervention respectively. The results show that income loss due to recurring climate shocks is higher for agents with small farm areas both with and without credit and technology policy. At higher farm sizes, income loss declines which indicate that affluent agents with higher farm sizes can better withstand extreme shocks compared to agents with small farm sizes. Likewise, affluent agents better benefit from individual policy interventions as the income loss tends to reduce compared to without policy.

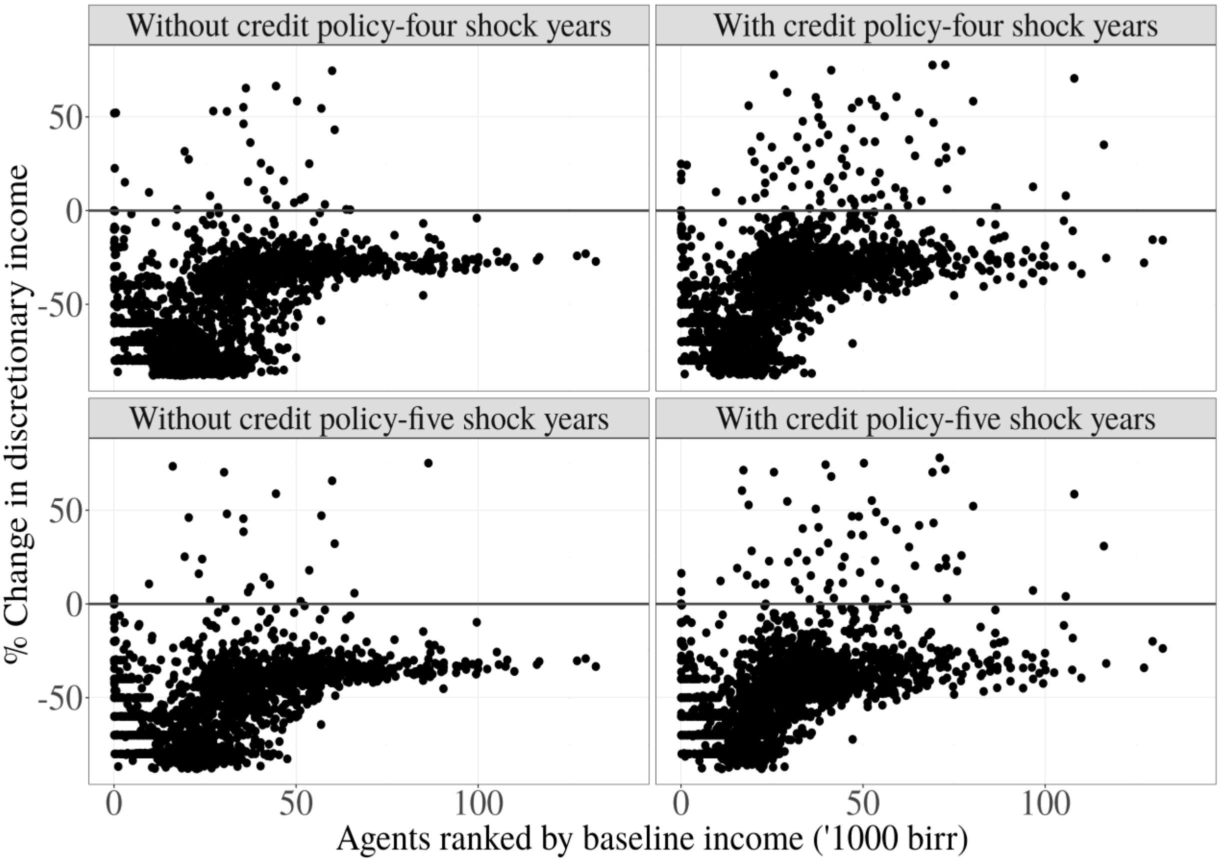
Figure 27*:* Income change by farm size with technology policy compared to without shocks and policy



Note*:* Change of agent discretionary incomes averaged over periods by the size of landholding

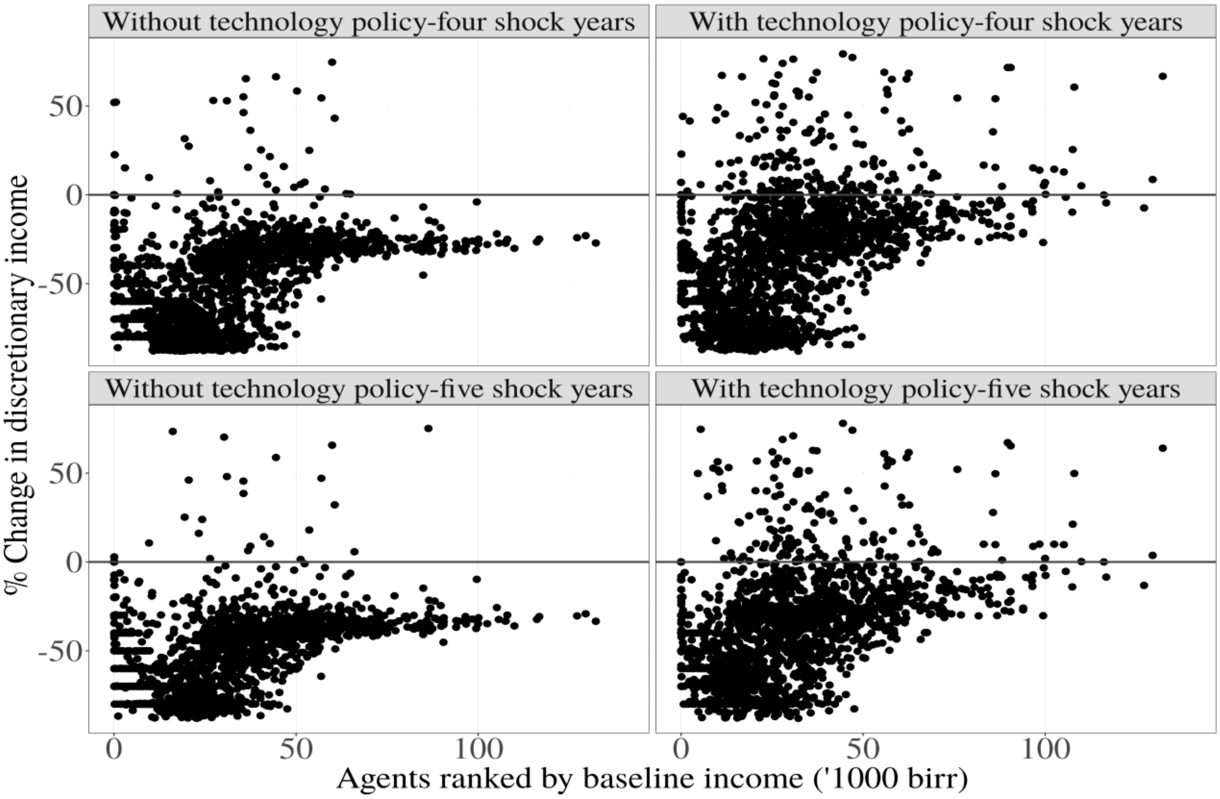
Figures 28 and 29 also show the distribution of average change of income over periods ranked by baseline (hypothetical case scenario-without shocks & policy) income for credit and technology policy respectively. Simulation results show that the adverse effects of extreme climate shocks are stronger for agents with a lower baseline income compared to agents with a higher baseline income without credit or technology policy interventions. With credit and technology policy interventions, income loss slightly declines. Agents with higher baseline income tend to better benefit from both policy interventions which gives them the leverage of responding to policy interventions which have the potential to reduce climate risk effects.

Figure 28: Income change of baseline income with credit policy compared to without shock and policy



Note: Individual agent discretionary incomes averaged over periods and ranked by agent hypothetical baseline incomes

Figure 29: Income change of baseline income with technology policy compared to without shock and policy



Note: Individual agent discretionary incomes averaged over periods and ranked by agent hypothetical baseline income

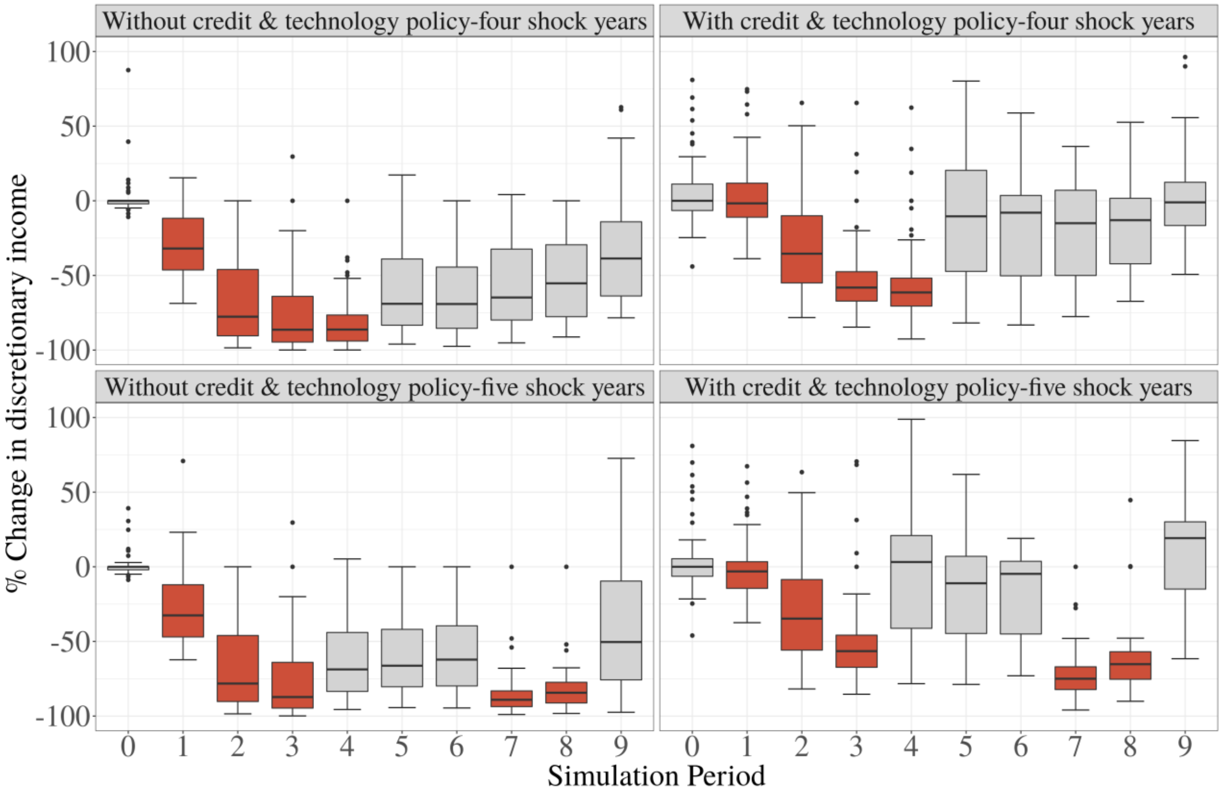
5.3.5. Joint policy interventions effects on reducing risk exposure

Effectiveness of joint credit and technology policy interventions under climate shocks

After simulation analysis of individual credit and technology policy interventions, two of these policy interventions were then analyzed jointly to assess their roles in reducing the vulnerability of agents against recurring climate shocks.

Figure 30 shows the effect of joint policy interventions on agent discretionary incomes by comparing with and without joint policy interventions under different climate trajectories. Without policy interventions, agent discretionary income declines by 53% and 56% over ten simulation periods under both four and five years climate shock frequencies respectively. With joint policy interventions, average agent income loss reduces to 29% and 32% under four and five shock years respectively (Table 11). This implies that agent income loss declines by 24 percentage points under both four and five shock years. The results suggest that the use of joint policy as climate adaptation has a stronger positive effect under different climate shock frequencies. The results also suggest that combined policy intervention is more effective to be used as climate adaptation measures than using individual credit and policy interventions as income loss considerably declines.

Figure 30: Income change with joint policy compared to without shock and policy



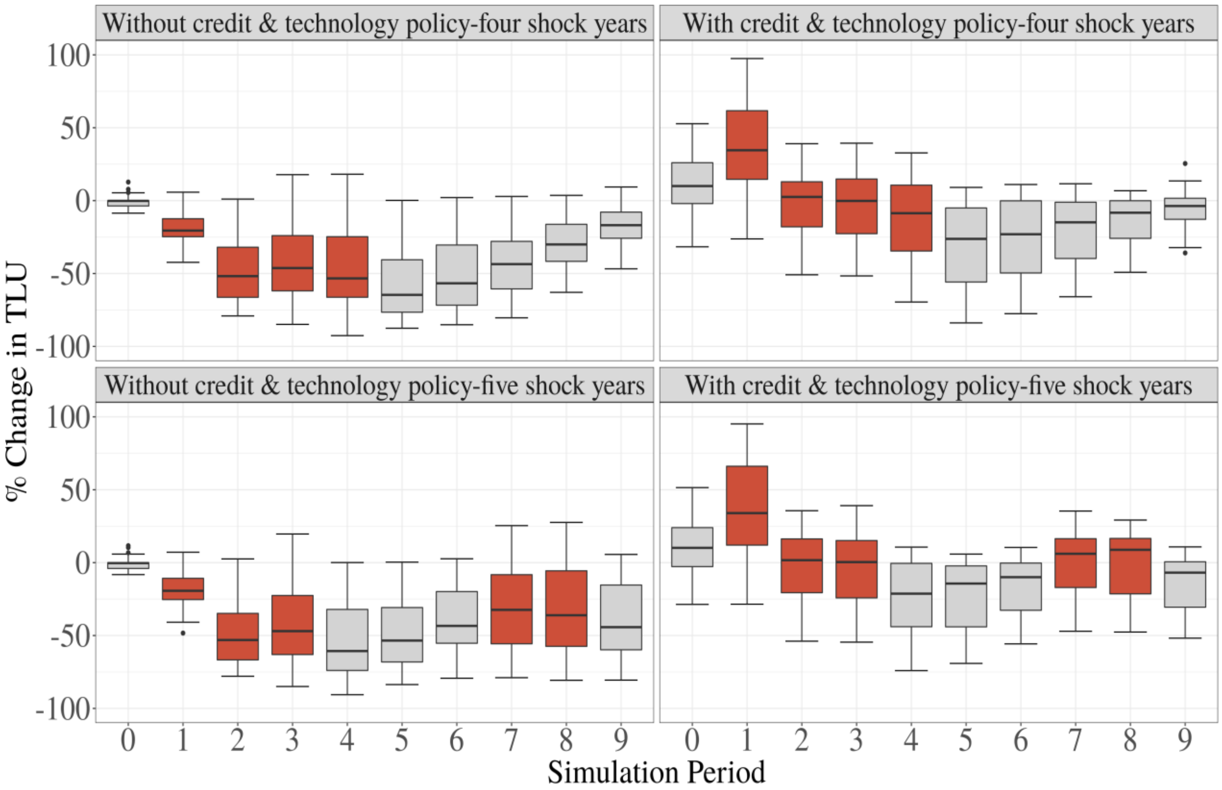
Note: Change of agent discretionary incomes averaged over repetitions in all simulation periods

Table 11: Average income change under individual and joint policy interventions

Scenario	**Income loss (%)**	
	Four shock years (4/10)	**Five shock years (5/10)**
Without policy	53	56
Credit policy	45	48
Technology policy	41	44
Joint credit and technology policies	29	32

Similarly, the simulation results of joint policy intervention on livestock assets show that joint policies are effective in reducing livestock losses to climate shocks (Figure 31). Under both four and five shock years, livestock asset loss substantially declines due to joint policy interventions. On average over periods, livestock loss is 37% and 39% under four and five shock years without policy interventions respectively. However, with joint policy interventions, there is a large reduction of livestock loss under both shock frequencies (the loss declined to 7% and 5% in four and five shocks respectively). Joint policy helps to reduce livestock loss by 30 and 34 percentage points under four and five shock years respectively.

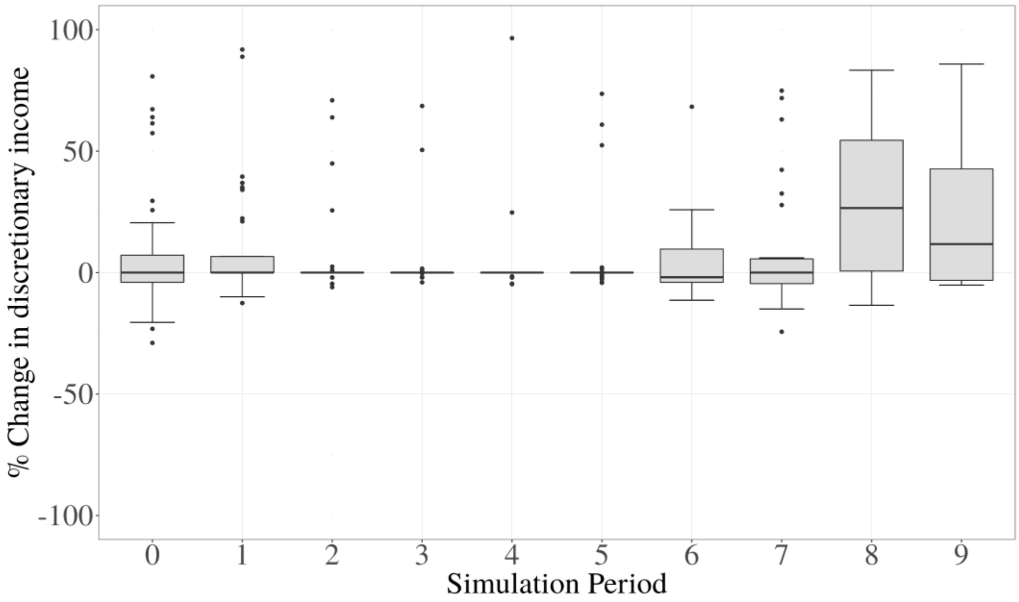
Figure 31*:* Livestock head change with joint policy compared to without shock and policy



***Note*:** Change of agent livestock holdings averaged over repetitions in all simulation periods

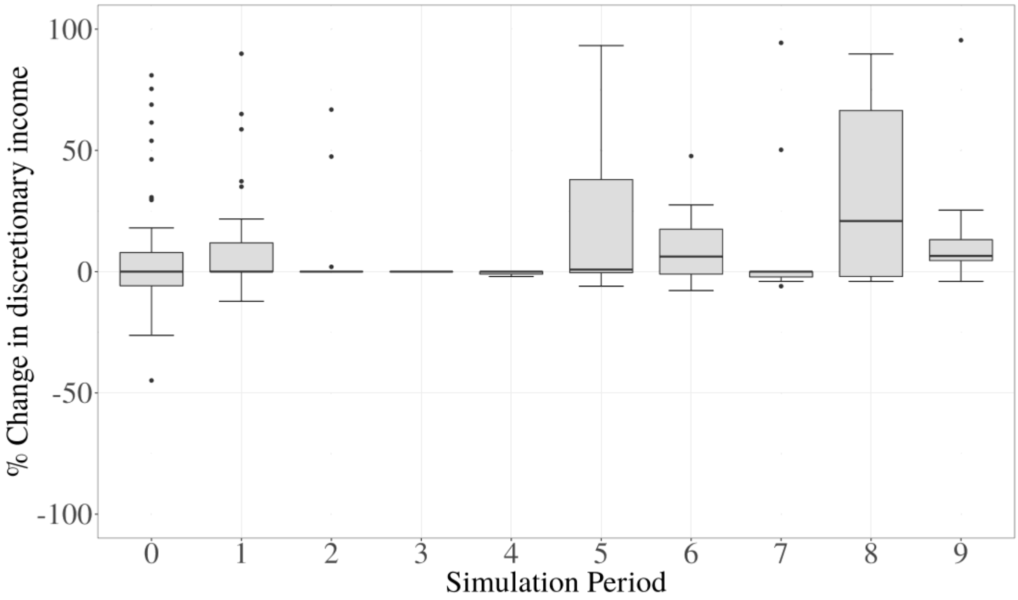
The preceding graphs help to understand the loss compensation level of joint policy intervention. This is possible by comparing shocks with policy to without shock and policy. To isolate the pure effect of joint policy intervention in all simulation periods, a separate analysis was conducted by comparing shock with joint policy to shock without joint policy under four and five shock years. Here the income difference was calculated from the shock without joint policy scenario, not from the hypothetical case scenario (without shock & policy). With this comparison, positive policy effects can be clearly distinguished. It answers "*What would have happened to the welfare of agents had the policy intervention never been implemented?"*. Figures 32 and 33 confirm that joint policy intervention has positive contributions in offsetting the negative effects of extreme shocks under both shock frequencies. In 'normal years' in ten simulation periods, where there are no shocks, agents are even able to gain additional positive incomes after some time.

