Climate Risk Management 33 (2021) 100330

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

Who is most vulnerable to climate change induced yield changes? A dynamic long run household analysis in lower income countries

Rienne Wilts [*], Catharina Latka, Wolfgang Britz

Institute for Food- and Resource Economics, University of Bonn, Nussallee 21, D-53115 Bonn, Germany

ARTICLE INFO

Keywords:
Climate Change
Long run analysis
Low Income Country
Household effect
Computable General Equilibrium Model

ABSTRACT

Climate change impacts on agricultural production will shape the challenges of reaching food security and reducing poverty across households in the future. Existing literature lacks analysis of these impacts on different household groups under consideration of changing socio-economic developments. Here, we analyze how crop yield shifts induced by climate change will affect different household types in three low- and lower-middle-income countries, namely Vietnam, Ethiopia and Bolivia. The long-run analysis is based on a recursive-dynamic Computable General Equilibrium model. We first construct a baseline scenario projecting global socio-economic developments up to 2050. From there, we implement business-as-usual climate change shocks on crop yields. In the baseline, all households benefit from welfare increases over time. Adding climate change induced yield changes reveals impacts different in size and direction depending on the level of the households' income and on the share of income generated in agriculture. We find that the composition of the factor income and the land ownership are of large importance for the vulnerability of households to climate change, since the loss for non-agricultural households is highest in absolute terms. The complementary comparative static analysis shows smaller absolute and relative effects for most households as the differentiated factor income growth over time is not considered, which makes household types more or less vulnerable. A sensitivity analysis varying the severity of climate change impacts on yields confirms that more negative yield shifts exacerbate the situation (especially) of the most vulnerable households. Furthermore, it underlines that yield shocks on staple crops are of major importance for the welfare effect. Our findings reveal the need for differentiated interventions to mitigate consequences especially for the most vulnerable households.

1. Introduction

Vulnerability to climate change is one of the main challenges faced by humankind in the 21st century (Godfray et al., 2010). Many low-income countries (LIC) are expected to face high vulnerability due to large population shares in high risk areas, poorly developed health infrastructure and weak adaptation capacities (Haines et al., 2006). Within countries, climate change vulnerability differs across population strata, for instance, depending on income sources and levels (e.g. Winsemius et al., 2015), and between rural and urban regions (e.g. Pandey et al., 2015; Ahmed et al., 2009). Farmers are often identified as especially vulnerable to direct impacts (Deressa et al., 2008) due to reduced average crop yields or more frequent crop failures. Market feedbacks from reduced production

---

[*] Corresponding author.
E-mail address: rienne.wilts@ilr.uni-bonn.de (R. Wilts).

https://doi.org/10.1016/j.crm.2021.100330
Received 2 October 2020; Received in revised form 4 March 2021; Accepted 21 May 2021

can, however, increase prices and thus (partially) offset income effects of yield losses, as seen during the food price crises around 2007 (Cohen and Garrett, 2010). Higher crop prices harm households that are poor net buyers of food, which are rural non-agricultural households (Aksoy and Isik-Dikmelik, 2008) and also urban residents (Cohen and Garrett, 2010). As net sellers and net buyers of food face different repercussions, distributional effects of agricultural climate change impacts need to be considered.

Some studies have addressed this by introducing household types in climate change assessments. Hertel et al. (2010) studied effects of climate change driven productivity shifts of six crops on seven household groups in fifteen developing countries. A similar study by Skjeflo (2013) for Malawi, with a focus on maize, differentiated eight household types. Both papers assess impacts of likely future crop yield changes in consequence of decades of climate change in the economic setting of today. This disregards that macro-economic and population dynamics happen in parallel to climate change and affect income levels, earning and consumption patterns, which determine vulnerability to changes in crop productivity.

Thus, a holistic forward-looking perspective in climate change assessments is needed as provided by the five Shared Socio-Economic Pathways (SSPs), developed for integrated long-term analyses of climate change mitigation and adaptation (Riahi et al., 2017). Each SSP describes a different qualitative narrative about the global socioeconomic developments with SSP2 depicting a “Middle of the Road” development. The narratives were the basis to develop long-term macro-economic projections of population dynamics and income growth (Dellink et al., 2017; KC and Lutz, 2017). These projections in combination with the narratives have been used for assessments in terms of e.g. climate change (Leimbach and Giannousakis, 2019) or land use change (Popp et al., 2017), or have been refined with sub-national detail (Dong et al., 2018; Britz et al., 2019). Studies based on the SSPs draw on various model types including dynamic computable general equilibrium (CGE) models as an established method for long-run economic analysis with sectoral detail (Fujimori et al., 2017; Doelman et al., 2018; Britz et al., 2019).

Direct impacts of climate change differ across crops, and their consequences for food availability depend on factors such as global market integration and regional diets. Existing work based on the SSPs does not combine macro-economic mechanisms including agri-food detail with household differentiation. A study from Hallegatte and Rozenberg (2017) assesses household level effects of climate change using a microsimulation approach under SSP4 and SSP5. However, in this study neither trade, nor investment changes over time are considered. We address these gaps by carrying out an ex ante assessment of climate change induced yield shifts based on dynamic global CGE modeling. To this end, we incorporate detail for nine different household types, grouped by income per capita and share of agricultural income, for Vietnam, Ethiopia, and Bolivia as low- and lower-middle-income countries (LMICs). With this framework, we can model crucial developments over time such as income dependent household demand curves, sector specific productivity growth, and endogenous national saving rates, which depend on demographics and income. The baseline draws on projections of population, educational levels and GDP for SSP2 until 2050. It captures increasing demographic pressures on cropland resources and the changing importance of the agri-food sector in the overall economy as GDP rises, which shape the impacts from crop yield changes. In order to isolate the effect of climate change on different household types, we compare our baseline without explicit climate change assumptions on agricultural production to a scenario in which we consider climate change induced yield shifts for eight crop aggregates globally. In addition, we run a comparative static analysis to show the added value of the dynamic analysis applied here i.e. revealing the relevant driving dynamics explicitly. These are ignored in a comparative static setting which can result in over- and underestimation of the effects. The uncertainty of the yield shocks is assessed as part of a sensitivity analysis varying crop yield changes in the recursive dynamic analysis by considering projections under different future atmospheric CO_2 concentrations.

Detailed information about the approach is provided in Section 2, which includes the model description, household representation, yield shift assumptions and the scenario design with the indicator descriptions. Section 3 then presents the results by describing country specific effects both economy wide and at household level. It further includes the results of the comparative static analysis and the sensitivity analysis. In Section 4, the results are compared to previous studies’ findings in tandem with a discussion of relevant limitations and uncertainties. Finally, a conclusion is drawn in Section 5.

2. Methods

2.1. Model description

We employ a recursive dynamic global CGE model implemented in the flexible and modular modeling framework CGEBox (Britz and van der Mensbrugghe, 2018), which takes as its core the standard GTAP model (Hertel and Tsigas, 1997) in its current version 7 (van der Mensbrugghe, 2018). It depicts constant-returns-to-scale industries without market power, revenue maximizing factor suppliers and utility maximizing consumers. Moreover, it comprises various exhausting conditions and macro-economic balances such as investments equal savings, and international capital flows offsetting the balance of trade (B.O.T.). The analysis employs the so-called “global bank” mechanism of the GTAP standard model where a global agent distributes all savings to equilibrate expected returns to capital in each region. The parameters that govern this distribution, as reported in the GTAP database, are set at the benchmark such that the in- and outflows of foreign savings from this “global bank” are equal to the B.O.T., after accounting for remittances. During simulation, changes in expected returns alter the balance of payments (B.O.P.) and thus the B.O.T. such that the latter changes endogenously. Bi-lateral trade is represented in two stages based on the ‘Armington assumption’ (Armington, 1969), which differentiates products by origin, considering transport margins, export taxes (or subsidies) and import tariffs. Various further subsidies and taxes in input and output markets are considered in prices for producers, factor suppliers and consumers.

We extend this core by the recursive-dynamic G-RDEM model (Britz and Roson, 2019) combined with elements of the GTAP-E (McDougall and Golub, 2009), GTAP-AGR (Keeney and Hertel, 2005) and GTAP-AEZ (Lee, 2005) modules, to consider detail for energy, agriculture and land use. G-RDEM is designed for the construction of internally consistent and detailed scenarios of long-run economic development (Britz and Roson, 2019). Besides the capital accumulation component typically applied in recursive dynamic CGEs, G-RDEM adds five features, capturing key adjustment processes in the long run: (1) an econometrically estimated implicitly directly additive demand system (AIDADS) with non-linear Engel curves to depict income dependent variations in household consumption patterns, (2) sectoral differentiated total factor productivity growth depending on GDP growth, (3) endogenous national aggregate saving rates driven by demographic and income dynamics, (4) time-varying and income dependent industrial input–output parameters, and (5) debt accumulation generated from foreign savings and trade imbalances (Britz and Roson, 2019, p. 69ff). This extends the "global bank" mechanism by assuming that the "global bank" will charge interest to foreign savings (= a negative B.O.T) and that the resulting debt has to be paid back. The interest received and the debt servings accrue to the regions with positive trade balances (i.e. net lenders), reflecting their share on total global foreign savings in each year. A feedback mechanism driven by outstanding debts relative to GDP prevents ever increasing negative B.O.T. for a region.

G-RDEM uses exogenous projections of real GDP and population by age and educational level provided by the SSP database (Riahi et al., 2017) during baseline construction. At each period *t,* the model is solved for a simultaneous equilibrium in all commodity and factor markets globally. Endogenous aggregate factor productivity adjusts in accordance with the exogenous GDP changes and drives the sector-specific productivity shifters (Britz and Roson, 2019). Real GDP per capita in each region is fixed during baseline construction to given exogenous projections, by adjusting endogenously an economy wide total factor productivity shifter (Britz and Roson, 2019). This shifter changes total factor productivity differently in the primary, secondary and tertiary sector (Britz and Roson, 2019, p. 61ff.) depending on the GDP per capita growth rate. The faster the GDP growth, the faster industry sectors and the slower services grow compared to primary sectors. The functional relation is based on empirical work by Roson (2019). Before each iteration, net investments define the capital stocks at $t + 1$, whereas population and labor stocks, saving rates and input–output coefficients are exogenously updated. In our counterfactual scenario runs we include climate change assumptions. Here productivity shifters turn exogenous and are taken from the baseline run, while GDP now reacts endogenously.

