Crops, Conflict and Climate Change*

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Abstract

This paper presents a general equilibrium trade model of heterogeneous households making consumption, land, and labor allocation choices, designed to make income percentile specific predictions of the welfare impact of agricultural shocks. Using household survey data from 51 developing countries the model is used to quantify the welfare consequences of the food price hikes induced by the war in the Ukraine and future climate change. Both repress income and exacerbate inequality. War-induced food inflation reduced real household incomes across developing countries by 2.06% on average, while changes in yields due to climate change will reduce real incomes by 9.72%. The welfare impacts of both shocks vary enormously across the income distribution, with already vulnerable households bearing the brunt of their costs. Poor households are suffering losses that are considerably larger and much more dispersed than predicted by models that do not feature household heterogeneity and rely exclusively on aggregate data.

Keywords: International trade policy, conflict, climate change, welfare, income inequality

JEL codes: F1, F18, O11, O13, Q17

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1 Introduction

Agricultural shocks can have large and highly uneven welfare consequences. Poor households in low-income countries are especially susceptible to these shocks because they depend heavily on agriculture for income and because they spend a large share of their budget on food. Agriculture is risky due to weather variability, crop diseases, natural hazards, and both domestic and international shocks to food markets. These risks are being amplified by conflict and climate change, which are changing yields, disrupting trade, and exacerbating food price volatility.

Quantification of the impact of agricultural shocks on income and inequality is challenging. Since agricultural products are traded globally, a general equilibrium trade model is required to assess how such shocks propagate and impact prices in different countries. In addition, agrarian households make different consumption and farming decisions and these choices, which can be adjusted in response to shocks, modulate the impact of price changes on real incomes. The international trade linkages interact with the heterogeneity in household choices and together they determine how agricultural shocks reverberate through the income distribution. Yet, existing trade models typically do not feature detailed household heterogeneity, and have consequently been largely silent on the distributional consequences of agricultural shocks within countries.

This paper aims to help fill this gap. We develop a discrete choice general equilibrium trade model of heterogeneous households as producers and consumers. As producers, households allocate their land and labor endowments to the production of different crops to maximize profits depending on their land and labor productivity. As consumers, households spend income on crops and products to maximize utility. Our framework captures household-level heterogeneity in labor income, crop sales and consumption allocations, similar to Deaton (1997), but with land supply decisions as in Sotelo (2020) and Costinot, Donaldson, and Smith (2016), and labor supply decisions inspired by Artuc, Chaudhuri, and McLaren (2010). The model is designed to leverage household survey data in order to enable an assessment of the impacts of agricultural shocks across the entire income distribution, as well as to provide more accurate measurement of the aggregation of those impacts than offered by representative agent models.

We exploit two major crises with global implications, notably the war in the Ukraine and climate change, to provide a fine-grained quantification of the impacts of agricultural shocks on real expenditures in 51 developing countries. For both the Ukraine war and climate change shocks, we quantify the average effects on real household expenditures and the implications for income inequality.

Throughout, we highlight the importance of trade linkages, household heterogeneity, and their interplay, in determining how agricultural shocks impact household welfare.

To take the model to the data, we combine information on trade flows from "International Trade and Production Database for Estimation" (henceforth ITPDE, introduced by Borchert, Larch, Shikher, and Yotov (2021)) with nationally representative household survey data from the "Household Impacts of Tariff" database (henceforth HIT, introduced by Artuc, Porto, and Rijkers (2020)). The HIT data is a key building block in our analysis because it contains information on income and expenditure shares for 24 different product categories and 100 representative households per country—each representing a percentile of that country's income distribution. Using HIT, we are able to work with households in 51 low and middle-income countries.[1] For the rest of the world, we work with a representative household using ITPDE data. Initial trade, factor allocation and consumption shares required to quantify the model are taken directly from these data. Importantly, the land and labor elasticities—parameters which govern household land and labor allocations—are estimated with a non-linear least squares estimator (similar to Costinot, Donaldson, and Smith (2016)) by combining the HIT database with the Global Agro-Ecological Zones database of the Food and Agriculture Organization (FAO and IIASA (2021), henceforth GAEZ).

We study the war and climate change shocks with counterfactual simulations. The economic effects of the Ukraine war are simulated by running the model conditional on the main trade restrictions on agriculture induced by the conflict. In our main simulation, Ukraine cannot export or import any agricultural products or inputs from the world. Russia, in turn, bans trading its major agricultural exports, namely wheat, rice, corn, other sugar, oilseeds, and fertilizers. Because the Ukraine war shock has already occurred, we can validate the model by assessing its goodness of fit. We compare the price changes predicted by the model with those observed after the onset of the war (using data from the FAO's Food Prices Monitoring and Analysis tool). Reassuringly, the price changes generated by the model correlate strongly with those observed in reality.

The impact of climate change is simulated with a version of the model in which we input the productivity of different crops across countries based on climate change projections arising from the main scenario of the UN's Intergovernmental Panel on Climate Change (IPCC). Following Costinot, Donaldson, and Smith (2016), we use GAEZ data to implement the climate change shock.

Turning to our main findings, the Ukraine war represses real incomes and exacerbates inequality

[1] The data covers all low and lower middle income countries for which nationally representative household surveys with both income and expenditure data are available.

across the developing world, with highly heterogeneous impacts both across and within countries. The overwhelming majority of households (96.49%) in our sample suffers a reduction in real incomes, with an average real income loss across countries of 2.06%. Had we used a representative household model instead, the average loss would have been -1.90%, approximately 7.77% smaller. The range in average impacts across countries is wide, varying from a minimum of –10.41% to a maximum of just 0.14%. The standard deviation is 2.12%. Losses are strongly correlated with reliance on imports from Russia and the Ukraine, which helps explain why the highest losses are incurred by households in Azerbaijan (–10.41% reduction in average incomes), Mongolia (–9.31% reduction) and Georgia (–7.08% reduction). Real income losses are primarily the result of higher consumption prices, which dominate the impacts of the war on earnings. The losses are concentrated among the poor, because they spend a higher share of their budget on food. Average income losses for the bottom 25% poorest households in a given country (–2.23% on average across countries) are 23.20% lower than the losses incurred by the top quartile (–1.81% on average). Within-country variation in the gains from trade is thus of first order importance, and increases with average impacts. Countries that are incurring the largest real income losses are also witnessing the greatest increases in inequality.

Climate change has even more devastating and even more heterogeneous impacts, leading to real income losses for three-quarters of the countries in our data, but gains for the remaining quarter. The variance in impacts across households is very large, ranging from a maximum average loss of –62.70% to a maximum average gain of 48.41%. On average real incomes decline by –9.72% but the standard deviation is 19.96%. In a model based on a single household, the average loss would be –8.64%, about 11.11% smaller. The projected productivity impacts of climate change are the key driver of differences across countries. Countries that experience an increase in their agricultural productivity tend to gain, whereas the countries in which productivity deteriorates are worse off. These productivity changes are strongly correlated with changes in land and labor incomes, which are the dominant mechanism by which climate change impacts household real income. By contrast and unlike the Ukraine war, changes in consumer prices are not an important contributor. Countries experiencing greater changes in average incomes are also characterized by a greater variance in gains across households.

The poor are disproportionately impacted by climate change because of their greater engagement in agricultural income-earning activities. Climate change reduces average incomes and exacerbates inequality in the majority of countries. In the small subset of countries for which climate change boosts average incomes, the poor enjoy a greater share of the gains. Across all countries in our sample the bottom 25% poorest households within a given country experience losses (–11.60% of real income) which are on average 43.92% larger than those incurred by households in the top quartile (–8.06%).

The paper builds on and complements several strands of existing literature. Our paper focuses on the relationship between agriculture and welfare, which is also the main theme in Costinot and Donaldson (2016), Costinot, Donaldson, and Smith (2016), and Sotelo (2020). A distinguishing feature of our approach is its focus on households which contrast with existing approaches that typically postulate a single household for each country. This not only allows us to quantify impacts on inequality but also improves estimates of the aggregate welfare effects. This is because of an inherent aggregation bias associated with using aggregate data instead of household level data. The average welfare impact across heterogeneous households making different production and consumption decisions does not coincide with the welfare impact for a single household characterized by aggregate level data. The bias can be sizeable for large shocks. In the case of climate change, which causes significant household adjustment, the estimates of the welfare effect using our heterogeneous household model are on average 11.11% larger than those obtained with a representative household model. For the Ukraine war, the bias is 7.77%. These findings dovetail with the heterogeneous firm literature that has shown that microstructure matters for the aggregate gains from trade (Melitz and Redding (2015); Costinot, Rodríguez-Clare, and Werning (2020)).

Second, our model accounts for a rich set of channels of impact and is characterized by product-level granularity. Just like Costinot and Donaldson (2016), Costinot, Donaldson, and Smith (2016), Fajgelbaum and Redding (2014), Sotelo (2020), and Tombe (2015) we depart from the common practice of aggregating agriculture into a broad (few) sector(s), and instead focus on 20 different crops. In our model, the land allocation problem of the household builds on Costinot, Donaldson, and Smith (2016) and Sotelo (2020), in which producers allocate plots to different crops to maximize their income in a discrete choice setup. Different from these papers, our unit of observation is the household rather than the plot, which allows us to incorporate heterogeneity in consumption baskets and differences in wage income. The labor allocation decision of the households is also modeled with a discrete choice framework, building on a static version of Artuc, Chaudhuri, and McLaren (2010), a la Lagakos and Waugh (2013), Lee (2020), Lee and Yi (2018) and Galle, Rodriguez-Clare, and Yi (2021). A paper close to ours with households in a trade model is Bergquist, Faber, Fally, Hoelzlein, Miguel, and Rodríguez-Clare (2022). Studies of the distribution of the gains from trade that are similar to our approach include Galle, Rodríguez-Clare, and Yi (2023), who incorporate labor heterogeneity, Fajgelbaum and Khandelwal (2016) and Nigai (2016), who introduce non-homothetic preferences, and Adao, Carrillo, Costinot, Donaldson, and Pomeranz (2022), who account for heterogeneity across the earnings distribution.

We also contribute to the burgeoning literature on the impact of climate change (Tol (2009)). Our paper is closest to Costinot, Donaldson, and Smith (2016), who use GAEZ projections to study aggregate welfare effects. We extend this analysis to accommodate household heterogeneity and show that impacts of climate change vary enormously not only across countries but also across households within countries. This also affects the aggregation of the average welfare effects. A related strand of literature includes Desmet and Rossi-Hansberg (2015) and Cruz and Rossi-Hansberg (2023). They quantify welfare effects, as we do, embedding climate change responses into the model instead of adopting GAEZ projections. Finally, this paper provides one of the first attempts to quantify the economic impact of the Russia-Ukraine conflict in general equilibrium.

The remainder of this paper proceeds as follows. Section 2 introduces the theoretical model. Section 3 discusses the data, in addition to calibration and estimation of model parameters. Section 4 presents our analysis of the impact of the war in the Ukraine on developing countries, while section 5 analyses the impact of climate change on developing countries. Section 6 concludes.

2 A Model of Trade and Agriculture with Households

In this section, we introduce the model of agricultural trade that we use to explore the impacts of the war and climate change. A distinctive feature of our paper is that we focus on households in low-income countries and their heterogeneous decisions in terms of both the consumption and production of different agricultural products. This requires detailed household-level data, which we take from the Household Impacts of Tariffs (HIT henceforth) database (see Section 3). Our model is designed to capture and exploit the main features of this household survey data. To facilitate exposition, we start by presenting the different building blocks of our theory.

Countries. We consider N countries indexed with n. We divide countries into two groups based on the availability of household data. In those countries with household data in the HIT database (a total of 51 "HIT countries"), there are H^n households which are engaged in both production and consumption. These countries are low-income, agrarian economies, which are small players in countries in international markets, accounting for only a small fraction of global trade.[2] To address this issue, we also include major trade players such as the U.S., the E.U., China, Brazil, and India. We refer to these countries as the "central" economies as opposed to the low-income agrarian countries in HIT.

[2]Together the 51 countries accounted for 4.80% of total global export and imports recorded in United Nation's COMTRADE database in 2021.

In these countries, since we do not have suitable household-level data, we work with a representative household.

Goods. Because we want to focus on agriculture, we exploit the HIT database and work with a set of 20 crops and agricultural products for which we have household-level consumption and production data. The details are provided in Section 3, which discusses the datasets we use. By focusing on disaggregated crop data at the household level, we are in a unique position to study the micro-level implications of price and productivity shocks, such as those generated by conflict and climate change, on agricultural outcomes. We assume that crops are differentiated across countries so that each country produces a different variety of each crop. Within countries, all households h produce the same variety of crop j (i.e., crops are differentiated by country but not by household). The rest of the non-agricultural economy is represented by three aggregate sectors. There is a manufacturing sector, M, which is traded. Manufactures are differentiated across countries. There is one agricultural input, F, (e.g., fertilizers), which is differentiated across countries and is traded. Lastly, there is a non-traded services sector, S.

