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Adaptation of farm-households to increasing climate variability in Ethiopia: Bioeconomic modeling of innovation diffusion and policy interventions

Thomas Berger,

Tesfamicheal Wossen, Christian Troost, Evgeny Latynskiy, Kindie Tesfaye, Sika Gbegbelegbe University of Hohenheim, Dept. of Land Use Economics in the Tropics and Subtropics (490d) 70599, Wollgrasweg 43, Stuttgart, Germany. E-mail: i490d at uni-hohenheim.de

Abstract.

Climate variability with unexpected droughts and floods causes serious production losses and worsens food security, especially in Sub-Saharan Africa. This paper applies stochastic modeling to analyze smallholder adaptation to climate and price variability in Ethiopia. It uses an agent-based simulation package to capture nonseparable production and consumption decisions at household level, considering livestock and eucalyptus for consumption smoothing as well as farmer response to policy interventions. We find the promotion of new maize and wheat varieties to be the most effective adaptation option, especially when accompanied by policy interventions such as credit and fertilizer subsidy. We also find that the effectiveness of available adaptation options is quite different across the heterogeneous smallholder population in Ethiopia. This implies that policy assessments based on average farm households may mislead policymakers to adhere to interventions which are beneficial on average albeit ineffective in addressing the particular needs of poor and food insecure farmers.

Keywords: food security, climate impacts, mixed rain-fed agriculture, multi-agent systems JEL codes: C61, Q54, C63, Q12, D12



1. Introduction

Ethiopia is highly exposed to climate variability, as agriculture forms the basis of the economy contributing roughly 43% to GDP, 90% of export earnings and 80% of employment (MoFed, 2010). Moreover, agriculture is predominately rain-fed with limited irrigation coverage, which means that shifts in the timing and amount of rainfall impinge on agricultural production and food security (Di Falco and Chavas, 2009). Smallholder farmers cultivating about 95% of the total crop area and producing more than 90% of Ethiopia's agricultural output are found to be the most affected by current and future climate variability (Milman and Arsano, 2013; Arndt et al., 2011; Deressa et al., 2009, Di Falco et al., 2011; Block et al., 2008).

According to the regional climate projections included in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), the effect of global warming will be larger in Sub-Saharan Africa (SSA) than on global average (Knox et al., 2012). Unfortunately, within SSA the horn of Africa will possibly be most affected by future climate variability, with Ethiopia often cited as an example (Conway, 2011; Di Falco, 2014). Although large model uncertainties still exist, rainfall patterns are expected to become more erratic with frequent flood and drought events, thereby seriously affecting rain-fed agriculture (Cooper et al., 2008; Arndt et al., 2011).

Disentangling the effects of current and future climate variability from other determinants of agricultural production and food security is crucial not only to design appropriate climate mitigation and adaption policies, but also to prioritize policy interventions. One of these other determinants of food security deserving special attention is price variability. The effect of price variability on household food security depends on the rate and speed of productivity-induced changes of market prices, the market position of households (net buyer vs. net seller), the extent of market integration of farm households, as well as changes in wages. In line with this, Mideksa (2010), Arndt et al. (2011), Robinson et al. (2012) and Hertel et al. (2010) indicated that analyzing only the production effects of climate variability without considering the effects of inherent market forces through price changes would underestimate the effects of climate variability, and hence overestimate the effectiveness of adaptation options.

Against this background, we make use of computer simulation in this paper to address two important research and policy questions. First, by quantifying climate and price variability effects at the household level, we examine the impacts of current and future climate variability on farm household welfare in Ethiopia. Our study identifies the socio-economic characteristics responsible for variation across households in their ability to cope with climate and price variability effects. It captures especially the role of smallholder assets such as livestock and eucalyptus, as well as lastresort emergency measures such as default on credit and temporary food shortage.

Second, we examine the distributional effects of innovation diffusion and production-related policy interventions in agriculture. In particular, we investigate the role of new improved maize and wheat varieties in enhancing food security under increasing climate variability. We consider the promotion of mineral fertilizer use, of which current application rates in Ethiopia stand at only 29 kg/ha (Spielman et al., 2011). Using panel data from the central highlands of Ethiopia, Alem et al. (2010) showed that rainfall variability affects fertilizer use decisions negatively, implying that with increasing climate variability, the application of mineral fertilizer and crop yields might further decline.