We add some features of the GTAP-E model, which provides detail in depicting the demand for energy carriers by industries and final households to better capture technical substitution. Similarly, the GTAP-AGR model depicts substitution among feedstuffs in livestock production, as well as specific groups of food products to capture cross-price effects in the top-level final demand for food. The GTAP-AEZ model disaggregates land into specific uses across different agro-ecological zones (AEZs). There are 18 AEZs in total, which result from differentiating tropical, temperate, and boreal zones further by the length of growing seasons. We extend the GTAP-AEZ formulation by considering land supply from natural vegetation. As land expansion to forestry and agriculture mostly serves to increase cropland, we use the remaining available cropland buffers as an estimate for the maximal area, which can be converted from natural vegetation. The land supply elasticities are adjusted to match forecasts by FAO (2018) from which we also take yield trends.

We draw on version 9 of the GTAP database (Aguiar et al., 2016), which provides a snapshot of the global economy for 2011. We keep the full differentiation of 57 sectors, which comprise, inter alia, 12 agricultural, 6 energy and 3 transport sectors. In Section 3, the results of the detailed agricultural sectors are often aggregated into a 'grains and crops' and a 'livestock and meat' sector. In addition, the processed food sector is studied, which is also contained when referred to the overall 'agri-food sector' in the following. All monetary values are presented in USD 2011 in line with the model database. We aggregate the 140 countries or country blocks included in GTAP 9 into 15 regions. This includes one LIC (Ethiopia) and two LMICs (Bolivia and Vietnam) considered with household details as well as China and the USA, and 10 country aggregates (see in Table A.1 for detail). We opted for the three case study countries as they are located in different regions around the world and thus face different conditions, both climatic and economic. In addition, the choice reflects data availability, i.e. we need LICs or LMICs represented as a single region in GTAP 9 for which a FAO household survey is available, see Section 2.2.

2.2. Household representation

As the standard GTAP model, G-RDEM normally considers only one representative consumer in each country or region. Here, we instead exploit information from a set of household surveys (FAO, 2017a), which provide, inter alia, information on income composition for selected LICs and LMICs, with detail and focus on farming households. The Ethiopian survey is called Ethiopian Rural Socioeconomic Survey and was constructed for rural areas and small towns. The surveys for Bolivia and Vietnam are representative for the whole population (FAO, 2017a). Besides data on household size and their weight in the population, we include information on the size of factor income, differentiating (self-) employment in ten different sectors. Furthermore, we take government or intra-household transfers, remittances and other income sources into account.[1] In the underlying survey data, both monetary and in kind (e.g. own produced food) receipts are used to depict income (ILO, 2003). Thus, also products that do not enter the market are valued as income. All flows are measured in real terms at the benchmark 2011.

We group the households into nine household types using the above-mentioned information. Specifically, we group the households into three quantiles by per capita income: poor (I30: 30% quantile), middle (I70: 30% up to 70%) and rich (I100: rest), considering their different weights in the total population given in the database. In doing so, we account for the unequal shares that these households represent in the population in the quantile definition process. Moreover, we use the share of their income generated in agriculture as second dimension for the household type aggregation. This allows to capture the distinction between net sellers and net buyers of food among the households. Again, we use the same percentage allocation, resulting in three quantiles encompassing the

---

[1] For details, see the chapter on the myGTAP module in the CGEBox documentation, Britz (Britz, 2019), p. 58 ff.

households with the lowest 30% (A30), the middle (A70: 30% up to 70%) and the highest 30% of the shares of agricultural in total income (A100). The combination of these quantiles results in the nine household types shown in Fig. 1. Table 1 reports the population shares represented by each household type. The household types are named according to the total income per capita quantile and the share of agricultural income quantile that they represent, as indicated in the brackets above. For instance, the poor non-agricultural household is named I30_A30, represented by the lower right dark blue shaded square in Fig. 1.

We employ the myGTAP module in CGEBox to introduce income and consumption related data from the household surveys in the social accounting matrix ensuring consistency with the aggregated GTAP data. Each household is assumed to own property rights to primary factors (skilled and unskilled labor, land, capital, and natural resources), which are allocated to the different sectors subject to the revenue maximization objective based on a Constant Elasticity of Transformation function.

For the integration of multiple household types into the accounting framework of the CGE model, the single representative consumer is disaggregated (with fixed weights obtained by the survey data) in each country. Household specific saving rates are updated based on a regression analysis underlying the saving rate dynamics (driven by demographic and income dynamics) in G-RDEM (Britz and Roson, 2019). Vectors of income from different sources are disaggregated based on income shares provided by the surveys. On the consumption side, the vector of final consumption is split down to the household types by using marginal budget shares from the AIDADS demand system, to determine fitting baskets as the surveys do not report household consumption patterns. The AIDADS (Rimmer and Powell, 1996) can be understood as an extended Linear Demand System (LES) where marginal budget shares are a function of the utility level. Britz and Roson (2019) perform a global cross-sectional estimation for the parameters of this demand system (see Table 1 in Britz and Roson, 2019), which includes a regression of the utility level on GDP per capita (Britz and Roson, 2019, p. 60). This regression is here applied to the per capita income level of the households at the base year, which allows estimating their utility level and from there their demand. A follow-up balancing step ensures that each household exhausts its spending on final consumption, while the sum of their demand exhausts given economy totals. During this step, the AIDADS parameters are adjusted to match the per capita demand, by minimizing squared deviations against the empirical parameter estimates. Further insight on how the estimated AIDADS system changes baseline outcomes compared to other solutions can be found in Ho et al. (2020). Consumption baskets vary in this study across household types, such that, for instance, poor households have higher expenditure shares for food.

Population development projections are available at country level only, so that we update all household types proportionally to total population. Capital income is assigned to the households on the basis of fixed ownership shares, which implies that household specific capital stocks vary proportionally. There is no migration from one household category to another and the proportion of skilled versus unskilled workers varies with the same rates across all households, reflecting projections of education levels.

2.3. Scenario design

To assess impacts of yield shifts, we first construct a baseline scenario upon 2050 using GDP, population and workforce assumptions from SSP2 from the IIASA database. We choose SSP2 for the assessment as it consists of narratives that build on historical development patterns for future trends and thus represent on average a medium challenges scenario. Yield developments are taken from country specific yield shifts from FAO (2018), available for different scenarios. Following SSP and Representative Concentration Pathways (RCP) assumptions[2], they differentiate the impact of technology and climate change on yield shifters for 36 crops. The SSP assumptions here determine the framework of technological change over time, while RCP assumptions form the basis for the climate change shifter. Like all other scenarios we develop here, our baseline includes yield changes that reflect evolving technology from the Business As Usual (BAU) scenario in FAO (2018) which matches SSP2. However, as the original SSP scenario narratives do not consider climate change feedbacks (Riahi et al., 2017), yield shifts induced by climate change are not incorporated in our baseline scenario.

We then compare the baseline to a counterfactual scenario (*bau_CC*), which considers impacts of climate change on yields at unchanged technological change. Both types of yield changes are taken from the BAU scenario of FAO (2018). Yield projections for the scenarios are incorporated by aggregating the productivity shifts from FAO (2018) to the available crops in the GTAP database and to model regions, using the crop acreage projections of the FAO as weights. The resulting shocks are depicted in Fig. 2, with rest of the world (ROW) representing the unweighted average of the shocks implemented in the regions which are not in the focus of the analysis. In the *bau_CC* scenario, the workforce and population data used in the baseline are adopted, while GDP adjusts endogenously.

We provide new insights as to how climate change induced yield shifts affect the equilibria in primary factor and product markets, and prices, considering bi-lateral trade to ultimately assess income effects on specific household types. To this end, we make a detailed comparison of the *bau_CC* scenario to the baseline. We use the equivalent variation (EV) as a welfare indicator for the household types, which can be interpreted as the income change needed to reach the new welfare level at old prices (Bockstael and McConnell, 1980). The EV is expressed in monetary units, allowing for an intuitive interpretation. Furthermore, as an ordinal welfare indicator, the EV enables to rank counterfactual prices and quantities to a given base price as a benchmark - as it is applied in our simulation (McKenzie, 1988). Additionally, we present the EV change induced by the yield shift relative to the real income of each household type in the baseline, which represents the total income deflated with the GDP price index, to illustrate the importance of the respective change for a household's welfare.

Complementary to the dynamic analysis, we perform a comparative static analysis similar to those used in previous studies (e.g.

---

[2] The scenarios contain of a "business as usual scenario" (BAU), a "stratified society scenario" (SSS), and a "towards sustainability scenario" (TSS). The climate change impacts are associated with the so-called Representative Concentration Pathways (RCP): RCP 6.0 (BAU), RCP 8.5 (SSS) and RCP 4.5 (TSS), while the socio-economic and technology developments draw on the SSPs (BAU: SSP2, TSS: SSP1, SSS: SSP4).

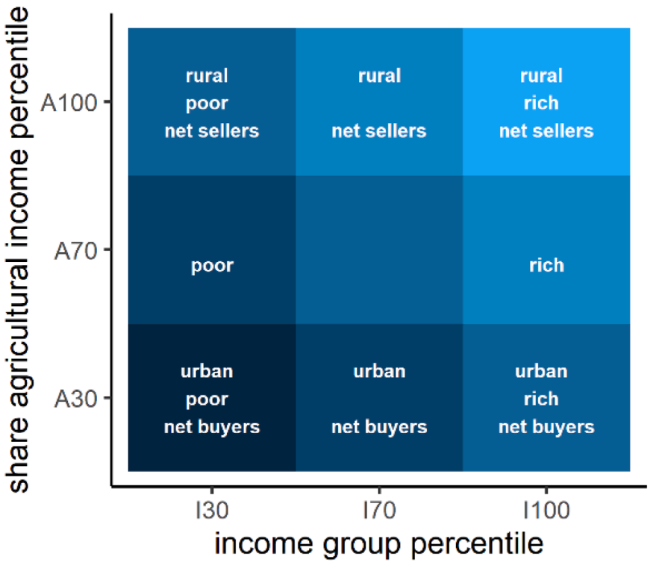

Fig. 1. Household types aggregated by income per capita and share of agricultural income as used in this study.

Table 1
Share of each household type in the population (%).