Households and firms. Households are heterogeneous in their consumption preferences. They have different endowments of land and labor. Land is not traded, while labor is freely mobile across crops and sectors. Households produce crops using their own land, but they can use their own labor, hire outside labor or work off-farm, either for other households or for manufacturing or services firms. Households are heterogeneous in land productivity and workers are heterogeneous in labor productivity. Even though we have information of thousands of households in the HIT database, for computational convenience and in order to facilitate data sharing we aggregate them to 100 households per country.[3] The aggregation is done over 100 bins of the distribution of per capita expenditure. This means that each household, in each country, represents one percentile of the income distribution. This is a natural aggregation given our interest in inequality. There are 5100 representative households in our setting. Firms, operating in a perfect competition environment, produce manufactures and services using labor and a specific factor (capital or structures). For simplicity, we assume that the intermediate input (fertilizers) is produced using only a specific factor.

Trade and Prices. The N countries trade agricultural products, manufactures and intermediate goods. Price of sector j product in country m is denoted with p_j^m. There are trade costs $\tau_j^{n,m}$ between countries n and m, which include transportation costs and tariffs. Services are not traded.

[3] Many of the household survey datasets we use are subject to data access restrictions; by aggregating households into income percentiles we are able to circumvent such restrictions and create a dataset that is publicly available.

2.1 Household Preferences and Demand

Households consume agricultural goods, manufactures and services. The preferences of household h are represented with a Cobb-Douglas utility function

$$U^{n,h} = \prod_j \left(C_j^{n,h}\right)^{\alpha_j^{n,h}}, \tag{1}$$

where $C_j^{n,h}$ is the consumption aggregate of goods j consumed by household h in country n, and $\alpha_j^{n,h}$ is the household-specific Cobb-Douglas share for j. Here, j indexes a set of agricultural products, a manufacturing aggregate and services. Note that households are heterogeneous in preferences and have different utility parameters. In particular, since our households are aggregated into 100 income bins, the utility function implies varying expenditure shares for different income levels. This captures non-homotheticity of preferences across households as consumers.

Each country produces a different variety of the various crops and of the manufactured product. These varieties are then combined and consumed by the household in an Armington setup. The composite product j is created using the following aggregator function

$$C_j^{n,h} = \left[\sum_m \left(\vartheta_j^{n,m} \left(C_m^{n,h}\right)^{\frac{\sigma-1}{\sigma}}\right)\right]^{\frac{\sigma}{\sigma-1}}, \tag{2}$$

where $\sigma > 0$ is the elasticity of substitution and each variety comes from a different country, indexed with m.[4] $\vartheta_j^{n,m}$ is a country-specific, but not household-specific, utility shifter. Since households have different Cobb-Douglas preferences, the shares spent on each composite j are household specific. Since households have the same Armington aggregator function (2) and face identical prices, the participation of each variety in the composite is the same across households. Concretely, the expenditure of household h residing in country n on a variety of agricultural good j produced in country m is

$$p_j^m \tau_j^{n,m} C_j^{n,h} = x_j^{n,m} E_j^{n,h}, \tag{3}$$

where $E_j^{n,h}$ is total household expenditure in good j and the import share is

$$x_j^{n,m} = \frac{\vartheta_j^{n,m} \left(p_j^m \tau_j^{n,m}\right)^{1-\sigma}}{\left(P_j^n\right)^{1-\sigma}}. \tag{4}$$

The price index for composite j is

[4] This specification makes the import decision problem isomorphic to the Eaton and Kortum (2002), but provides a simpler formulation which facilitates the exposition.

$$P_j^n = \left[\sum_{m'} \vartheta_j^{n,m'} \left(p_j^{m'} \tau_j^{n,m'} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}. \tag{5}$$

Given the Cobb-Douglas shares, we have that

$$E_j^{n,h} = \alpha_j^{n,h} E^{n,h}, \tag{6}$$

where $E^{n,h}$ is total household expenditure.

Similarly, total household expenditures on the manufacturing aggregate is:

$$E_M^{n,h} = \alpha_M^{n,h} E^{n,h}, \tag{7}$$

and the expenditure of h on the variety produced in country m is

$$p_M^m \tau_M^{n,m} C_M^{n,h} = x_M^{n,m} E_M^{n,h}, \tag{8}$$

where the import share is

$$x_M^{n,m} = \frac{\vartheta_M^{n,m} \left(p_M^m \tau_M^{n,m} \right)^{1-\sigma}}{\sum_{m'} \vartheta_M^{n,m'} \left(p_M^{m'} \tau_M^{n,m'} \right)^{1-\sigma}}. \tag{9}$$

The price index for manufactures is

$$P_M^n = \left[\sum_{m'} \vartheta_M^{n,m'} \left(p_M^{m'} \tau_M^{n,m'} \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}. \tag{10}$$

The non-traded good S is homogeneous within countries. Thus, there is no Armington aggregator for services, consumption is $C_S^{n,h}$ and the household-specific Cobb-Douglas budget share is $\alpha_S^{n,h}$ so that household expenditure on services is

$$E_S^{n,h} = \alpha_S^{n,h} E^{n,h}. \tag{11}$$

The index price for services is the equilibrium price $P_i^n = p_S^n$.

2.2 Production, Supply and Factor Demand

The economy produces varieties of several crops, a variety of the manufacture aggregate, services and a variety of the intermediate input. While crops are produced by households, manufactures, services and the intermediate inputs are produced by firms.

2.2.1 Household Agricultural Production

Households own land and labor. Land endowments are exogenous. There is a continuum of land in country n, with measure $\overline{T}^n$. Land is divided across households and a measure $\overline{T}^{n,h}$ of this land belongs to household h, where $\sum_h \overline{T}^{n,h} = \overline{T}^n$. We index the zero measure land plots on this continuum with

ω_T. Households can allocate land freely to produce any of the crops. In this formulation, we assume there is no market for land.[5]

Similarly, there is a continuum of workers with measure $\overline{L}^n$ in the economy and the labor endowment of the household is denoted with $\overline{L}^{n,h}$. We index the zero measure workers on this continuum with ω_L. Unlike land, labor is freely mobile, not only across crops, but also across the other aggregate sectors (manufactures and services) as well as across households. In other words, household members can work on their own plots, work on other farms, or work in manufacturing and services.

Households are heterogeneous in land productivity. When allocated to crop j, the plot ω_T has productivity $\xi_{T,j}(\omega_T)$. This is the same as Sotelo (2020) and Costinot, Donaldson, and Smith (2016). Unlike these papers, we also allow for labor heterogeneity, as Lagakos and Waugh (2013), Lee (2020) and Galle, Rodriguez-Clare, and Yi (2021). A worker indexed with ω_L has productivity $\xi_{L,j}(\omega_L)$ in sector j. This heterogeneous labor productivity applies not only to agricultural crops, but also to manufactures and services (as we will explain in more detail below). The combination of heterogeneous productivity in both land and labor is a novel feature of our work, and crucial for appropriate quantification of the distributional impacts of shocks.

The household production decision problem consists of allocating different plots ω_T of land to different crops. The production process combines land, labor and the intermediate input using a constant returns to scale Cobb-Douglas production function. Output for plot ω_T when producing crop j is

$$q_j^n(\omega_T) = \left[F_j^n(\omega_T)\right]^{\beta_F} \left[\tilde{L}_j^n(\omega_T)\right]^{\beta_L} \left[\xi_{T,j}(\omega_T)\right]^{\beta_T}, \tag{12}$$

where $\tilde{L}_j(\omega_T)$ is the effective units of labor (with productivity $\xi_{L,j}(\omega_L)$) demanded to work on plot ω_T. The intermediate input, which is a composite of varieties purchased from the market, is denoted by $F_j(\omega_T)$. The variable $\xi_{T,j}(\omega_T)$ is the productivity shock for plot ω_T. The Cobb-Douglas shares of production inputs add up to one, $1 = \beta_F + \beta_L + \beta_T$, and are common across crops. Due to the productivity shock $\xi_{T,j}(\omega_T)$, each plot will specialize in producing one crop.

To solve the household land allocation problem, consider a plot ω_T with productivity $\xi_{T,j}(\omega_T)$. Given this productivity and given the price of the national variety of crop j, p_j^n, the index price of intermediate inputs, P_F^n, and the effective wage, w_j^n, the farmer can derive the optimal use of effective labor and intermediate inputs to maximize the profits of producing $q_j(\omega_T)$ units of output in said plot. Replacing optimal factor use, the revenue derived from crop j is

[5] As in Sotelo (2020), the solution of the model is the same if we allow for land to be rented.

$$y_j^n(\omega_T) = \left(p_j^n\right)^{\frac{1}{\beta_T}} \left(\frac{\beta_F}{P_F^n}\right)^{\frac{\beta_F}{\beta_T}} \left(\frac{\beta_L}{w_j^n}\right)^{\frac{\beta_L}{\beta_T}} \xi_{T,j}(\omega_T). \tag{13}$$

Thus, the land revenue from this plot is equal to $r_j^n \xi_{T,j}(\omega_T)$, where the effective return to land can be expressed as

$$r_j^n = \beta_T \left(p_j^n\right)^{\frac{1}{\beta_T}} \left(\frac{\beta_F}{P_F^n}\right)^{\frac{\beta_F}{\beta_T}} \left(\frac{\beta_L}{w_j^n}\right)^{\frac{\beta_L}{\beta_T}}. \tag{14}$$

We assume that the distribution of the productivity shocks is Frechet, with scale and shape parameters given by $\widetilde{\gamma}_T A_{T,j}^{n,h}$ and θ_T respectively, where $\widetilde{\gamma}_T \equiv \left[\Gamma\left(1 - \frac{1}{\theta_T}\right)\right]^{-1}$. The household will allocate plot ω_T with productivity $\xi_{T,j}(\omega_T)$ to crop j if this crop delivers the maximum land revenue. That is, if

$$\xi_{T,j}(\omega_T) r_j^n \geq \xi_{T,k}(\omega_T) r_k^n; \;\; \forall k \neq j. \tag{15}$$

Given the Frechet assumption, the probability of allocating a plot to product j can be expressed as (see Supplementary Material)

$$\pi_{T,j}^{n,h} = \frac{(r_j^n A_{T,j}^{n,h})^{\theta_T}}{(\Phi_T^{n,h})^{\theta_T}}, \tag{16}$$

where $\Phi_T^{n,h} = \left(\sum_{j \in \mathcal{S}} \left(r_j^n A_{T,j}^{n,h}\right)^{\theta_T}\right)^{\frac{1}{\theta_T}}$ and $\mathcal{S}$ is the set of all crops.

The effective units of land allocated to product j is

$$T_j^{n,h} = \pi_{T,j}^{n,h} \frac{\Phi_T^{n,h}}{r_j^n} \overline{T}^{n,h}. \tag{17}$$

The total return on land for household h is equal to

$$R_T^{n,h} = \Phi_T^{n,h} \overline{T}^{n,h}. \tag{18}$$

We can now derive factor demands and output supply. To get the household demand for labor when producing crop j, we write optimal labor use at plot ω_T as

$$\tilde{L}_j(\omega_T) = \left(p_j^n\right)^{\frac{1}{\beta_T}} \left(\frac{\beta_F}{P_F^n}\right)^{\frac{\beta_F}{\beta_T}} \left(\frac{\beta_L}{w_j^n}\right)^{\frac{\beta_L+\beta_T}{\beta_T}} \xi_{T,j}(\omega_T). \tag{19}$$

Integrating this across all plots ω_T allocated to crop j, we get

$$\tilde{L}_j^{n,h} = \left(p_j^n\right)^{\frac{1}{\beta_T}} \left(\frac{\beta_F}{P_F^n}\right)^{\frac{\beta_F}{\beta_T}} \left(\frac{\beta_L}{w_j^n}\right)^{\frac{\beta_L+\beta_T}{\beta_T}} \left(\pi_{T,j}^{n,h}\right)^{\frac{\theta_T - 1}{\theta_T}} \frac{\overline{T}^{n,h}}{A_{T,j}^{n,h}}. \tag{20}$$

Thus, aggregate labor demand for crop j across all households is

$$\tilde{L}_j^n = \sum_h \tilde{L}_j^{n,h}. \tag{21}$$

Similarly, aggregate demand for the composite of the intermediate input is

$$F^n = \sum_h \sum_j \left(p_j^n\right)^{\frac{1}{\beta_T}} \left(\frac{\beta_F}{P_F^n}\right)^{\frac{\beta_F+\beta_T}{\beta_T}} \left(\frac{\beta_L}{w_j^n}\right)^{\frac{\beta_L}{\beta_T}} \left(\pi_{T,j}^{n,h}\right)^{\frac{\theta_T-1}{\theta_T}} \frac{\overline{T}^{n,h}}{A_{T,j}^{n,h}}. \tag{22}$$

With respect to output, we can integrate (13) to derive the value of output of product j for household h

$$y_j^{n,h} = \left(p_j^n\right)^{\frac{1}{\beta_T}} \left(\frac{\beta_F}{P_F^n}\right)^{\frac{\beta_F}{\beta_T}} \left(\frac{\beta_L}{w_j^n}\right)^{\frac{\beta_L}{\beta_T}} \left(\pi_{T,j}^{n,h}\right)^{\frac{\theta_T-1}{\theta_T}} \frac{\overline{T}^{n,h}}{A_{T,j}^{n,h}}. \tag{23}$$

Summing across households, the value of national output of crop j is

$$y_j^n = \sum_h y_j^{n,h}. \tag{24}$$

2.2.2 Firms

Firms produce manufactures, services and intermediate inputs. We assume there are many identical firms operating in perfect competition with zero profit. Manufactures (M) and services (S) combine (effective) labor and a specific factor, and the value of their output is

$$y_i^n = p_i^n (\tilde{L}_i^n)^{\beta_{L,i}} (K_i^n)^{\beta_{K,i}}, \tag{25}$$

where y_i is the value of total aggregate output of good $i = \{M, S\}$, p_i^n is the price of one unit of output, $\tilde{L}_i$ is effective units of labor demanded by the producer (with productivity $\xi_{L,i}$) and K_i is a fixed, specific factor.