Figure 32: Joint policy intervention effect compared to shock without policy under four shock years



***Note**:* Change of agent discretionary incomes averaged over repetitions in all simulation periods

Figure 33*: Joint policy intervention effect compared to shock without joint policy under five shock years*

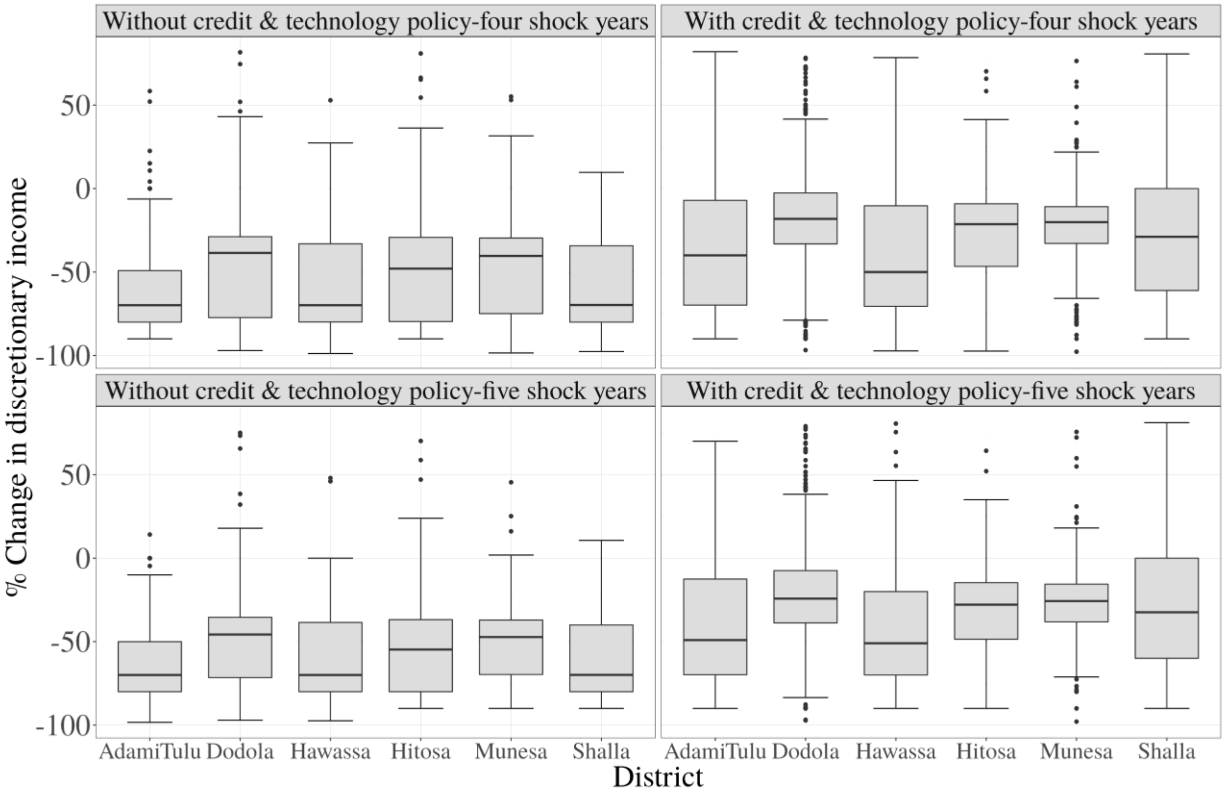


Note: Change of agent discretionary incomes averaged over repetitions in all simulation periods

5.3.6. Heterogeneous effect of joint policy intervention

Figure 34 shows the distribution of the heterogeneous effects of joint policy interventions over districts. Under both with and without joint credit and technology policy intervention, income loss is relatively smaller in wheat-growing districts (Hitosa, Dodola, and Munesa) compared to the other remaining districts which are in the maize production system. This is because agents in the wheat production system have a relatively larger land size and crop production diversity compared to maize-growing areas which help them to be better resilient against climate shocks.

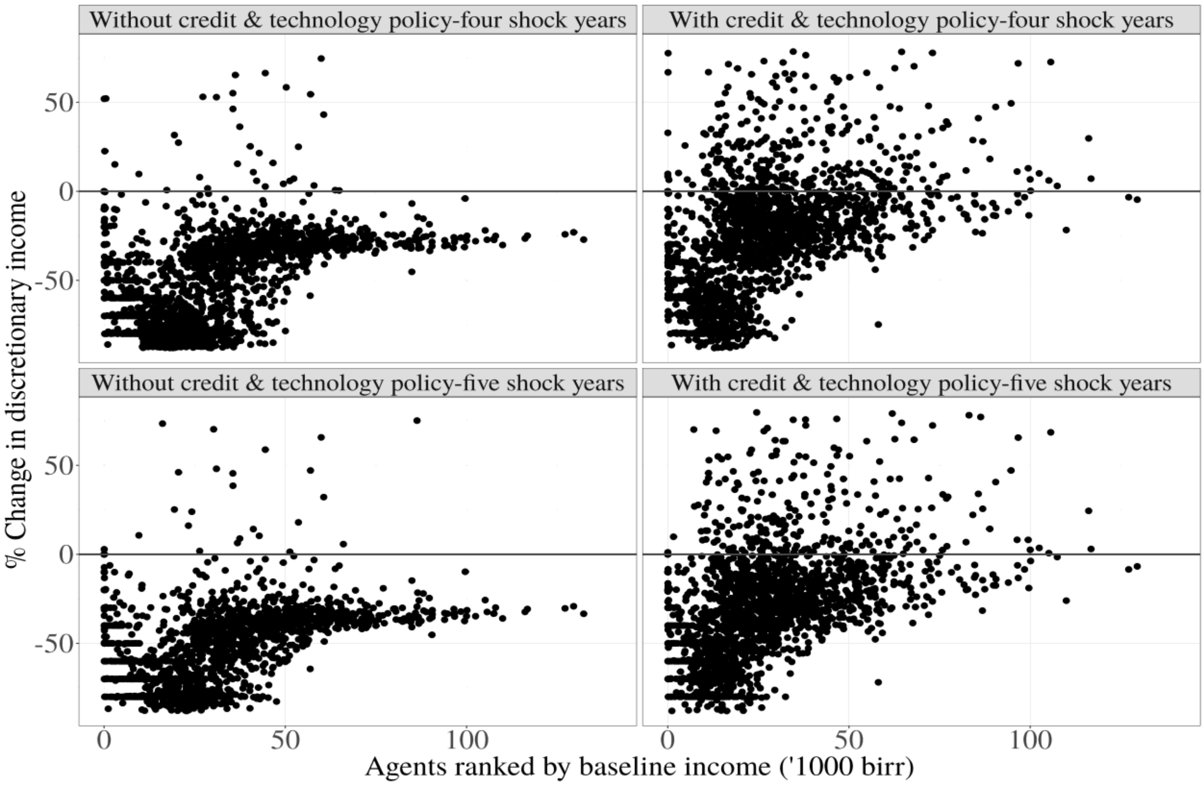
Figure 34: Income change by districts with joint policy intervention under shocks



Note: Change of agent discretionary incomes averaged over periods for all districts

Simulation results also suggest that combined policy interventions considerably improve the income status of model agents (Figure 35). The income loss of many agents to extreme climate shocks is largely compensated by combined policy intervention compared to without policy. Similar to the effect of individual credit and technology policy, agents with higher baseline income benefit the most from the combined policy interventions under the two shock frequencies.

Figure 35: Income change of baseline income with joint policy compared to without shocks and policy



Note: Individual agent discretionary incomes averaged over periods and ranked by agent hypothetical baseline income

Chapter 6: Farm-level simulations of impact of desert locust invasions on household welfare: Evidence from Central Rift Valley of Ethiopia

6.1. Introduction

On top of extreme climate shock challenge, desert locust invasions have become an important shock affecting the well-being of many smallholder farmers in Ethiopia. This migratory pest largely destroys strategic food security crops like sorghum, maize, and wheat. As the swarm moves in mass propelled by wind and feed on large quantities of crops, it can cause up to 100% crop yield loss. This exposes, not households who are already in dreadful food insecurity situations, but also relatively better-off farm households to face food insecurity, indebtedness, and livestock asset depletion (FAO, 2020b).

The crop damages due to the desert locust outbreak have already brought a massive humanitarian crisis to the country. When such shocks are not tackled properly and effective mitigation measures are not in place, they can have long-term impacts on household livelihood conditions. In the early 1960s and 1970s, locust plague prevention teams monitored and fought locust outbreaks which are understaffed and largely abandoned nowadays[8]. Whenever emergency responses and livelihood protection interventions are missing or not provided timely, households often start to employ their emergency livelihood coping strategies. These coping measures include forced livestock sales, usually with lower prices, early harvesting of crops before getting mature and consuming seed stocks. Such forced coping measures could have long-term implications on the well-being of households as it depletes the existing resource bases including assets which in turn exacerbate household vulnerability to shocks.

It is predicted that the locust resurgence will likely continue in the coming years and become a multi-year crisis. This could result in long-term consequences on household welfare by increasing erosion of productive assets and continuing to damage crop production and pasture land. Increased cyclone frequency and extreme climate events - would likely increase future locust breeding and spread (Salih et al., 2020).

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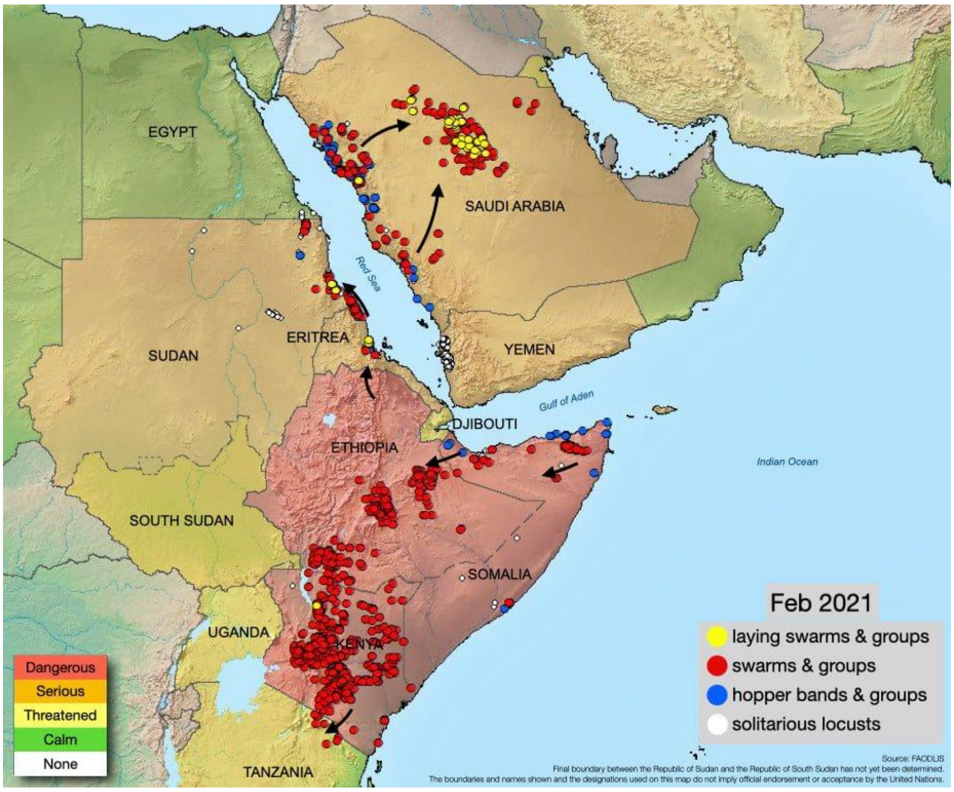
[8] Experts discussion and reflection during CLIFOOD project block seminar meeting



Source: FAO locust situation in the horn of Africa, 2021

In the locust affected areas, government and non-governmental organizations devised and implemented different locust relief policy interventions to support the livelihood of farm households and reduce or protect productive asset depletion. Most relief programs are often designed and implemented without sufficient economic analysis like *ex-ante* relief policy analysis mainly due to urgencies in humanitarian support provision. Moreover, after implementing relief interventions, assessment of policy impact and identification of effective intervention(s) that work better in a given location is often missing. To the best of my knowledge, there are no studies in Ethiopia which quantified the impacts of desert locust shock and evaluated the effectiveness of locust relief policy interventions in reducing the vulnerability of smallholder farmers. Quantifying the welfare effect of prolonged locust shock and identifying effective locust relief interventions has paramount importance to provide insight to policymakers to prioritize and choose the best policy option for upscaling the approach in other similar places.

6.2. Locust relief policy interventions

The government of Ethiopia has designed locust outbreak response mechanisms in collaboration with different organizations mainly with NGOs such as FAO and others operating in the country to minimize humanitarian crises. These are locust relief responses designed and implemented in locust-affected areas to support locust vulnerable households. The main purpose of these policy interventions is to bridge temporary food shortages, restore household livelihood through agricultural input provision and protect the existing asset bases.

From the desk reviews, four locust relief interventions meant to reduce locust upsurge adverse effects were identified and implemented in MPMAS_CRV. These are (i) cash transfer (ii) food transfer (iii) agricultural inputs provision – support households to bring back on their feet and (iv) asset recuperation. Cash and food transfers are a direct substitute for each other. Households who receive food assistance are not eligible to get cash which is controlled via scenarios in MPMAS_CRV implementation. Other interventions are complementary support with either food or cash transfers extended to affected households aimed at protecting household livelihood and assets.

Cash/food transfers

In the severely locust-affected areas, emergency responses in cash or in-kind food transfers have been provided to affected households through government and non-governmental organizations. Emergency food or cash transfers at the time of locust shock have been intended primarily to sustain short-term food security, protect against asset depletion and improve welfare in the long run.

Inputs provision

Farm households often buy inputs, including improved seed, or use their own saved seed for crop production. Cash requirement to finance input purchases is generated mainly from crop and livestock sales. Locust outbreak damage crops, limiting farm households ability to generate enough cash to buy necessary inputs. To reduce the crisis, emergency inputs relief is considered as one of locust relief policy interventions to ensure planting in the subsequent cropping seasons. The support includes seed provision and other complementary inputs like mineral fertilizer and agrochemicals.

Asset recuperation/recovery support

In addition to cash or food transfers, some NGOs also provide complementary assistance to enhance household livelihood recovery. They usually offer breeding does/ewes to enhance asset building. This intervention is meant to improve the capacity of households to be more resilient in the face of locust shock.

6.3. Methods and data

For this thesis chapter, MPMAS_CRV built for the simulation of climate shocks, credit, and technology policy was adapted by adding new activities and constraints relevant to the simulation of locust impacts and responses to locust relief policy interventions. New activities were defined for relief policy interventions and respective constraints of input, food and cash consumption, and livestock balances were also adapted in MPMAS_CRV. Extensive desk reviews were made to documents of ministry of agriculture and NGOs to identify locust relief interventions, implementation modalities, and the amount of support to households in locust-hit areas. Data from desk review on the locust relief policy interventions were then used for adding new features in MPMAS_CRV and establishing locust and relief policy scenarios. Scenario-based analysis using MPMAS_CRV are useful for disentangling or netting out the effects of locust outbreak and identify better relief policy interventions. It enables to assess what would have happened to the welfare of agents had the locust relief interventions never been designed and implemented.

6.4. Locust simulation experiments

To simulate the desert locust outbreak impacts and the effectiveness of locust relief policy interventions, the thesis adapted the benchmark or hypothetical case scenario used for simulating climate shock and policies. In this hypothetical case scenario, there are no locust outbreaks and locust relief policy interventions. The thesis used this scenario to compare locust impact analysis and associated relief policy interventions. Locust shock was introduced in the second, third, and fourth simulation periods in a row (1,2, and 3 periods) in MPMAS_CRV. Desert locust relief policy interventions and simulation experiments in ten simulation periods are summarized in Table 12.

Table 12: Locust simulation experiments

Scenario	Relief interventions	Locust outbreak (3/10)
Baseline	Without locust invasions	
	Locust invasions – without any relief support	1,2,3
	Locust invasions – food transfer only	1,2,3
	Locust invasions – food and input transfers	1,2,3
Counter-factual	Locust invasions – food, inputs & asset transfers	1,2,3
	Locust invasions – cash transfer only	1,2,3
	Locust invasions – cash and input transfers	1,2,3
	Locust invasions – cash, inputs & asset transfers	1,2,3

Locust simulations were run for 50 repetitions to check the robustness of simulation results for outcome variables.