	I30_A30	I30_ A70	I30_A100	I70_ A30	I70_A70	I70_ A100	I100_A30	I100_A70	I100_A100
VNM	9	12.5	17.1	8.9	15.2	8.8	13.5	9.8	5.1
ETH	6.5	8.7	12.3	5.1	20.7	15.9	6	13.8	10.9
BOL	11.4	1.6	15.2	27.3	3.2	8.9	27.4	2.5	2.4

Remark: VNM = Vietnam, ETH = Ethiopia, BOL = Bolivia, Household type (e.g. I30_A30) are named according to the total income per capita quantile (e.g. 30% quantile of total income: I30) and share of agricultural income (e.g. 30% quantile of agricultural income: A30) that they represent. *Source: Model simulation based on data from* FAO (2017a)

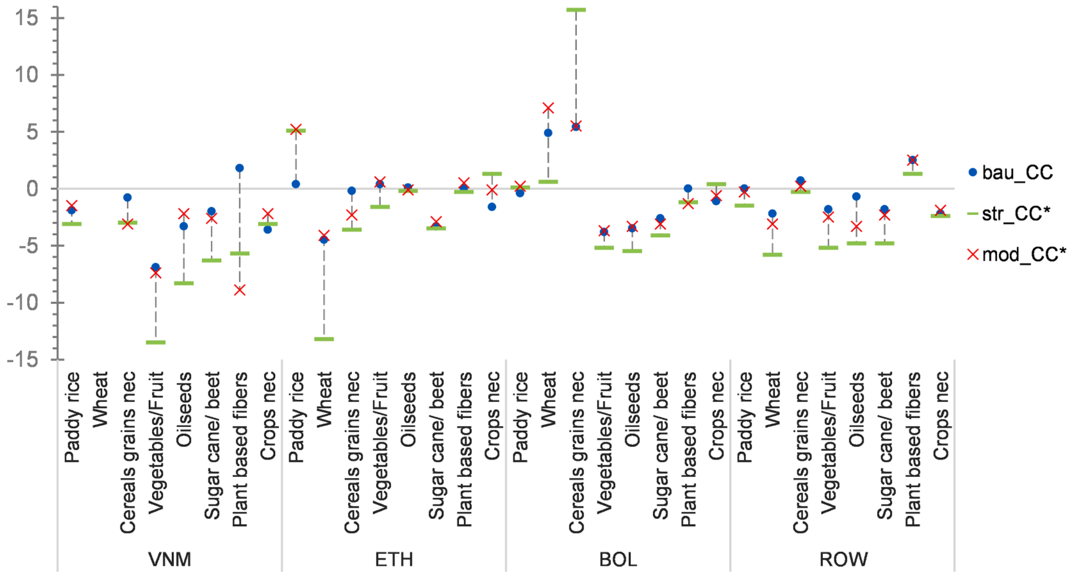

Fig. 2. Percentage yield changes induced by climate change, as implemented in scenarios until 2050. Remark. bau_CC = business as usual Climate change scenario, str_CC = strong climate change scenario, mod_CC = moderate climate change scenario, * = sensitivity analysis scenarios, VNM = Vietnam, ETH = Ethiopia, BOL = Bolivia, ROW = unweighted average of the rest of the world, nec = not elsewhere classified. *Source. Based on data from FAO (2018).*

Skjeflo, 2013). Through comparison of both analyses, it is possible to determine the additional contribution of considering long-run global economic changes. Using the same model on the same database enables us to pinpoint the impact of considering long-term dynamics. In both experiments, we implement the same yield shock, while we do not consider inter alia GDP development or population growth over time in the comparative static run.

Finally, as part of a sensitivity analysis, we vary the severity of climate change impacts on crop yields in our two additional scenarios *str_CC* (based on rather strong climate change effects (RCP 8.0)) and *mod_CC* (based on moderate climate change effects (RCP 4.5)), see Fig. 2, by using the respective climate change yield shifters from FAO (2018). All scenarios are constructed on the basis of the baseline scenario. This includes the SSP2 assumptions on population and education, along with total factor productivity changes and other parameter updates derived in the baseline as well as the SSP2 technology shifters on yield from FAO (2018). In the scenarios, GDP adjusts endogenously driven by climate change induced yield shifts of FAO (2018) aiming to disentangle the consequences of climate change severity ceteris paribus. As shown in Fig. 2, the yield shocks are not always in a linear order from lower (*mod_CC*), to moderate (*bau_CC*), to strong climate change assumptions (*str_CC*). This nonlinearity reflects simulations with crop growth models that account for regional climatic differences and specific crop growth requirements. However, CO_2 fertilization is not considered in these yield projections, in order to compensate for other negative temporary and small-scale climate phenomena that are not accounted for (FAO, 2018).

3. Results

3.1. Baseline development

The SSP2 projections imply that until 2050 global population grows by 32% and real GDP by 186%, resulting in a considerable GDP per capita growth (117%) compared to 2011. For the study countries, even higher changes in real GDP are projected over time increasing approximately by factor six in Vietnam and Bolivia and by factor eleven in Ethiopia (‘solid lines’ Fig. 3 A). Combined with population increases of 18% in Vietnam, of 42% in Bolivia and of 87% in Ethiopia until 2050 (‘dashed lines’ Fig. 3 A), this implies strong GDP per capita increases (Fig. 3 B). These exogenous trends require considerable endogenous adjustments such as massive capital accumulation and sizable improvements in factor productivity in the baseline, and imply strong structural change in the economies. This relates, for instance, to the composition of consumption and production, primary factor endowments and their relations, and prices of inputs and outputs.

3.1.1. Economy wide effects

The combination of a growing world population and increases in per capita purchasing power let global economic output increase by 217% from 2011 to 2050. Compared to the overall global economic output increase, output growth of the agri-food sectors is more modest (see Table 2), reflecting mostly lower income elasticities for these products. Thus, the share of agricultural and processed food outputs in total output decreases from 4% to 2%, respectively. An even stronger trend of falling agricultural importance is observed in the study countries. Ethiopia faces the largest decrease (by −17 percentage points), resulting from the strong GDP increase over time (Fig. 3). Yet, the share of agriculture in the overall economy still remains largest. Likewise, the importance of the processed food sector decreases in all three countries, by at most 5 percentage points. For the three countries in focus, output developments differ substantially from global averages, as summarized in Table 2. While growth rates vary, output of all crops is projected to increase in all three countries until 2050.

Due to the improvements in factor productivity, which imply falling production costs, average product prices tend to decrease globally and in the three countries. Large decreases are especially visible in the livestock sector and the processed food sector, while the prices for grains and crops increase on average. The overall increase in prices of the latter reflects strong demand growth meeting limited land reserves.

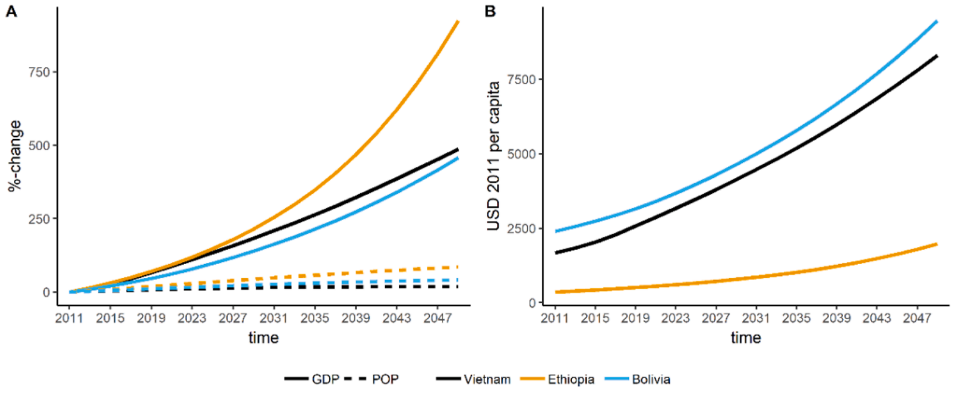

Fig. 3. (A) Percentage change of population and GDP relative to 2011 and (B) GDP per capita development until 2050 in the study countries in USD 2011. Source: Based on data from Riahi et al. (2017).

Table 2
Output changes for the total economy and for agri-food sectors in all study regions and globally from 2011 to 2050 (%).

	Total output	Grains and crops	Livestock and meat	Processed food
Global	217	59	120	74
VNM	608	43	491	151
ETH	1293	198	1334	349
BOL	549	47	217	120

Remark: VNM = Vietnam, ETH = Ethiopia, BOL = Bolivia. *Source: Model simulations*

Globally trade becomes more important as the share produced for domestic use decreases, and the importance of imports for consumption increases. In line with this trend, approximately 29% of the final demand of agricultural products in Vietnam are supplied by imports in 2050, whereas in the two other study countries imports are of negligible importance for livestock products and make up at most 10% for grains and crops. With respect to processed food, a large share of the demand is covered by imports in Vietnam (29%) and Bolivia (22%), while Ethiopia relies mainly on domestic production. These differences are to a lesser extent already found in 2011. In Vietnam agri-food systems are highly integrated in global markets in terms of exports. In Ethiopia and Bolivia, they are again of less importance, except for the Ethiopian meat sector, where export dependency strongly increases.

In response to the previously described changes, factor demand adjusts. The global factor demand for land increases only little over time, both overall and in the grain and crops sector. In Bolivia, similar trends are observed while in Vietnam decreases in the land use of the livestock sector overshadow extension in the grains and crops sector. In contrast, in Ethiopia demand for land increases substantially. Thus, rapid cropland expansion is projected in Africa including Ethiopia. Expansions are projected to be smaller in South America (including Bolivia), and even smaller in Asia (including Vietnam). These changes are also determined by the remaining suitable land available. They originate mainly from conversion of unmanaged forests, while in Ethiopia conversion of savanna is more important. In all regions, relative cropland expansion is below population growth, such that the available cropland per capita is reduced. Cropland use adjusts to meet changes in yields, i.e. generally more land is allocated to crops with reduced yields and vice versa. In line with the strong output increase (Table 2), the land devoted to the livestock and meat production increases substantially in Ethiopia, while it decreases or remains unchanged globally and in the other study countries. The capital stock increases substantially in all study countries. However, the capital employed in the grains and crops sector falls, expressing its shrinking importance in the overall economy. Increasing scarcity, lets land prices rise on average over all sectors and in the agricultural sectors in Ethiopia and Bolivia, while in Vietnam they increase only in the grains and crops sector. This relative increase is especially large in Ethiopia in the grains and crops sector. The output increases (Table 2) substantially outweigh factor demand change in all study countries, reflecting strong technological progress. These economic developments shape the impacts of crop yield changes: on the one hand, sensitivity to changing yields increases as less land is available for food production per capita while, on the other hand, relatively less people draw income from agriculture.