Given the price p_i^n and the effective wage w_i^n, the FOC of the firms profit maximization gives the effective labor demand in sector i

$$\tilde{L}_k^n = \left(\frac{p_i^n \beta_{L,k}}{w_i^n}\right)^{\frac{1}{\beta_{K,i}}} K_i^n. \tag{26}$$

The return per unit of the fixed factor K_i^n is given by

$$r_i^n = \beta_{K,i} \left(p_i^n\right)^{\frac{1}{\beta_{K,i}}} \left(\frac{\beta_{L,i}}{w_i^n}\right)^{\frac{\beta_{L,i}}{\beta_{K,i}}}. \tag{27}$$

The total return to the specific factor in sector i is $R_i^n = r_i^n K_i^n$. We assume that households own the fixed factor, such that $K_i^n = \sum_h K_i^{n,h}$, and household rents are

$$R_i^{n,h} = r_i^n K_i^{n,h}. \tag{28}$$

This holds for manufacturing M and services S.

To better fit the available data (see Section 3 below), we adopt a linear production function for intermediates

$$F^n = K_F^n, \tag{29}$$

with revenues $R_F^n = p_F^n K_F^n$.

2.3 Factor Supply

In each country n, the total supply of the specific factors K_M^n, K_S^n and K_F^n is exogenous. This implies that the factor supply to each sector is also exogenous. Factor rewards are given by the rents generated by this specificity. The total land endowment, $\overline{T}^n$, as well as the household land endowments, $\overline{T}^{n,h}$, are also exogenous. The land supply to different sectors, and the value of land rents, was addressed above. The total labor endowment, $\overline{L}^n$, as well as the household labor endowments, $\overline{L}^{n,h}$, are also exogenous. The remaining task is to determine labor supply to different sectors, which we do next.

Consider a household with labor endowment $\overline{L}^{n,h}$. Each unit of labor ω_L can be allocated to the production of J different products, including crops, manufactures and services. Households make their labor allocation decisions based on the productivity of labor for different crops and products, which we denote $\xi_{L,j}(\omega_L)$, and the market wage for producing each good, w_j^n. When labor indexed with ω_L is allocated to crop/product j, the return is equal to $\xi_{L,j}(\omega_L)w_j^n$. For each ω_L, the household will maximize labor income by allocating each labor unit to the sector with the highest return. If the optimal choice is a crop, then a given unit of labor can be allocated either to own-household plots or to off-farm plots. If the optimal choice is manufactures or services, then labor is hired by firms.

We assume that $\xi_{L,j}(\omega_L)$ is Frechet distributed with scale and shape parameters $\widetilde{\gamma}_L A_{L,j}^{n,h}$ and θ_L respectively. The scale parameter, which determines average productivity, depends on the product and country, where $\widetilde{\gamma}_L \equiv \left[\Gamma\left(1-\frac{1}{\theta_L}\right)\right]^{-1}$. Characterization of the optimization problem requires calculating the probability of choosing a specific production activity for labor and the effective units of labor based on this allocation decision.

A unit of labor will be allocated to sector j when

$$\xi_{L,j}(\omega_L)w_j^n \geq \xi_{L,k}(\omega_L)w_k^n;\ \ \forall k \neq j. \tag{30}$$

Based on the properties of Frechet distribution, we can write the probability of allocating one unit of labor to market j, given the parameters $(\widetilde{\gamma}_L A_{L,j}^{n,h}, \theta_L)$, as

$$\pi_{L,j}^{n,h} = \frac{\left(A_{L,j}^{n,h} w_j^n\right)^{\theta_L}}{\left(\Phi_L^{n,h}\right)^{\theta_L}}, \tag{31}$$

where $\Phi_L^{n,h} = \left(\sum_{j\in\mathcal{S}'}\left(A_{L,j}^{n,h} w_j^n\right)^{\theta_L}\right)^{\frac{1}{\theta_L}}$ and $\mathcal{S}'$ is the set of sectors that employ workers, including all crops, manufacturing and services.

The next step is to calculate the effective units of labor supply for each crop, taking productivity draws into account. From the Frechet assumptions, the total effective units of labor allocated to j, conditional on optimality, is equal to

$$L_j^{n,h} = \pi_{L,j}^{n,h} \frac{\Phi_L^{n,h}}{w_j^n} \overline{L}^{n,h}, \tag{32}$$

This delivers the productivity adjusted labor supply by household h to each crop/product j. Note that the probability of allocating labor to j is also equal to the share of the return to labor allocated to j relative to the total return to labor, that is $\pi_{L,j}^{n,h} = L_j^{n,h} w_j^n / \sum_k L_k^{n,h} w_k^n$.

Finally, the total wage income (return on labor) of household h defined as $R_L^{n,h} \equiv \sum_j L_j^{n,h} w_j^n$ is equal to

$$R_L^{n,h} = \Phi_L^{n,h} \overline{L}^{n,h}. \tag{33}$$

The proof for this statement is provided section A2 in the Supplementary Material.

2.4 Equilibrium

Definition. The international trade equilibrium is given by a vector of crop prices for each crop variety in each country, p_j^n; a vector of manufacturing prices for each country variety, p_M^n; a vector of services prices in each country, p_S^n; a vector of intermediate input prices for each country variety, p_F^n; a vector of wages for each product (crops, manufacturing and services), for each country w_j^n; a vector of return on land r_j^n; and rental rates for the specific factors in manufacturing r_M^n, services r_S^n and intermediate inputs r_F^n, such that:

Goods Market. For each product, global demand equals national supply. For crops j, we combine total household expenditures (6) and the value of national output (24) to express the equilibrium condition as

$$\sum_n \sum_h x_j^{n,m} \alpha_j^{n,h} \left(R_T^{n,h} + R_M^{n,h} + R_S^{n,h} + R_L^{n,h} \right) = y_j^m, \tag{34}$$

where $x_j^{n,m}$ is the import share based on the price vector p_j^n defined by (4) and (5), $R_M^{n,h}$ and $R_S^{n,h}$ are the fixed factor revenues in sectors M and S (defined by (28)) accruing to household h, $R_T^{n,h}$ and $R_L^{n,h}$ are given by (18) and (33) and $R_T^{n,h} + R_M^{n,h} + R_S^{n,h} + R_L^{n,h} = E^{n,h}$ is total household expenditure. The revenue function of crops at the national level, (24), gives the right hand side of the equation.

The equilibrium for manufactures is the same as (34) with $j = M$

$$\sum_n \sum_h x_M^{n,m} \alpha_M^{n,h} \left(R_T^{n,h} + R_M^{n,h} + R_S^{n,h} + R_L^{n,h} \right) = y_M^m, \tag{35}$$

where the revenue function (25) gives the right hand side of the equation.

Supply and demand of the non-traded good requires that

$$\sum_h \alpha_S^{n,h}\left(R_T^{n,h}+R_M^{n,h}+R_S^{n,h}+R_L^{n,h}\right)=y_S^n. \tag{36}$$

For the intermediate input F, we have $\sum_n \sum_h \sum_j x_F^{n,m}\beta_F y_j^{n,h}=y_F^m$.

Factor Markets. The labor allocation problem of households imply that

$$\sum_h \left(\pi_{L,j}^{n,h}\right)^{\frac{\theta_L-1}{\theta_L}} \frac{\overline{L}^{n,h}}{A_{L,j}^{n,h}}=\frac{\beta_{L,j}y_j^n}{w_j^n}, \tag{37}$$

for each sector j (any crop, manufacturing or services) where $\pi_{L,j}^{n,h}$ is a function of w_j^n given equation (31). The land allocation problem of the households imply that

$$\sum_h \left(\pi_{T,j}^{n,h}\right)^{\frac{\theta_T-1}{\theta_T}} \frac{\overline{T}^{n,h}}{A_{T,j}^{n,h}}=\frac{\beta_{T,j}y_j^n}{r_j^n}, \tag{38}$$

for any crop j where $\pi_{T,j}^{n,h}$ is a function of r_j^n given equation (16). For services and manufacturing, we have $K_i^n=\beta_{K,i}^n y_i^n/r_i^n$ and for the inputs we have $K_F^n=y_F^n/r_F^n$. The equilibrium price satisfies

$$p_j^n=\left(\frac{p_F^n}{\beta_{F,j}^n}\right)^{\beta_{F,j}}\left(\frac{w_j^n}{\beta_{L,j}}\right)^{\beta_{L,j}}\left(\frac{r_j^n}{\beta_{T,j}}\right)^{\beta_{T,j}}, \tag{39}$$

for crops, and $p_j^n=\left(\frac{w_j^n}{\beta_{L,j}}\right)^{\beta_{L,j}}\left(\frac{r_j^n}{\beta_{T,j}}\right)^{\beta_{T,j}}$ for services and manufacturing, and finally $p_F^n=r_F^n$ for inputs since there is only one factor of production for inputs (i.e. fertilizers).

Note that the model could be solved in levels using the equations above by plugging in productivity parameters for each choice. Alternatively, it can also be solved in changes, i.e. using hat algebra, which considerably reduces the data requirements. We provide the full solution method using hat algebra in detail in section A1 in the Supplementary Material.[6]

2.5 Welfare

To explore distributional issues, we measure household welfare with household real expenditures

$$V^{n,h}=\frac{E^{n,h}}{P^{n,h}}=\frac{R_L^{n,h}+R_T^{n,h}+R_M^{n,h}+R_S^{n,h}}{P^{n,h}}. \tag{40}$$

This is the ratio of nominal income/expenditure, which is the sum of household revenues from land, labor, and specific factors in manufactures and services, and a household-specific price index given by $P^{n,h}=\prod_j\left(P_j^n\right)^{\alpha_j^{n,h}}$, where j is now all goods demanded by the household.

[6] The equilibrium can alternatively be characterized without using the return on land as discussed in the appendix.

3 Data and Estimation

To solve the model, we need to characterize household decisions using the initial allocations and response elasticities. Since the solution is in changes, using hat-algebra as in Dekle, Eaton, and Kortum (2008), Alvarez and Lucas (2007) and Caliendo and Parro (2015), the data requirements comprise household land and labor allocations, household utility function parameters, household and firm production function parameters, international trade shares, and elasticity parameters. In our setting all, of this is data, except for the elasticity parameters, which are estimated. These data requirements, data sources, and the estimated parameters are reported in Table 1.

3.1 Data

Household data. We begin with household-level variables. Information on households' utility function parameters $\alpha_j^{n,h}$, crop-specific land allocation shares $\overline{\pi}_{T,j}^{n,h}$, and sector-specific labor shares $\overline{\pi}_{L,j}^{n,h}$ is taken from the the Household Impacts of Tariffs database (Artuc, Porto, and Rijkers (2020)). This dataset contains highly disaggregated information on household budget and income shares from representative harmonized household surveys for 51 low- and middle income countries.[7] These surveys cover 300 million households and 1.6 billion people. For each country, households are grouped into 100 income bins each representative of a percentile of the income distribution. Cobb-Douglas consumption shares $\alpha_j^{n,h}$ and labor allocation shares, $\overline{\pi}_{L,j}^{n,h}$, are taken directly from the data. Land shares $\overline{\pi}_{T,j}^{n,h}$ are calculated by using the fact that a crop's total output share must equal it's total land allocation share in equilibrium. The initial shares of household income from land and labor, denoted by $\kappa_T^{n,h}$ and $\kappa_L^{n,h}$, are also taken directly from the data. These shares enable us to calculate the changes in household income based on changes in land and labor income implied by the model. Fixed factor shares are also calculated based on households' sales of manufacturing and services in HIT database. To close the model, for each country we construct a residual household which is excluded from the 100 bins per country we use in our analysis, and allocate fixed factors that are not owned by households to it.