6.5. Locust simulation results

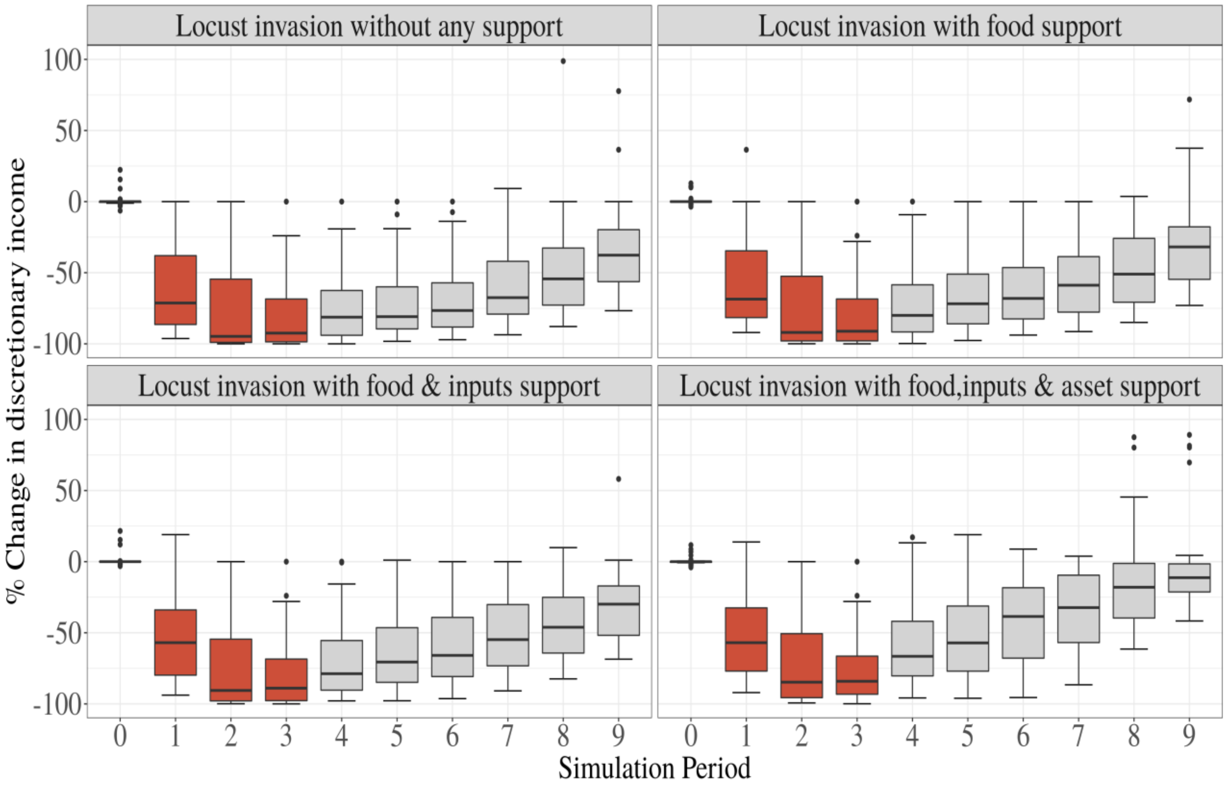
Under this topic, the thesis presents the locust simulation results on locust welfare impact and effectiveness of different locust relief interventions according to their level of compensation to welfare losses to locust shock.

6.5.1. Welfare impact of locust invasions and the role of locust relief policy interventions

Income effect of recurring locust invasions

Discretionary income is used to measure the status of agent incomes under different scenarios in locust simulations. Figures 36 and 37 present the change in discretionary income over 50 repetitions with and without locust response relief interventions compared to baseline. Simulation results depict that agent incomes are affected severely without relief policy interventions when locust occurs three years in a row. Implementations of individual relief programs have a minimal compensation effect in reducing discretionary income loss, as the adverse effect on agent incomes is still considerable. Among the relief policy interventions implemented in MPMAS_CRV, food or cash transfers combined with inputs and assets interventions have better compensational effects in reducing income loss compared to other interventions. After the locust shock is over, the income of agents gradually improves over time in normal years though there is still a pronounced income loss in normal years as well due to the effect of the preceding locust shock.

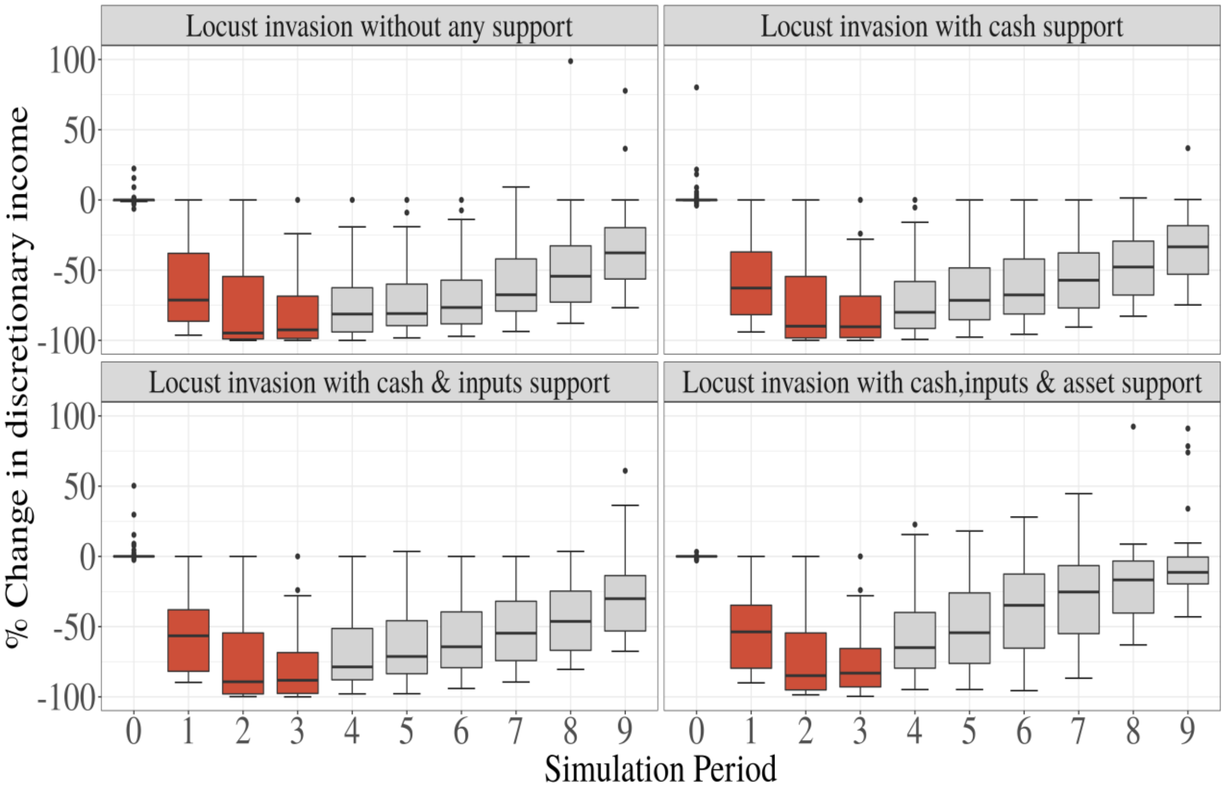
Figure 36: Income change with food and complementary interventions compared to without policy



Note*:* Change of agent discretionary incomes averaged over repetitions in all simulation periods

On average over periods, discretionary income loss is 58% when locusts occur three years in a row and when there are no relief responses. However, under food transfer alone, food transfer with input support, food transfer with input, and asset intervention, agent income loss declines to 55%, 53%, and 44% on average respectively. Similarly, under cash transfer alone, cash transfer with input interventions, cash transfer with input, and asset scenarios agent income loss decline to 54%, 52%, and 42% on average respectively which is much similar to food transfer with complementary locust relief interventions. Overall, it implies that recurring locust outbreak has long-term adverse effects on agent incomes and recovery takes more extended periods for resource-poor agents after perturbation. Compared to individual relief interventions combined joint relief interventions are better at helping agents to recover from income loss at end of the simulation year. With individual relief intervention and when there is no intervention during locust shock, income loss recovery takes even more than ten years.

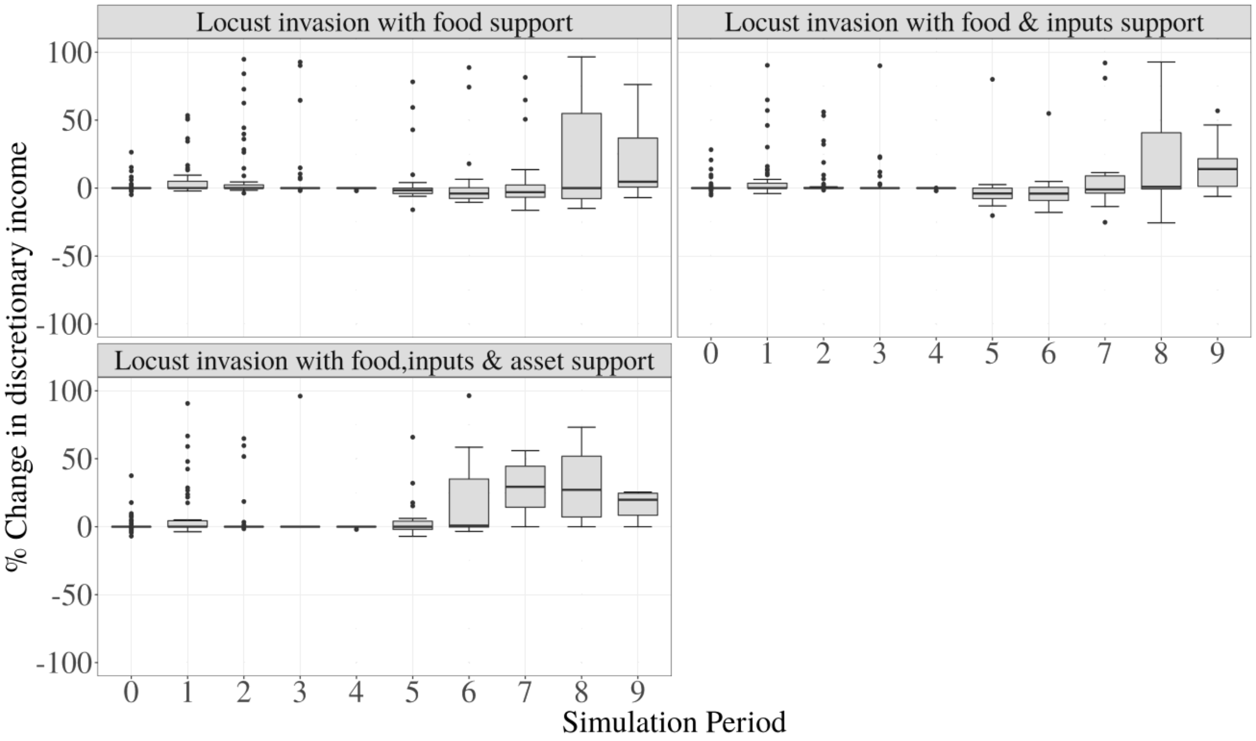
Figure 37: Income change with cash and complementary interventions compared to without policy



***Note**:* Change of agent discretionary incomes averaged over repetitions in all simulation periods

Apart from analyzing the compensatory effect of locust relief interventions in the previous distribution graphs, the pure positive policy effect was disentangled by comparing locust invasions with and without policy. Figure 38 below shows the distribution of agent incomes computed by subtracting income of policy interventions from income without policy- both scenarios under locust invasions. The result shows that locust policy interventions are better at reducing the adverse effect of recurring locust impacts. In the latter years, when there is no locust shock, agents start to gain positive income though it takes some time to realize. It also shows that income benefit is higher for joint relief policy interventions compared to individual locust relief policy interventions.

Figure 38: **Comparison of income change with and without relief interventions under locust invasions**



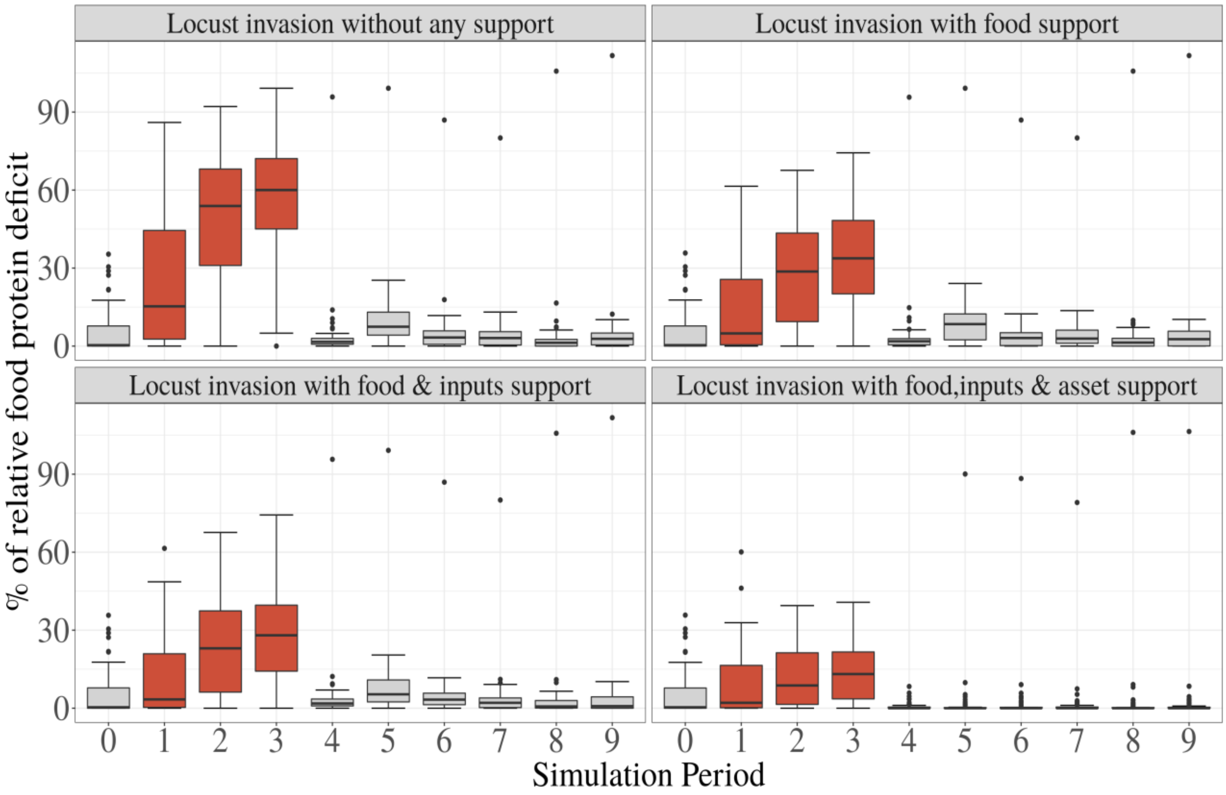
Note: Income change was computed from without policy interventions with locust, not from without policy & locust

Food security effect of locust invasions

Under this topic, the simulation results that show the impacts of recurrent locust outbreak on food security are described by comparing the level of relative food nutrition deprivation between locust with relief policy interventions scenarios to locust without relief policy interventions scenario. Moreover, the effectiveness of food or cash transfers with associated complementary relief interventions in improving food consumption is compared. In hypothetical case conditions, where there is no locust outbreak and no policy interventions (used as a benchmark for impact analysis), agents are not running into food protein and energy deficits. However, they run into temporary consumption shortages during severe shocks due to the shock effect on commodities production and price.

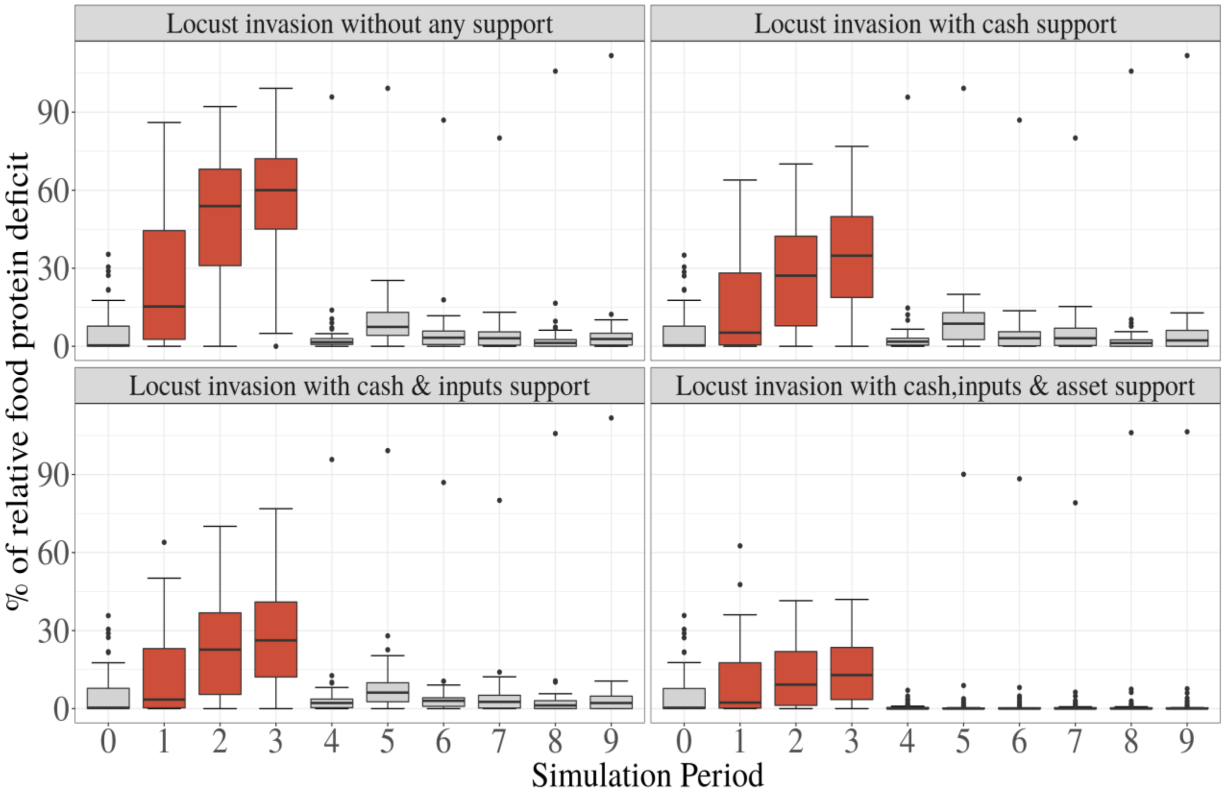
Figures 39 to 42 compares the distribution of relative protein and energy consumption deficit under recurring locust outbreak but under different relief interventions over 50 repetitions for all agents in all periods. The simulation results show that many model agents run into food protein and energy deficits due to locust upsurge when there are no locust relief programs compared to conditions where there are relief policy interventions. Even with either food or cash transfer intervention alone under locust shock, food nutrition deprivation shows little improvement compared to the without relief policy scenario. The food security effect of relief policy interventions starts to be more noticeable when different relief policy interventions are implemented together. Joint relief policy interventions (food/cash, input, and assets) tend to better reduce the relative food consumption deficit followed by food/cash and input transfers compared to individual locust relief policy interventions. Despite the positive compensatory effect of the joint policy interventions in reducing the food consumption deficit, the problem remains considerable in shock years though the degree of food shortage is minimal compared to other scenarios. This shows that relief interventions are necessary but not sufficient to fully compensate for the negative effect of locust invasions. However, after locust shock is over, in the 'normal' years, except for some agents, many of them can fulfill minimum food protein and energy consumption requirements (Figures 39 to 42).