3.1.2. Households effects

As seen from Fig. 4 below, all households in our study countries benefit from the projected GDP increase under SSP2. However, how much a household gains in absolute terms depends strongly on its initial income level and its sourcing. Absolute gains are larger for richer households in all three study countries and, in tendency, decrease with the higher share of agricultural income. The latter can be explained by the fact that the agricultural sectors show more limited output growth (Table 2) such that capital and labor demand in agriculture increase slower compared to the rest of the economy. Households therefore shift capital and labor towards other sectors with higher wages and returns to capital. This reallocation comes, however, at the cost for the households that remain in the agricultural sector, as a specialization into a shrinking sector implies lower income increases. The negative impact of a specialization into agriculture is true for all household types in Vietnam and Ethiopia, while in Bolivia this is not entirely true for the lower income households (I30 and I70), as for them the A70 households benefit most over time instead of A30. In fact, for I30 the household type A30 also gains slightly less than A100 in this income group. Furthermore, for the rich households (I100) in Bolivia the welfare gain strictly

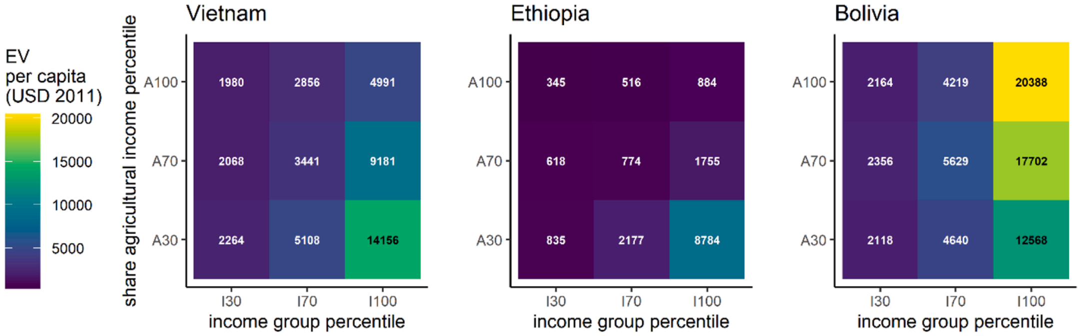

Fig. 4. Absolute welfare (EV) change in USD per capita up to 2050 by household type and study country. Source. Model simulations.

increases with increasing share of agricultural income, such that A100 benefits most.

One reason for the lower EV over time for farmers (A100) compared to the other household types is the absolutely lower change in real total income for these households (Table 3). The absolute increase in factor income is lower for these households as they have a lower factor income from capital compared to other households (Table 3). Factor income stemming from capital increases most until 2050, reflecting the strong capital accumulation mentioned before in Section 3.1.1. This benefits households with a higher initial share of capital income. Thus, the income of non-agricultural households, that tend to have larger shares of income from capital, increases in absolute terms more than for other households. In Bolivia, the divergent total real income changes (higher increases for richest agricultural household) also explains the deviations in the EV change over time. Here, land endowment is very unequally distributed across households. According to the Agricultural Census in 2013 of the National Institute of Statistics (INE = Instituto Nacional de Estadística) in Bolivia, more than 50% of the agricultural land is cultivated by less than 1% of the total numbers of farms (INE, 2015). Thus, the agricultural household types (especially the richest agricultural household type) collect almost all factor income from land, benefitting strongly from land price increases. This overcompensates for lower capital endowments and results overall in a higher income increase over time. Furthermore, the richest agricultural household type has further important income sources, especially its income shares from skilled labor exceeds the ones of other agricultural household types in Bolivia. In the other countries, the highest income shares from skilled labor are found in the A30 household types, instead. This results in the inverted increase of income in Bolivia, increasing most for A100 and least for A30, which explains the divergent EV change pattern. Similar reasoning applies to a smaller extent also to the other household types that show exceptional behavior.

The difference in income also results in different expenditure shares. In Ethiopia, the households' income is lower compared to Vietnam and Bolivia (Table 4), such that the share of income spent on food remains on average largest. In all three study countries, the share decreases on average over time, making them all less vulnerable to price increases for food. Farmers (A100) have in tendency a lower income, which leads to higher expenditure shares for food compared to other household types in all three study countries. Farmers in Bolivia do not always have the highest share of expenditure for food as their income is higher compared to other households.

Household demand per capita increases over time for all commodities on average, by 358%, 781% and 458% in Vietnam, Ethiopia and Bolivia, respectively. In contrast, the value of the demand for food increases only by 34% in Vietnam, 162% in Ethiopia and 125% in Bolivia. Decreasing demand for grains and crops is observed on average only in Vietnam, while demand for processed food increases on average in all three study countries. Comparing all food products, the demand for meat and livestock products increases in all three study countries at the strongest rate being about twice as high as for processed food products on average, reflecting the development of the economic output increase described in Section 3.1.1. In Ethiopia and Vietnam, the agricultural households (A100) always change demand less than the other households in the same income group. In contrast, in Bolivia this observation holds for the non-agricultural households.

3.2. *Climate change effect*

3.2.1. *Economy wide impact*

The *bau_CC* scenario reveals that, up to 2050, impacts of macro-economic growth outweigh by far the effects of climate change induced yield shifts. The latter reduce GDP per capita by less than 0.01% on global average and at most by 0.8% in the three study countries compared to the baseline scenario in 2050. The importance of the agri-food sectors also remains mainly unchanged. Thus, the simulated climate change effects on crop yields generate only slight feedbacks in aggregated indicators for the overall economy. The production of livestock increases globally (+0.1%) through the climate change induced yield shifts, whereas the production of grains and crops (-0.4%) and processed food (-0.2%) shrinks. In the three study countries, the output of all three sectors declines, with Vietnam showing the largest reduction. As expected, the production of crops with positive yield shifts tends to increase and vice versa, leading, for instance, to an increase of the wheat production in Bolivia. Prices for grains and crops increase globally (+2%) and in the three study countries (+4% in Vietnam, +1% in Ethiopia, +3% in Bolivia). For single crops, price increases can be more substantial, as for instance for sugar cane and beet in Ethiopia (+8%). Prices for crops with positive yield shifts tend to fall.

Import dependency increases for grains and crops both globally and in Vietnam and Ethiopia, whereas in Bolivia it decreases. For

Table 3

Real total and factor income changes per capita in USD, by household type and country over time.

		Real total income change								
	average	I30_A30	I30_ A70	I30_A100	I70_ A30	I70_A70	I70_ A100	I100_A30	I100_A70	I100_A100
VNM	5653	2720	2556	2483	5630	3900	3304	15,068	9809	5405
ETH	1500	934	762	502	2402	893	633	9085	1861	936
BOL	6845	2481	2710	2564	4968	6038	4614	11,851	17,489	19,905
		Factor income change								
	average	I30_A30	I30_ A70	I30_A100	I70_ A30	I70_A70	I70_ A100	I100_A30	I100_A70	I100_A100
VNM	1644	300	257	271	1564	922	672	5640	3554	1704
ETH	483	209	147	50	772	287	167	3245	696	317
BOL	2327	377	479	506	1468	1948	1457	4485	6953	8408

Remark: VNM = Vietnam, ETH = Ethiopia, BOL = Bolivia. *Source: Model simulations*

Table 4
Real income per capita in 2050 in USD, by household type and country.

		Real total income								
	average	I30_A30	I30_ A70	I30_A100	I70_ A30	I70_A70	I70_ A100	I100_A30	I100_A70	I100_A100
VNM	7106	3193	3149	3014	6886	5140	4470	18,517	12,282	7975
ETH	1824	1065	915	646	2639	1162	903	9827	2381	1466
BOL	9010	3204	3481	3234	6590	7625	5900	16,005	21,354	25,074

Remark: VNM = Vietnam, ETH = Ethiopia, BOL = Bolivia. *Source. Model simulations*

single crops, import changes follow the exogenous yield shifts as they counterbalance the resulting domestic production impacts. In Vietnam only, an increase in import dependency is visible for livestock and meat production. Likewise, in Vietnam, exports relative to production are reduced most in all three agri-food sectors, while this relation increases in Ethiopia for grains and crops and processed food.

Negative yield shifts trigger cropland expansion and thus render land scarcer. Overall, the three study countries show small expansions about 0.1%. The area allocated to crops varies in accordance with the yield shock and trade changes. For instance, cropland used for plant based fiber decreases in Vietnam, while production increases as the positive yield shift (1.8%) allows to produce more on the same area.

Overall, global factor demand remains unchanged while it slightly decreases through climate change in Vietnam and Bolivia, and slightly increases in Ethiopia. In contrast to the other two agri-food sectors, in the grains and crops sector factor demand increases on average in the study countries and globally. In this sector, the percentage increase is lowest in Vietnam compared to the other study countries and to the global average, as in Vietnam demand for all other factors than land decreases. In Ethiopia (0.3%) and Bolivia (0.4%), the lowest increase in demand occurs for land in this sector. Factor prices decrease in all regions on average. However, as land gets scarcer, it is the only factor that faces increasing prices in the grains and crops sector through climate change, besides unskilled labor in Ethiopia of which prices increase by 0.1%.

3.2.2. Household effects

The difference between the baseline and the *bau_CC* scenario reveals that the climate change impact on yields leads on average to a welfare loss for households in all three study countries. The highest losses on average per capita are visible for households in Vietnam (-43 USD), followed by Bolivian households (–22 USD), while Ethiopian households lose on average less (-4 USD). This ranking persists also when comparing single household types between countries. Large variances within one country can emerge when comparing the effect on single household types, as shown in Fig. 5. However, all study countries reveal the same pattern, namely that the higher the share of agricultural income is in the total income, the lower is the projected loss resulting from climate change. Conversely to Vietnam and Ethiopia, in Bolivia the household type that already showed the highest positive effect over time in the baseline (I100_A100) even benefits (+108 USD) from the yield shift. Apart from this, in most cases the absolute welfare loss is higher for richer households in all three study countries. The household type I100_A70 in Bolivia (-42 USD) and I100_A30 in Vietnam (-82 USD) and Ethiopia (-9 USD), respectively, faces overall the highest EV reduction.