The initial shares of each household in the national supply of land and labor, denoted by $\eta_{T,j}^{n,h}$ and $\eta_{L,j}^{n,h}$, and the initial share of each household in the national demand of crop j, denoted by $\overline{D}_j^{n,h}$, are also taken from the HIT database. This information is used to calculate the change in aggregate labor

[7]The 51 countries are Armenia, Azerbaijan, Bangladesh, Benin, Bhutan, Bolivia, Burkina Faso, Burundi, Cambodia, Cameroon, Central African Republic, Comoros, Cote d'Ivoire, Ecuador, Egypt, Arab Rep., Ethiopia, Gambia, Georgia, Ghana, Guatemala, Guinea, Guinea-Bissau, Indonesia, Iraq, Jordan, Kenya, Kyrgyzstan, Liberia, Madagascar, Malawi, Mali, Mauritania, Moldova, Mongolia, Mozambique, Nepal, Nicaragua, Niger, Nigeria, Pakistan, Papua New, Guinea, Rwanda, Sierra Leone, South Africa, Sri Lanka, Tajikistan, Tanzania, Togo, Uganda, Uzbekistan, Vietnam, Yemen and Zambia.

and land supply to each specific crop, as well as the change in aggregate expenditures.

Trade and production data. The second piece of data is the trade data, which we take from the "International Trade and Production Database for Estimation" project by Borchert, Larch, Shikher, and Yotov (2021) and Borchert, Larch, Shikher, and Yotov (2022). ITPD-E provides product specific import and export shares $\overline{x}_j^{n,m}$ and $\widetilde{x}_j^{n,m}$ respectively. The ITPD-E data also provides domestic absorption rates, which are necessary to calculate the total output.

In order to harmonize the HIT and ITPDE data, it is necessary to create consistent product categories. Since the HIT data is more detailed for agricultural products, we aggregate some products in HIT to match ITPD-E.[8]

Since the HIT countries do not cover a significant proportion of the world production for the crops we consider in the model, we add 47 relatively large countries for which we have ITDPE-data to account for the rest-of-the-world production and trade.[9] We assume a single representative household for countries that were not included in HIT data. This representative household produces all agricultural products as well as services and manufacturing outputs using fixed factors.

A key parameter that we need to solve for the international trade equilibrium is the trade elasticity. We use the estimate from Simonovska and Waugh (2014), which gives us $1 - \sigma = -4.0$.

3.2 Estimation of land and labor elasticities

Central to the model are the Frechet shape parameters θ_T and θ_L which govern land and labor allocation decisions. These are the most important two parameters of the model. We estimate the elasticities with a non-linear least squares estimator. Since θ_T and θ_L govern the allocation of factors to the production of different crops, we match revenues from each crop across countries.

The estimation of the elasticities requires information on crop productivity and crop prices. Since these data are not available (on a consistent basis) at the household level, we use aggregate country-level data at instead. Note that the revenue from crop j as a function of θ_L and θ_T, for a given aggregate

[8] Table A5 in the Supplementary Material presents the concordance between HIT and ITPD-E we developed. The final set of sectors is as follows: 1. Wheat, 2. Rice, 3. Corn, 4. Other cereals, 5. Soya, 6. Other oilseeds, 7. Sugar, 8. Legumes, 9. Fruits and vegetables, 10. Nuts, 11. Eggs, Meat and Dairy, 12. Confectionery and Cocoa, 13. Oils and Fats, 14. Other staple food, 15. Beverages, 16. Cotton, 17. Tobacco, 18. Spices/herbs, 19. Alcohol, 20. Fish, 21. Manufacturing, 22. Services, and 23. Fertilizers and other chemicals as agricultural inputs.

[9] These additional economies are Argentina, Australia, Austria, Belgium, Bulgaria, Brazil, Canada, Switzerland, Chile, China, Colombia, Czech Republic, Germany, Denmark, Spain, Finland, France, United Kingdom, Greece, Hungary, India, Israel, Italy, Japan, Kazakhstan, South Korea, Laos, Morocco, Mexico, Malaysia, Netherlands, Norway, Peru, Philippines, Poland, Portugal, Romania, Russia, Saudi Arabia, Singapore, Slovakia, Sweden, Thailand, Tunisia, Turkey, Taiwan and United States.

Table 1: Parameters and initial shares

Initial Household Allocations (data)			
$\alpha_j^{n,h}$		Utility function parameters	HIT
$\overline{\pi}_{T,j}^{n,h}$, $\overline{\pi}_{L,j}^{n,h}$		Land and labor shares	HIT
$\kappa_T^{n,h}$, $\kappa_L^{n,h}$		Share of income from land and labor	HIT
$\eta_{T,j}^{n,h}$, $\eta_{L,j}^{n,h}$		Households' share in total factor supply	HIT
$\overline{D}_j^{n,h}$		Households' share in demand	HIT
Initial International Trade Shares (data)			
$\overline{x}_j^{n,m}$, $\widetilde{x}_j^{n,m}$		Import and export shares	ITPDE
Parameters			
$1-\sigma$	-4.00	Trade elasticity	Simonovska and Waugh (2014)
$\beta_{L,j}$	0.55	Labor elasticity agriculture	Sotelo (2020)
$\beta_{T,j}$	0.22	Land elasticity agriculture	Sotelo (2020)
$\beta_{F,j}$	0.23	Fertilizer elasticity agriculture	Sotelo (2020)
$\beta_{L,j}$	0.75	Labor elasticity manufacturing and services	Cobb-Douglas
Response Elasticities			
θ_T	1.70	Frechet shape - land elasticity	Own estimate
	(1.22, 1.95)	95% confidence interval	
θ_L	1.83	Frechet shape - labor elasticity	Own estimate
	(1.49, 3.38)	95% confidence interval	

Notes: HIT=Household Impacts of Tariffs Database (Artuc, Porto, and Rijkers (2020)), ITPDE=International Trade and Production Database for Estimation, (Borchert, Larch, Shikher, and Yotov (2021)). Note that utility function parameters and initial shares vary both across countries and by income percentile which is why it is not practical to display them in one table. For the same reason, import and and exports shares, which vary by country and product, are not displayed.

labor $\overline{\pi}^n_{L,j}$ and land $\overline{\pi}^n_{L,j}$ allocation is

$$Y^n_j(\theta_T, \theta_L) = \overline{p}^n_j \overline{A}^n_j \left(\left(\overline{\pi}^n_{T,j} \right)^{\frac{\theta_T - 1}{\theta_T}} \right)^{\frac{\beta_T}{1-\beta_F}} \left(\left(\overline{\pi}^n_{L,j} \right)^{\frac{\theta_L - 1}{\theta_L}} \right)^{\frac{\beta_L}{1-\beta_F}}, \tag{41}$$

where $\overline{p}^n_j$ is the price of crop j in country n. Assuming $A^n_{T,j}$ and $A^n_{L,j}$ are common across households within a given country, the crop-specific productivity is

$$\overline{A}^n_j = \left(\frac{\beta_M}{P^n_M} \right)^{\frac{\beta_M}{1-\beta_M}} \left(A^n_{L,j} \right)^{\frac{\beta_L}{1-\beta_M}} \left(A^n_{T,j} \right)^{\frac{\beta_T}{1-\beta_M}}. \tag{42}$$

These productivities are calculated using Food and Agriculture Organization's Global Agro-Ecological Zones (GAEZ) data set. The aggregate land and labor allocations, $\overline{\pi}^n_{L,j}$ and $\overline{\pi}^n_{T,j}$, are computed using the Household Impacts of Tariffs database (Artuc, Porto, and Rijkers (2020)).

The elasticities are estimated as

$$\{\theta^*_T, \theta^*_L\} = \arg \min_{\theta_T, \theta_L} \sum_n \sum_j \left[\overline{Y}^n_j - \frac{Y^n_j(\theta_T, \theta_L)}{\sum_k Y^n_k(\theta_T, \theta_L)} \right]^2. \tag{43}$$

We are thus implicitly matching the share of output j, $\overline{Y}^n$, taken from Artuc, Porto, and Rijkers (2020), with the share of output predicted by the model (given the parameters). The sample size includes the 51 HIT countries and 13 crops.[10] To improve the estimates, we impute the production function shares for the agricultural products from Sotelo, that is we set $\beta_T = 0.22$, $\beta_L = 0.55$ and $\beta_F = 0.23$. We assume $\beta_L = 0.75$ for the manufacturing and services sectors following the original Cobb-Douglas estimate.

The estimated elasticities are reported in the bottom panel of Table 1. Our procedure yields estimates of the land elasticity $\theta^*_T = 1.70$ and of the labor elasticity $\theta^*_L = 1.83$, which are both significantly larger than 1. The confidence intervals are calculated by bootstrapping the sample 5000 times. These estimates are in line with those obtained in related literature. For example, the estimated land elasticity in Costinot, Donaldson and Smith is 2.46, slightly higher than ours (1.70). Our estimate of the labor elasticity (1.80) is well within the range of elasticities reported by Galle, Rodriguez-Clare, and Yi (2021) which vary between 1.42 and 2.79, as well as those reported by Hiesh et al. (2013) and Burnstein et al. (2019) which range from 1.2 to 3.44.

[10]We exclude a few crops that cannot be matched to GAEZ (eggs/meat, cocoa, oils/fat, other staple food, spices, alcohol, and fish).

4 Agriculture and The Ukraine War

The war between Ukraine and Russia has a myriad of political, economic, and humanitarian consequences. We focus on its impacts on agricultural trade and production. In particular, this section uses our model to assess how the agricultural trade disruptions caused by the war have impacted the well-being and inequality across households in developing countries.

The onset of the Ukraine war coincided with a surge in food prices. These price increases were predictable. Ukraine and Russia—'the breadbasket of Europe'–are important agricultural suppliers, jointly accounting for 19% of global wheat exports, 8% of corn exports, 6% of oilseeds, and 17% of fertilizer exports (on the eve of the war). The war resulted in substantive supply disruptions, higher uncertainty, increased stockpiling, and various trade bans and retaliatory trade sanctions. The observed surge in food prices is thus plausibly, at least in part, attributable to the war.

The price hikes affect real incomes. Exposure to war-induced supply disruptions varies with how reliant countries are on food and fertilizer supplied by the Ukraine and Russia. In our sample, the majority of all wheat imports by Armenia, Egypt, Georgia, Jordan and Nicaragua were supplied by Russia and the Ukraine prior to the onset of the war. The Ukraine and Russia also supplied over half of all fertilizers imported by Georgia, Mongolia, Moldova and Azerbaijan. These countries may experience severe losses due to the war. By contrast, countries that rely less on imports from Ukraine and Russia, such as Comoros or Madagascar, may lose little, while countries that are themselves net exporters of wheat and fertilizer might yet benefit.

Within countries, household exposure depends on their consumption and income earning patterns. If food prices increase, net food consumers lose while net producers gain. The overwhelming majority of households in developing countries are net buyers of agricultural products and fertilizers (61% in our sample). On average, across the countries in the HIT dataset, households spend 44% of their income on agricultural products and derive 39% of their income from selling agricultural goods. Poorer households spend a larger share of their budget on food and are thus systematically more exposed to food price inflation. The high variation in household income and consumption portfolios is at the root of the heterogeneity in the impact of the war on different households.

We assess the welfare and inequality effects of the Ukraine war with counterfactual simulations. We focus primarily on the agricultural trade and production disruption in the countries directly involved in the conflict. Our main simulation assumes (i) that the Ukraine cannot import or export any agricultural products, or fertilizers and (ii) that Russia bans exporting wheat, rice, corn, other cereals, sugar, other oilseeds, and fertilizers to the world. These bans were well documented in the media. Among others, CNBC (2022), NPR (2022) and The Wall Street Journal (2022) have reported them. Export bans are conceptualized as prohibitive increases in transportation costs that push exports of banned products to zero.[11]

The remainder of this section is organized as follows; Section 4.2 presents the results of the simulations; Section 4.3 unpacks the mechanisms by which the Ukraine war has impacted household welfare in developing countries. Before doing that, we evaluate the goodness of fit of our model by assessing whether its predictions correlate with actual food price increases observed in developing country markets.

4.1 Goodness of Fit

The fact that the Ukraine-Russia war shock has already occurred can be exploited to assess the goodness of fit of our model. To do that, observed country and crop specific price changes are compared with price changes predicted by our model.

Observed price changes come from the FAO's Global Information and Early Warning System (GIEWS) Food Price Monitoring and Analysis (FPMA) dataset, which collects price changes for the most commonly consumed staple commodities. These data cover 19 different products that we can match to the harmonized HIT-ITPDE data for 37 out of the 51 HIT countries.[12] The sample is not balanced, i.e., the number of products covered varies across countries. In interpreting the goodness of fit results, it is important to bear in mind that our model abstracts from many relevant aspects of reality, such as uncertainty, stockpiling, and speculation, which influence the pricing of agricultural commodities.

Nonetheless, the model has strong predictive power, as is shown in Table 2. We report the results of regressions in which observed price changes are regressed on the price change predicted by our model. The observed price changes are computed as the the difference in average monthly price observed between April 2022 and January 2023 relative to the average monthly price observed between April 2021 and January 2022. We use a 10 month average to minimize the impact of seasonality and temporary price fluctuations.[13] All regressions include country fixed effects to account for differences

[11]The spectrum of potential simulations to run with our model is vast. To illustrate, we present in the Supplementary Material a number of additional complementary simulations. In particular, we examine the role of supply disruptions in Ukraine production and we explore the role of retaliatory protectionism by other countries.