Figure 39: Relative protein deficit under food & complementary interventions compared to without policy



***Note**:* Percentage of relative food protein deficit averaged over repetitions in all simulation periods

Figure 40: Relative protein deficit with cash & complementary interventions compared to without policy



Note: Percentage of relative food protein deficit averaged over repetitions in all simulation periods

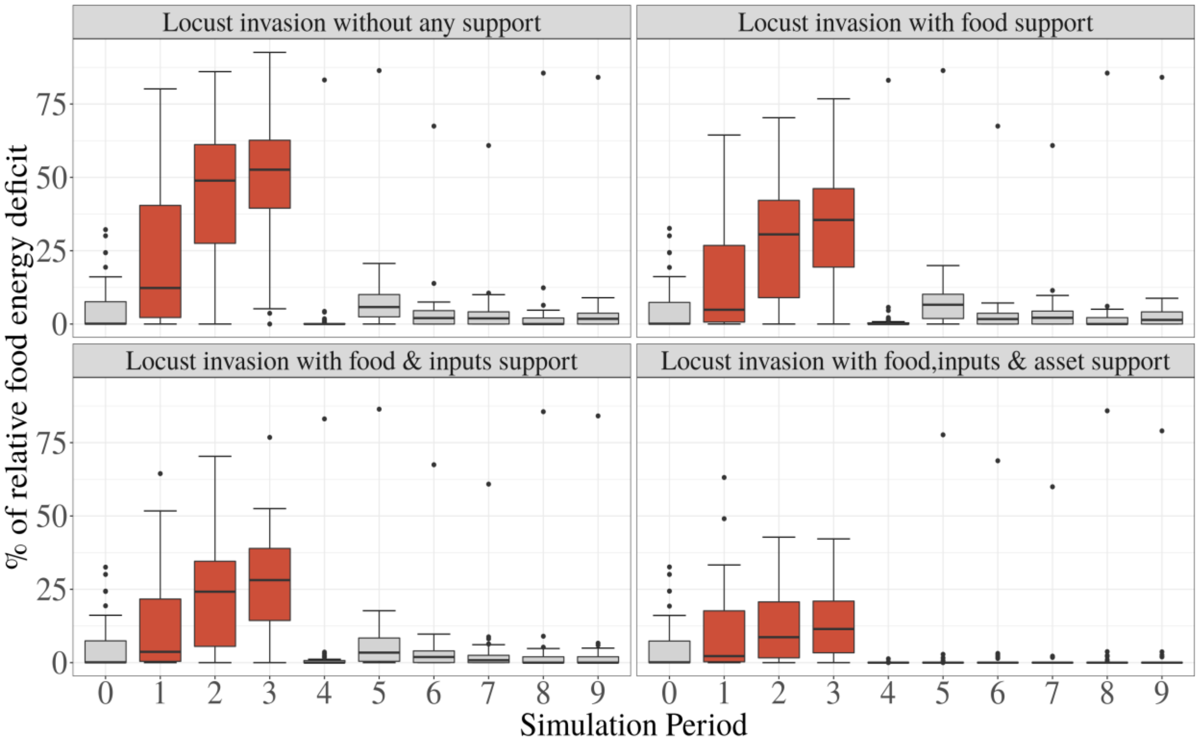
Alike income effects, the simulation results further depict that the food security effect of combined relief interventions is more pronounced. On average over periods for agents, the relative food energy deficit reduces from 14% (locust invasions without policy) to 5% (locust invasions with combined policy (food/cash, input, and asset interventions)) followed by food and input transfer support (Table 13). Individual locust relief interventions contribute to the reduction of the food energy deficit to some extent but less than the three combined relief interventions (food, inputs, and assets). This shows the importance of combined relief policy interventions as food energy deprivation is largely compensated.

Table 13: Effectiveness of locust relief policy interventions

Interventions	Starvation rate – food energy(%)
Without policy support	14
Food transfer only	10
Food and inputs transfers	9
Food, inputs, and assets transfers	5

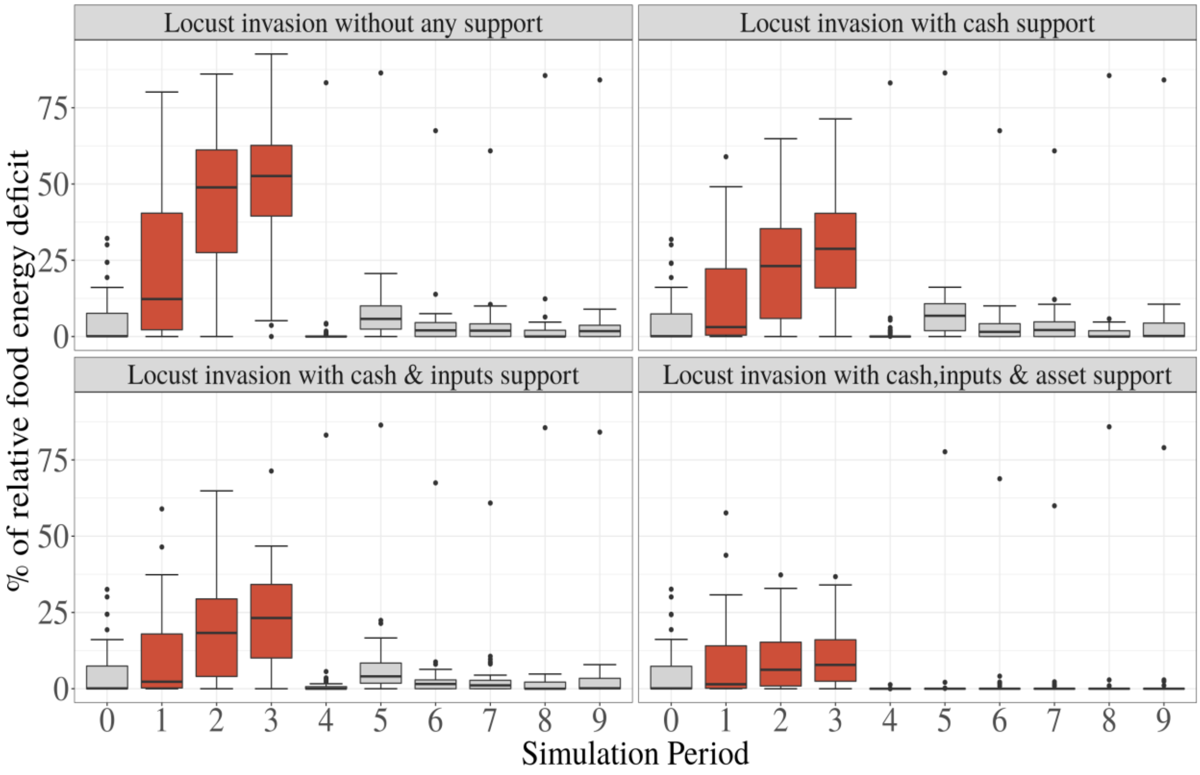
Further disaggregation of simulation results to individual locust years shows that without any interventions under locust outbreak, the relative food energy deficit is 48% on average over 50 repetitions in the 4th simulation year when it occurs three years in a row. The average food energy deprivation reduces to 33%, 27% and 13% in the 4th locust year with food transfer alone, food and input transfers, food, input and asset relief transfers respectively (Figure 41) which is similar for cash transfer and other complementary interventions. After shock is over in all scenarios, there are no agents who suffer from food energy deficits under the three combined relief interventions. However, some agents face transitory food insecurity under individual relief policy interventions after the locust is over (Figures 41 and 42).

Figure 41: Relative energy deficit with food & complementary interventions compared to without policy



***Note**:* Percentage of relative food energy deficit averaged over repetitions in all simulation periods

Figure 42: Relative energy deficit with cash & complementary interventions compared to without policy



Note: Percentage of relative food energy deficit averaged over repetitions in all simulation periods

The proportion of agents who meet/unmet the minimum food consumption requirements is further compared in each scenario as depicted in Table 14. Without relief policy interventions under locust shock, 30% and 36% of the agent population temporarily run into food energy and protein deficits respectively. However, with food and input combinations 24% and 30% of model agents cannot meet minimum food energy and protein consumption respectively. With combined relief policy interventions (food, inputs, and assets) only 17% and 19% of agents on average are unable to meet minimum food energy and protein requirements respectively. The proportions of agents in all scenarios are fairly similar for cash and complementary interventions as well (Table 14).

Table 14: Proportion of agents by food nutrition deprivation status

Scenario	Statistics	Minimum energy		Minimum protein	
		met	unmet	met	unmet
Locust infestation – without any relief interventions	N	376	164	343	197
	%	70	30	64	36
Locust infestation – food transfer only	N	395	145	363	177
	%	73	27	67	33
Locust infestation – food and input transfers	N	408	132	379	161
	%	76	24	70	30
Locust infestation – food, input and asset transfers	N	450	90	440	100
	%	83	17	81	19
Total	N	**1629**	**531**	**1525**	**635**
	%	**75**	**25**	**71**	**29**
Locust infestation – cash transfer only	N	396	144	370	170
	%	73	27	69	31
Locust infestation – cash and input transfers	N	417	123	385	155
	%	77	23	71	29
Locust infestation – cash, input and asset transfers	N	460	80	445	95
	%	85	15	82	18
Total	**N**	**1649**	**119**	**1525**	**635**
	%	**76**	**24**	**72**	**28**

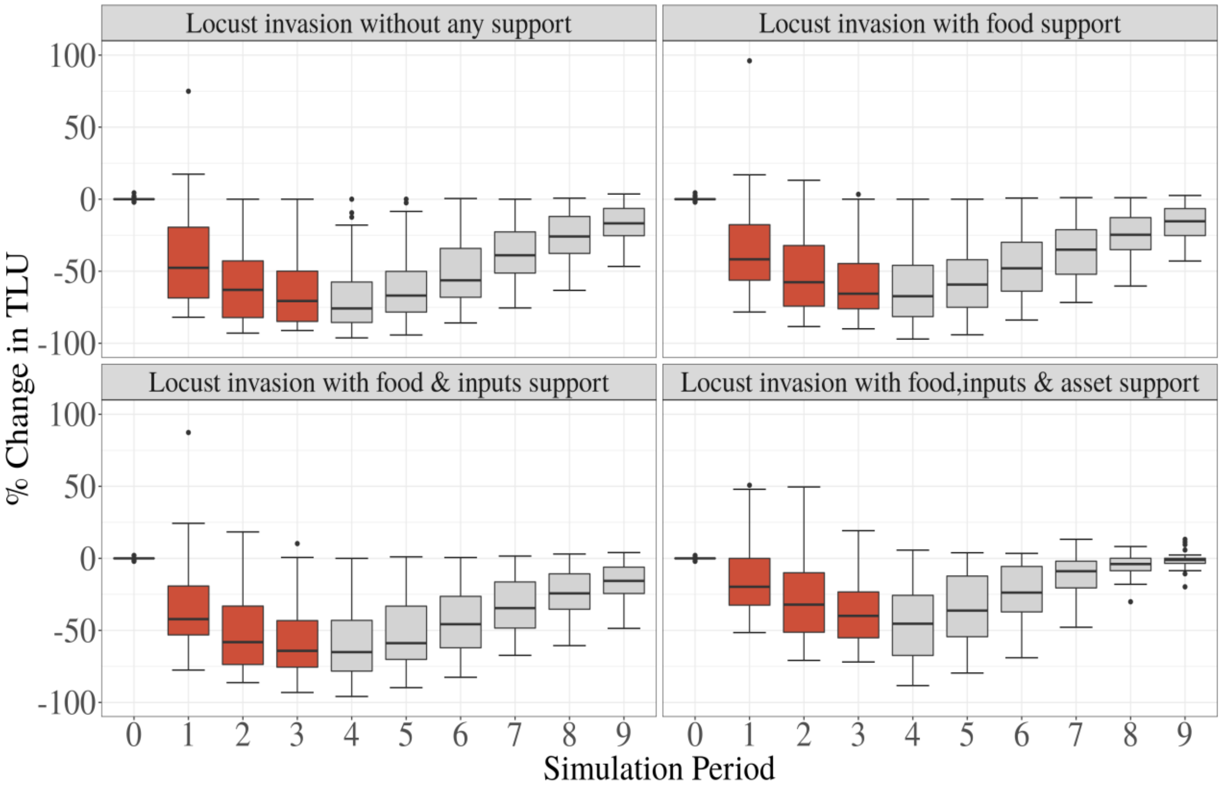
Note: After aggregating relative food consumption over repetitions, the number of cases where agents met/unmet minimum food consumption requirements was counted in all periods for all scenarios (overall observation is 2160)

The overall results suggest that relief policy interventions are necessary at times of extended locust shocks in reducing temporary food insecurity. Agents who face temporary food nutrition deprivation considerably decline with three combined relief interventions. However, as locust outbreaks may continue in the future and devastate crops and fodders, such relief programs may not last long which need long-term planning and vigilance to get prepared beforehand than managing the crisis after its occurrence.

Impact of locust invasions on household livestock assets

Apart from food security and income effects, the livestock asset effect of locust invasions was evaluated in the locust simulation. Figures 43 and 44 compare livestock asset distributions over all repetitions for each scenario. The simulation results show that agent livestock holdings measured by TLU are affected severely by locust shock without any relief policy interventions compared to without locust outbreaks and relief policy interventions. After the locust outbreak is over in the non-locust shock years, livestock holdings continue to be affected under both with and without locust relief policy interventions though the degree of livestock loss is larger without policy under locust shock. When three of the relief policy interventions are used together, losses of livestock holding substantially decline. With close observation of the distribution graphs, when these three interventions are used jointly, agents fully recover from livestock losses at the end of the simulation period which is not possible with other relief interventions. (Tables 43 and 44).

Figure 43: Livestock change with food and complementary interventions compared to without policy

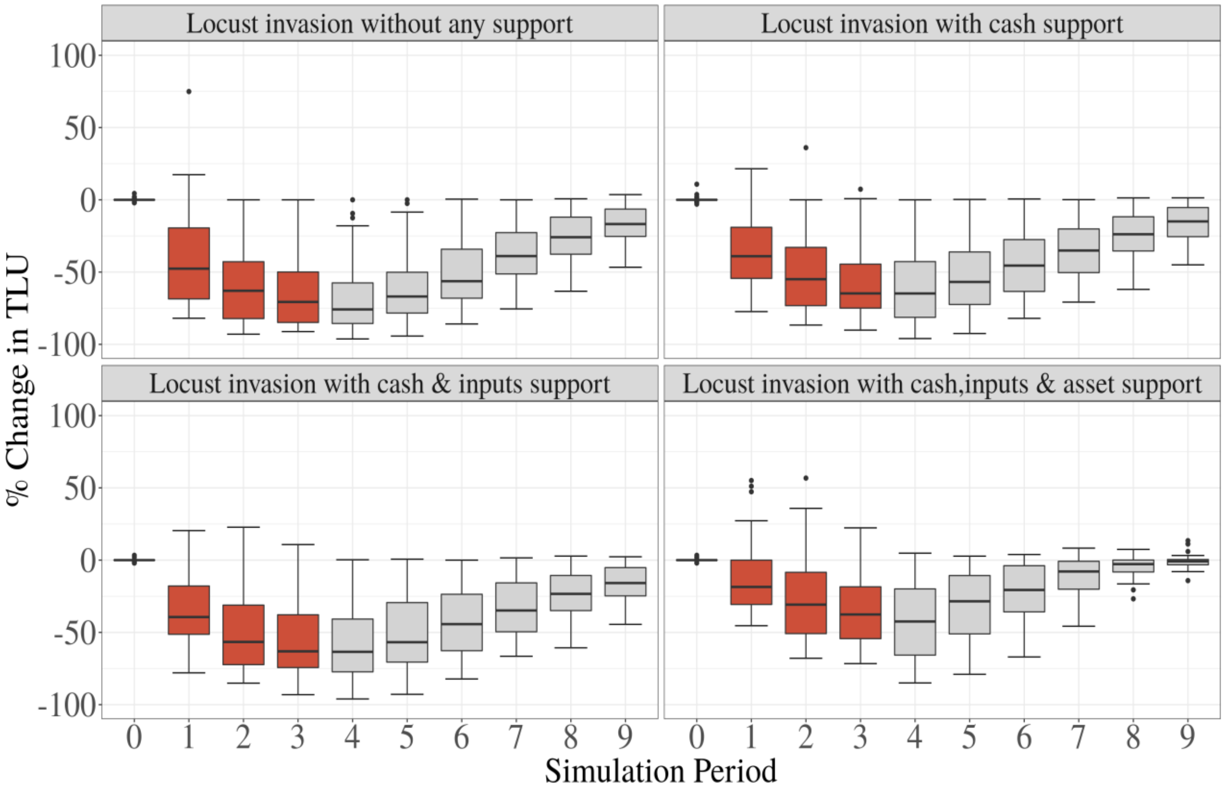


***Note*:** Change of agent livestock holdings averaged over repetitions in all simulation periods

On average over periods with desert locust invasions without any support, agent livestock holding declines by 42%. Livestock loss reduces to 38%, 37% and 20% under food/cash transfer alone, food/cash combined with inputs, food/cash, inputs and asset interventions respectively. When agents access food with complementary supports, their livestock holding improves considerably.

The considerable livestock loss compensation effect of combined food/cash, inputs and asset intervention is mainly due to the inclusion of asset recuperation which plays a key role in asset building over time.