These differences in EV result, inter alia, from changes in household's factor returns. In contrast to the EV, factor returns slightly increases on average per capita in Ethiopia (+0.1%), while it decreases in Vietnam (-0.6%) and Bolivia (-0.2%). Similar to the EV, factor income change rises with increasing agricultural share at constant income per capita level, see Table 5. In fact, it increases most for farmers (A100) or decreases least in all three study countries compared to the other households in the same income per capita quantile. This is because factor returns to land increase through climate change, while other returns that are most relevant for non-agricultural households tend to decrease overall. Land rents increase through climate change, as demand for food is rather inelastic such that overall demand for food adjusts only slightly, even if production costs rise. The fact that households in Vietnam face comparably larger absolute welfare losses than the same household types in the other study countries can be explained by lower increases in factor returns to land and, as a result, higher factor income reductions. As mentioned in the baseline run, the Bolivian

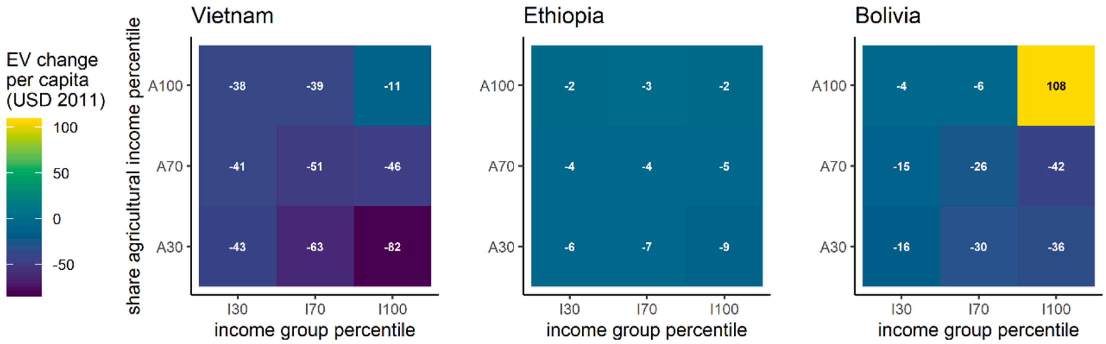

Fig. 5. Absolute welfare (EV) change through climate change in 2050 in USD, by household type and study country. Source: Model simulations.

Table 5
Absolute change in factor income per capita in USD through climate change by household and country.

	average	I30_A30	I30_ A70	I30_A100	I70_ A30	I70_A70	I70_ A100	I100_A30	I100_A70	I100_A100
VNM	−16	−3	−2	0	−16	−9	−1	−66	−30	−4
ETH	0	0	0	0	−1	1	1	−5	1	2
BOL	−7	−2	−1	5	−8	−7	10	−24	−30	48

Remark: VNM = Vietnam, ETH = Ethiopia, BOL = Bolivia. *Source: Model simulations.*

household type I100_A100 owns a very large share of the land, which results in an overall EV rise through climate change. For this household type the benefits from the land price increase are not offset by higher spending on foods, due to its high income and the resulting low share spent on food. Households with higher per capita income and the same share of agricultural income face more negative factor income changes in absolute terms. Hence, as for the EV, the household types I100_A30 in Vietnam and Ethiopia, and I100_A70 in Bolivia face the largest reduction in factor income through climate change. The exceptional outcome of household type I100_A70 reflects reduced factor returns to capital which are its main source of income.

Average demand per capita decreases in all three study countries. The demand for the agri-food products is reduced through climate change. In Ethiopia and Bolivia, overall demand increases for some A100 households only, while their demand for agricultural products decreases. These households are thus able to consume more from other sectors, whereas the other households consume overall less. Induced by price increases for all three agri-food sectors, the expenditure shares for grains and crops, livestock and meat, and processed food remain nearly unchanged on average through climate change, despite the overall demand decrease.

Setting the absolute welfare loss in 2050 expressed by the EV in USD in relation to the total real income deflated by the GDP price index under the baseline scenario in 2050 (Fig. 6) shows that richer households, despite higher absolute EV changes, lose less relative to their income. In all income groups, agricultural household types are never the most affected ones. In contrast, mainly non-agricultural (net food buying) households (A30) are identified as most vulnerable to yield shocks. This shows decreasing vulnerability with increasing agricultural share of income. It results from the higher absolute EV change for non-agricultural households combined with decreases in real income per capita. In contrast, A100 households face lower absolute EV changes and slightly increasing real incomes per capita. As an exception, in Ethiopia, two of the three A70 household groups are the most affected households, namely in the I70 and I100 income quantile, while then the A100 households are the second most affected. The A30 household in Ethiopia is considerably richer than the other households in the I70 and I100 quantiles (see Table 4), which leads albeit the absolute highest EV change (see Fig. 5) to the lowest relative importance. Hence, besides this, farmers face mostly the lowest relative effect. The rich agricultural household in Bolivia is the only household type showing welfare gains, due to its positive absolute EV change and the increase in real income, reflecting a high income share from land combined with a low expenditure share for food.

Additionally, the shares that each household represents in the total population are relevant for the interpretation of the distribution of the welfare changes (see Table 1). For instance, the household that gains from climate change (I100_A100) represents only 2.4% of the Bolivian population in 2050, while the household type that loses most relative to their initial consumption (I30_A30) represents 11.4% of the total population. Similarly, in Vietnam, the poor (I30) household types represent in sum about 38% of the population, such that the most affected encompass more than one third of the population. In Ethiopia, the relatively most affected household type encompasses 6.5% of the population.

3.3. *Comparative static analysis*

Existing studies analyzing climate change induced yield shift introduced the resulting crop productivity changes in a comparative static setting, i.e. into the currently observed global economy. In order to highlight the contribution of our long-run perspective presented in the previous section, we also conduct a comparative static analysis where population, GDP, demand and production pattern reflect a snapshot of the global economy in 2011. As expected, the comparative static analysis shows that, on average,

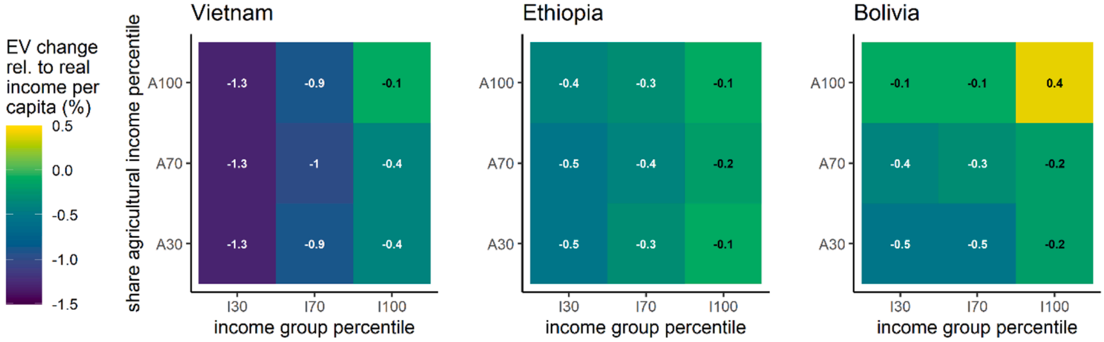

Fig. 6. Absolute welfare (EV) change in 2050 (bau_CC) relative to the real income in 2050, by household type and study country. Source: Model simulations.

households would face a welfare loss if the cumulative yield changes through climate change up to 2050 would instead happen immediately. However, size and order of welfare changes by household type partly differs from the dynamic analysis. The household type that gained from the simulated climate change effects in Bolivia (I100_A100) in the dynamic assessment faces a welfare loss in the comparative static case, see Fig. 7. In addition, the I30_A70 household now loses more than the I30_A30 in Vietnam. Besides this, the direction of welfare changes and the ranking of households are unchanged from the dynamic analysis and show again that absolute losses in EV are higher for richer households and, in tendency, lower for agricultural households. For Bolivia, the divergent results from this general pattern also found in the long-run analysis, are again observed under the comparative static analysis. However, absolute changes in EV under a comparative static setting are considerably smaller than in the recursive dynamic analysis for all household types.

The trend of decreasing relative EV change with increasing agricultural income share is also observed here (Fig. 8) as absolute and relative EV show the same trend in the comparative static analysis (besides I30_A70 in Vietnam). Thus, it would also result in an identification of non-agricultural households as more vulnerable than others, besides in Bolivia where the A70 household is always most affected. The comparative static analysis does not show that the effect decreases with increasing income per capita, as also many I70 households are among the most affected when comparing households with the same agricultural share on income.

In comparison to the dynamic assessment, the relative EV changes are smaller for most households in the comparative static analysis, i.e. it might underestimate the economic importance of these yield shifts. This might come at a surprise given a decreasing weight of the agri-food sector in the global economy over time, considered in the dynamic analysis. Only some (rich) households, especially in Bolivia, show higher relative effects under a comparative static setting, as summarized in Table 6.

However, the comparative static analysis cannot consider that the income of the different household types changes at a different pace over time, depending on their respective income sources, which can make households over time relatively more or less vulnerable. Therefore, especially for poor non-agricultural households, the welfare effect is thus underestimated in the comparative static analysis, while for rich households it is overestimated compared to the recursive dynamic approach. Since the comparative static analysis does not consider GDP growth over time, the importance of the agricultural sector is larger in all three study countries than in the dynamic analysis while total factor productivity remains unchanged. The latter causes overall prices to be higher than in the dynamic analysis. Additionally, income remains at 2011 level and thus lower than the 2050 income level, resulting together with the higher prices in larger agri-food expenditure shares. For some household types, especially in Ethiopia, the shares are twice as high as in the dynamic analysis in 2050. As income over time increases most for non-agricultural households, their income shares for grains and crops show the largest positive difference in the comparative static analysis. Hence, the prices of agri-food are still of larger importance for these households in a comparative static setting. Only the two household types in Ethiopia that have a higher relative negative effect (Table 6: I70_A30 and I100_A30) spend less on grains and crops in the comparative static analysis than in the dynamic analysis. In terms of their real income per capita, they lose substantially more than other households, as private transfers sent to both households decline through climate change and their factor income decreases. This effect can be explained by decreasing returns to capital, which is the main income source of these two household types. Thus, also the slight increase in factor returns to land does not compensate the loss of these households, as it does for all other (A70 and A100) households.