[12]The concordance between the HIT-ITPD-E data and the WFP food prices dataset is presented in Table A6 in the Supplementary Material.

[13]February and March are excluded to minimize the impact of initial price spices which partially reflect elevated uncertainty. In robustness tests that are not presented here to conserve space but available upon request we verify that

in overall inflation association with country-specific conditions (such as monetary policy, exchange rate shocks etc.). The model predicted price changes have high explanatory power and strongly and significantly predict realized price changes. The coefficient on predicted price changes is 0.640. This coefficient rises to 0.752 once we exclude the top and bottom 1% of the observed price changes, as is done in column 2, and to 0.885 when they are winsorized at the 1% level, as is done in column 3. Note also that the explanatory power of the model improves when outliers are either excluded or winsorized.

Table 2: Goodness of Fit

Dependent variable	**Observed price change**					
Sample	All products			Selected products corn, wheat, rice, soya, sugar, and other cereals		
		No outliers	Winsorized		No outliers	Winsorized
	(1)	(2)	(3)	(4)	(5)	(6)
Predicted price change	0.640***	0.752**	0.885***	0.687**	0.989**	0.952**
	(0.185)	(0.156)	(0.203)	(0.231)	(0.234)	(0.241)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.319	0.415	0.367	0.674	0.732	0.696
Adj. R-squared	0.227	0.331	0.281	0.486	0.565	0.520
Obs.	311	295	311	102	92	102

Notes: *, **, and *** denote significance at the 10%, 5%, and 1% significance level respectively. Standard errors are reported in parentheses, and are clustered two ways, by country and product. All estimates are obtained using Ordinary Least Squares (OLS) estimation. Columns 1-3 present regressions for the entire sample of products for which we have price data, spanning 19 products from 37 different countries. The dependent variable is changes in average monthly prices observed between April 2022 and February 2023 versus April 2021 and February 2022. Note that these are annual averages excluding March, the first full month after the war started, to limit the impact of potential overshooting of initial price responses. Columns 4-6 present regressions for a selected sample of products, notably corn, wheat, rice, soya, sugar, and other cereals. Columns 2 and 4 present regressions in which observations in the top and bottom 1% of the realized price change distribution are excluded. Columns 3 and 6 present regressions in which price changes are winsorized at the 1% level.

The explanatory power of the model is even more striking when attention is confined to a subset of product categories—corn, wheat, rice, soya, sugar, and other cereals— less susceptible to measurement error due to being fairly homogeneous.[14] These results are reported in columns 4 through 6. The coefficient on model predicted price changes is 0.687 when raw data are used (column 4), rises to 0.989 once outliers are excluded (column 5) and is 0.952 when they are winsorized at the 1% (column 6). The model thus accurately predicts observed agricultural price responses to the Ukraine war.

the results are also robust to using different time windows.

[14]The other product categories are Beverages, Confectionery/Cocoa, Eggs/Meat/Dairy, fertilizers, fruits and vegetables, fish, other oilseeds, oils/fats, nuts, manufacturing, legumes, spices/herbs.

4.2 Results

The Ukraine war leads to substantial economic losses across developing countries.[15] This is expected. Our most striking result, however, is the massive heterogeneity in those welfare losses, which vary both across and within countries. This heterogeneity is shown in Figure 1. The top panel presents a kernel density of the real income gains associated with the war pooling all households in our sample. The bottom panel reports a "joyplot" of kernel densities for each country separately—sorted in order of their average gains (with the highest gains at the top). The collage of welfare effects is apparent in Figure 1. Table 3 presents the results by country. The overwhelming majority of households in our sample (96.49% of observations) experiences a reduction in their real incomes as a consequence of the war. The average loss across households is –2.06% and the standard deviation of losses is 2.12% (column 1). More than three quarters of all households experience losses in the range of –3 to 0 percent, but the distribution of losses is skewed and has a large left tail with the maximum loss incurred by a single household being –12.78% and the biggest gain being 0.40%. The largest losses are incurred by households living in countries located close to Russia such as Azerbaijan where average real income decreases by 10.41%, Mongolia (–9.31% reduction), Georgia (–7.08%) and Armenia (-6.51%). On the other end of the spectrum, the average income gains in Nepal and Pakistan are positive, albeit very small (0.14%).

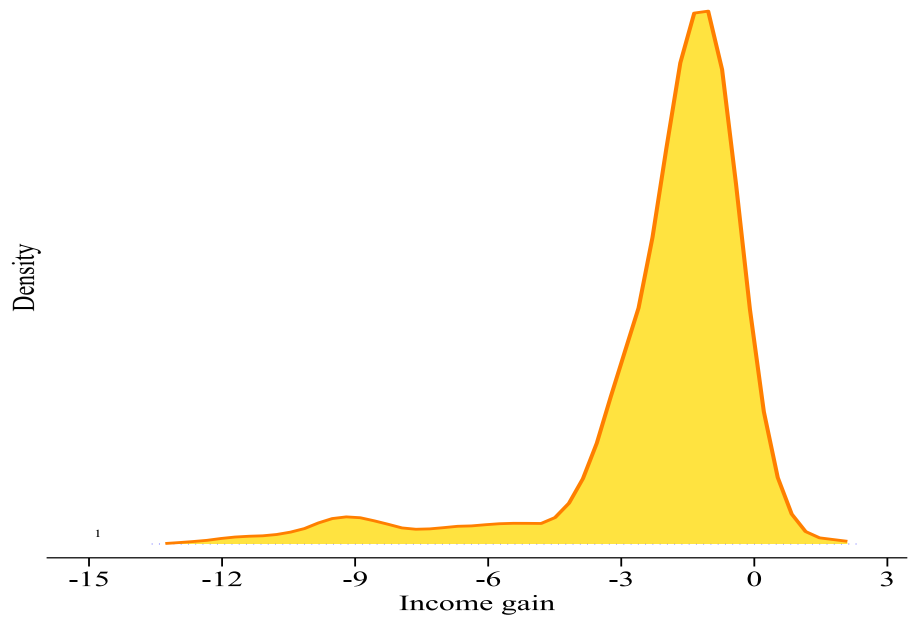
As striking as the large variation in gains across countries is the variation within countries. This pattern cannot be captured by most existing trade models based on a single aggregate agent. The within country heterogeneity can be seen in panel b) of Figure 1, which reveals the wide dispersion in the household welfare effects in each country and, in turn, how this dispersion varies across countries. In Azerbaijan for instance, all households lose from the war, but the span of losses range from –8.07% to –12.78%. In Togo, all households lose, too, but the range of losses goes from –1.64% to –0.97%. By contrast, in Pakistan, impacts are mixed. Just over half of the population (52%) loses real income, but the remainder gains because of the war and the impacts range from –1.07% to 1.60%. The dispersion of the welfare effects increases with their average. This has implications for inequality, and we explore those next.

A unique advantage of our approach is that it not only yields granular estimates of the distribution of impacts, but also allows us to pinpoint who these accrue to. In particular, since we have information

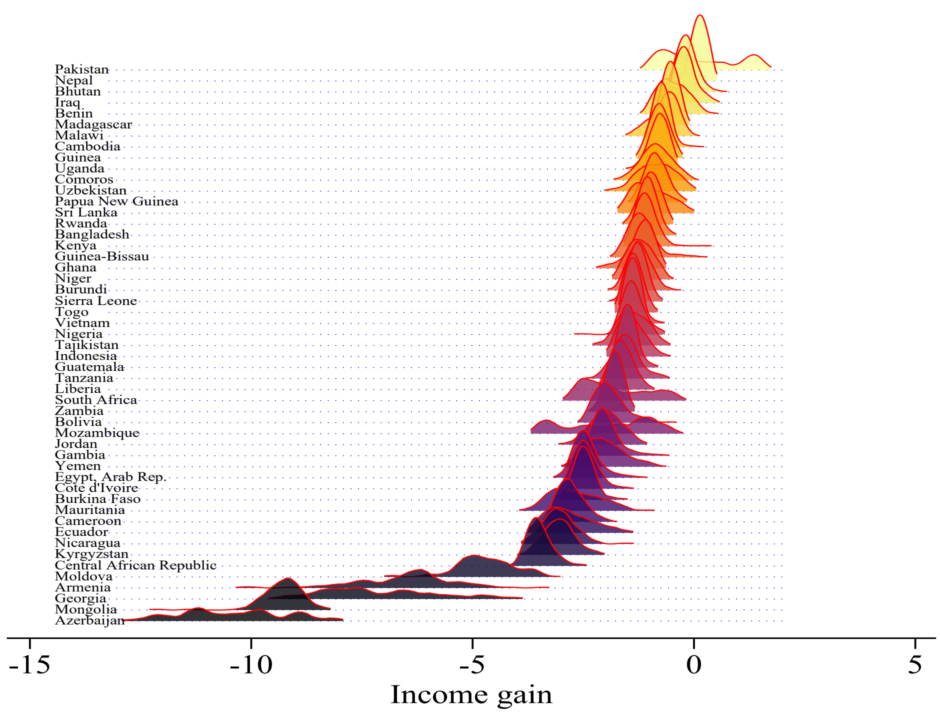
[15] It is important to emphasize that we study the economic consequences of the war in terms of real income/expenditure gains or losses. We do not discuss impacts on Ukranian households themselves, since they suffer from the war in a multitude of ways that our model does not capture.

Figure 1: Distribution of welfare effects of the Ukraine war

(a) Across countries



(b) By country



Notes: The top graph depicts the kernel density distribution of the estimated welfare impacts of the Ukraine war via its impacts on agricultural and fertilizer trade, expressed in real income gains (in percent), across all countries in our sample. The bottom graph presents kernel density graphs by country, sorting countries in terms of the average real income gain (in percent), with countries with the highest average gains, such as Nepal an Iraq at the top, and those with the lowest gains, such as Azerbaijan and Mongolia at the bottom. Darker shades denote greater average losses.

Table 3: Impact of the Ukraine war

	ΔWelfare				ΔIncome			ΔCPI	Exposure
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Imports
Panel A: All countries (pooled)									
Average	-2.06	-2.23	-1.81	-1.90	-0.10	-0.07	-0.18	2.02	5.42
Pop w. average	-1.33	-1.54	-1.02	-1.12	0.36	0.29	0.45	1.72	4.30
SD	2.12	2.41	1.91	2.05	1.63	1.23	2.26	1.25	5.35
Minimum	-10.41	-11.79	-9.27	-9.92	-7.11	-5.11	-8.74	0.03	0.30
Median	-1.38	-1.42	-1.33	-1.31	0.28	0.24	0.32	1.76	3.66
Maximum	0.14	0.06	1.35	0.89	1.84	1.81	2.60	8.24	19.97
Panel B: By country									
Azerbaijan	-10.41	-11.79	-8.90	-9.92	-7.11	-5.11	-8.68	3.70	18.25
Mongolia	-9.31	-9.69	-9.27	-9.20	-5.46	-3.73	-8.74	4.24	6.10
Georgia	-7.08	-8.29	-5.30	-6.22	-1.80	-1.50	-2.27	5.71	19.97
Armenia	-6.51	-7.91	-5.26	-5.98	1.17	0.91	1.72	8.24	17.85
Moldova	-4.72	-5.23	-4.02	-4.59	-3.59	-2.57	-6.59	1.18	17.72
Cent. Afr. R	-3.49	-3.19	-3.57	-3.55	-1.15	-1.18	-1.15	2.42	1.12
Kyrgyzstan	-3.04	-3.34	-2.72	-2.90	-0.69	-0.55	-0.90	2.43	11.60
Nicaragua	-3.04	-3.40	-2.60	-2.80	-1.50	-1.37	-1.66	1.59	1.42
Ecuador	-2.82	-3.40	-2.11	-2.45	-1.41	-1.25	-1.69	1.46	14.18
Cameroon	-2.78	-3.02	-2.43	-2.53	-0.99	-0.98	-1.00	1.83	0.63
Mauritania	-2.67	-3.23	-1.93	-2.22	-0.12	-0.13	-0.12	2.63	2.85
Burkina Faso	-2.48	-2.59	-2.36	-2.34	-1.27	-1.19	-1.30	1.24	1.36
Cote d'Ivoire	-2.45	-2.69	-2.14	-2.24	-1.32	-1.06	-1.39	1.16	4.09
Egypt	-2.42	-2.71	-2.02	-2.20	0.82	0.64	1.06	3.32	6.91
Yemen	-2.01	-2.50	-1.42	-1.65	0.49	0.42	0.60	2.56	3.76
Gambia	-1.99	-1.73	-1.96	-1.97	-0.14	-0.14	-0.13	1.89	2.13
Jordan	-1.98	-2.42	-1.54	-1.76	0.28	0.23	0.46	2.31	0.76
Mozambique	-1.95	-0.86	-3.28	-2.78	0.17	0.08	0.20	2.17	6.77
Bolivia	-1.90	-2.10	-1.45	-1.56	0.03	0.00	0.05	1.97	1.54
Zambia	-1.80	-1.92	-1.69	-1.73	0.57	0.43	0.77	2.41	2.96
South Africa	-1.78	-2.58	-0.73	-0.90	-0.06	-0.06	-0.05	1.76	3.66