Figure 44: Livestock change with cash and complementary interventions compared to without policy

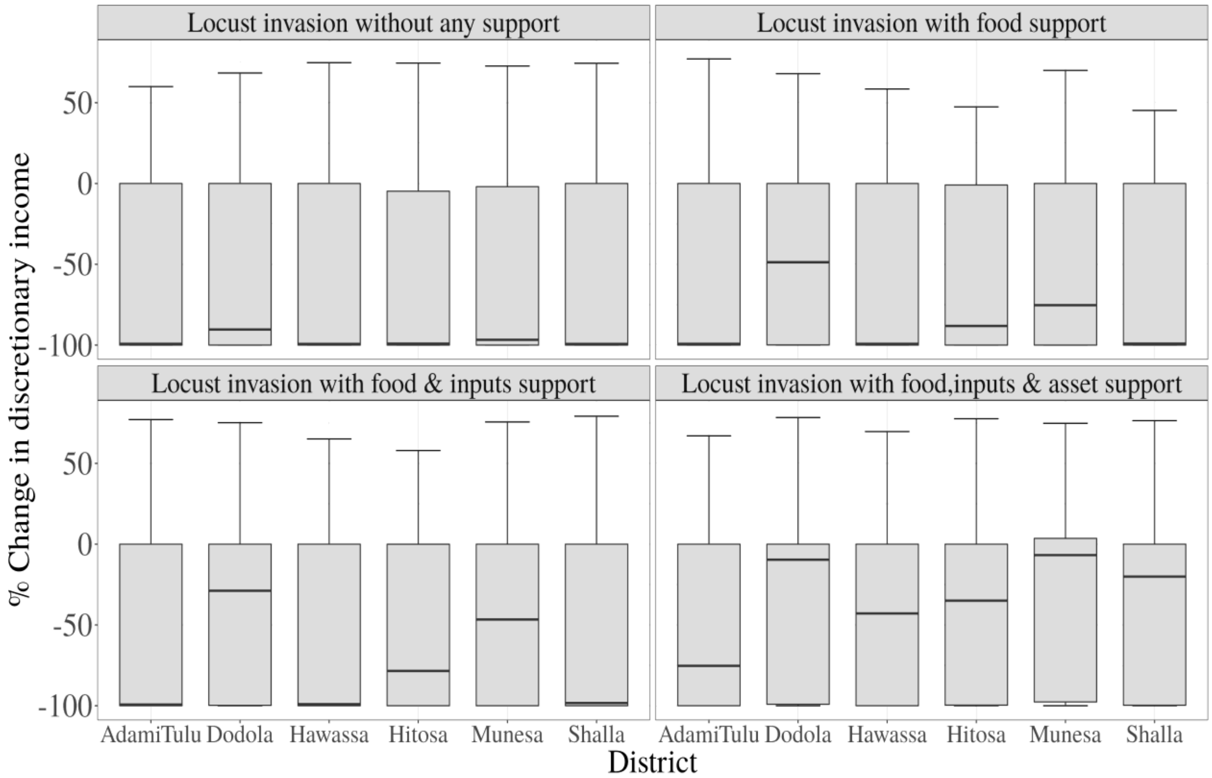


***Note**:* Change of agent livestock holdings averaged over all repetitions in all simulation periods

6.5.2. Heterogeneous effect of locust shock and role of relief policy interventions

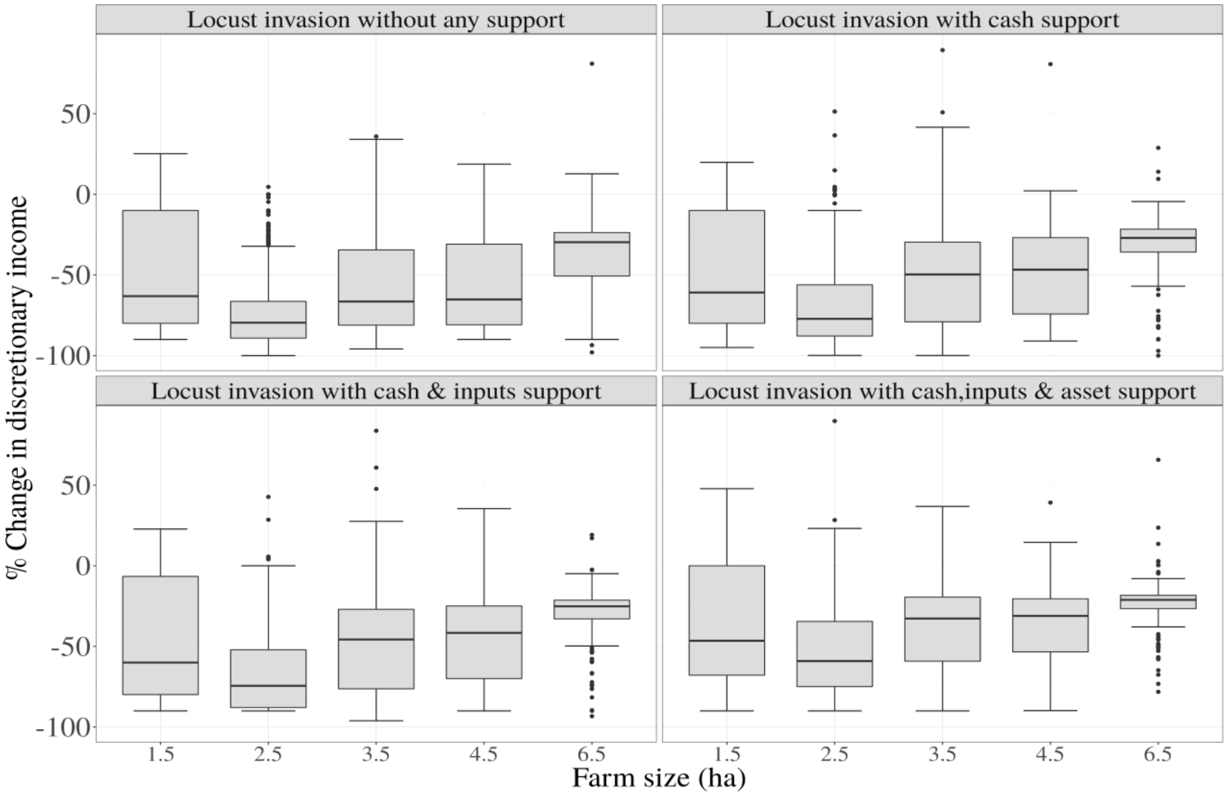
Figures 45 and 46 show the disaggregated analysis of agent income changes to the individual agent by districts and farm sizes on average over periods. Simulation results show that agents in wheat-growing areas benefit the most from locust policy interventions (Figure 45). Moreover, in general agents with higher farm sizes are less affected by recurring locust invasion than agents with lower farm sizes (Figure 46).

Figure 45: Income change by district with locust relief interventions compared to without policy



Note: Change of agent discretionary incomes averaged over periods for all districts

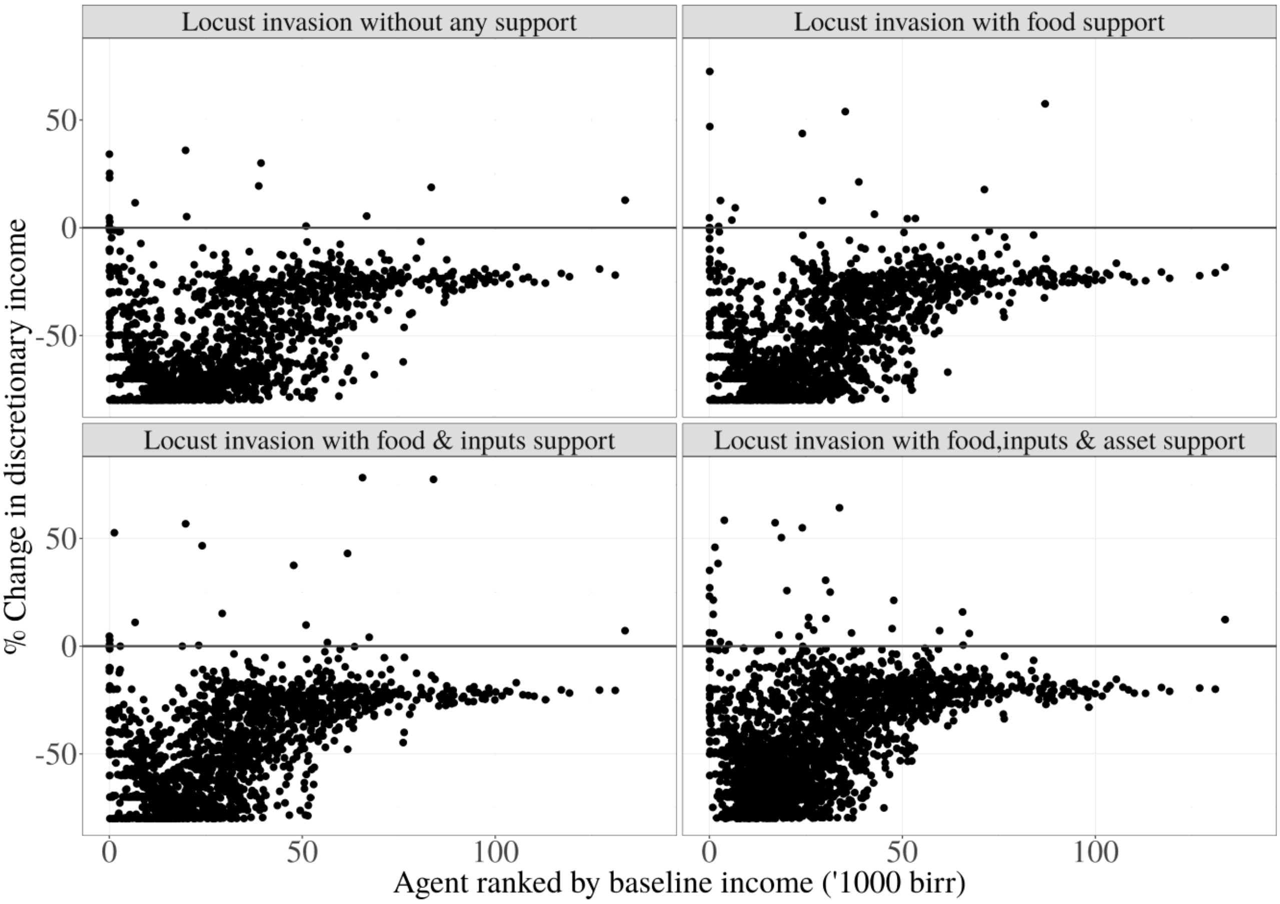
Figure 46: Income change by farm size under locust relief interventions compared to without policy



Note: Change of agent discretionary incomes averaged over periods by the size of landholding

Disaggregated analysis of agent discretionary incomes by their baseline income also shows that income loss is higher without interventions and for agents with lower baseline income. With food/cash and complementary relief policy interventions, though there are still considerable income losses, relief policy interventions have a positive contribution in compensating agent income losses (Figure 47). It appears that many agents benefit from the relief policy interventions, but a close visualization of the distributions shows that gents with higher baseline income appear to benefit better from relief policy interventions similar to the effect of credit and technology interventions with climate impacts and adaptation simulations.

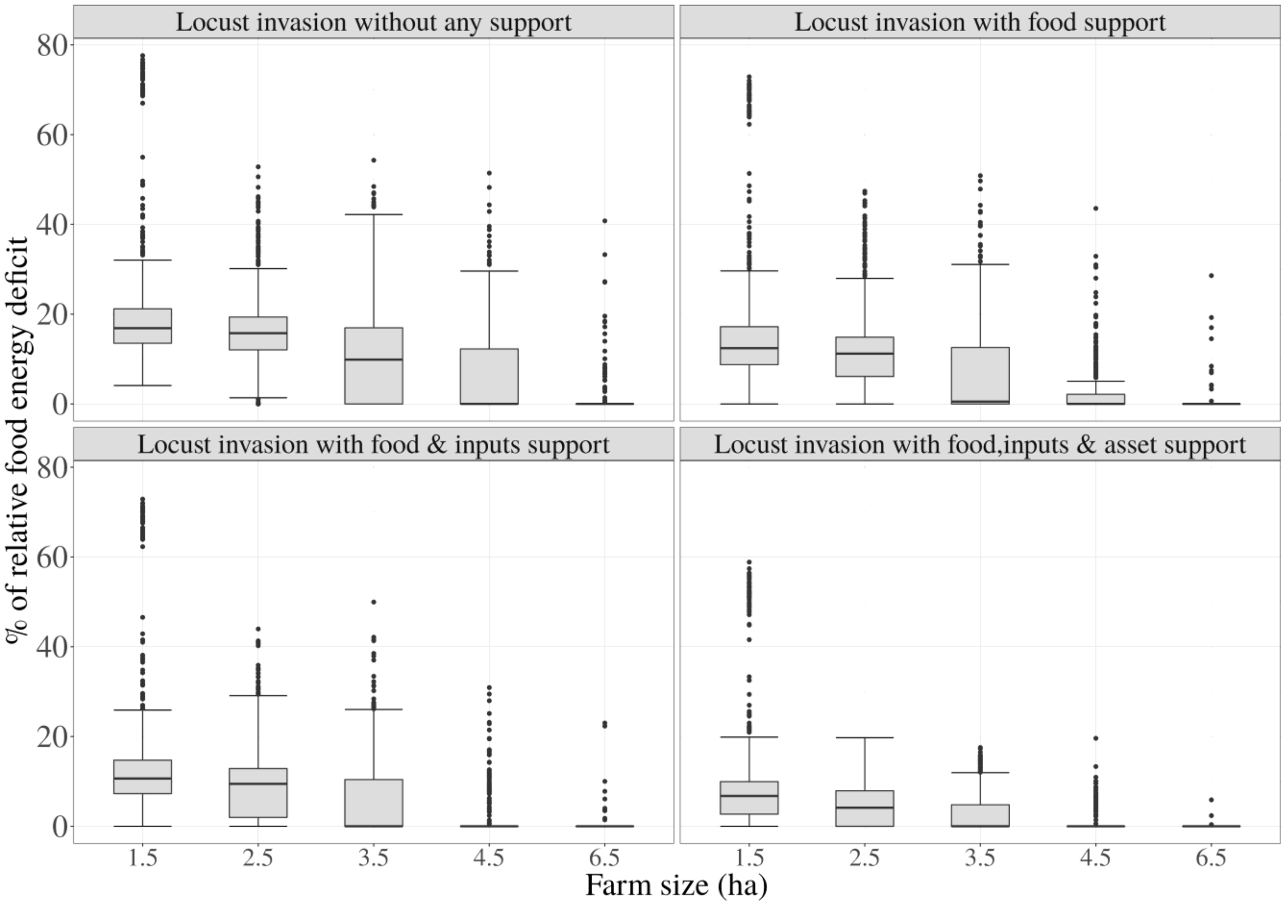
Figure 47: Income change of baseline income with food relief interventions compared to without policy



Note: Individual agent discretionary incomes averaged over periods and ranked by agent hypothetical baseline income

To understand the effect of landholding size on the food security status of agents, simulation results show that in all scenarios agents with lower farm sizes are more food insecure compared to agents with higher farm sizes (Figure 48). The severity of food insecurity is high when there is no relief policy intervention compared to individual and combined locust relief interventions. When the three relief interventions are used jointly, the temporary food shortage of agents drastically reduces. The food shortage reduction is very prominent for agents with higher farm sizes as it has buffering potential to reduce consumption shocks.

Figure 48: Relative food energy deficit by farm size under locust relief interventions compared to without policy



***Note**:* Percentage of relative food energy deficit averaged over 10 periods by farm size

6.6. Conclusion

This thesis applied farm-level simulation models to quantify the impact of desert locust invasions on smallholder farmers livelihoods and assess the role of different locust relief response programs in the CRV of Ethiopia. MPMAS application in CRV allows capturing resource and agroecological heterogeneity between model agents and enables simulation analysis by introducing recurring locust shock over the simulation period and conducting uncertainty analysis of model inputs to check the simulation results robustness. It enables establishing different locust and policy scenarios to quantify the extended locust impacts and isolate the effectiveness of individual and joint locust policy in the face of a recurrent locust invasion.

The simulation results reveal that locust invasions have a devastating impact on agent incomes, food security, and livestock holdings. Due to prolonged locust occurrence, overall, 25% and 29% of the agent population run into temporary food energy and protein shortages respectively. However, in the post-shock, most agents can quickly recover from shock effects in terms of food nutrition deficit. It takes long periods for agents to recover from income and livestock losses to locust shock. Realization of positive income gains starts after a long time after the shock is over.

The locust simulation results also suggest that relief policy interventions play key roles in compensating the severe welfare losses against recurring locust shocks even if it doesn’t fully compensate for the losses. Income and livestock losses and food consumption deficit are substantially reduced when either food or cash transfer programs are accompanied by other complementary supports than implemented individually. Among the relief policy interventions, the three combined interventions (food/cash, inputs, and asset) play crucial roles in reducing agent exposures to the adverse effect of locust shock. This policy intervention has higher welfare compensational effects than other policy combinations or individual relief policies. The results further suggest that the inclusion of asset recuperation combined with other relief policy interventions has a substantial positive effect in reducing livestock loss to locust invasions effect. Considering provision of breeding ewes or does with other locust relief programs, if not large ruminants like cattle, have a crucial positive contribution for farm agents affected by locust invasions as they often use the asset for selling to smooth consumption during hardships or rebuild the herd over time.

Similarly, findings from the locust simulation also suggest that relief policy interventions are quite heterogeneous across individual agents. Agents in the wheat-dominated system, with higher baseline income and agents with lower household sizes, tend to be less affected by recurring locust shock than agents in the maize-dominated farming system, with lower baseline income and agents with large household sizes. This is mainly because agents in the wheat production system are better off in terms of resource endowments which allow them for livelihood diversification.

Chapter 7. Discussion and general conclusion

7.1. Discussion

This thesis applied farm-level agent-based simulation to address key empirical research questions of quantifying the effects of climate and locust shocks and the role of policy interventions in reducing smallholder farmers vulnerability. The model helps to disentangle different pathways through which recurring external shocks may affect smallholder farmers livelihoods. It is a very suitable approach for policy simulations compared to reduced models like the Ricardian approach and other statistical methods. Moreover, the model is suitable for targeting policy interventions and evaluating *ex-ante* technology development potential benefits which can guide public investments in agricultural research for development and for prioritizing development interventions. The application of the simulation model enables answering if agents can adapt to the effect of shocks by autonomous adaptation measures and/ or through policy interventions including locust relief program interventions. MPMAS enables to assess which policy intervention(s) are effective in reducing the vulnerability of agents to recurring external factors.

The thesis extends the study by Berger et al. (2017) in Ethiopia by adding new features like storage activities to the existing model and using new data for MPMAS_CRV parametrization. In addition to specific local-level simulations in CRV, *ex-ante* measure considerations for possible climate risks were explicitly captured and modeled to simulate its effects. This is to capture the behavior of real-world farm households in the model as they often take necessary precautionary measures for possible worst cases while making production decisions. By capturing their behavior explicitly in MPMAS_CRV the effect of considering *ex-ante* measures in planning was evaluated. In the model locust impact and the role of different locust relief programs were also simulated. The following sections discuss extreme climate and locust shock impacts, farmer adaptations, and the effectiveness of policy interventions in reducing farm household vulnerability to shocks and make comparisons to Berger et al. (2017) study and other similar studies.

Climate shocks effect, effectiveness of farmer autonomous adaptation and policy interventions

The effect of climate shocks was captured by comparing without shocks and policy scenario to with shocks and without policy scenario in 10 simulation periods. Likewise, the role of considering *ex-ante* measures in planning which can be used *ex-post* during any hardships was isolated by comparing with and without *ex-ante* measure consideration under different climate trajectories.

The simulation results suggest that extreme climate shocks severely affect agent food security and discretionary incomes. The results underline that model agents run into severe income shocks and food energy and protein deficits due to recurring climate shocks. Agents face transitory food insecurity in the short run due to extended climate shocks. The results further reveal that starvation rate and income losses are higher in five shock years than in four shock years. This clearly shows that even if climate shock frequency reduces in a row but happens in some intervals over extended periods, it progressively leads to depletion of income and food consumption shortage. This implies that extended shocks without policy and *ex-ante* measure consideration can recursively weaken the adaptation capacity of agents, making them unable to adapt and manage even smaller perturbations in subsequent production conditions (Shiferaw et al., 2014b).

Simulation analysis results also suggest that livestock wealth is affected severely by climate shocks up to the extent that no livestock is left to some agents when severe and prolonged climate shocks happen. Even after shock years, it takes longer years for resource-poor agents to rebuild the livestock asset bases. Livestock asset base is an important component in the mixed crop-livestock production system to use as coping measures against covariate shocks like drought which make the whole risk-sharing network less effective (Gebrehiwot et al., 2021; Pandey et al., 2007; Wossen et al., 2016). Severe shocks have an erosive effect on farm households that are endowed with a few heads of livestock assets and have only thin opportunities to diversify and share the climate risks. To withstand the effect of shocks they often rely on selling livestock assets at times of hardship to smooth food and cash consumption (Acosta et al., 2021; Megersa et al., 2014; Scott, 2019). Though there are livestock selling practices in normal years as well the number of livestock sales normally increases in shock years. Increased sales of livestock are meant to compensate for crop production loss to severe climate shocks which subsequently affect income level and household food security. Households with more livestock herds can manage to smooth consumption by disposing of more livestock assets which improves their adaptive capacities in the short run (Gebrehiwot et al., 2021).

Simulations were also analyzed on whether consideration of *ex-ante* measures by agents in reducing the welfare losses to climate shocks. This was possible by comparing with and without *ex-ante* measure scenarios. The simulation results suggest that *ex-ante* considerations by agents have a minimal role in compensating agent welfare losses. Under four shock years, there are no welfare differences between agents who plan with *ex-ante* measures and those who don't. However, under five shock years, there are small positive contributions to compensating for food nutrition deficit and livestock losses when agents plan with *ex-ante* measures.