In contrast to the dynamic analysis, factor returns to land decrease through climate change in Vietnam and Bolivia as less pressure (also demographic) is on land and more land is still available, making it less scarce, such that land price changes are more muted. In both countries, this results together with the stronger decreasing returns to capital in a relatively higher reduction in factor income for all households. In Vietnam, it decreases percentagewise largest for all rich households. Together with the large EV change this leads to the higher relative effect compared to the dynamic analysis. Since, in Bolivia also factor returns to land decrease for all households, the agricultural households' factor income declines through climate change. As they already had lower income levels on average per capita compared to the other households in the same income quantile, the reduction leads to a relatively higher EV change than in the dynamic analysis, where their income increases. Increases in factor returns over time in the dynamic analysis result in strong income growth for the agricultural household types (A100) and also for type I70_A70, and I100_A30 and A70. Thus, the EV change is of higher relative importance in the comparative static analysis, even if it is absolutely lower, due to the lower real income per capita underlying in the static analysis, as this income rise is not considered.

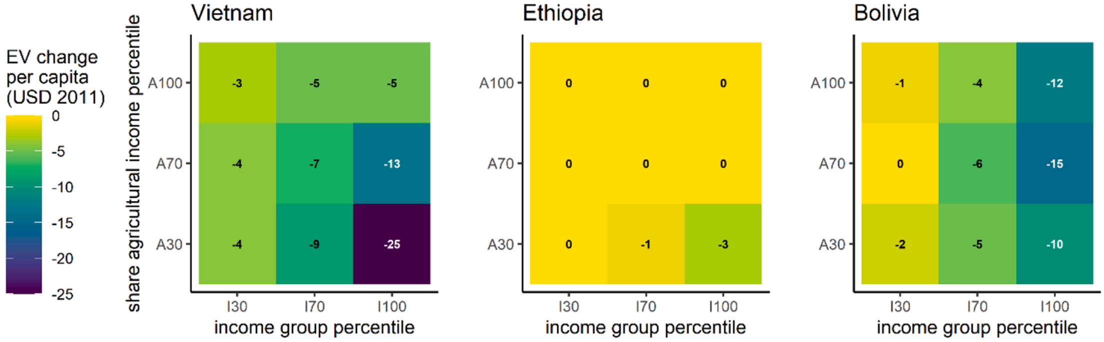

Fig. 7. Absolute welfare (EV) change in USD in the comparative static analysis by household type and study country. *Source: Model simulations.*

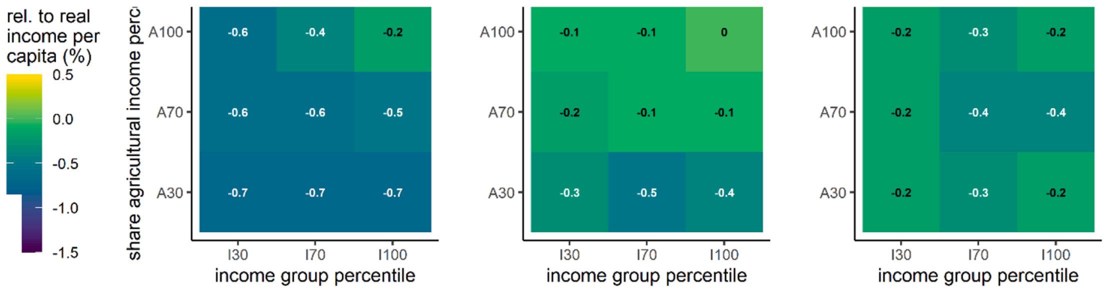

Fig. 8. Absolute welfare (EV) change relative to the real income in 2011, by household type and study country. *Source: Model simulations.*

Table 6
Absolute difference in relative EV change between the comparative static and recursive dynamic analysis, by household type and country.

	average	I30_A30	I30_ A70	I30_A100	I70_ A30	I70_A70	I70_ A100	I100_A30	I100_A70	I100_A100
VNM	−0.02	−0.6	−0.68	−0.69	−0.18	−0.42	−0.48	0.28	0.16	0.05
ETH	−0.09	−0.25	−0.32	−0.28	0.2	−0.27	−0.24	0.29	−0.12	−0.11
BOL	0.03	−0.32	−0.21	0.09	−0.12	0.08	0.22	0.02	0.18	0.67

Remark: VNM = Vietnam, ETH = Ethiopia, BOL = Bolivia. *Source: Model simulations*.

3.4. *Sensitivity analysis*

The two additional scenarios developed for the sensitivity analysis generally support the previous results of the economic development change induced by climate change. The *mod_CC* scenario results often into a slightly stronger effect than the *bau_CC* in the study countries while the *str_CC* scenario provokes the strongest effect on economic indicators. Here, it is recalled, that the yield shocks displayed in Fig. 2 are not always in a linear order from *mod_CC* (RCP4.5) to *bau_CC* (RCP6.0) to *str_CC* (RCP8.5) for all regions and crops.

3.4.1. *Household effects*

The *mod_CC* and *str_CC* scenario result on average in household welfare losses compared to the baseline, which are higher in both scenarios than in the *bau_CC* scenario in Vietnam and Ethiopia, while they are only larger on average in the *str_CC* scenario in Bolivia. More precisely, comparing the single household types between the scenarios shows that the *mod_CC* scenario results in a lower welfare loss only for household I100_A100 in Vietnam and all I100 households in Ethiopia. In Bolivia, only the (poor) non-agricultural households (I30_A30, I30_A70 and I70_A30) lose more of their welfare. As in the *bau_CC* scenario, households with a higher share of agricultural income face lower welfare reductions in the sensitivity scenarios. Again, the exception among the I100 households in Bolivia emerges, so that household type I100_A30 is better off than I100_A70. Furthermore, in the *mod_CC* not only the I100_A100 household gains but also the I70_A100 household faces a welfare gain. In the *str_CC*, in addition household I30_A100 increases its welfare.

The *mod_CC* yield shock is more negative for 4 of the 8 crop aggregates in Vietnam (see Fig. 2), explaining the reduction in EV compared to the *bau_CC* scenario. The decrease in total real income exceeds on average and for all non-agricultural households under the *bau_CC* scenario. Thus, most households increase expenditure for the agri-food sectors due to higher prices, an effect which is negligible or even reversed only for a few households.

In Ethiopia, the yield shock under *mod_CC* is less negative for all crop aggregates but cereal grains nec, which decreases by 2.1 percentage points. This aggregate includes main staple crops of Ethiopian diets such as maize and sorghum, which remain besides ‘vegetables, fruits and nuts’, and ‘food products nec’ the agri-food products that are most demanded in 2050. Given the large demand, the price increase (+5%), which is considerably stronger than for all other crops, affects household expenditure visibly. Even if factor income rises for all households, improving their real income compared to the *bau_CC* (besides A30 households), nearly all households increase their expenditure for grains and crops in both scenarios, while for meat it is mainly reduced. The discussion underlines the importance of a disaggregated analysis of several food products, as staple crops matter more in poorer countries and household groups and can be differently affected by climate change.

Poor non-agricultural households and the I70_A30 lose more in the *mod_CC* than in the *bau_CC* scenario in Bolivia. This is caused by increasing prices for most crops compared to the *bau_CC* scenario. This increase lets poor non-agricultural households increase their expenditure share for grains and crops, and processed food more than in the *bau_CC* scenario. Whereas, the majority of the households change expenditure for food like in the *bau_CC* scenario, especially for meat. Agricultural households slightly lower their food expenditure because of their increasing income. For richer households, price increases in grains and crops are of less importance as they consume more processed food and livestock.

Setting the EV change in relation to the real income of each household type in 2050 shows in both scenarios mainly the same effects as in the *bau_CC* scenario. In Ethiopia, some deviations from the *bau_CC* arise in both additional scenarios, as among the poorest households (I30), the A70 household is most vulnerable, followed by the A30 household. The same is observed among the I100 households, opposite to the *bau_CC* scenario. In Vietnam and Ethiopia, all households are worse off in the *mod_CC* and the *str_CC*, besides rich households which partly face an absolute welfare gains in the *mod_CC* scenario (Vietnam: I100_A100 and Ethiopia all I100). In Bolivia, in both scenarios, some households are better off and others are worse off compared to the *bau_CC*. On average though, in the *mod_CC* households are better off, while in the *str_CC* they are worse off.

4. Discussion

The baseline constructed using the SSP2 data for GDP and demographic developments are in line with Popp et al. (2017). Most prices for agricultural products fall in the baseline until 2050. Furthermore, the trade with agricultural products increases in the baseline as also found in their analysis. Similarly, the authors find additional cropland to result from conversion of unmanaged forest, which is also found in our study. The locations of cropland expansion are similar in both analyses, being largest in Latin America and Africa. Consequently, our results show similarities with the Fricko et al. (2017), who study SSP2 developments. They find livestock demand to increase globally which can also be seen here, as production and consumption increase.

The effect of the yield shift induced by climate change on different household groups are similar to results found by previous studies. Hertel et al. (2010) analyze the agricultural impacts of climate change in 2030 on global commodity prices, national economic welfare, and the incidence of poverty of 7 household strata in 15 developing countries in the economic setting of 2001. The effects are simulated using the static GTAP model, by including low, medium, and high productivity shifts for six commodities in the developing countries and the rest of the world by 2030. The authors determine costs of living and earnings as two channels of poverty impacts. Thus, increasing food prices result in falling poverty rates for households specialized in agriculture and rising rates for non-agricultural households (especially urban wage earners). This is in line with our results, where farmers are absolutely less affected through climate change. Similarly, our results align with Skjeflo (2013), who simulates the importance of access to the markets on household vulnerability to climate change in 2000 in a CGE model for Malawi by inducing productivity shocks and an exogenously adjusted global price for maize from 2030. Skjeflo (2013) finds that large farms with access to markets can actually benefit from the yield reduction through increased maize prices. According to her analysis, urban poor and small-scale farmers are most vulnerable. This is because these households do not exploit increasing returns to land and agricultural labor while they have high expenditures for food and face increasing food prices. This is in line with our results of the dynamic analysis that show that some farmers even gain, and the other agricultural households at least lose less than the other households in their income group. While the analysis by Skjeflo (2013) is focused on Malawi only, our study assesses further countries, applying country specific climate change shocks with global coverage. Thus, our analysis verifies that the patterns are transferable to other LICs and LMICs. However, the size of the effects deviates from our analysis, our findings being considerably smaller in both the comparative and the recursive dynamic analysis. Differences emerge inter alia as the price and yield shocks are higher in Skjeflo (2013) and the EV is calculated relative to the initial household expenditure while we use the total real income. Hallegatte and Rozenberg (2017) study the effects of climate change on households in 92 countries using a bottom up approach (microsimulation). The analysis is based on SSP4 and SSP5 upon 2030. Hallegatte and Rozenberg (2017) find that impoverished people are relatively more affected than the population average and that alleviate poverty is a good way to reduce future impacts. However, they name as a limitation of their study that they do not consider investments and trade. The latter is identified by Xie et al. (2019) to have a large impact on food security (especially if distorted) as it transmits price signals.