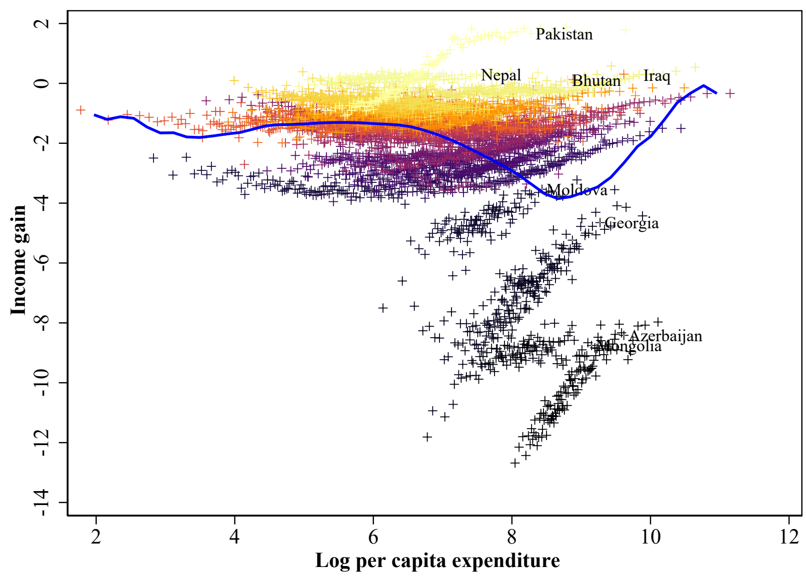
Notes: This table presents the results of a simulation in which (i) the Ukraine cannot import or export any agricultural products, or fertilizers and (ii) Russia bans exporting wheat, rice, corn, other cereals, sugar, other oilseeds, and fertilizers. Statistics in Panel A refer to average welfare impacts across countries. Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the (pre-war) status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single HH. denotes a representative household and presents the results of a single agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption. Exposure measures what share of imports of a given country were accounted for by imports from the Ukraine and Russia before the war. Countries are ordered in terms of average real income gains (from lowest to highest).

Table 3: Impact of the Ukraine war (continued)

	ΔWelfare				ΔIncome			ΔCPI	Exposure
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Imports
Liberia	-1.62	-1.42	-1.69	-1.66	0.30	0.25	0.32	1.95	1.70
Tanzania	-1.53	-1.73	-1.26	-1.26	-0.32	-0.30	-0.35	1.23	5.04
Guatemala	-1.48	-1.47	-1.33	-1.38	0.05	0.04	0.08	1.55	1.02
Indonesia	-1.42	-1.69	-1.08	-1.20	-0.17	-0.15	-0.27	1.27	2.62
Tajikistan	-1.38	-1.27	-1.49	-1.39	0.65	0.64	0.70	2.06	9.41
Nigeria	-1.38	-1.16	-1.42	-1.40	0.40	0.32	0.48	1.80	2.11
Vietnam	-1.37	-1.36	-1.25	-1.31	-0.05	-0.05	-0.04	1.34	2.72
Togo	-1.37	-1.23	-1.35	-1.34	0.25	0.28	0.25	1.64	2.90
Sierra Leone	-1.27	-1.30	-1.28	-1.24	0.62	0.47	0.64	1.91	4.12
Burundi	-1.23	-1.24	-1.01	-1.08	0.40	0.31	0.42	1.65	4.74
Niger	-1.21	-0.90	-1.45	-1.30	0.28	0.24	0.30	1.52	5.40
Ghana	-1.19	-1.55	-0.95	-1.02	-1.16	-1.02	-1.73	0.03	3.23
Guinea-Bissau	-1.17	-1.30	-0.81	-0.80	0.90	0.86	0.92	2.09	3.65
Kenya	-1.07	-1.03	-0.92	-0.84	0.99	0.89	1.12	2.09	4.81
Bangladesh	-1.04	-1.18	-0.85	-0.94	0.72	0.52	0.84	1.77	4.65
Rwanda	-0.98	-1.18	-0.78	-0.86	-0.05	-0.08	-0.00	0.94	1.77
Sri Lanka	-0.97	-1.43	-0.43	-0.60	0.20	0.14	0.30	1.19	15.57
Papua N.G.	-0.85	-0.77	-0.85	-0.80	0.97	0.70	1.09	1.83	1.29
Uzbekistan	-0.85	-0.63	-1.29	-1.02	1.31	0.23	2.47	2.18	17.31
Comoros	-0.85	-0.92	-0.83	-0.80	1.42	1.28	1.50	2.29	0.30
Uganda	-0.79	-0.85	-0.91	-0.82	0.42	0.38	0.45	1.22	2.13
Guinea	-0.78	-0.61	-0.89	-0.81	0.85	0.68	0.87	1.65	0.96
Cambodia	-0.72	-0.75	-0.61	-0.62	0.55	0.37	0.66	1.27	3.32
Malawi	-0.66	-0.41	-1.05	-0.87	0.45	0.36	0.51	1.12	8.34
Madagascar	-0.53	-0.46	-0.64	-0.53	0.80	0.66	0.87	1.34	0.59
Benin	-0.48	-0.10	-0.81	-0.65	0.97	0.82	1.04	1.45	1.75
Iraq	-0.18	-0.19	0.05	-0.05	1.50	1.02	2.60	1.68	4.14
Bhutan	-0.16	-0.12	0.04	-0.01	1.18	1.05	1.44	1.34	3.80
Nepal	0.14	0.06	0.20	0.18	1.82	1.81	1.85	1.68	7.72
Pakistan	0.14	-0.82	1.35	0.89	1.84	1.67	2.25	1.70	3.77

Notes: This table is a continuation from the table on the previous page. It presents the results of a simulation in which (i) the Ukraine cannot import or export any agricultural products, or fertilizers and (ii) Russia bans exporting wheat, rice, corn, other cereals, sugar, other oilseeds, and fertilizers. Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the (pre-war) status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single HH. denotes a representative household and presents the results of a representative agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption. Exposure measures what share of imports of a given country were accounted for by imports from the Ukraine and Russia before the war. Countries are ordered in terms of average real income gains (from lowest to highest).

Figure 2: Impact of the Ukraine war versus initial income - by country

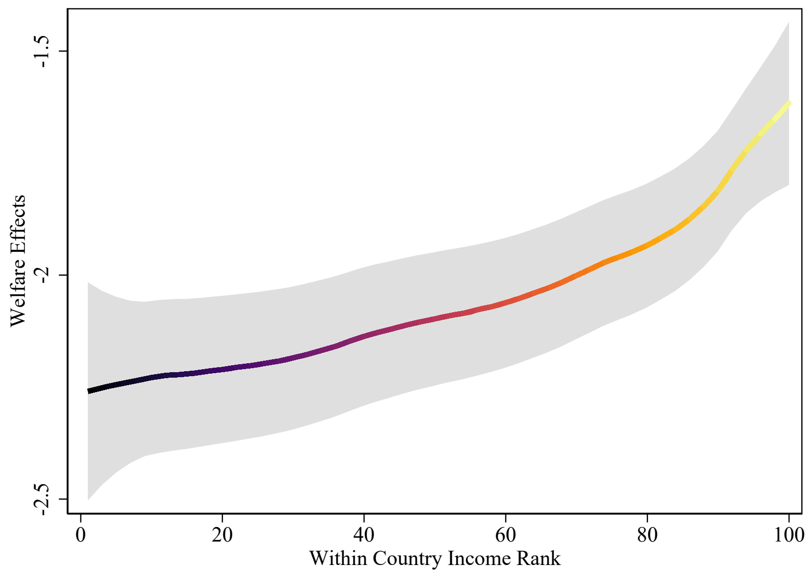


Notes: The graph plots the estimated welfare impacts of the Ukraine war via its impacts on agricultural and fertilizer trade, expressed in real income gains, across all countries in our sample against pre-war log per capita expenditure. Each observation (denoted by a "+") represents an income percentile in a different country. Each country is demarcated by a different color - with lighter colors denoting higher average gains. The blue line is a fitted polynomial line.

on each household's per capita expenditure, we can examine how much households in different parts of the income distribution gain or lose. Figure 2 presents country-specific scatter plots of real income gains against the pre-war log of household expenditure per capita (in real 2010 USD) using all observations in our data. Recall that each observation presents a percentile of the population in a particular country. The graph illustrates the collage of welfare effects and their distribution across the income spectrum. It shows losses across the entire income distribution of low- and middle-income countries. However, the heaviest losses show up towards the right tail because the countries with the highest losses tend to have higher per capita incomes (relative to the other countries in our sample) as well. A local polynomial regression of real income gains versus log per capita expenditure exhibits a roughly V-shaped pattern. By implication inequality across the developing world decreases due to the war.

Domestic inequality does not follow the same pattern. In fact, we find that, within countries, poor households tend to incur the largest losses. This is illustrated in Figure 3 which presents a local polynomial plot of welfare gains against households' rank in their country's own income distribution, with rank 1 being the bottom percentile and rank 100 being the top percentile. The graph is clearly upward sloping. On average households at the bottom of the income distribution suffer larger losses than households at the top. The losses for the bottom 25% (-2.2% on average) are 23% higher than

Figure 3: Impact of the Ukraine war versus initial income



Notes: The graph depicts a local polynomial fitted line of the percentage change in welfare, measured as real income, associated with the Ukraine war's impact on agricultural and fertilizer trade against a household's rank in the initial per capital income distribution, with rank 100 denoting the richest percentile and rank 1 denoting the poorest percentile. The shaded area depicts the 95% confidence interval. Darker colors depict larger average losses.

the losses for the top 25% (-1.8% on average). See columns 2 and 3 of Table 3. On average, within country inequality increases.

One merit of our model is that by featuring household heterogeneity, we can measure the aggregate welfare effects with more precision than single-household models. This is because the average welfare impact across heterogeneous households making different production and consumption decisions does not coincide with the welfare impact for a single household characterized by aggregate level data. There are two drivers of this bias. The structure of the crop production technology and of preferences prevents linear aggregation of the individual household welfare effects. On top of that, the differences in household choices from the choice of a single household affect the equilibrium of the model (because household heterogeneity interacts with the international trade linkages in equilibrium—see also section 4.3). We show this bias formally and discuss the mechanisms underpinning it in the supplementary material A3. In the case of the Ukraine war, the bias is 7.77% on average. Column 4 of Table 3 presents the average welfare effects calculated from a version of our model based on a single household for each country.[16] According to this model the average loss across countries is –1.90%, which is

[16]This single household is characterized by the country-level aggregate land and labor allocation shares as well as by the budget shares of the median household in HIT.

7.77% smaller than the average loss estimates based on heterogeneous households (-2.06%). There are, however, instance where the bias is much bigger. Some notable examples are Bhutan, Iraq, South Africa, Mozambique, and Pakistan.

4.3 Mechanisms

The impact of the Ukraine war on a given household depends on two interconnected factors. First, it hinges on the trade relationship between the country in which the household resides and Russia and Ukraine. This relationship shapes the localized price impacts resulting from the conflict. Second, the impact is influenced by the household's consumption, land, and labor allocation choices, which determine how much the local price responses affect its real income. We will refer to the former as the "trade channel" and the latter as the "household choices channel". These mechanisms are intertwined, and jointly determine the impact of the war on a given household.

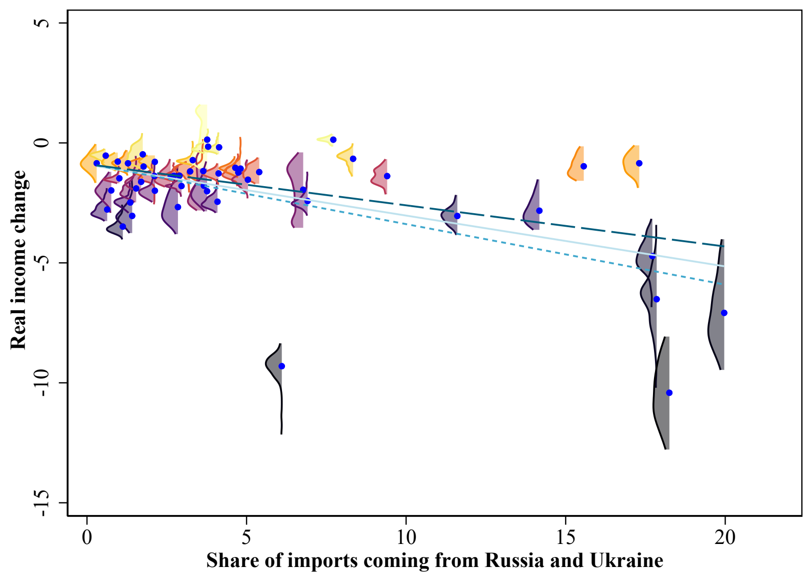
The trade channel is shown in panel a) of Figure 4. This graph depicts the welfare impacts against the pre-war exposure measured by the share of imports coming from Russia and the Ukraine. We plot the average welfare effect for each country against exposure with a blue dot; we also plot the distribution of estimated welfare impacts (the kernel densities) against exposure. The fitted line between the average welfare effects and exposure is negatively sloped, indicating that the average losses are larger in countries that imported more from Russia and the Ukraine before the war started. As shown above, these are generally the highest income countries in the sample so that the trade mechanism explains the overall increase in inequality across the developing world uncovered in the previous section.