There could be two possible explanations for the minimal contribution of *ex-ante* consideration by agents tested and evaluated in this thesis. First, since the decision-making of subsistence farmers was represented in MPMAS_CRV, agents might not have enough resources and capacities to adopt adequate adaptation strategies. Similar finding is also indicated by Gebrehiwot et al. (2021) who state that resource limitations can cause adaptation deficits where it is difficult for smallholder farm households to undertake *ex-ante* adaptation strategies or they don't normally sufficiently implement them to improve their well-being. Due to this, they choose a few options to implement though they anticipate the worst cases and plan for them. The second possible explanation is that agents may employ strategies with small costs such as changing the planting dates as a coping strategy which might not help to get big benefits. Investing in agricultural technologies which potentially yield higher benefits often requires higher investment costs like covering the expenses of improved crop varieties and chemical fertilizer that farm agents might not be able to afford. In the current simulations, less resource-endowed model agents who started to use existing modern technologies switch back to choosing local varieties due to the recurring shock which limits their ability to buy yield-enhancing inputs. When climate shock effects are stronger and the *ex-ante* considerations by agents are not sufficient to fully compensate for welfare losses, farm agents implement multiple *ex-post* coping options that can lead to the depletion of their capital and assets which have been accrued over time (Gebrehiwot et al., 2021). These *ex-post* coping options include last-resort measures such as defaulting on credit to smooth consumption (Berger et al., 2017; Shiferaw et al., 2014b).

Simulation results disaggregated by agent resource endowments and agroecological heterogeneity confirm that less resource-endowed agents are severely affected by extended climate risks. These results corroborate with the simulation results of Berger et al. (2017) in Ethiopia. Moreover, farm agents in the wheat production system are relatively less affected by severe climate-induced shocks compared to the maize-dominated production system.

On top of farmer autonomous adaptation through *ex-ante* considerations, credit and technology policies were also simulated to assess their effectiveness in compensating the income and livestock losses as well as reducing food nutrition deficits. Simulation results regarding the effect of individual and combined credit and technology policy interventions reveal that joint policy interventions have a large compensating effect for welfare losses compared to individual policy interventions. With joint credit and technology policy interventions, income losses are substantially compensated by 45% and 43% under four and five shock years respectively. Simulation results disaggregated to individual agents also show that many agents benefit from combined policy interventions as the income losses are compensated substantially. However, agents with higher baseline income tend to better benefit from joint policy interventions. Similarly, with joint policy interventions, livestock losses to climate shocks are compensated by 81% and 87% under four and five shock years respectively. This policy also helps to lift 52% ad 54 % of the agent population from food energy deficit status under four and five shock years respectively. The simulation results, in this thesis, further suggest that even if agents employ joint policies, they cannot be fully compensated. This doesn’t necessarily mean that such measures with different amounts of implementations cannot over or fully compensate for agent welfare losses to the extreme climate shocks. Existing empirical studies also reveal that managing climate-induced shocks and adapting to them through combinations of various policy interventions are effective in reducing farm households risk exposure by improving welfare losses and asset depletion (Berger et al., 2017; Shiferaw et al., 2014b). Studies in Sub-Saharan African countries also found that improved technological access like improved wheat and maize are effective in reducing poverty incidence, improving household income, and reducing food insecurity (Di Falco et al., 2011a; Di Falco and Veronesi, 2013; Wossen et al., 2017a).

Agents also benefit from individual credit and technology policy interventions but the degree of welfare loss compensation is smaller compared to the joint policy interventions. In reducing food nutrition deficits individual credit and technology have almost similar effects but technology policy is superior in compensating income and livestock loss to credit policy alone. Individual credit and technology policy intervention compensate for income losses by 15% and 23% under four shock years respectively. Likewise, under five shock years, credit policy compensates for 14% of income losses while technology policy contributes by 21%. Moreover, under four shock years, credit and technology compensate for livestock assets losses by 22% and 30% while under five shock years, the livestock loss is compensated by 28% and 38% with credit and technology respectively. The results reveal that credit policy has minimal compensatory effects in reducing agents exposure to climate risks compared to other policies. A similar finding was reported from policy impact simulations by Berger et al. (2017) in Ethiopia where credit policy alone contributes to the smallest positive shift of income among other individuals and joint policy interventions.

Simulation analysis in Northern Ghana by (Wossen et al., 2014; Wossen and Berger, 2015), however, point out that climate adaptation through credit access has a substantial positive impact in reducing poverty levels and increase agent incomes by enabling households to change their land use from subsistence to growing high-value crops and increased input use intensity. This could be attributed to the credit disbursement scheme, credit limit, and policy differences between Ethiopia and Ghana. Empirical results in Ethiopia using the econometrics estimation procedure also show that credit access is a key driver of climate adaptation (Asfaw and Lipper, 2016; Di Falco and Veronesi, 2013, 2011; Jaleta et al., 2013). The difference in the result is due to the application of different methods as a model set up of simulations and reduced models like econometrics models are different.

The simulations of climate shocks and effectiveness of policy interventions in this thesis are compared to the simulation results of Berger et al. (2017) in Ethiopia. MPMAS_ERHS of Berger et al. (2017) study was parameterized from the national level based on datasets from the Nile Basin survey and ERHS whereas this thesis focuses on CRV to parametrize MPMAS_CRV with the new data from the local-specific area by adding new features. Climate impacts and adaptation simulation results are largely similar to the previous findings of Berger et al. (2017). Similar to their findings, this thesis results confirm that farm households cannot adapt to ever-increasing climate risks on their own even if they plan with different *ex-ante* considerations. Moreover, results from policy simulation indicate that joint policy contributes considerably to the reduction of welfare loss to extended climate risks but won't fully compensate for it. Overall the simulation results suggest that farmer autonomous climate adaptation measures are necessary but need to be supported by targeted policy interventions to be more effective and better compensate for welfare losses which were also highlighted in previous findings of Berger et al. (2017).

Impact of desert locust invasions and effectiveness of relief policy interventions

The other novelty of this thesis is simulations of locust impact through the application of MPMAS which is suitable to quantify the effects of locust shock and identify effective relief policy interventions. Besides the simulation of extreme climate shocks with MPMAS_CRV in CRV, this is the original piece of contributions of this thesis in quantifying the magnitude of locust devastation on the livelihood of smallholder farmers and assess which locust relief policy interventions are better to curb welfare losses.

Locust simulation results reveal that extreme and extended locust invasions have adverse livelihood impact which leads to household income reduction and fluctuations, food energy, and protein consumption deficits, and livestock asset losses compared to without locust invasions and policy simulation runs. Without any relief policy interventions, severe locust incidence leads to long-term income and livestock losses in shock years which also continue to affect the livelihood of agents in the normal years in a given scenario. This indicates that income and livestock recovery takes a longer period after actual locust shock occurrences while agent recovery from food nutrition deficits can be archived immediately after shock incidences are over.

Simulation of locust relief policy interventions suggests that in-kind food or cash transfer programs alone have a minimal positive effect in reducing agent livelihood crises. However, when either food or cash transfer is combined with other complementary interventions like provisions of farm input meant to continue farming in the subsequent years and livestock assets, it appears to be more effective in reducing income losses and improving agent food security status. When livestock assets recuperation is combined with other relief policy interventions, livestock holdings improve substantially which suggests that combined locust relief policy interventions can make livestock asset loss recovery relatively shorter compared to other relief policy interventions. In the simulations, food or cash transfers with input provisions alone cannot rebuild livestock assets depleted by extreme locust invasions in the simulation periods though this intervention also plays a minimal role in protecting livestock assets.

The simulation results further show that combined relief policy interventions (food/cash, inputs, and assets) have considerable compensational effects on reducing the starvation rate. The food energy deficit is compensated by 90% with the three combined locust relief interventions compared to locust without policy cases. Likewise, food energy shortage is compenetrated by 50% and 40% with food and inputs and food transfer alone interventions respectively.

Model limitations and future research areas

The thesis used the CIMMYT household survey collected in 2013 to parameterize the MPMAS_CRV complemented from CSA. These datasets are relatively old which might not reflect the current values of some parameters as the most recent data were not obtained. By revising the values of some parameters in MPMAS_CRV where necessary from a recent dataset, new insights can be obtained on welfare indicators used in the model.

In the current simulation experiments, constant average price and yield over many simulation years were used. In designing simulation runs and model repetitions, these variables vary between runs and not within simulation runs. Varying prices and yield within simulation runs need longitudinal data that can be customized to the specific study areas to capture inter-annual price and yield variability. Implementation of inter-annual price and yield variability requires empirical data to understand the trends over the years that reflect the specific locations from where the model is parametrized - which are often quite challenging. Where appropriate, it would be worth capturing inter-annual price and yield variability within the simulation runs and explore its effects by comparing different climate and policy scenarios.

Agents are disconnected and interactions between them and the environment are not explicitly captured in MPMAS_CRV setup but are worth investigation. Capturing interactions between agents in the simulation experiments can provide different dimensions of insights that may help policy targeting (like technology generations and diffusion) and prioritization of other interventions.

Social networks play a vital role with farm households in developing countries like Ethiopia where technology innovation access is limited and poor communication infrastructure is prevalent. Farmers with higher network size/social capital have a higher probability of adopting improved technological innovations, and management practices and innovations diffuse swiftly thereby smoothing food and income consumption (Jaleta et al., 2018; Shiferaw et al., 2014a; Wossen et al., 2015). But when shock affects the whole risk-sharing network (from kinship ties and social networks), food and non-food consumption requirements are not fully insured through social capital (Wossen et al., 2016). Subsistence farming populations often rely on their existing social network and capital for many social and economic activities (labor exchange to ease labor shortage, sharing food and cash under hardship, and sources of information for decision-making processes). The social network features were not implemented in the current MPMAS_CRV as this is also linked with the implementation of agent interactions in the model. This could be another potential area of research to explore and simulate its effectiveness in consumption smoothing under extreme climate risks and agricultural innovation diffusions.

7.2. General conclusion and outlook

The livelihood of smallholder farmers in Ethiopia is being affected by two compounding factors - extreme climate shocks and recent locust invasions. These two factors are production risks which can lead to total production failure and subsequent welfare losses and productive asset depletions. The current study seeks to quantify the effect of these two development impediments through the application of a novel ABM. Moreover, the current research seeks to identify effective policy intervention(s) in the face of recurring external factors using the ABM simulation package MPMAS. By running different simulation experiments, several results are found where important conclusions also are drawn from each simulation experiment.

As expected, simulation results reveal that extreme and recurring climate shocks severely affect the welfare of farm agents. Due to the shock effect in the preceding years, agents cannot recover income and livestock losses immediately after the shock is over in normal years. However, many agents can quickly recover from food nutrition deprivation after the shock years are over. Simulation results also show that there are no or minimal contributions of *ex-ante* measure considerations by agents in reducing severe climate shocks effect which inflict severe welfare losses. Even if agents consider *ex-ante* measures as precautionary to counter possible climate shocks, they cannot cope with a pronounced negative effect of different frequencies of climate shocks implemented and tested in MPMAS_CRV. The simulation results could be improved by implementing other adaptation strategies like agroforestry, *enset* production, water management, soil, and water conservation practices with their adaptation costs which were not captured and tested in the current study. In the current MPMAS_CRV implementation, not all adaptation strategies available were captured and evaluated but only the common ones practiced by many smallholder farmers in the study area.

Furthermore, simulation analysis for individual agent trajectories underlines that the poorest agents having lower baseline income, and lower farm size are disproportionately affected by the extreme climate shocks. Pro-poor agents who already live on meager resources and limited livelihood opportunities often have precarious living conditions which are further worsened by the occurrence of extended climate shocks.

Simulations of policy interventions underscore that they help agents by compensating a large part of welfare losses but do not completely offset the negative effects of severe climate shocks. Compared to individual policy interventions, joint credit and technology policies are superior and largely compensate for income and livestock losses and substantially help many agents to improve their food security status. The simulation results also reveal that technology policy has better potential in reducing food depravations compared to credit policy. The adoption of new shock-resistant crop varieties with the potential of reducing yield variability in the face of shocks appears to be effective in reducing the livelihood crisis. As credit access enhance technology adoption, under severe liquidity constraints, the effectiveness of technology access is larger when these two interventions are combined. The results imply that continuous agricultural technology development and promotion are crucial to respond to changing risks in agricultural production (new crop disease emergence and increased frequency of drought risk).

A disaggregated analysis of who benefits the most from policy interventions suggests that many of the poorest agents are still vulnerable to climate shock effects even if they do have access to credit and technology. This implies that for pro-poor farm households access to credit and technology only might not be enough to support their livelihood as access doesn’t necessarily ensure utilization. Due to additional cost implications of technologies and repayment cost of loans, the poorest agents may not be able to afford to use technologies and choose to continue the existing practices even if access is ensured. These agents are often endowed with smaller land sizes and own fewer livestock assets that don’t allow them for economically viable investments. Even though the land shortage is critical in the study area, the poorest real-world farm households often don’t have the minimum land area that would be necessary to achieve a living income from farming. This group of people needs special policy attention to support their livelihoods like safety net programs or voluntary based resettlement to other places where better and more productive farmland is available.

Alike, climate shock simulations, locust simulation results also suggest that locust shock leads to agent livelihood crisis and makes slower recovery of income and livestock losses in the post locust years. With the combination of relief policy interventions, welfare losses are substantially reduced to individual relief policy interventions. In reality, however, individual relief intervention dominates in response to catastrophic shocks such as locust due to high capital requirements and investment costs associated with combined relief intervention as more people need support due to the covariate nature of the locust outbreak and its devastation intensity. Moreover, as these are a response to the humanitarian crisis and involve huge investments from government and non-government organizations, they may not be sustainable in the long run as locust incidence is highly likely to continue in the future owing to increased climate variability and change. Whenever rain and vegetations are plentiful, desert locust would likely continue to multiply due to conducive conditions for breeding.

Desert locust plague preventions need to have short as well as long-term plans that require well-coordinated responses and preparations by all concerned bodies including farm households to sustainably manage the crisis. As locust occurrence and breeding are highly dependent on favorable climate conditions, strengthening early warning systems by including seasonal weather forecasting is critical to prepare a priori than reactively managing to reduce the crisis after the actual desert locust plague. These include monitoring of weather and ecological conditions, regular surveillance, rapid data transmission, and easy access. Seasonal weather forecasting needs to include not only Ethiopia but also neighboring countries and beyond due to the migratory nature of locust pests across the countries and beyond the boundaries.

In general, simulation results show that locust invasions have formidable adverse effects on the livelihood of smallholder farmers. On top of recurring extreme climate shocks, the recent locust outbreak exacerbates the livelihood crisis of resource-poor farm households and further undermines their autonomous coping abilities. The use of combined policy interventions can considerably support in compensating welfare losses of farmers and help them to gradually recover over years.

References

Abate, T., Shiferaw, B., Menkir, A., Wegary, D., Kebede, Y., Tesfaye, K., Kassie, M., Bogale, G., Tadesse, B., Keno, T., 2015. Factors that transformed maize productivity in Ethiopia. Food Secur. 7, 965–981. https://doi.org/10.1007/s12571-015-0488-z

Acosta, A., Nicolli, F., Karfakis, P., 2021. Coping with climate shocks: The complex role of livestock portfolios. World Dev. 146, 105546. https://doi.org/10.1016/J.WORLDDEV.2021.105546

Adams, R.M., 1989. Global Climate Change and Agriculture: An Economic Perspective, American Journal of Agricultural Economics. https://doi.org/10.2307/1243120

Adams, R.M., Hurd, B.H., Lenhart, S., Leary, N., 1999. Effects of global climate change on agriculture: An interpretative review. Clim. Res. 11, 19–30. https://doi.org/10.3354/cr011019

Amsalu, T., Addisu, S., 2014. Assessment of Grazing Land and Livestock Feed Balance in Gummara-Rib Watershed, Ethiopia. Curr. Agric. Res. J. 2, 114–122. https://doi.org/10.12944/carj.2.2.08

Angassa, A., Oba, G., 2007. Relating long-term rainfall variability to cattle population dynamics in communal rangelands and a government ranch in southern Ethiopia. Agric. Syst. 94, 715–725. https://doi.org/10.1016/j.agsy.2007.02.012

Arndt, C., Robinson, S., Willenbockel, D., 2011. Ethiopia's growth prospects in a changing climate: A stochastic general equilibrium approach. Glob. Environ. Chang. 21, 701–710. https://doi.org/10.1016/j.gloenvcha.2010.11.004

Asfaw, S., Lipper, L., 2016. Managing climate risk using climate-smart agriculture FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS Rome, 2016.

Asfaw, S., Pallante, G., Palma, A., 2018. Diversification Strategies and Adaptation Deficit : Evidence from Rural Communities in Niger. World Dev. 101, 219–234. https://doi.org/10.1016/j.worlddev.2017.09.004

Asresie, A., Zemedu, L., 2015. Contribution of Livestock Sector in Ethiopian Economy: A Review. Adv. Life Sci. Technol. 29, 79–90.

Badebo, A., and Hundie, B., 2016. Incidence and challenges of rusts in wheat production, in Bishaw et al. (Ed.), containing the Menace of Wheat Rusts: and Impacts, ISBN: 9789994466344, EIAR, Addis Ababa, Ethiopia

Bailey, R., 2011. Growing a Better Future Food justice in a resource-constrained world www.oxfam.org/grow, Oxfam Policy and Practice: Agriculture, Food and ….

Berger, T., 2001. Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. Agric. Econ. 25, 245–260. https://doi.org/10.1111/j.1574-0862.2001.tb00205.x

Berger, T., Schreinemachers, P., 2006. Research, part of a Special Feature on Empirical based agent-based modeling Creating Agents and Landscapes for Multiagent Systems from Random Samples 11.

Berger, T., Schreinemachers, P., Woelcke, J., 2006. Multi-agent simulation for the targeting of development policies in less-favored areas. Agric. Syst. 88, 28–43. https://doi.org/10.1016/j.agsy.2005.06.002

Berger, T., Troost, C., 2014. Agent-based Modelling of Climate Adaptation and Mitigation Options in Agriculture. J. Agric. Econ. 65, 323–348. https://doi.org/10.1111/1477-9552.12045

Berger, T., Troost, C., 2012. Agent-based modelling in the agricultural economics tradition of recursive farm modelling and adaptive micro-systems. iEMSs 2012 - Manag. Resour. a Ltd. Planet Proc. 6th Bienn. Meet. Int. Environ. Model. Softw. Soc. 1319–1326.

Berger, T., Troost, C., Wossen, T., Latynskiy, E., Tesfaye, K., Gbegbelegbe, S., 2017. Can smallholder farmers adapt to climate variability, and how effective are policy interventions? Agent-based simulation results for Ethiopia. Agric. Econ. 14.

Bert, F.E., Rovere, S.L., Macal, C.M., North, M.J., Podestá, G.P., 2014. Lessons from a comprehensive validation of an agent based-model: The experience of the Pampas Model of Argentinean agricultural systems. Ecol. Modell. 273, 284–298. https://doi.org/10.1016/j.ecolmodel.2013.11.024

Bewket, W., 2012. Climate change perceptions and adaptive responses of smallholder farmers in central highlands of Ethiopia. Int. J. Environ. Stud. 69, 507–523. https://doi.org/10.1080/00207233.2012.683328

Beyene, L.M., Ferede, T., Diriba, G., 2020. The economywide impact of the COVID-19 in Ethiopia: Policy and Recovery options. EEA-Ethiopia.