The sensitivity analysis shows that the results are robust and that not only the severity of the yield shock matters but also which crops are affected. Hirvonen et al. (2015) find that cereals account on average for 60% of the energy intake of Ethiopian households. Thus, the small variety of staple crops in their diets makes Ethiopian households especially vulnerable to the yield shock. This is in line with Aksoy and Isik-Dikmelik (2008), who state, that a more diverse food basket decreases vulnerability to price changes. Since, this increases substitutability and flexibility to adjust.

For the assessment, we used a recursive dynamic CGE model which depicts adoption processes in the long term and reflects changes in demography and income, along with some core structural change processes. However, projecting possible future scenarios requires various assumptions strongly shaping baseline outcomes, but linked to uncertainties (Dellink et al., 2020). Elasticities and regressions build on data from past years and might not account for all potential future behavioral changes (Bijl et al., 2017). Still, the applied model reflects the state-of-the-art in this field by depicting important dynamic development processes in the overall economy and at household level (as discussed in Section 2).

The integration of yield shifts as the only impact of climate change on the agricultural sector in the model misses other potential impact channels of climate change in the agri-food nexus. Consequences on health, migration and food security stemming from catastrophic climate change events such as extreme weather events, weed and disease pressures, tropospheric ozone, and sea-level rise, are not captured in our model assessment. Catastrophic climate change events might exacerbate losses in land productivity, as pointed out by FAO (2018). For instance, sea-level rises could affect arable land near coastlines. Thus, better quantification of impacts on crop yields and including more climate change impacts such as for instance sea level rise (see Nauels et al. (2017)) will improve the representation of climate change in this analysis. In our simulation, this could be especially relevant for Vietnam as a country with long sea borders. Furthermore, rising temperatures might decrease labor productivity especially in the agricultural sector, as this work is carried out mainly on the field, exposed to the weather (Kjellstrom et al., 2009).

We assess average yields over a year. However, interannual scarcities in crops as, for instance, before each harvest (Vaitla et al., 2009) are also of large importance for vulnerability. Similarly, local differences in yields among regions in a country can result in differentiated effects for households depending on their residence. Wossen et al. (2018) find poor households to be especially vulnerable to price and climate variability, aggravating poverty and inequality, in their assessment for Ethiopia and Ghana. Likewise, Ahmed et al. (2009) determine urban employees to be most vulnerable to volatile climatic events and Ahmed et al. (2011) find overall large increases in Tanzanians poverty if precipitation gets more volatility. Furthermore, climate variability increases uncertainty. Nevertheless, we do not consider risk and risk behavior of firms which could especially in LICs play a crucial role in production decisions under climate change and how this affects markets, and households' income. We assume that land is owned by households working in agriculture. This ignores the actual institutional settings in different countries, which make households owning property rights to land benefit from increases in land rents rather than those producing with this factor. However, for instance, in Vietnam, the percentage of households that rented out (some of) their land between 2008 and 2016 averaged only 21% and 16% for female and male headed households, respectively. Of this total land rented out, 44% (female headed) and 54% (male headed) were even rented out for free (Ayala-Cantu and Morando, 2020). Renting land for production plays a minor role in Bolivia, where only about 1.4% of the land is rented and 0.4% is lend in exchange of a share of the production (INE, 2015). In Ethiopia, land rental is restricted by a law implemented in 2006 which does not allow to rent out more than 50% of the household's land (Holden and Ghebru, 2016). Yet, many households rented out more than the allowed share of their land in 2010, as sharecropping is the predominant rental concept that the households did not consider to be covered by the law (Holden and Ghebru, 2016).

We assume complete access to the market for all households. The underlying household data is built such that goods are accounted for as income (based on the market price of the products), which is then spent on these goods, even if they are produced for own consumption. Thereby, we assume that all goods dedicated to consumption are sold and bought from the market. In case of subsistence farmers, the interpretation of our results can thus be misleading. In reality, for subsistence farmers with no access to markets, a negative yield change would directly affect the amount harvested while they do not benefit from increasing prices, threatening their food security. The number of small-holders makes up about 75%, 88% and 93% in Ethiopia, Vietnam and Bolivia, respectively. The share of agricultural products sold from these farms equals on average 21%, 47% and 34%, respectively, in the years the surveys were conducted (FAO, 2017b), illustrating especially the higher share of subsistence farmers in Ethiopia and Bolivia. Furthermore, catastrophic events can reduce food availability as transport is distorted impeding households from selling or buying products (Ziervogel and Ericksen, 2010). Additionally, pressure on land can be raised through land-based mitigation efforts (Doelman et al., 2018) affecting the wellbeing of households. We refrain from including mitigation and adaptation strategies and their consequences in order to focus on an unmitigated shock on crop yields. Due to data availability, the Ethiopian households represent mainly rural households, thus urban households are underrepresented for this study country. However, according to the census 2007, more than 83% of the population lived in rural areas (CSA, 2008). In 2019, it was still 79% of the population according to World Bank (2020), such that this survey still represents a large part of the population.

This study provides new insights in the context of vulnerability assessments of households regarding climate change effects. The sole assessment of the effects on macroeconomic indicators (GDP) can be misleading, as its response to the limited crops yield shocks is small. Previous assessments which have considered households level effects of yield shifts used mainly comparative static modeling frameworks. However, for such climate change assessments the demographic dynamics are of large importance as over time consumption patterns change and the importance of agricultural sectors decrease. Furthermore, pressure on land increases and thus mitigation options are reduced, and intensification potentials decrease. In addition, income develops differently over time depending on the source of income, determining vulnerability. This study determined again the importance of disaggregation of different household types, as on average all households lose through climate change, which does not represent the variances between household types and would not reflect that some even gain from climate change. Yet, this is important to target climate change vulnerability policies to the households most in need.

5. Summary and conclusion

We assess the effects of yield shifts induced by climate change on low and lower-middle-income countries in terms of the economic changes (production, trade, demand) and of the welfare of nine household types distinguished by level and source of income in 2050. To this end, we apply a recursive dynamic CGE model with household detail, which draws on the SSP2 projections for GDP per capita, population and workforce data, and include yield shifts for 8 crop aggregates. Additionally, we perform a sensitivity analysis to test the robustness of the results, considering the uncertainty of the effects of the climate change on yields and a comparative static analysis to disentangle the difference to our dynamic long run model. The results show that effects vary between the nine household types and that not only the level of income is of relevance for the vulnerability to climate change but also the factor endowment. We show that agricultural households are both absolutely and relative to their income in most cases the least affected ones and that richer households face absolutely larger effects; while relative to their income the poor are the most affected. The sensitivity analysis shows that results are robust and that the yield shock on the staple crops largely determine the effect on the households (especially for the poor).

Thus, it is important to disaggregate the yield shifts and different household types and to take not only income levels, but also other aspects such as agricultural income share into account. Various studies have identified that higher food prices can benefit agricultural households. In addition, our modeling framework gave new insides, especially into the long run development. It shows both under- and overestimations of vulnerability for some household types in a comparative static analysis with an otherwise identical model set-up. This is a consequence of missing key dynamic developments in comparativestatics, such as varying importance of sectors, sector specific productivity growth, and income dependent consumption change.

Our results stress the need for a differentiated assessment of climate change impacts, considering regional and household differences. The results, even if limited to three countries and to nine household groups, emphasize quite divergent income impacts of climate change induced yield shifts across households, with ownership to land as one key determinant. Across countries, consequences were found to be comparable, while remaining differences show the need for country- and household-specific strategies and support, considering regional priorities for mitigation and land reforms.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research has recieved funding by the Funding Priority “Bioökonomie als gesellschaftlicher Wandel” of the Bundesministerium für Bildung und Forschung (BMBF, Federal Ministry of Education and Research) under the project “BEST: Bioökonomie in Europa und SDGs: Entwicklung, Beitrag, Trade-offs” (grant no. 031B0792B).

References

Aguiar, A., Narayanan, B., McDougall, R., 2016. An overview of the GTAP 9 data base. J. Global Econ. Anal. 1 (1), 181–208. https://jgea.org/resources/jgea/ojs/index.php/jgea/article/view/23.

Ahmed, S.A., Diffenbaugh, N.S., Hertel, T.W., 2009. Climate volatility deepens poverty vulnerability in developing countries. Environ. Res. Lett. 4 (3), 8. https://doi.org/10.1088/1748-9326/4/3/034004.

Ahmed, S.A., Diffenbaugh, N.S., Hertel, T.W., Lobell, D.B., Ramankutty, N., Rios, A.R., Rowhani, P., 2011. Climate volatility and poverty vulnerability in Tanzania. Global Environ. Change 21, 46–55. https://doi.org/10.1016/j.gloenvcha.2010.10.003.

Aksoy, M.A., Isik-Dikmelik, A. 2008. Are low food prices pro-poor? Net food buyers and sellers in low-income countries. The World Bank. https://openknowledge.worldbank.org/handle/10986/6660.

Armington, P.S., 1969. Theory of demand for products distinguished by place of production. IMF Econ. Rev. 16 (1), 159–178. https://doi.org/10.2307/3866403.

Ayala-Cantu, L., Morando, B., 2020. Rental markets, gender, and land certificates: Evidence from Vietnam. Food Policy 94. https://doi.org/10.1016/j.foodpol.2020.101842.

Bijl, David L., Bogaart, Patrick W., Dekker, Stefan C., Stehfest, Elke, de Vries, Bert J.M., van Vuuren, Detlef P., 2017. A physically-based model of long-term food demand. Global Environ. Change 45, 47–62. https://doi.org/10.1016/j.gloenvcha.2017.04.003.