Inspection of the relationship between the kernel densities and trade exposure reveals that the countries with the largest average losses also have a more unequal distribution of such losses. This can be seen by noticing that the density plots of the distribution of the gains widen with reliance on imports from the countries at war. The trade mechanism thus drives the within country increase in inequality as well. As an alternative way of showing this, we also plot in panel a) of Figure 4 fitted lines of the average impact of the top 25% richest (the long-dashed dark blue line) and bottom 25% poorest (the short-dashed light blue line) households against exposure. The line reflecting losses for the bottom 25% is always below the one reflecting losses for the top 25% and, importantly, more steeply downwards sloping; the Ukraine war tends to widen income disparities. Greater reliance on imports from the two countries at war is not only associated with reduced incomes but also with exacerbated inequality.

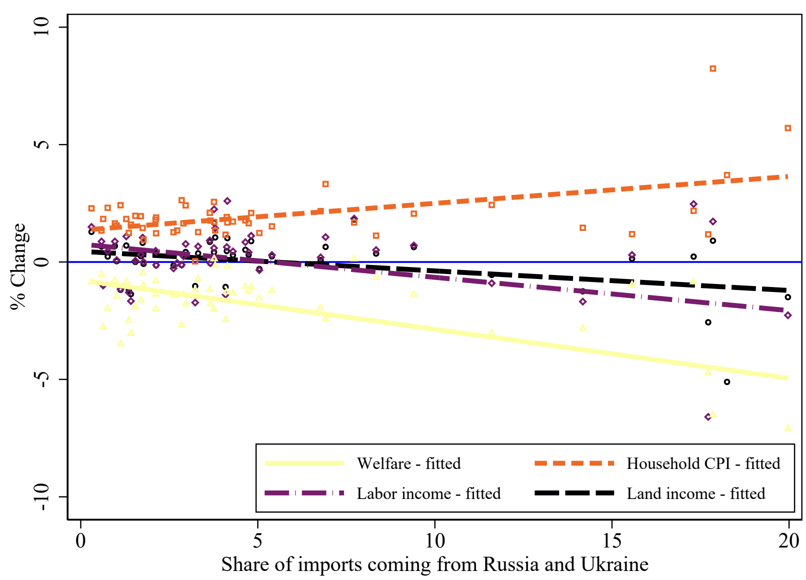
The household choices channel refers to how these choices shape the transformation of shocks into

Figure 4: Impacts by reliance on imports from Russia and the Ukraine

(a) Distributional and average impacts by exposure



(b) Channels of impact by exposure



Notes: The top graph plots the estimated distribution of welfare impacts, proxied by real income changes, of the Ukraine war (via its impacts on agricultural and fertilizer trade) against exposure proxied by the pre-war share of a country's total imports coming from Russia and the Ukraine. Blue dots denote average impacts by country. The bottom graph depicts average income effects, changes in the Consumer Price Index, changes in land income and changes in labor income against exposure proxied by the pre-war share of a country's total imports coming from Russia and the Ukraine.

impacts on real expenditures. Consumption choices are captured by the household expenditure pattern, which determines how much changes in consumer prices impact household real income. Land and labor allocation choices are captured by the household income portfolio, which determines how changes in producer prices and input (fertilizer) costs impact household real income. The role of household choices is shown in panel b) of Figure 4 which plots average welfare gains, and its constituent components (changes in consumer prices, land income and labor income), against the pre-war share of imports coming from the Ukraine and Russia.

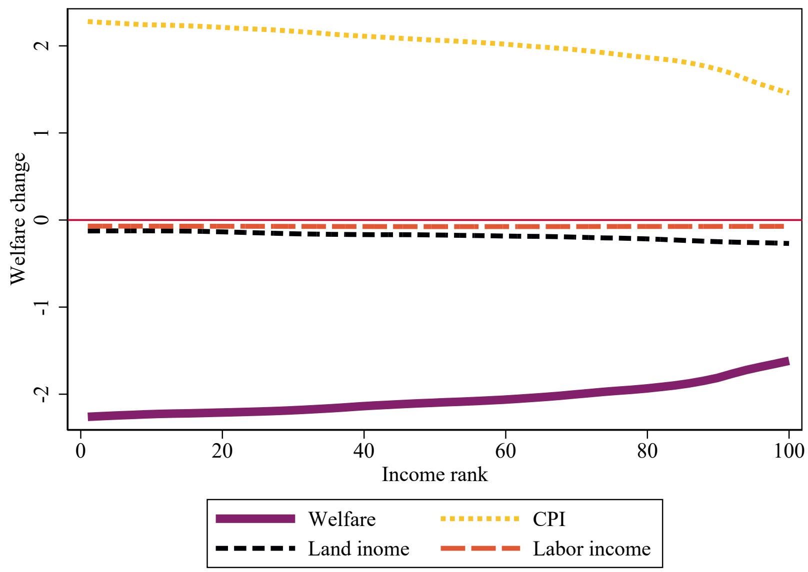
The war increases in consumer prices which result in an increase in the household CPI. The fitted line of the average household CPI effect for each country against trade exposure is depicted in orange. This channel creates welfare losses for all countries. The war also triggers increases in both crop and fertilizer prices, which result in (ambiguous) welfare effects on profits. The fitted line of the average land and labor income effects net of fertilizer costs against exposure are depicted with long dashes and dots (the purple line), and with long dashes only (the black line) respectively. For most countries, we find average welfare losses via both the land and labor income effects because the increase in input costs dominates the increase in the value of sales.[17]

It is important to note that the three channels are particularly pronounced in countries highly reliant on trade with the Ukraine and Russia. This can be seen in the upward sloping fitted lines for the household CPI, the land income and the labor income effects. The trade mechanism thus operates on—and interacts with—the three household choice mechanisms.

Within countries the welfare effects also vary substantially, and are also primarily a function of initial consumption and income portfolios. The net reduction in real incomes is larger for poor than for rich households. This is shown in Figure 5, which depicts average welfare changes and the mechanisms that modulate these changes, against the household's rank in their own country's income distribution. To start with, rich households are less impacted by increases in the cost of consumption, as the orange line, which depicts the average impact of the war on real expenditure, shows. On average higher prices lead to a reduction in real incomes of 2.02%, but the burden of inflation is unevenly distributed. The bottom 25% poorest households see their real incomes erode by 2.24% on average

[17]We explored this in more detail by running two additional simulations in which respectively only trade in agricultural goods and only trade in fertilizers are banned. The results are reported in section A5 in the Supplementary Material. In the former case, labor and land income effects are positive; higher profits for farmers partially offset the deleterious effects of higher food prices. By contrast, in a scenario in which only trade in fertilizers is restricted the land and labor effects are even more negative. The negative impacts on land and labor income are thus due to the increase in the cost of fertilizers. Households also partially mitigate the shock by changing their income earning portfolio, choosing different crops and different wage jobs, but this type of adjustment is quantitatively limited in the case of the Ukraine shock since on only 0.55% of households change their crop choice (i.e. land income) and 0.72% their wage income.

Figure 5: Impact of the Ukraine war versus initial (within-country) income rank



Notes: The graph presents the percentage change in welfare, measured as real income, associated with the Ukraine war (via its impacts on agricultural and fertilizer trade) against a household's rank in the initial per capita income distribution, with rank 100 denoting the richest percentile and rank 1 denoting the poorest percentile.

whereas the reduction experienced by the richest quartile is 1.72% since they spend proportionately less on food items. Inflation is thus disequalizing. Second, households experience a reduction in their labor incomes, depicted by the dashed black line, which is quantitatively small on average, notably -0.07% of their pre-war labor income, and appears to be distributionally neutral. Third, households suffer a reduction in their income from land equivalent to -0.18% of their pre-war land income on average. This reduction is larger for richer households which have more land; on average households in the top income quartile experience a reduction in their land income equivalent to 0.24%, whereas households in the bottom income quartile lose 0.12% of their incomes on average. The land income effect thus partially offsets the disequalizing effects of higher consumer prices, but since the expenditure effects are an order of magnitude larger than the income effects, the overall impact of the Ukraine war tends to be disequalizing.

To summarize, the Ukraine war leads to a surge in food and fertilizer price inflation which our model accurately predicts. These price hikes adversely impact household welfare in low- and middle-income countries hitting those who relied most on imports from the Ukraine and Russia the hardest. Within countries, impacts are highly heterogeneous and disequalizing on average, with the poor bearing the brunt of the shock, primarily because they spend a bigger share of their net budgets on food items.

While higher prices benefit farmers, their income gains are largely offset by higher fertilizer costs. The losses for households in the bottom income quartile are on average 23.20% larger than those for households in the top income quartile.

5 Agriculture and Climate Change

An arguably much more potent shock to agriculture than the Ukraine war is climate change. By impacting temperature, precipitation and wind patterns, humidity, soil degradation and other environmental factors, climate change is influencing yields across the globe, with highly uneven impacts both across countries and crops. The resulting changes in the relative productivity of different crops in turn impact prices, comparative advantage and production patterns. In this section we study the impact of climate change on household well-being and on the income distribution in developing countries.

Following Costinot, Donaldson, and Smith (2016) we use GAEZ data to examine the implications of climate change for the productivity of different crops. Specifically, we focus on the main scenario adopted by the UN's Intergovernmental Panel on Climate Change (IPCC), the FAO GAEZ Hadley CM3 A1 model. This model predicts a future world of accelerated economic growth and also accounts for the introduction of more efficient fossil technologies. We adjust the productivity of land given the predictions of this model, and simulate its impact on household welfare across developing countries. By comparing households' real incomes, consumption, land and labor allocations in this counterfactual scenario with their observed choices we can quantify the likely impact of climate change.

Our experiments complement Costinot, Donaldson, and Smith (2016) in two ways. First and foremost we quantify heterogeneity in the impact of climate change *within* countries. We examine in which countries climate change exacerbates inequality, which households adjust their land and crop choices and by how much they do so. Second, their focus is on 50 countries which are the top agricultural producers and account for almost 90% of global agricultural output. This paper focuses instead on the implications of climate change for low-income countries. Because our target countries are specialized in climate-sensitive sectors such as agriculture, have less resilient infrastructure and lower investment capacity in adaptation and mitigation, we focus on households that are arguably more vulnerable to climate change and suffer larger productivity shocks.[18]

[18] Only 18 of the countries in our sample are included in the analysis of Costinot, Donaldson, and Smith (2016)

5.1 Results

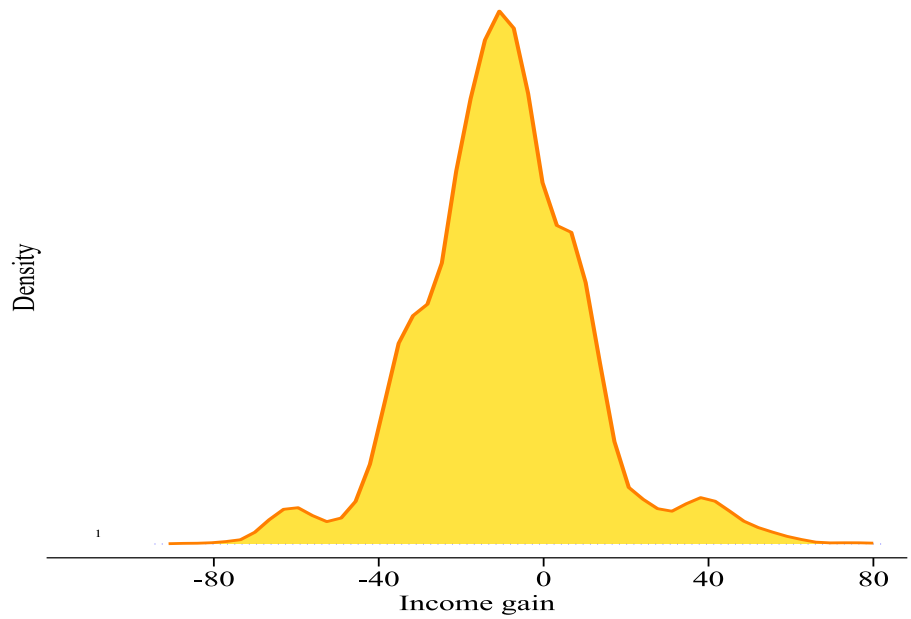
Climate change has much larger, and much more variable effects on welfare than conflict. This is because it impacts a much broader set of products than the Ukraine war and has very sizable productivity effects, as is shown in Table 4 which presents the results. The majority of countries in our sample, 39 out of 51, is projected to have substantially lower yields, but the remainder gain. Productivity changes range from a minimum of -63.43% in Cambodia to a maximum of 259.88% in Mongolia. Across countries the median change in productivity is -37.81% and the average is -17.41%. Productivity impacts thus vary considerably across space.