For computer simulation, we employ a novel stochastic bioeconomic household modeling approach implemented with the agent-based software package MPMAS (Schreinemachers and Berger, 2011). MPMAS is able to simulate agent decision-making while explicitly considering high degrees of heterogeneity, nonlinearity, interaction and feedbacks, and finally emergence (Berger and Troost, 2014). To the authors' knowledge, this study is the first to employ agent-based modeling for quantifying both climate and price variability effects in SSA. The remainder of the article is organized as follows: section 2 briefly introduces the data and methods used; section 3 reports on model validation and scenario design; section 4 presents the results of our simulation analysis; section 5 discusses our findings and their relevance for climate impact assessments; section 6 concludes with a list of open questions and an outlook on next research steps.

2. Data and methods

2.1. Data sources

The Ethiopian Rural Household Survey (ERHS) serves as the main data source for parameterization of our bioeconomic model. ERHS, a nation-wide longitudinal data set, is the best available representative household level information, capturing well the diversity of agro-ecological conditions in Ethiopia. In general, data quality is sufficient for use in bioeconomic modeling except for the estimation of crop-specific labor and fertilizer production functions. We, therefore, used IFPRI's Nile Basin survey (Deressa et al., 2009) as a complementary data source for the estimation of these parameters.

In order to capture current and future climate variability in agriculture, historical rainfall records over the last 60 years (1951-2010) were obtained from the National Meteorology Agency (NMA) of Ethiopia. We then grouped the years into very dry, dry, normal, wet and very wet years using the standardized annual rainfall anomaly index. The expected future frequency of very dry, dry, normal, wet and very wet years (2011-2040) was derived from downscaled CIMP5 (Coupled Model Intercomparison Project - Phase5) simulation data for the Ethiopia grid, precisely the ensemble mean for the RCP4.5 scenario (http://climexp.knmi.nl/). Since the CIMP5 simulations imply considerable uncertainties related to rainfall, we calculated the frequencies for annual rainfall totals and for May-September rainfall totals (the main rainy season in Ethiopia). The two approaches, however, gave quite different frequency distributions: The classification based on annual rainfall shows a pronounced decrease in the frequency of normal years with increasing frequencies of extreme years, compared to current climatic conditions. In contrast, the classification based on May-September rainfall shows much less differences compared to current climatic conditions but suggests a future shift from wet to dry years. Crop data from the Ethiopian Central Statistical Agency (CSA), including yield damage assessments, were used to compute crop yields for very dry, dry, normal, wet and very wet years for each site of the ERHS. Crop yields under future climate conditions were simulated using the Decision Support System for Agrotechnology Transfer (DSSAT version 4.5; Jones et al., 2003; Hoogenboom et al., 2010).

For the same representative climate years, we compiled price data for each site (or peasant association, PA) of the ERHS. In the price dataset, we found considerable variation of selling and buying prices on output and input markets across PAs. Therefore, we decided to use PA-level prices instead of regional/country average prices in our bioeconomic modeling. For this paper, however, we could not yet implement local level linkages of weather and market prices (work is ongoing and results will be presented at the ICAE 2015 conference). For the parameterization of the economic model component, especially innovation diffusion, we used data from the recent SIMLESA household survey collected by Teklewold et al. (2013) at the International Maize and Wheat Improvement Center (CIMMYT). In addition, we identified various credit sources and computed the corresponding interest rates from the ERHS survey and secondary literature.

[Insert Figure 1 here]

Following Berger and Troost (2014), we applied a highly disaggregate bioeconomic modeling approach to capture the heterogeneity of smallholder agriculture in Ethiopia. The characteristics of each smallholder household, its demographic composition, land rights, ownerships of durable assets and geographical location within agro-ecological zones and administrative units were directly estimated from the ERHS data set. Each model agent can then be said to represent a farm household from the ERHS, i.e. there is a one-to-one correspondence of model agents and their real-world analogues (see Figure 1). As a consequence, the bioeconomic model is representative of rural Ethiopia to the same extent that the ERHS sample is representative

2.2. Micro-level simulation

For our bioeconomic modeling, we employed MPMAS, an agent-based simulation package using whole-farm mathematical programming to simulate farmer decision-making in agricultural systems (Schreinemachers and Berger, 2011). The strength of MPMAS is its ability to capture agent and landscape heterogeneity as well as spatial and social dynamics and interactions (van Wijk et al., 2012). Schreinemachers et al. (2007), Schreinemachers et al. (2010), and Quang et al. (2014) demonstrate the empirical use of MPMAS in developing countries. Model equations and software architecture of MPMAS have been described in Schreinemachers and Berger (2011) following the ODD-protocol and are therefore not repeated in this article. Technical documentations, executable programs and software manuals can be downloaded from the developer website at https://mp-mas.uni-hohenheim.de.