Bockstael, N.E., McConnell, K.E., 1980. Calculating equivalent and compensating variation for natural resource facilities. Land Econ. 56 (1), 56–63. https://doi.org/10.2307/3145829.

Britz, W. 2019. CGEbox – a flexible and modular toolkit for CGE modelling with a GUI, Institute for Food Resource Economics, University Bonn. Available at: http://www.ilr.uni-bonn.de/em/rsrch/cgebox/cgebox_GUI.pdf.

Britz, W., van der Mensbrugghe, D. 2018. CGEBox: A Flexible, Modular and Extendable Framework for CGE Analysis in GAMS, J. Global Econ. Anal. 3(2): 106–176. https://doi.org/10.21642/JGEA.030203AF.

Britz, W., Roson, R., 2019. G-RDEM: A GTAP-based recursive dynamic CGE model for long-term baseline generation and analysis. J. Global Econ. Anal. 4 (1), 50–96. https://doi.org/10.21642/JGEA.040103AF.

Britz, W., Roson, R., Sartori, M. 2019. SSP Long Run Scenarios for European NUTS2 Regions. University Ca'Foscari of Venice, Dept. of Economics Research Paper Series No, 22.

Central Statistical Agency of Ethiopia (CSA). 2008. Population and Housing Census Report-Country – 2007. Addis Ababa: CSA.

Cohen, M.J., Garrett, J.L., 2010. The food price crisis and urban food (in)security. Environ. Urban. 22 (2), 467–482. https://doi.org/10.1177/0956247810380375.

Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environ. Change 42, 200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004.

Dellink, R., Van der Mensbrugghe, D., Saveyn, B. 2020. Shaping Baseline Scenarios of Economic Activity with CGE Models: Introduction to the Special Issue. J. Global Econ. Anal., 5(1): 1–27. https://doi.org/10.21642/JGEA.050101AF.

Deressa, T., Hassan, R.M., Ringler, C. 2008. Measuring Ethiopian farmers' vulnerability to climate change across regional states. IFPRI Discussion Paper 00806.

Doelman, J.C., Stehfest, E., Tabeau, A., van Meijl, H., Lassaletta, L., Gernaat, D.E.H.J., Hermans, K., Harmsen, M., Daioglou, V., Biemans, H., van der Sluis, S. and van Vuuren, D.P. 2018. Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation, Global Environ. Change 48: 119–135. https://dx.doi.org/10.1016/j.gloenvcha.2017.11.014.

Dong, N., You, L., Cai, W., Li, G., Lin, H., 2018. Land use projections in China under global socioeconomic and emission scenarios: Utilizing a scenario-based land-use change assessment framework. Global Environ. Change 50, 164–177. https://doi.org/10.1016/j.gloenvcha.2018.04.001.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D.L., Obersteiner, Michael, Pachauri, S., Rao, S., Schmid, E., Schoepp, W. and Riahi, K. 2017. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century, Global Environ. Change 42: 251–267. https://dx.doi.org/10.1016/j.gloenvcha.2016.06.004.

Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D.S., Dai, H., Hijioka, Y., Kainuma, M., 2017. SSP3: AIM implementation of Shared Socioeconomic Pathways. Global Environ. Change 42, 268–283. https://doi.org/10.1016/j.gloenvcha.2016.06.009.

FAO - Food and Agriculture Organization, 2017a. Small family farms data portrait. Basic information document. Methodology and data description. FAO, Rome.

FAO - Food and Agriculture Organization, 2017b: Family Farming Knowledge Platform, online: http://www.fao.org/family-farming/data-sources/dataportrait/indicator-details/en/?ind=83450.

FAO - Food and Agriculture Organization, 2018. The future of food and agriculture – Alternative pathways to 2050. Rome. 224 pp.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C. 2010. Food security: the challenge of feeding 9 billion people. Science, 327(5967): 812–818. https://dx.doi.org/10.1126/science.1185383.

Haines, A., Kovats, R.S., Campbell-Lendrum, D., Corvalán, C., 2006. Climate change and human health: Impacts, vulnerability and public health. Publ. Health 120 (7), 585–596. https://doi.org/10.1016/j.puhe.2006.01.002.

Hallegatte, S., Rozenberg, J., 2017. Climate change through a poverty lens. Nat. Clim. Change 7 (4), 250–256. https://doi.org/10.1038/nclimate3253.

Hertel, T.W., Tsigas, M.E. 1997. Structure of GTAP. Global Trade Analysis: modeling and applications, 13–73.

Hertel, T.W., Burke, M.B., Lobell, D.B., 2010. The poverty implications of climate-induced crop yield changes by 2030. Global Environ. Change 20 (4), 577–585. https://doi.org/10.1016/j.gloenvcha.2010.07.001.

Hirvonen, K., Taffesse, A.S., Hassen, I.W. 2015. Seasonality and household diets in Ethiopia, Publ. Health Nutr., 19(10): 1723–1730. https://dx.doi.org/10.1017/S1368980015003237.

Ho, M., Britz, W., Delzeit, R., Leblanc, F., Roson, R., Schuenemann, F., Weitzel, M., 2020. Modelling consumption and constructing long-term baselines in final demand. J. Global Econ. Anal. 5 (1), 63–80. https://doi.org/10.21642/JGEA.050103AF.

Holden, S.T., Ghebru, H., 2016. Land rental market legal restrictions in Northern Ethiopia. Land Use Policy 55, 212–221. https://doi.org/10.1016/j.landusepol.2016.04.006.

Instituto Nacional de Estadística (INE) Bolivia. 2015. Censo Agropecuario 2013 BOLIVIA, La Paz, Bolivia. Available at: https://www.sudamericarural.org/images/en_papel/archivos/CENSO-AGROPECUARIO-BOLIVIA_final.pdf.

International Labour Organization (ILO) 2003. Report II: Household income and Expenditure Statistics, Prepared for the Seventeenth International Conference of Labour Statisticians, Geneva, 24 November.

KC, S., Lutz, W. 2017. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environ. Change, 42: 181–192. https://dx.doi.org/10.1016/j.gloenvcha.2014.06.004.

Keeney, R., Hertel, T., 2005. GTAP-AGR: A framework for assessing the implications of multilateral changes in agricultural policies. GTAP Technical Papers 25.

Kjellstrom, T., Holmer, I., Lemke, B., 2009. Workplace heat stress, health and productivity–an increasing challenge for low and middle-income countries during climate change. Global Health Action 2 (1), 2047. https://doi.org/10.1038/nclimate3253.

Lee, H.L. 2005. The GTAP Land Use Data Base and the GTAPE-AEZ Model: incorporating agro-ecologically zoned land use data and land-based greenhouse gases emissions into the GTAP Framework.

Leimbach, M., Giannousakis, A., 2019. Burden sharing of climate change mitigation: Global and regional challenges under shared socio-economic pathways. Clim. Change 155 (2), 273–291. https://doi.org/10.1007/s10584-019-02469-8.

McDougall, R. and Golub, A., 2009. GTAP-E: A Revised Energy-Environmental Version of the GTAP Model (GTAP Research Memorandum No. 15). In: Global Trade Analysis Project (GTAP). West Lafayette: Purdue University.

McKenzie, G. 1988. Applied Welfare Economics and Frisch's Conjecture, in: Bös, D., Rose, M., Seidl, C. (Eds.), Welfare and Efficiency in Public Economics, Springer Verlag, pp. 1–20. https://dx.doi.org/10.1007/978-3-642-73370-3_1.

Nauels, A., Rogelj, J., Schleussner, C.F., Meinshausen, M., Mengel, M., 2017. Linking sea level rise and socioeconomic indicators under the shared socioeconomic pathways. Environ. Res. Lett. 12 (11) https://doi.org/10.1088/1748-9326/aa92b6.

Pandey, R., Kala, S., Pandey, V.P., 2015. Assessing climate change vulnerability of water at household level. Mitig. Adapt. Strat. Glob. Change 20 (8), 1471–1485. https://doi.org/10.1007/s11027-014-9556-5.

Popp, A., Calvin, K.V., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.-P., Doelman, J.C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K. and van Vuuren, Detlef, P. 2017. Land-use futures in the shared socio-economic pathways. Global Environ. Change, 42: 331–345. https://dx.doi.org/10.1016/j.gloenvcha.2016.10.002.

Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K.V., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D.E.H.J., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M. 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environ. Change, 42: 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Rimmer, M.T., Powell, A.A., 1996. An implicitly additive demand system. Appl. Econ. 28 (12), 1613–1622. https://doi.org/10.1080/000368496327589.

Roson, R., 2019. Sectoral differences in labor productivity growth: Estimation and modeling. Res. Appl. Econ. 11 (1), 1–8. https://doi.org/10.5296/rae.v11i1.14145.

Skjeflo, S., 2013. Measuring household vulnerability to climate change - Why markets matter. Global Environ. Change 23, 1694–1701. https://doi.org/10.1016/j.gloenvcha.2013.08.011.

Vaitla, B., Devereux, S., Swan, S.H., 2009. Seasonal hunger: a neglected problem with proven solutions. PLoS Med. 6 (6) https://doi.org/10.1371/journal.pmed.1000101.

van der Mensbrugghe, D., 2018. The Standard GTAP Model in GAMS, Version 7. J. Global Econ. Anal. 3 (1), 1–83. https://doi.org/10.21642/JGEA.030101AF.

Winsemius, H.C., Jongman, B., Veldkamp, T.I., Hallegatte, S., Bangalore, M., Ward, P.J., 2015. Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. Environ. Dev. Econ. 23 (3), 328–348. https://doi.org/10.1596/1813-9450-7480.

Wossen, T., Berger, T., Haile, M.G., Troost, C., 2018. Impacts of climate variability and food price volatility on household income and food security of farm households in East and West Africa. Agr. Syst. 163, 7–15. https://doi.org/10.1016/j.agsy.2017.02.006.

World Bank. 2020. The World Bank Data. Rural population (% of total population) - Ethiopia https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=ET (last accessed 19.08.2020).

Xie, W., Cui, Q., Ali, T., 2019. Role of market agents in mitigating the climate change effects on food economy. Nat. Hazards 99 (3), 1215–1231. https://doi.org/10.1007/s11069-019-03646-9.

Ziervogel, G., Ericksen, P.J., 2010. Adapting to climate change to sustain food security. WIREs Clim. Change 1 (4), 525–540. https://doi.org/10.1002/wcc.56.