Bezabih, M. ewab, Co, S. vat ore D.F., Mekonnen, A. emu, 2014. On the Impact of Weather Variability and Climate Change on Agriculture. Environ. Dev. 29, 1–38.

Bryan, E., Deressa, T.T., Gbetibouo, G.A., Ringler, C., 2009. Adaptation to climate change in Ethiopia and South Africa: options and constraints. Environ. Sci. Policy, Special Issue: Food

Security and Environmental Change 12, 413–426. https://doi.org/10.1016/j.envsci.2008.11.002

Carauta, M., Parussis, J., Hampf, A., Libera, A., Berger, T., 2021a. No more double cropping in Mato Grosso , Brazil ? Evaluating the potential impact of climate change on the profitability of farm systems. Agric. Syst. 190, 103104. https://doi.org/10.1016/j.agsy.2021.103104

Carauta, M., Troost, C., Guzman-Bustamante, I., Hampf, A., Libera, A., Meurer, K., Bönecke, E., Franko, U., Ribeiro Rodrigues, R. de A., Berger, T., 2021b. Climate-related land use policies in Brazil: How much has been achieved with economic incentives in agriculture? Land use policy 109, 105618. https://doi.org/10.1016/J.LANDUSEPOL.2021.105618

Challinor, A.J., Müller, C., Asseng, S., Deva, C., Nicklin, K.J., Wallach, D., Vanuytrecht, E., Whitfield, S., Ramirez-Villegas, J., Koehler, A.K., 2018. Improving the use of crop models for risk assessment and climate change adaptation. Agric. Syst. 159, 296–306. https://doi.org/10.1016/j.agsy.2017.07.010

Ciaian, P., Espinosa, M., Paloma, S.G. y, Heckelei, T., Langrell, S., Louhichi, K., Sckokai, P., Thomas, A., Vard, T., 2013. Farm level modelling of CAP: a methodological overview.

Cline, W.R., 1996. The Impact of Global Warming of Agriculture: Comment.

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., Twomlow, S., 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? Agric. Ecosyst. Environ. 126, 24–35. https://doi.org/10.1016/j.agee.2008.01.007

Darwin, R., 2017. The impact of global warming on agriculture: A ricardian analysis: Comment. Clim. Chang. 84, 125–128.

De Janvry, A., Fafchamps, M., Sadoulet, E., 1991. Peasant Household Behaviour with Missing Markets: Some Paradoxes Explained, Source: The Economic Journal.

Deaton, A., 1991. Saving and Liquidity Constraints, Econometrica. https://doi.org/10.2307/2938366

Dercon, S., 2002. Income Risk, Coping Strategies, and Safety Nets, The World Bank Research Observer.

Deressa, T.T., 2007. Measuring the Economic Impact of Climate Change on Ethiopian Agriculture: Ricardian Approach. Soc. Sci. Res. Netw. 4342, 32-pp.

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. Glob. Environ. Chang. 19, 248–255. https://doi.org/10.1016/j.gloenvcha.2009.01.002

Di Falco, S., 2014. Adaptation to climate change in Sub-Saharan agriculture: Assessing the evidence and rethinking the drivers. Eur. Rev. Agric. Econ. 41, 405–430. https://doi.org/10.1093/erae/jbu014

Di Falco, S., Chavas, J.-P.P., Smale, M., 2007. Farmer management of production risk on degraded lands: The role of wheat variety diversity in the Tigray region, Ethiopia. Agric. Econ. 36, 147–156. https://doi.org/10.1111/j.1574-0862.2007.00194.x

Di Falco, S., Veronesi, M., 2013. How Can African Agriculture Adapt to Climate Change? A Counterfactual Analysis from Ethiopia. Land Econ. 89.

Di Falco, S., Veronesi, M., 2011. ON ADAPTATION TO CLIMATE CHANGE AND RISK EXPOSURE IN THE NILE BASIN OF ETHIOPIA. EAAE 2011 Congr. 1–15.

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. Environ. Resour. Econ. 52, 457–478. https://doi.org/10.1007/s10640-011-9538-y

Di Falco, S., Yesuf, M., Kohlin, G., Ringler, C., 2011. Estimating the Impact of Climate Change on Agriculture in Low-Income Countries: Household Level Evidence from the Nile Basin, Ethiopia. Environ. Resour. Econ. 2011 524 52, 457–478. https://doi.org/10.1007/S10640-011-9538-Y

Dillon, A., McGee, K., Oseni, G., 2015. Agricultural Production, Dietary Diversity and Climate Variability. J. Dev. Stud. 51, 976–995. https://doi.org/10.1080/00220388.2015.1018902

Doti, T. 2010. Climate variability, pastoralists’ vulnerability and options. The case of the Borana of Northern Kenya. In D. A. Mwiturubani & J. A. van Wyk (Eds.), Climate change and natural resources conflicts in Africa. Monograph 170. Pretoria, South Africa: Institute for Security Studies.

Eisele, M., Troost, C., Berger, T., 2021. How Bayesian Are Farmers When Making Climate Adaptation Decisions? A Computer Laboratory Experiment for Parameterising Models of Expectation Formation. J. Agric. Econ. 72, 805–828. https://doi.org/10.1111/1477-9552.12425

Ejigu, L., 2009. Performance analysis of a sample microfinance institutions of Ethiopia. Int. NGO J. 4, 287–298.

FAO, IFAD, UNICEF, W.& W., 2020. THE STATE OF AND NUTRITION FOOD SECURITY IN THE WORLD:TRANSFORMING FOOD SYSTEMS FOR AFFORDABLE HEALTHY DIETS. https://doi.org/10.4060/ca9692en

FAO, 2020a. Appeal for rapid response and anticipatory action in the Greater Horn of Africa. Fao.

FAO, 2020b. Desert locust upsurge: Progress report on the response in the Greater Horn of Africa and Yemen January–April 2020.

FAO, 2018. Livestock production systems spotlight. Cattle sectors in Ethiopia. Africa Sustain. Livest. 2050 9.

Fernández, F.J., Blanco, M., 2015. Modelling the economic impacts of climate change on global and european agriculture. Review of economic structural approaches. Economics 9. https://doi.org/10.5018/economics-ejournal.ja.2015-10

Fisher, M., Abate, T., Lunduka, R.W., Asnake, W., Alemayehu, Y., Madulu, R.B., 2015. Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in eastern and southern Africa. Clim. Change 133, 283–299. https://doi.org/10.1007/s10584-015-1459-2

Gebreegziabher, Z., Mekonnen, A., Bekele, R.D., Zewdie, S.A., Kassahun, M.M., 2020. Crop-Livestock Inter-linkages and Climate Change Implications for Ethiopia’s Agriculture: A Ricardian Approach, in: Climate Change Management. Springer, pp. 615–640. https://doi.org/10.1007/978-3-030-37425-9_31

Gebrehiwot, T., Teklewold, H., Bezabih, M., Seifemichael, R., 2021. Does a portfolio of consumption adjustment coping strategies erode resilience? Panel data evidence from Ethiopia. World Dev. Perspect. 23. https://doi.org/10.1016/j.wdp.2021.100347

Gebrehiwot, T., van der Veen, A., 2020. Farmers’ drought experience, risk perceptions, and behavioural intentions for adaptation: evidence from Ethiopia. Clim. Dev. 13, 493–502. https://doi.org/10.1080/17565529.2020.1806776

Gebrehiwot, T., Van Der Veen, A., 2013. Farm level adaptation to climate change: The case of farmer’s in the ethiopian highlands. Environ. Manage. 52, 29–44. https://doi.org/10.1007/s00267-013-0039-3

Gebremedhin, B., Tegegne, A., 2012. Market Orientation and Market Participation of Smallholders in Ethiopia: Implications for Commercial Transformation. 2012 Conf. August 1824 2012 Foz do Iguacu Brazil.

GETNET, M., Van Ittersum, M., HENGSDIJK, H., DESCHEEMAEKER, K., 2016. YIELD GAPS AND RESOURCE USE ACROSS FARMING ZONES IN THE CENTRAL RIFT VALLEY OF ETHIOPIA. Exp. Agric. 52, 493–517. https://doi.org/10.1017/S0014479715000216

Giller, K.E., 2020. The Food Security Conundrum of sub-Saharan Africa. Glob. Food Sec. 26, 100431. https://doi.org/10.1016/j.gfs.2020.100431

Girvetz, E., Ramirez-Villegas, J., Claessens, L., Lamanna, C., Navarro-Racines, C., Nowak, A., Thornton, P., Rosenstock, T.S., 2019. Future Climate Projections in Africa: Where Are We

Headed?, in: The Climate-Smart Agriculture Papers. Springer International Publishing, pp. 15–27. https://doi.org/10.1007/978-3-319-92798-5_2

Gurmessa, N.E., 2017. Smallholders' Access to a nd Demand for Credit and Influencing Factors: Policy and Research Implications for Ethiopia. J. Bus. Econ. Policy 4, 48–60.

Hazell, P.B. and Norton, R.D.,1986.Mathematical programming for economic analysis in agriculture. New York, NY, USA: Macmillan.

Helton, J.C., Johnson, J.D., Sallaberry, C.J., Storlie, C.B., 2006. Survey of sampling-based methods for uncertainty and sensitivity analysis. Reliab. Eng. Syst. Saf. 91, 1175–1209. https://doi.org/10.1016/j.ress.2005.11.017

Hengsdijk, H., 2010. Competing claims for water resources in the Central Rift Valley of Ethiopia : Global drivers and local opportunities Competing claims for water in the Central Rift Valley of Ethiopia : Global drivers and local opportunities 11, 742–750.

Hertel, T.W., Burke, M.B., Lobell, D.B., 2010. The poverty implications of climate-induced crop yield changes by 2030. Glob. Environ. Chang. 20, 577–585. https://doi.org/10.1016/j.gloenvcha.2010.07.001

Hertel, T.W., Lobell, D.B., 2014. Agricultural adaptation to climate change in rich and poor countries: Current modeling practice and potential for empirical contributions. Energy Econ. 46, 562–575. https://doi.org/10.1016/j.eneco.2014.04.014

Holden, S., Shiferaw, B., 2004. Land degradation, drought and food security in a less-favoured area in the Ethiopian highlands: A bio-economic model with market imperfections. Agric. Econ. 30, 31–49. https://doi.org/10.1016/j.agecon.2002.09.001

Holden, S., Shiferaw, B., Pender, J., 2004. Non-farm income, household welfare, and sustainable land management in a less-favoured area in the Ethiopian highlands. Food Policy 29, 369–392. https://doi.org/10.1016/J.FOODPOL.2004.07.007

Holden, S.T., Quiggin, J., 2017. Climate risk and state-contingent technology adoption: shocks, drought tolerance and preferences. Eur. Rev. Agric. Econ. 44, 285–308. https://doi.org/10.1093/ERAE/JBW016

Howden, S.M., Soussana, J.-F., Tubiello, F.N., Chhetri, N., Dunlop, M., Meinke, H., 2007. Adapting agriculture to climate change.

IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 10, Intergovernmental Panel on Climate Change.

Jaleta, M., Hodson, D., Abeyo, B., Yirga, C., Erenstein, O., 2019. Smallholders' coping mechanisms with wheat rust epidemics: Lessons from Ethiopia. PLoS One 14, 1–23. https://doi.org/10.1371/journal.pone.0219327

Jaleta, M., Kassie, M., Marenya, P., Yirga, C., Erenstein, O., 2018. Impact of improved maize adoption on household food security of maize producing smallholder farmers in Ethiopia. Food Secur. 10, 81–93. https://doi.org/10.1007/s12571-017-0759-y

Jaleta, M., Yirga, C., Kassie, M., Groote, H. De, Shiferaw, B., 2013. Knowledge , adoption and use intensity of improved maize technologies in Ethiopia. 4th Int. Conf. African Assoc. Agric. Econ. 1–30.

Janssen, S., van Ittersum, M.K., 2007. Assessing farm innovations and responses to policies: A review of bio-economic farm models. Agric. Syst. 94, 622–636. https://doi.org/10.1016/j.agsy.2007.03.001

Kassie, B., Hengsdijk, H., Rötter, R., Kahiluoto, H., Asseng, S., Van Ittersum, M., 2013. Adapting to climate variability and change: Experiences from cereal-based farming in the central rift and kobo valleys, Ethiopia. Environ. Manage. 52, 1115–1131. https://doi.org/10.1007/s00267-013-0145-2

Kassie, B.T., Rötter, R.P., Hengsdijk, H., Asseng, S., Van Ittersum, M.K., Kahiluoto, H., Van Keulen, H., 2014a. Climate variability and change in the Central Rift Valley of Ethiopia: Challenges for rainfed crop production. J. Agric. Sci. 152, 58–74. https://doi.org/10.1017/S0021859612000986

Kassie, B.T., Van Ittersum, M.K., Hengsdijk, H., Asseng, S., Wolf, J., Rötter, R.P., 2014b. Climate-induced yield variability and yield gaps of maize (Zea mays L.) in the Central Rift Valley of Ethiopia. F. Crop. Res. 160, 41–53. https://doi.org/10.1016/j.fcr.2014.02.010

Ketema, M., Diriba, G., 2021. Economic Development, Population Dynamics, and Welfare. Ethiop. Econ. Assoc.

La Rovere, R., Abdoulaye, T., Kostandini, G., Guo, Z., Mwangi, W., Macrobert, J., Dixon, J., 2014. ECONOMIC, PRODUCTION, AND POVERTY IMPACTS OF INVESTING IN MAIZE TOLERANT TO DROUGHT IN AFRICA: AN EX-ANTE ASSESSMENT, Source: The Journal of Developing Areas.

Lewis, K., 2017. Understanding climate as a driver of food insecurity in Ethiopia. Clim. Change 144, 317–328. https://doi.org/10.1007/s10584-017-2036-7

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., Naylor, R.L., 2008. Prioritizing climate change adaptation needs for food security in 2030. Science (80-.). 319, 607–610. https://doi.org/10.1126/science.1152339

Mahoo, H., Radeny, M., Kinyangi, J., Cramer, L., 2013. Climate change vulnerability and risk assessment of agriculture and food security in Ethiopia: Which way forward? CCAFS Working Paper no. 59. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Ethiopian Institute of Agricultu.

Mamo, G., Getnet, M., Legesse, G., 2016. Managing Dry Spell Risks to Improve Rainfed Maize Productivity in the Semi-Arid Central Rift Valley of Ethiopia 26, 99–109.

Mano, R., Nhemachena, C., 2016. ASSESSMENT OF THE ECONOMIC IMPACTS OF CLIMATE CHANGE ON AGRICULTURE IN ZIMBABWE: A RICARDIAN APPROACH, CEEPA Discussion Paper No. 11, Centre for Environmental Economics and Policy in Africa, University of Pretoria. Core. https://doi.org/10.1093/jae/eju011

Maplecroft, 2015. Climate change vulnerability index 2015 Maplecroft's Climate Change and Environmental Risk Atlas (CCERA) Maplecroft, UK

Megersa, B., Markemann, A., Angassa, A., Valle Zárate, A., 2014. The role of livestock diversification in ensuring household food security under a changing climate in Borana, Ethiopia. Food Secur. 6, 15–28. https://doi.org/10.1007/s12571-013-0314-4

Mendelsohn, R., Nordhaus, W.D., Shaw, D., 1994. The Impact of Global Warming on Agriculture: A Ricardian Analysis.

Meshesha, D.T., Moahmmed, M., Yosuf, D., 2019. Estimating carrying capacity and stocking rates of rangelands in Harshin District, Eastern Somali Region, Ethiopia. Ecol. Evol. 9, 13309–13319. https://doi.org/10.1002/ece3.5786

Mideksa, T., Fininsa, C., Hundie, B., 2018. Analysis of Climate Variability Effects on Wheat Stem Rust (Puccinia graminis f . sp tritici) Epidemics in Bale and Arsi Zones of Oromia Regional State , Ethiopia 4, 49–65. https://doi.org/10.11648/j.ajbes.20180402.12

Molotoks, A., Smith, P., Dawson, T.P., 2021. Impacts of land use, population, and climate change on global food security. Food Energy Secur. 10, e261. https://doi.org/10.1002/fes3.261

Moreland, S., Smith, E., 2013. Climate Change : Impacts and Responses. https://doi.org/10.18848/1835-7156/CGP/v04i02/37158

Mukasa, A.N., Simpasa, A.M., Salami, A.O., 2017. Credit constraints and farm productivity: Micro-level evidence from smallholder farmers in Ethiopia, In Working Paper Series No. 247.

African Development Bank Abidjan.

Mupangwa, W., Yahaya, R., Tadesse, E., Ncube, B., Mutenje, M., Chipindu, L., Mhlanga, B., Kassa, A., 2022. Crop Productivity, Nutritional and Economic Benefits of No-Till Systems in Smallholder Farms of Ethiopia. Agronomy 13, 115. https://doi.org/10.3390/agronomy13010115

NBE, 2020. Annual Report 2019-2020.

NMA (National Meteorological Agency), 2001. Initial National Communication of Ethiopia to the United Nations Framework Convention on Climate Change, Addis Ababa, Ethiopia

Ouedraogo, M., Some, L., Dembele, Y., 2006. Economic impact assessment of climate change on agriculture in Burkina Faso: A ricardian approach, Policy Research Working Papers. The World Bank. https://doi.org/10.1596/1813-9450-4292

Pandey, S., Bhandari, H., 2009. Drought, coping mechanisms and poverty: Ingishts from rainfed rice farming in Asia, Policy.

Pandey, S., Bhandari, H., Ding, S., Prapertchob, P., Sharan, R., Naik, D., Taunk, S.K., Sastri, A., 2007. Coping with drought in rice farming in Asia: insights from a cross-country comparative study: Coping with drought in rice farming in Asia. Agric. Econ. 37, 213–224. https://doi.org/10.1111/j.1574-0862.2007.00246.x

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B., Travasso, M.I., Aggarwal, P., Hakala, K., Jordan, J., 2015. Food security and food production systems. Clim. Chang. 2014 Impacts, Adapt. Vulnerability Part A Glob. Sect. Asp. 485–534. https://doi.org/10.1017/CBO9781107415379.012

Ragsdale, C.T., 2012. Spreadsheet modeling & decision analysis: a practical introduction to management science.

Ringler, C., Bryan, E., Hassan, R.M., Alemu, T., Hillesland, M., 2011. INTERNATIONAL FOOD POLICY RESE ARCH INSTITUTE sustainable solutions for ending hunger and poverty HOW CAN AFRICAN AGRICULTURE ADAPT TO CLIMATE CHANGE? INSIGHTS FROM ETHIOPIA AND SOUTH AFRICA.

Robinson, S., Strzepek, K., Cervigni, R., 2013. The Cost of Adapting to Climate Change in Ethiopia : Sector-Wise and Macro-Economic Estimates.