Climate variability affects household income in many ways, notably through changes in crop yields, prices, rural wages and productivity (Hertel et al., 2010). Typically, these effects are household-specific, as households differ in production and consumption decisions as well as in their adaptive capacity. As consequence, for disentangling the different pathways through which climate variability may affect food security, bioeconomic microsimulation is required. Only then the model can explicitly capture heterogeneity of households in terms of access to resources, poverty levels, and adaptive capacity to climate and price variability. The agent-based decision module of MPMAS (see Figure 2) simulates farmer investment decisions (e.g. growing perennial crops, keeping livestock, acquisition of land and machinery etc.), production decisions (e.g., allocation of land for annual crops etc.) and consumption decisions (e.g. selling crops, buying food etc.) in a non-separable set-up using Mixed Integer Linear Programming (MILP) . Since the choice of crop-mix is agent-specific, individual household agents achieve different levels of crop yields based on their investment and production decisions. The agent choice of crop-mix depends, among other

parameters, on expected crop yields, expected market prices, actual input prices, and initial agent resource endowments. We included in our decisions module monthly land, labor, and water constraints to capture multiple cropping, peak labor needs and monthly variations in irrigation water supply. During simulation, agents may then adapt through adjusting their resource use (e.g. land, labor, livestock etc).

[Insert Figure 2 here]

Climate variability is reflected not only in the production-related decisions but also in the consumption decisions of farm households. In response to climate variability, households might change their planned consumption after harvest, shifting towards goods that are less sensitive to climate variability and sell or buy different food items. Building on the approach developed by Schreinemachers et al. (2007), consumption behavior of agents in MPMAS was parameterized using ERHS data and by means of a three-stage budgeting process. First, each agent makes a decision on how to allocate achieved income into savings and expenditure. Then, a decision is made on how to allocate expenditures between food and non-food expenditures. Finally, agents decide on the allocation of food expenditures into different types of food items, taking into consideration the price of goods and their consumption preferences. In this after-harvest decision, agents in MPMAS can react to food shortages due to bad harvests or lower than planned cash inflows through various coping options. These coping options at agent level include purchase of additional food, consuming different, less expensive or inferior food and credit default, selling of livestock and eucalyptus. Among these agent coping strategies, reduced food uptake and selling of assets are implemented as last-resort decisions, which households in the study area are typically reluctant to make. If these coping measures are insufficient to satisfy the individual food energy needs in MPMAS, agents default on credit (if taken) and/or run into food energy deficits.

3. Simulation

3.1. Model sensitivity

For purposes of model verification, validation and parameterization, we tested the sensitivity of simulated land use to variations of key model parameters. Derived from theory and literature, we tested the following parameters using the elementary effects method of Morris (1991) and Campolongo et al. (2007): access to off-farm labor, livestock weights, and labor required for livestock herding, household energy requirements, appreciation of future production of perennial crops, and labor capacity of household members. In examining the sensitivity of our results, the simulation model was run by randomly choosing a theoretical value for the aforementioned

parameters based on literature and expert opinions. The process was repeated for each parameter until the parameter space was fully explored by changing one parameter at a time. The model results were then evaluated for the new combination of parameters to identify the elementary effects. The sensitivity testing helped to identify and correct inconsistencies and prioritize parameters for model calibration and validation.

3.2. Model validation

Having parameterized MPMAS, it was necessary to validate the agent-based model against realworld observations. This was done at various levels of aggregation by comparing simulation results to observed values from ERHS (2009). Since household food expenditure is a key policy indicator for food security, validation of this indicator deserves high priority. Figure 3 shows the simulated and observed distribution of household food expenditures in MPMAS and ERHS. Generally, goodness-of-fit is high across the full agent population, with slight under-estimation for medium expenditure levels and slight over-estimation for high expenditure levels.

[Insert Figure 3 here]

As the second key policy indicator for model validation, we selected household land use of the five most important crops (teff, wheat, barley, maize and sorghum). Figure 4 presents simulated and observed distribution of household cropland use in MPMAS and ERHS. Goodness-of-fit is high with some over-estimation for very small land areas, which can be explained by the internal spatial resolution used in MPMAS¹.

[Insert Figure 4 here]

3.3. Scenarios

The baseline scenario was designed using re-sampling techniques to simulate the impacts of climate and price variability on household poverty and food security over a simulation horizon 15 years. For each repetition of these 15 year simulations, each year in the sequence was randomly chosen from the climate dataset, and the corresponding crop damage factors were applied to the various crop production functions. For traditional and minor crops, these crop damage factors were calculated from CSA (2012). For major crops, the crop damage factors were simulated with DSSAT. Running the simulation with climate variability but without any form of policy intervention enabled the

 $^{^{1}}$ In this study, we set cell size to 0.125 ha. As agent land endowments can only be represented in MPMAS as multiples of this value, very small land holdings are more affected by rounding up or rounding down.

effects of climate variability to be disentangled from the results of policy intervention and to determine what self-coping strategies agents may use independent of intervention.