Sadiq, S., Saboor, A., Mohsin, A.Q., Khalid, A., Tanveer, F., 2019. Ricardian analysis of climate change–agriculture linkages in Pakistan. Clim. Dev. 11, 679–686. https://doi.org/10.1080/17565529.2018.1531746

Salih, A.A.M., Baraibar, M., Mwangi, K.K., Artan, G., 2020. Climate change and locust outbreak in East Africa. Nat. Clim. Chang. 10, 584–585. https://doi.org/10.1038/s41558-020-0835-8

Schreinemachers, P., Berger, T., 2011. An agent-based simulation model of human-environment interactions in agricultural systems. Environ. Model. Softw. 26, 845–859. https://doi.org/10.1016/j.envsoft.2011.02.004

Schreinemachers, P., Berger, T., 2006. Land use decisions in developing countries and their representation in multi-agent systems. J. Land Use Sci. 1, 29–44. https://doi.org/10.1080/17474230600605202

Schreinemachers, P., Berger, T., Aune, J.B., 2007. Simulating soil fertility and poverty dynamics in Uganda: A bio-economic multi-agent systems approach. Ecol. Econ. 64, 387–401. https://doi.org/10.1016/J.ECOLECON.2007.07.018

Schreinemachers, P., Potchanasin, C., Berger, T., Roygrong, S., 2010. Agent-based modeling for ex ante assessment of tree crop innovations: litchis in northern Thailand. Agric. Econ. 41, 519–536. https://doi.org/10.1111/j.1574-0862.2010.00467.x

Scott, D., 2019. Income shocks and poverty traps: asset smoothing in rural Ethiopia., CREDIT Research Paper.

Shiferaw, B., Kassie, M., Jaleta, M., Yirga, C., 2014a. Adoption of improved wheat varieties and impacts on household food security in Ethiopia. Food Policy 44, 272–284. https://doi.org/10.1016/J.FOODPOL.2013.09.012

Shiferaw, B., Tesfaye, K., Kassie, M., Abate, T., Prasanna, B.M., Menkir, A., 2014b. Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. Weather Clim. Extrem. 3, 67–79. https://doi.org/10.1016/j.wace.2014.04.004

Shimeles, A., Legesse, G., 2014. Analysis and mapping of climate change risk and vulnerability in Central Rift Valley of Ethiopia. African Crop Sci. J. 22, 807–818. https://doi.org/10.13140/RG.2.1.1671.1209

Simtowe, F., Amondo, E., Marenya, P., Rahut, D., Sonder, K., Erenstein, O., 2019. Impacts of drought-tolerant maize varieties on productivity, risk, and resource use: Evidence from Uganda. Land use policy 88. https://doi.org/10.1016/j.landusepol.2019.104091

Smithers, J., Smit, B., 1997. Human adaptation to climatic variability and change. Glob. Environ. Chang. 7, 129–146. https://doi.org/10.1016/S0959-3780(97)00003-4

Tadesse, W., Bishaw, Z., Assefa, S., 2019. Wheat production and breeding in Sub-Saharan Africa:

Challenges and opportunities in the face of climate change. Int. J. Clim. Chang. Strateg. Manag. https://doi.org/10.1108/IJCCSM-02-2018-0015

Tarantola, S., Becker, W., Zeitz, D., Commission, E., Becker, W., Data, B., 2012. A comparison of two sampling methods for global sensitivity analysis. Comput. Phys. Commun. 183, 1061–1072. https://doi.org/10.1016/J.CPC.2011.12.015

Teklewold, H., Mekonnen, A., Kohlin, G., DI Falco, S., 2017. Does adoption of multiple climate-smart practices improve farmers’ climate resilience? Empirical evidence from the Nile Basin of Ethiopia. Clim. Chang. Econ. 8, 1750001. https://doi.org/10.1142/S2010007817500014

Tesfaye, K., Kruseman, G., Cairns, J.E., Zaman-Allah, M., Wegary, D., Zaidi, P.H., Boote, K.J., Rahut, D., Erenstein, O., 2018. Potential benefits of drought and heat tolerance for adapting maize to climate change in tropical environments. Clim. Risk Manag. 19, 106–119. https://doi.org/10.1016/j.crm.2017.10.001

Thomas, K.J.A., Zuberi, T., 2012. Demographic Change, the IMPACT Model, and Food Security in Sub-Saharan Africa. UNDP Reg. Bur. Africa Work. Pap.

Troost, C., Berger, T., 2020. Formalising validation? Towards criteria for valid conclusions from agent-based simulation. Int. Congr. Environ. Model. Softw.

Troost, C., Berger, T., 2015. Dealing with uncertainty in agent-based simulation: Farm-level modeling of adaptation to climate change in southwest Germany. Am. J. Agric. Econ. 97, 833–854. https://doi.org/10.1093/ajae/aau076

Troost, C., Huber, R., Bell, A.R., van Delden, H., Filatova, T., Le, Q.B., Lippe, M., Niamir, L., Polhill, J.G., Sun, Z., Berger, T., 2023. How to keep it adequate: A protocol for ensuring validity in agent-based simulation. Environ. Model. Softw. 159, 105559. https://doi.org/10.1016/j.envsoft.2022.105559

Troost, Christian, Calberto, G., Berger, Thomas, Ingwersen, J., Priesack, E., Warrach-Sagi, K., Walter, T., Troost, C, Berger, T, 2012. Agent-based modeling of agricultural adaptation to climate change in a mountainous area of Southwest Germany, Sixth Biennial Meeting.

Tulman, D.E.S.P., 2014. Access to Finance for Smallholder Farmers 1–84.

United Nations, Department of Economic and Social Affairs, Population Division. 2019. World Population Prospects 2019, Volume II: Demographic Profiles (ST/ESA/SER.A/427).

Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance-A review. F. Crop. Res. 143, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009

White, J.W., Hoogenboom, G., Kimball, B.A., Wall, G.W., 2011. Methodologies for simulating impacts of climate change on crop production. F. Crop. Res. 13.

World Bank, 2006. Ethiopia: Managing Water Resources Managing Water Resources to Maximize, Report No.36000-ET 1–119.

World Bank Group, 2018. Piecing Together the Poverty Puzzle, Poverty and shared prosperity. World Bank, Washington, DC. https://doi.org/10.1596/978-1-4648-1330-6

Wossen, T., Abdoulaye, T., Alene, A., Feleke, S., Menkir, A., Manyong, V., 2017a. Measuring the impacts of adaptation strategies to drought stress: The case of drought tolerant maize varieties. J. Environ. Manage. 203, 106–113. https://doi.org/10.1016/j.jenvman.2017.06.058

Wossen, T., Berger, T., 2015. Climate variability, food security and poverty: Agent-based assessment of policy options for farm households in Northern Ghana. Environ. Sci. Policy 47, 95–107. https://doi.org/10.1016/J.ENVSCI.2014.11.009

Wossen, T., Berger, T., Di Falco, S., 2015. Social capital, risk preference and adoption of improved farm land management practices in Ethiopia. Agric. Econ. (United Kingdom) 46, 81–97. https://doi.org/10.1111/agec.12142

Wossen, T., Berger, T., Haile, M.G., Troost, C., 2017b. Impacts of climate variability and food price volatility on household income and food security of farm households in East and West Africa. Agric. Syst. https://doi.org/10.1016/j.agsy.2017.02.006

Wossen, T., Berger, T., Swamikannu, N., Ramilan, T., 2014. Climate variability, consumption risk and poverty in semi-arid Northern Ghana: Adaptation options for poor farm households Environmental Development. Environ. Dev. 12, 2–15. https://doi.org/10.1016/j.envdev.2014.07.003

Wossen, T., Di Falco, S., Berger, T., McClain, W., 2016. You are not alone: social capital and risk exposure in rural Ethiopia. Food Secur. 8, 799–813. https://doi.org/10.1007/s12571-016-0587-5

Zerga, B., Gebeyehu, G., 2016. Climate Change in Ethiopia Variability , Impact , Mitigation , and Adaptation Journal of Social Science and Humanities Research. Int. J. Sci. Humanit. Res. 2, 66–84.

Zwedu, G., 2014. Financial inclusion, regulation and inclusive growth in Ethiopia. Achiev. Financ. Stab. Growth Africa 137–157. https://doi.org/10.4324/9781315648668

Annex 3

Declaration in lieu of an oath on independent work

according to Sec. 18(3) sentence 5 of the University of Hohenheim's Doctoral Regulations for the Faculties of Agricultural Sciences, Natural Sciences, and Business, Economics and Social Sciences

1. The dissertation submitted on the topic

Extreme Climate Shock and Locust Infestation Impacts in Ethiopia:
Farm-level Agent-based Simulation of Adaptation and Policy Options

is work done independently by me.

2. I only used the sources and aids listed and did not make use of any impermissible assistance from third parties. In particular, I marked all content taken word-for-word or paraphrased from other works.

3. I did not use the assistance of a commercial doctoral placement or advising agency.

4. I am aware of the importance of the declaration in lieu of oath and the criminal consequences of false or incomplete declarations in lieu of oath.

I confirm that the declaration above is correct. I declare in lieu of oath that I have declared only the truth to the best of my knowledge and have not omitted anything.

Stuttgart, 27.04.2022	
Place, Date	Signature

Curriculum Vitae

Alemu Tolemariam Ejeta
Nationality: Ethiopian
Year of birth: 1983
Place of birth: Bako, West Shoa, Ethiopia
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EDUCATION and TRAINING

07/2017-date**: PhD candidate**
Universität Hohenheim, Stuttgart, Germany

Chair of Land-Use Economics (Josef G. Knoll Professorship), Hans-Ruthenberg-Institute (490d)

***PhD thesis topic**: Extreme Climate Shock and Locust Invasion Impacts in Ethiopia: Farm-level Agent-based Simulation of Adaptation and Policy Options*

10/2008-10/2010**: Master of Science (MSc) degree**
Haramaya University, Haramaya, Ethiopia

- Faculty of Agricultural Sciences – Agricultural Economics

MSc thesis topic: Impact Evaluation of Input and Output Market Development Interventions in Jimma Zone, Ethiopia: Application of a non-parametric project evaluation approach – propensity score matching

09/2000-07/2004**: Bachelor of Science (BSc) degree**
Haramaya University, Haramaya, Ethiopia

- Faculty of Agricultural Sciences – Agricultural Extension

BSc thesis topic: *Socio-Economic Effects of Women Participation in Off-Farm Activities: The Case of Haramaya District, Ethiopia*

20-21 June 2017**: Certificate**
International Maize and Wheat Improvement Centre (CIMMYT), Addis Ababa, Ethiopia

Presentation Skills

9 January -31 March 2017**: Certificate**
UNIVERSTE LAVAL, Quebec, Canada

Online course on Evaluation of Public Policies

22 -28 April 2017**: Certificate**

International Maize and Wheat Improvement Centre (CIMMYT), Addis Ababa, Ethiopia

Gender mainstreaming in research projects and addressing gender issues in workplaces

31 October -11 November 2016**: Certificate**

In depth Research Services, Nairobi, Kenya

Advanced data management and analysis for survey using STATA software

19-21 August 2015**: Certificate**

International Maize and Wheat Improvement Centre (CIMMYT), Addis Ababa, Ethiopia

Geo-referenced data collection tools (GPS and ODK) training)

25 -27 March 2015**: Certificate**

International Maize and Wheat Improvement Centre (CIMMYT), Addis Ababa, Ethiopia

Basic GIS Training

04-08 November 2013**: Certificate**

Ethiopian Economics Association (EEA), Addis Ababa, Ethiopia

Training on Econometrics Software Applications (STATA, REVIEWS and PGCE)
31 October – 04 November 2011**: Certificate**

Consortium for Christian Relief and Development Association (CCRDA), Addis Ababa, Ethiopia
Training on Value Chain Development

08-12 August 2011**: Certificate**

Consortium for Christian Relief and Development Association (CCRDA), Addis Ababa, Ethiopia

Training on Climate Change, Adaptation and Mitigation

WORK EXPERIENCES

07/2021- 11/2021: Extension and Gender Advisor

Deutsche Gesellschaft fuer Internationale Zusammenarbeit (GIZ) GmbH

By being seconded staff at Ministry of Agriculture (MoA), I was responsible for

- contribute to the coordination and implementation of activities aiming at the establishment of farmer, research, extension and data (FRED) coordination mechanism, including SWOT analysis, road map development and implementation of activities to strengthen and test the FRED mechanism
- develop guidelines on mandate zonation approach and on how to strengthening linkage

between stakeholders

- implement mandate zonation approach and pluralistic agricultural extension services in pilot *kebeles* across regions
- promotion of gender and youth friendly agricultural activities
- support popularization and promotion of climate smart feasible technologies
- support collaboration of MoA with other relevant actors
- contribute to digitization of agricultural extension and advisory services
- plan and organize multi-stakeholder workshops and meetings and ensure documentation of their outputs and action points
- contribute to strengthening gender and nutrition sensitive extension service system in crop, livestock and natural resources project activities in collaboration of ministry of agriculture

10/2012- 08/2018: Research Associate – SocioEconomics Program

International Maize and Wheat Improvement Centre (CIMMYT, www.cimmyt.org)

key responsibilities

- contribute to project design and implementations (projects like adoption and impact studies, market and value chain studies, production economics, policy research, impacts of climate variability, climate change adaptations using climate smart agriculture)
- contribute to designing and implementation of field (household and market) surveys and other socio-economic research activities
- design data collection instruments and coordinate data collection using smartphone assisted applications (like ODK) and conventional paper based systems
- supervise overall field data collection process (training and coaching enumerators, field supervision etc.)
- coordinate baseline, mid-line and end-line household survey for different research projects
- checking consistence of the collected data
- data cleaning and analysis using SPSS, STATA softwares and R programming
- coordinate different research project evaluations
- develop research reports and policy briefs from the household survey datasets
- technical report writing for donors
- preparation of paper draft manuscripts for journal articles
- undertake literature reviews from print and digital resources
- establish partnership with key stakeholders like National Agricultural Research System (NARS), regional bureau of agriculture and other relevant government offices
- provision of technical support to research project partners and stakeholders
- capacity development of partner staffs on project management, technical report writing and scientific data analysis using statistical softwares
- establish lead and follower farmers in the field research experimentation and technology promotion

- organize field days with experimenting(lead) households for enhanced learning
- lead extension material preparations like leaflets, pamphlets and manuals for agricultural experts and farm households using different local languages
- produce success stories from the project interventions for learning and scaling up

06/2011-10/2012 Livelihood and Marketing Officer
Ethiowetland and Natural Resource Association (website: www. ewnra.net)

key responsibilities

- project document preparation for grant application in areas of natural resource management, climate change adaptations and livelihood diversification
- promotion of climate change adaption and mitigation activities through multipurpose agroforestry and livelihood diversification
- support business plan development to maximize the income gains from different income generating activities
- ensure and support project implementation at grass-root levels
- build the capacity of stakeholders and partners staffs
- establish project log-frame work in the project document preparations
- periodic monitoring and evaluation of project activities as stated on the project log-frame work
- take part in commissioning external consultants for project evaluation
- preparation of extension materials for wider dissemination of success stories and awareness creation
- facilitation of stakeholders’ workshops for joint project planning and activity implementation
- lead assessment and identification of livelihoods and marketing challenges and opportunities
- provide technical support for field projects staffs
- lead stakeholders and partner staffs capacity needs assessment and capacity building
- identify and prioritize local development problems through stakeholder and beneficiary consultations
- lead value chain and market studies and interventions
- develop technical and annual reports for donors and relevant government line offices
- establish and maintain partnership with key partners and stakeholders for better project impacts
- facilitate community/group meeting to elicit community level data

01/2005-05/2011: Socio-Economics Researcher

Oromiya Agricultural Research Institute (OARI)

key responsibilities

- develop concept notes and project proposals relevant to socio-economics research thematic areas
- participate in research review process at different stages
- implement approved socioeconomics related research projects
- lead design and implementation of field surveys (relevant to market, household, and community)
- contribute to survey instrument development and pretesting with small groups of households
- quantitative socioeconomics data collection through formal survey
- qualitative data collection using participatory rural appraisal methods
- data analysis using statistical software packages (like STATA and SPSS)
- agricultural market collection and dissemination for informed decision making in the pilot testing of JICA collaborative project
- participate in on-farm crop and livestock technology testing and evaluation
- literature search
- coordinate planning and reporting quarterly and annual research activities
- lead development of full write-up (research reports)

CONSULTANCY SERVICE EXPERIENCE

05/2021- 06/2021: RESEARCH CONSULTANT

PRIME CONSULTING SERVICES

The consultancy firm was commissioned by Deutsche Gesellschaft fuer Internationale Zusammenarbeit (GIZ) GmbH – Agricultural mechanization and technology for smallholder productivity (AMTP) project to conduct *baseline study on status of agricultural mechanization in Ethiopia*

Main responsibilities

- participate in designing and revising data collection instruments
- coordinate and monitor field data collection (household survey)
- collect qualitative data from key stakeholders and mechanization services recipients along the supply chain
- data management and analysis
- full report write-up

01-31 August 2015: Research consultant

DAB development research and training PLC

- coordinate proposal development in the area of agriculture, environment, gender and food security

February – April 2012: Assisting associate

International Institute of Rural Reconstruction (IIRR)

Main responsibilities

- assist in provision of training on outcome mapping
- assist in developing research protocols (for focused group discussion, key informant interview and questionnaire)
- supervise baseline data collection and compilation of datasets from each project partner
- data management and cleaning
- contribute to research report write-up

March-May 2011: Consultant

International Livestock Research Institute(ILRI) - IPMS (Improving Productivity and Market Success) Project

Main responsibilities

- develop a report outline
- clean large project end-line datasets from different pilot learning districts
- develop detailed analysis plan using statistical and graphical methods
- analyze the datasets using STATA software
- develop research report from the quantitative household survey

MEMBERSHIP

- Ethiopian Economic Association
- Agricultural Economics Society of Ethiopia
- Ethiopian Society of Animal Production
- Ethiopian Society of Rural Development and Agricultural Extension

LANGUAGE SKILLS

Language	**Read**	**Write**	**Speak**	**Understand**
English	Proficient	Proficient	Proficient	Proficient
German	Basic	Basic	Basic	Basic
Afaan Oromo	Proficient	Proficient	Proficient	Proficient
Amharic	Proficient	Proficient	Proficient	Proficient

SELECTED PUBLICATIONS

Tolemariam A., Jaleta M., Hodson D., Alemayehu Y., Yirga C., and Abeyo B. (2018). Wheat Varietal Change and Adoption of Rust Resistant Wheat Varieties in Ethiopia from 2009/10 to 2013/14. Socioeconomics Program Working Paper 12. Mexico, CDMX: CIMMYT.

Tolemariam, A., and Mamo, D. (2014). Gender and Energy Nexus in Ethiopia: An Analytical Review of the nexus between Gender and Energy in Sub-Saharan Africa. In Paschal B. Mihyo and Truphena E. Mukuna (eds.) The Gender-Energy Nexus in Eastern and Southern Africa. Organization of Social Science Research for Eastern and Southern Africa (OSSREA), ISBN: 978-99944-55-84-3 (Chapter two)

Jaleta, M., Jena, P., Weya, B., Njeru, J., **Tolemariam, A**., Michieni, A., & Kagendo, K. (2015). Lessons from CASFESA Project on the adoption of CA practices through demonstrations and institutional/market arrangements. Paper presented on project closing workshop, Embu, Kenya

Tolemariam A., Micheni, A., Kitonyo, O., Okitoi, O., Kassa, E., Degefa, K., and Jaleta, M. (2013). Economic Return Analysis of Conservation Agriculture Based Practices in Maize-Legume Systems of Eastern Africa. Research Finding Report from Ethiopia and Kenya

Signature of doctoral candidate

Alemu Tolemariam Ejeta