For the analysis of price variability, we made use of the FAO dataset on yearly producer prices for Ethiopia from 1996–2010 (we considered only prices under the current political and economic system after the transition). With this country-average data, we constructed projections of PA-specific prices for the same period, correcting them by estimated linear trends. Residuals for each year (i.e., the distances from point observations to the regression line) were calculated providing the absolute effects of price variability corrected by the linear trend and expressed in 2009 prices. Absolute price effects were then transformed to relative price effects through normalization by 2009 prices. Adding the relative price effects to the respective PA-level prices enabled projections of detrended real PA-level prices of 1996-2010 (in 2009 real terms). As a consequence, simulation results in this paper only reflect co-variation of weather and prices at the country level. Work is ongoing to implement linkage of climate variability and price variability also at the local level.

As mentioned in the introduction, one possible intervention in response to food insecurity is the introduction of new technologies, which increase agricultural productivity under climate and price variability. The innovation considered in this study was the promotion of improved maize and wheat varieties as promoted by CIMMYT. To determine the role that improved technology plays in general and in response to climate and price variability, innovation diffusion was simulated using the network threshold approach originally developed by Berger (2001). The resulting baseline innovation diffusion was then compared to scenarios without technical change (innovation diffusion was fixed to current levels) and ideal technical change (full access for all agents to innovation immediately).

According to ERHS (2009), only 12% of the households received credit from microfinance organizations (interest rate of 18% p.a.) and 22% received credit from the government (interest rate of 9% p.a.). In the baseline, MPMAS was parameterized such that agents could access credit from these sources. As the adoption of new crop varieties implies additional cash requirements for buying seeds, the first policy intervention considered in MPMAS was improving access to short-term credit for productive purposes. In this intervention, agents are given the option to take short-term credit at the onset of the cropping season for all production-related costs, but not for consumption, using interest rates of current microfinance programs in Ethiopia. New crop varieties also have higher fertilizer demands, and we therefore considered fertilizer subsidies as another type

of policy intervention. Currently, Ethiopia has no formal fertilizer subsidy, lack of which can aggravate cash constraints of smallholder farmers. As no current Ethiopian subsidy program exists, a scenario was developed following expert suggestions to introduce fertilizer subsidies of 25%.

In total, we conducted 299 simulation experiments with 1,280 agents over 15 years, which accounts to about 17.2 million mixed-integer LP problems solved (size of each problem: 8,175 columns, 769 rows, 133 integers). One simulation run took about 15 hours to complete on a Linux computer with 8 Gbyte RAM.

4. Results

This section presents our simulation results divided in three parts: (1) baseline with current climate and price variability, (2) technical change and policy interventions under current climate and price variability, (3) future climate and price variability. Due to the simplifications applied when classifying future climatic conditions, simulation results from part (3) must be considered speculative to a certain extent. The outcome indicators used are per-capita household income (to measure the impacts of policy intervention and technology diffusion) and minimum food requirements met (to measure changes in food security). Other indicators used are livestock and eucalyptus endowments (to capture the special role of these assets for consumption smoothing), as well as credit default and temporary food shortage (to capture failure coping strategies in case of crisis).

4.1. Current climate and price variability

In order to assess the individual and combined impacts of climate and price variability, we ran a number of baseline scenarios with 10 repetitions each in which we considered: (i) current climate and price variability jointly, (ii) current climate variability alone, keeping prices constant, and (iii) price variability alone, keeping climate constant (iv) without any climate and price variability. In our simulation analysis, we found an overall negative effect of climate variability alone, reducing agent incomes by 8% on average as compared to the hypothetical baseline without any variability at all. For price variability alone, we found a stronger negative effect; agent income declines by 14% on average compared to the baseline without any variability. Combining both types of variability in Figure 5 shows a compensating effect on agent income, which then declines by 7% on average².

 $^{^{2}}$ Since we could not establish with our available data any correlation at national level between weather and agricultural prices, both drivers are working independently in our simulation experiments. As mentioned above, we are currently compiling local rainfall and price data from Ethiopia and will re-run our simulation experiments once this new data set has been made available.

[Insert Figure 5 here]

As Figure 5 shows, climate and price variability have an overall negative effect on agent income compared to the baseline without any variability. On average, 46% of agent households fall below the poverty line of 1.25 USD per person per day. It is worth noting that this international poverty line is quite high for a country like Ethiopia. In fact, applying the official poverty line of 648 Birr per adult equivalent at 1994/95 constant prices, 36% of the agents are found to be poor. Our simulation results are therefore in line with announcements of the Ethiopian government, which reports total food poverty rate of 34.7% for the year 2010/11 (CSA 2012). Next, we examined the distributional impacts of climate variability, price variability and joint climate and price variability. A closer investigation at the household level – Figure 6 ranks the individual agents by their baseline income –, reveals that the adverse effects of climate variability on agent incomes tended to be more negative on agents with higher baseline incomes.

[Insert Figure 6 here]

The reason is considerable differentiation in crop areas under teff and barley. Particularly, growing teff is a profitable enterprise and better-off agents assign relatively large areas to this crop. As mentioned above, crop damage factors for teff and barley were calculated for this study using data from CSA reports. For the other major crops, crop damage factors were simulated with DSSAT. Since the assumed effect of climate variability is rather high on teff and barley, incomes of agents with proportionally more area devoted to teff and barley are more adversely affected than in the case of poorer households who mainly grow maize. To test the robustness of our results to distinct crop damage factors, we ran special scenarios with CSA crop damage factors applied also to the DSSAT crops. Using CSA crop damage factors for all crops leads to highly uniform negative effect of climate variability, reducing agent incomes by 11% on average. We must therefore conclude that simulation results differ to a certain extent depending on the assumed crop yield response, which calls for more investment into crop simulation and damage assessment. For this study, we continued using CSA and DSSAT yields side-by-side in this study, as this represents the best available data on crop yields under climate variability in Ethiopia.

For price variability alone, the effect at the household level is quite uniform and almost all agents are adversely affected (Figure not shown here). As a result, the detailed analysis for combined effects of price and climate variability reveals compensating impacts throughout the agent population (Figure 7). Whereas agents with lower baseline incomes slightly benefit on average from climate and price variability – agents with higher baseline incomes are more uniformly and more

negatively affected. Again, the reason is that poorer agents growing fewer crops with CSA damage factors are, on average, less affected by climate variability.

[Insert Figure 7 here]

As explained above, our agent-based simulation in Ethiopia confirmed that farm households show considerable variation when coping with climate and price variability. We therefore made an effort to disentangle the socio-economic characteristics leading to different agent response using multivariate analyses. We specifically analyzed which socio-economic characteristics are the most responsible for variation across different agents and what exactly enables agents to successfully cope with climate and price variability. We combined Principal Component Analysis (PCA) and Cluster Analysis (CA) in order to identify an agent typology based on their response to variability. We found that agents who are adversely affected by climate and price variability are characterized by low usage of improved seeds, low application rates of fertilizer, limited livestock endowments and small crop area. Agents who managed to cope well with variability are characterized by large crop areas and livestock endowments, extensive use of fertilizer and higher levels of improved seed.

Since we simulated agent decisions recursively over time, we could observe trajectories of individual agents under climate and price variability. Figure 8 shows the evolution of agent incomes as box plots over 15 years for each of the 10 repetitions. The white line shows the median agent income for one period in each repetition. Although agent incomes are slightly growing with increasing variation, the growth in income is quite modest due to the effects of climate and price variability.

[Insert Figure 8 here]

Furthermore, we investigated the effects of autonomous adaptation options under climate and price variability in Ethiopian smallholder agriculture. As mentioned above, MPMAS includes a detailed livestock module to capture its role in consumption smoothing under climate and price variability. Figure 9 demonstrates this role by showing the change of consumption under joint variability relative to consumption levels in the baseline without any variability. Accordingly, agents with higher livestock endowments were able to smooth consumption to a higher degree over time than agents with lower endowments.

[Insert Figure 9 here]

In addition to selling livestock assets as a coping strategy, it is also becoming common in Ethiopia to sell eucalyptus in times of hardship. Using the same procedure, we found that agents with larger plantation areas are better positioned to cope with climate and price variability. (Figure not shown

here). The analysis confirms that – very similar to livestock – agents with larger eucalyptus areas can maintain their consumption levels to higher degree under climate and price variability.

4.2. Innovation and policy intervention

Moreover, we simulated the impacts of the following possible policy interventions: (i) improved information communication to speed up technology diffusion, (ii) extension of credit availability, (iii) extension of credit together with fertilizer subsidies, and (iv) improved information communication accompanied by improved credit availability together with fertilizer subsidies. Figure 10 shows the maximum possible effect of improved information communication at the individual agent level ("ideal" technical change). In this scenario, all agents received immediate access to novel maize and wheat varieties. With few exceptions, the majority of agents can improve their income as compared to the baseline without any variability.

[Insert Figure 10 here]

Figure 11 compares the impacts of "maximum innovation communication" with "credit" and "credit plus fertilizer" interventions. On average, all interventions are effective in improving agent incomes under climate and price variability, although policy impacts differ. "Maximum innovation communication" shows the largest positive shift of income (7% on average), "credit plus fertilizer" a medium positive shift (3% on average), and "credit" the smallest positive shift (2% on average). In terms of winners and losers under each policy intervention, "maximum innovation communication" enables 88% of the agents to maintain or increase their income as compared to the baseline with variability. In contrast, "credit" has 74% "winners" and "credit plus fertilizer" has 80% "winners", compared to the baseline with variability.

[Insert Figure 11 here]

We then analyzed in more detail the effectiveness of credit interventions under climate and price variability. In the baseline without any variability, about 15% of the total borrowed credit is not repaid on average. Under climate and price variability, the overall default rate increases to about 32% for current credit availability. As explained before, agents in our Ethiopian MPMAS application revert to credit default only in case of food shortage and after having sold livestock/eucalyptus and already reduced their food consumption. To compare the degree of food shortage across scenarios, we normalized the food energy deficits from individual agent MILPs by dividing them with the maximum energy deficit ever chosen in our experiments. Table 1 shows the degree to which agents were forced into food energy deficit under climate and price variability. Here, about 22% of the agent population never experienced food energy deficits over the simulation

horizon of 15 years. All other agents had to struggle at least temporarily with severe food shortages, represented by a relative food energy deficit of 7% on average.

[Insert Table 1 here]

4.3. Future climate and price variability

For simulation of future climate and price variability, the re-sampling of weather and crop yields was based on two alternative climatic classifications using annual rainfall totals and May-September rainfall season totals. For future prices, we assumed no change in variability as compared to the current situation. Figure 12 depicts the agent income distributions averaged over 10 repetitions each for current variability, future variability re-sampled on annual rainfall totals, and future variability re-sampled on May-September rainfall totals. Compared to the baseline with current variability, where 41% of the agents were below the international poverty line, this poverty indicator increases to 48% under future climate variability based on the May-September classification. However, when future climate variability is based on the annual rainfall classification, poverty increases to about 58%.

[Insert Figure 12 here]

To analyze the effectiveness of policy interventions, we also ran policy scenarios under future climate and price variability with 10 repetitions each. Scenarios for innovation diffusion have not been included here, as data of future crop varieties that are part of current plant breeding programs of CIMMYT were not yet available to us. Results of the policy simulation under current and future variability are summarized in Tables 2 and 3, using the following key policy indicators: (i) poverty – share of agents below the 1.25 USD poverty line; (ii) income – average change of income compared to the baseline without any variability; (iii) food security – share of agents failing to meet their minimum food consumption expenditure; (iv) heterogeneity of impact – here measured as the share of agents able to maintain or increase their income as compared to the baseline without any variability.

Differences in impact on agent incomes are rather small when comparing the "credit" and "credit plus fertilizer" interventions under the two future climatic classifications. Differences in impact on agent incomes, however, are significant when comparing the same intervention under current and future variability.

[Insert Tables 2 and 3 here]

5. Discussion

In this section, we interpret the results of our simulation experiments, addressing the two main research questions posed in the introduction: (i) what are the likely impacts of current and future climate variability on smallholder households in Ethiopia, and considering this variability (ii) how could policy interventions in response to climate and price variability affect food security outcomes? We start with discussing our simulations of current climatic conditions in agreement with the statement of Arribas et al. (2011): *"There is no better way of adapting to climate change tomorrow than adapting to climate variability today"*. Having discussed policy options under current conditions, we then focus on future climate variability and policy impacts.

5.1. Impacts under current climate variability

Climate and price variability offer opportunities and threats to agriculture that could – if smallholders had perfect foresight at the onset of the cropping season – be exploited or mitigated by anticipating the optimal crop choice and crop management accordingly. In reality, however, smallholder farmers usually make land-use decisions that are optimized for "normal" average years, including some margin of flexibility and risk aversion. As a consequence, benefits in years more favorable than average cannot be fully exploited, and losses in years more adverse than average cannot be fully avoided. This implication of imperfect foresight has been quantified with MPMAS, by running hypothetical simulation experiments without any variability, with climate and price variability ceteris paribus and finally with joint variability. For now, we treated weather and price variability as independent, since we could not identify correlation at country level in our available datasets. Accordingly, the isolated effects of climate variability (change of agent income -8% on average) and price variability (change of income -14%) at least partially compensate under joint variability (change of income -7%). Once local level linkages between weather and prices have been implemented, however, we expect more heterogeneity in agent impacts.

Even without implementation of local effects, our simulation results underline the importance of considering climate and price simultaneously in integrated assessment studies of climate-adaptation policies. As our simulations suggest, current climate and price variability effects are heterogeneous. Although variability aggravate poverty and food security levels (about 5% of agents were additionally below the poverty line and about 8% of the agents ran additionally into food deficits), still some 17% of the agents in MPMAS maintained or increased their income against the hypothetical baseline without any variability. In terms of coping strategies, high-income agents

relied more on their assets (livestock and eucalyptus), which could be sold for consumption smoothing. Although these more affluent agents tended to grow more profitable crops, the crops were more risky; this caused them occasionally to lose more income in percentage terms than low-income agents.

5.2. Failure of agent coping strategies

According to Cooper et al. (2008), farm households in developing countries use both ex-ante and ex-post strategies in response to climate and price variability. In our simulation experiments, we implemented various coping strategies such as purchasing additional food, consuming less expensive and inferior food as well as selling livestock and eucalyptus or ensuring additional cash inflows through credit. Some of the coping strategies implemented here, however, are last-resort decisions that households are only willing to make in under extreme hardship. These involve for example selling assets, defaulting on credit and - in case that all these measures fail - severe food shortage. The above mentioned coping strategies are crucial for smallholders in rural Ethiopia since many of them are poor and vulnerable to deviations in production value due to climate and price variability. Our simulation results show that the effects of climate and price variability on consumption are considerable, but smaller for those agents with relatively large livestock endowments and eucalyptus plantations. Still, only about a fifth of the agent population never faced food deficits, while all other agents at least struggled temporarily with severe food shortages, represented by a relative food energy deficit of 7% on average. Therefore, our results suggest that 'self'-coping strategies are important but not sufficient and should be complemented with appropriate policy interventions.

5.3. Effectiveness of policy interventions

Policy interventions aimed at promoting new crop varieties appear to be effective in our simulations if implemented under optimal conditions (that is, if innovation diffusion could be sped up to the maximum through farm extension and credit and fertilizer subsidies were used on-farm for productive purposes only). Under these implementation conditions, the three types of policy intervention could at least compensate, in the case of innovation diffusion even over-compensate, the overall adverse effects of variability on poverty and food security. Regarding the efficiency of current and additional credit programs, we found an increase of average credit default from 15% in the baseline without any variability to 32% under current climate and price variability. As explained before, credit default – even in the situation without variability – is associated with the occasional reversal of agent decisions which we think is a realistic assumption.

5.4. Impacts under future climate variability

Using two alternative approaches for future climate classification, we conducted 6 simulation experiments with the same policy-relevant indicators as under current conditions. According to our simulations, future impacts differ considerably under both classification approaches. Based on the first climate classification (May-September rainfall totals), overall levels of poverty and food security did not change much compared to the baseline with variability under current conditions. In this scenario 48% of the agents fell below the poverty line with a decrease of income of 3% on average and a slight increase in the share of food insecure agents from 39% to 40%. When applying the second classification approach (annual rainfall totals), the situation changed significantly: 58% of the agents fall below the poverty line with a decrease of an an increase in the share of food insecure agents from 39% to 40%. Policy interventions were at least partially successful in compensating the effects of future variability as could be seen in Table 3.

5.5. Model limitations

Finally, we would like to discuss the model limitations and comment on the credibility of our simulation results. As mentioned above, this study uses the sampling frame and data from ERHS 2009 and is therefore to the same degree representative of rural Ethiopia as is this dataset. Where data gaps needed to be filled, we complemented ERHS 2009 with other datasets such as IFPRI's Nile Basin survey and CIMMYT's SIMLESA technology adoption survey. When validating our model outputs for key parameters such as food consumption, land use and overall poverty levels, we found high levels of fit with available observations. In addition, cross-checking with local experts confirmed large resemblance with actual adaptation behavior of smallholder farmers in Ethiopia, although certain decision rules in case of severe food shortages (whether to default on credit or not) require more empirical investigation. In general, we believe that our stochastic simulation runs with 10 repetitions for each variability condition and more than 17 million agent MILPs produced valid and robust results.

For the lack of detailed crop data, we had to rely on national average damage assessments of CSA when calibrating the yield response of traditional and minor crops under current climate variability. We did neither implement all possible agent-coping strategies of smallholders in Ethiopia nor consider local safety nets and kinship ties explicitly (see, for example, the study of Wossen et al., 2013). Implicitly, we assumed that these strategies could help to recover agent livelihoods to the

extent that agents would again receive credit after credit default and survive even in case of severe food shortages.

6. Conclusion

This study applied stochastic bioeconomic household modeling to analyze smallholder adaptation to increasing climate variability in Ethiopia. It used the agent-based simulation package MPMAS, which allowed capturing non-separable production and consumption decisions under price volatility, the role of livestock and eucalyptus as a means of consumption smoothing, default on credit and temporary food shortages, as well as policy options related to the promotion of new crop varieties such as innovation diffusion, credit and fertilizer subsidies.

Our simulation results point to several important findings. First, the study underscores that climate and price variability indeed matters for smallholder agriculture in Ethiopia, and both autonomous and planned adaptation options are urgently needed. We found that the promotion of new crop varieties through improved information communication was the most effective adaptation option followed by the expansion of credit along with fertilizer subsidies. In addition, adaptation strategies composed by a portfolio of interventions (new crops accompanied by credit and fertilizer subsidies) were more effective compared to single-measure interventions.

Second, our simulations showed that the effectiveness of specific adaptation options is quite different across the agent population. In particular, while households with more abundant livestock and eucalyptus endowments were largely able to cope with increasing variability especially through the promotion new crop varieties, most households with a limited asset base were found to be vulnerable. This implies that policy recommendations based on "representative" farms may mislead policy makers to adhere to interventions which are beneficial on average albeit ineffective in addressing the needs of the poor and food insecure farmers. As a consequence, new planned adaptation options for the very poor might get less support in favor of options which are rather effective for households who could have coped relatively well with the effects of climate variability through autonomous adaptation options.

Third, the simulation experiments suggest that more innovation is indeed needed to alleviate poverty and improve food security among smallholder farmers in Ethiopia. It would, therefore, be highly interesting to include in our simulation analysis new stress-tolerant crop varieties developed in current plant breeding programs as additional technology options in MPMAS. The simulationbased assessments for future climatic conditions could then be repeated in MPMAS, yielding possible new insights for research prioritization and policy development. In addition, it might also be worth to integrate MPMAS with economy-wide CGE and/or global trade models so that improved price variability scenarios can be run.

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Tables and Figures

Table 1: Food security under climate and price variability

Indicator	Without any variability	With current climate and price variability
Never with food energy deficit (%)	66	22
Food energy deficit (%)	4	7
At least once with food energy deficit (%)	34	78

Table 2: Comparison of impacts across scenarios (current conditions)

Indicator	Without variability	Current climate and price variability				
	Baseline	Baseline	Ideal technical change	Improved credit	Credit plus fertilizer subsidy	
Agents below poverty line (%)	41.0	46.3	44.1	45.9	45.5	
Average change of income (%)	n/a	-6.6	7.1	1.61	2.87	
Food insecure agents (%)	31.2	38.7	36.6	38.5	37.9	
Share of winners (%)	n/a	16.8	88.2	73.8	80.2	

Table 3: Comparison of impacts across scer	narios (future conditions)
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Indicator	Future climate and price variability					
Classification	(May-Sep)	(annual)	(May-Sep)	(annual)	(May-Sep)	(annual)
Policy intervention	None	None	Improved access to credit	Improved access to credit	Credit + fertilizer subsidy	Credit + fertilizer subsidy
Agents below poverty line (%)	48.1	57.5	47.0	56.6	46.6	56.0
Average change of income (%)	-3.4	-20	2.1	1.6	3.4	3.0
Food insecure agents (%)	39.8	40.2	39.4	39.8	39.0	38.5
Share of winners (%)	13.3	0.0	73.0	72.2	81.0	81.0





Figure 2: Sequence of agent decision-making in MPMAS





Figure 3: Distribution of household food expenditures

Figure 4: Distribution of crop-land use





Figure 5: Change of per-capita income under various types of variability

Figure 6: Change of per-capita income under climate variability alone





Figure 7: Change of per-capita income under joint climate and price variability

Figure 8: Income trajectories under joint variability



Note: Box plots for the full agent population over time in 10 repetitions, indicating quartiles and outliers.



Figure 9: Livestock endowment and consumption smoothing

Figure 10: Change of income under "ideal" technical change





Figure 11: Income change under various types of policy interventions

Figure 12: Distribution of income under current and future variability of climate and prices