The collage of household-level welfare effects of these climate change productivity changes is presented in Figure 6. Panel a) displays the density plot of estimated gains pooling all households in our sample, whereas panel b) presents "joyplot" estimates of the distribution of gains by country. The country-specific impacts are also presented in Table 4. On average households in our sample see their incomes decline by 9.72% but the standard deviation of the estimated average welfare effects across countries large, notably 19.96%. At the household level, they range from a minimum –87.47% to a maximum of 76.47% . The majority of households in our sample suffers very sizable losses due to negative productivity shocks. A striking 28.02% of households, however, are expected to gain real income because of increased agricultural yields. The average real income gains are negative in 37 out of 51 countries in our sample. Countries located close to the equator, where average temperatures are already high, such as Guinea Bissau, the Gambia, Cote d'Ivoire, Central African Republic, Nigeria, Mozambique, Bolivia and Papua New Guinea experience average losses exceeding 30.00%. By contrast, average gains in Kenya, Tajikistan, Madagascar, Kyrgystan, Rwanda and Mongolia exceed 10.00%.

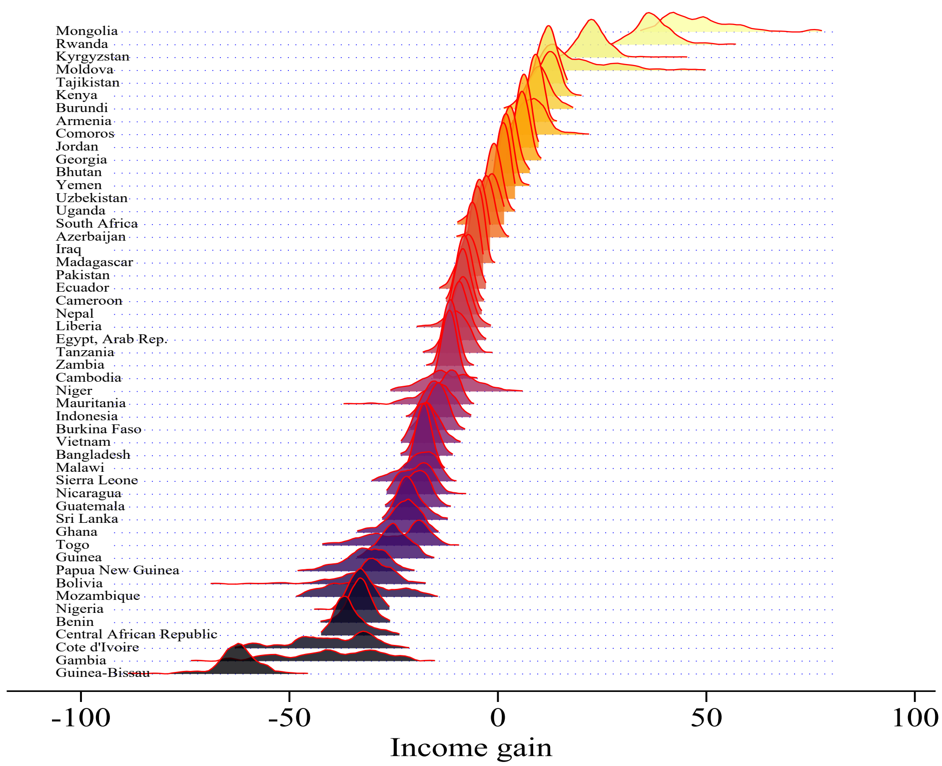
Within countries, gains vary a lot, as is shown in panel b) of Figure 6. On average the range between the smallest and the largest gain within a country is 16.86%. To illustrate the wide disparities, note the cases of Guinea-Bissau and The Gambia where all household lose from climate change, with losses ranging from -87.47% to -46.80% and -72.36% to -16.34% respectively. In Bangladesh, there are widespread losses, but they are less dispersed ranging from -22.11% to -12.06% of real household income. By contrast, in Mongolia all households gain, with real income growth rates ranging from 35.38% to 76.47%, while in Kenya, everybody gains, but with less dispersed welfare effects (with income gains ranging from 5.87% to 18.82%). In places like Uzbekistan or Yemen, there are instead winners and losers from climate change. Within-country heterogeneity in the impact of climate change is thus of first order importance.

Figure 6: Distribution of the effect of climate change

(a) Across countries



(b) By country



Notes: The top graph depicts the kernel density distribution of the estimated welfare impacts of climate change, expressed in percentage changes in real household income relative to the status quo, across all countries in our sample. The bottom graph presents kernel density graphs by country, sorting countries in terms of their average real household income gains, with countries with the highest average gains, such as Mongolia and Rwanda at the top, and those with the lowest gains, such as Gambia and Guinea-Bissau at the bottom. Darker shades denote greater average losses.

Table 4: Impact of Climate Change

	ΔWelfare				ΔIncome			ΔCPI	Exposure
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Yield
Panel A: All countries (pooled)									
Average	-9.72	-11.60	-8.06	-8.64	-9.55	-8.24	-10.18	-0.05	-17.41
Pop w. average	-13.06	-15.10	-10.95	-11.86	-11.62	-9.32	-15.62	1.79	-29.48
SD	19.96	22.41	18.18	18.97	20.91	17.99	25.03	3.80	54.81
Minimum	-62.70	-67.17	-62.00	-61.90	-66.54	-64.27	-67.96	-10.32	-63.43
Median	-9.83	-10.69	-8.06	-8.82	-10.59	-9.24	-12.17	0.55	-37.81
Maximum	48.41	46.49	53.64	51.70	44.18	36.73	68.29	8.46	259.88
Panel B: By country									
Guinea-Bissau	-62.70	-67.17	-62.00	-61.90	-66.54	-64.27	-67.96	-10.32	-49.20
Gambia	-40.26	-54.73	-28.93	-33.41	-45.52	-45.56	-45.32	-8.78	-39.38
Cote d'Ivoire	-40.05	-52.75	-29.96	-33.95	-45.79	-35.61	-48.66	-9.34	-44.56
Cent. Afr. R.	-35.36	-37.47	-31.24	-32.43	-34.74	-31.49	-34.79	1.02	-45.67
Benin	-33.32	-34.08	-31.34	-31.72	-34.22	-30.06	-36.65	-1.34	-51.84
Nigeria	-32.83	-35.54	-30.05	-31.16	-27.22	-22.93	-31.88	8.46	-55.76
Mozambique	-32.73	-38.74	-22.34	-27.55	-29.93	-17.32	-34.56	4.16	-56.44
Bolivia	-32.16	-41.46	-26.88	-28.52	-33.21	-26.51	-38.43	-1.16	-62.51
Papua N.G.	-32.00	-36.73	-27.51	-29.73	-32.34	-22.73	-36.69	-0.47	-56.92
Guinea	-24.85	-28.38	-20.54	-23.05	-25.49	-20.60	-26.12	-0.83	-49.97
Togo	-24.05	-33.08	-17.01	-19.61	-25.71	-28.16	-24.42	-2.17	-47.94
Ghana	-22.61	-27.08	-19.77	-20.52	-28.65	-25.42	-43.86	-7.76	-47.54
Sri Lanka	-21.14	-22.97	-17.83	-18.90	-24.45	-18.58	-33.47	-4.17	-58.42
Guatemala	-19.52	-22.76	-16.57	-18.22	-19.18	-18.30	-20.38	0.48	-42.48
Nicaragua	-19.24	-22.63	-16.00	-17.47	-18.70	-16.10	-21.92	0.73	-49.02
Sierra Leone	-19.01	-20.60	-15.80	-17.45	-22.07	-16.95	-22.99	-3.79	-51.21
Malawi	-17.78	-16.91	-17.77	-17.66	-16.34	-13.09	-18.20	1.76	-43.61
Bangladesh	-17.06	-19.22	-14.80	-16.28	-16.52	-12.00	-19.40	0.67	-55.24
Vietnam	-16.96	-19.61	-13.83	-15.67	-14.13	-9.60	-17.72	3.45	-50.27
Burkina Faso	-14.63	-14.08	-13.67	-14.01	-16.22	-14.68	-16.75	-1.85	-48.71
Indonesia	-14.21	-17.11	-10.54	-12.10	-11.90	-9.82	-24.87	2.74	-42.56
Mauritania	-14.18	-17.63	-13.88	-13.78	-12.85	-10.86	-13.16	1.56	-52.64

Notes: This table presents the results of a simulation of the impacts of climate change based on the FAO GAEZ Hadley CM3 A1 model. Welfare changes and changes in income are expressed as percentage changes in real household income relative to the status quo. Statistics in Panel A refer to average welfare impacts across countries. Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single HH. denotes a representative household and presents the results of a single agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption. Exposure refers to the change in agricultural productivity (i.e. crop yields) relative to the status quo. Countries are ordered in terms of average real income gains (from lowest to highest).

Table 4: Impact of Climate Change (continued)

	ΔWelfare				ΔIncome			ΔCPI	Exposure
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Yield
Niger	-11.80	-12.95	-15.19	-13.48	-12.72	-12.31	-13.32	-1.02	-36.30
Cambodia	-11.53	-11.71	-10.63	-10.95	-5.32	-3.37	-6.64	7.04	-63.43
Zambia	-11.41	-11.92	-10.17	-10.80	-6.65	-4.80	-9.12	5.38	-39.72
Tanzania	-9.83	-10.33	-8.06	-8.82	-10.59	-9.24	-12.17	-0.83	-30.77
Egypt	-8.89	-10.69	-6.57	-7.99	-6.40	-4.98	-8.37	2.75	-13.12
Liberia	-8.72	-10.15	-7.92	-7.84	-13.03	-11.57	-13.76	-4.72	-46.36
Nepal	-8.35	-9.50	-6.76	-7.38	-12.05	-11.97	-12.26	-4.03	-26.67
Cameroon	-8.05	-8.67	-6.68	-6.98	-4.28	-4.17	-4.36	4.11	-37.81
Ecuador	-7.39	-9.78	-5.30	-6.46	-6.89	-5.77	-8.73	0.55	-36.91
Pakistan	-6.20	-7.42	-5.85	-5.39	-5.37	-4.87	-6.45	0.90	10.12
Madagascar	-4.90	-5.29	-4.20	-4.78	-2.14	-1.62	-2.41	2.91	-25.79
Iraq	-4.49	-5.96	-3.47	-3.95	-4.19	-2.83	-7.31	0.32	13.21
Azerbaijan	-2.94	-4.01	-3.09	-2.57	-2.14	-1.11	-2.91	0.83	-30.48
South Africa	-2.43	-5.68	-0.18	-0.72	-1.04	-0.94	-8.11	1.46	-19.67
Uganda	-0.88	-0.44	-1.01	-0.65	0.97	1.29	0.79	1.87	-11.27
Uzbekistan	1.30	1.22	1.97	1.41	-0.39	1.20	-2.09	-1.67	-4.65
Yemen	2.02	1.65	2.35	2.24	1.38	1.19	1.60	-0.62	0.00
Bhutan	3.02	4.62	1.75	2.72	1.59	1.12	2.54	-1.38	-8.69
Georgia	5.84	6.94	4.56	5.21	4.25	3.76	5.11	-1.49	1.21
Jordan	6.25	7.23	5.19	5.60	4.39	3.78	6.52	-1.75	31.51
Comoros	8.58	11.28	6.07	8.04	6.98	6.63	7.28	-1.42	-8.79
Armenia	9.00	9.37	7.78	8.51	10.40	8.69	14.12	1.28	65.79
Burundi	9.77	9.93	9.09	8.85	14.24	10.23	14.62	4.09	28.24
Kenya	11.95	13.76	8.97	9.60	13.94	12.47	15.90	1.80	7.06
Tajikistan	12.02	13.35	10.71	10.69	14.86	14.74	15.27	2.55	6.07
Moldova	19.55	23.60	14.32	19.42	23.55	16.01	44.71	3.36	41.05
Kyrgyzstan	23.26	26.05	20.31	22.76	26.25	20.94	34.54	2.45	91.96
Rwanda	37.54	37.88	35.48	36.38	40.97	36.73	45.92	2.51	98.05
Mongolia	48.41	46.49	53.64	51.70	44.18	31.20	68.29	-2.87	259.88

Notes: This table is a continuation from the table on the previous page.It presents the results of a simulation of the impacts of climate change based on the FAO GAEZ Hadley CM3 A1 model. Welfare changes and changes in income are expressed as percentage changes in real household income relative to the status quo. Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single HH. denotes a representative household and presents the results of a single agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption. Exposure refers to the change in agricultural productivity (i.e. crop yields) relative to the status quo. Countries are ordered in terms of average real income gains (from lowest to highest).

To assess the inequality impacts of climate change, we present in Figure 7 a scatter plot of the corresponding welfare impacts against present day (log) per capita expenditure pooling all countries in our sample (each demarcated with a different color). Across the low- and middle-income countries in our sample the poor lose more than the middle-class or the (comparatively) rich. This is because poor countries are more likely to suffer productivity losses and because, among these countries, poorer households suffer larger losses than richer ones: the bottom income quartile experiences a 21.59% reduction in their real incomes, while the top income quartile loses 15.90% of their incomes. Intriguingly, in countries that benefit from climate change-induced productivity improvements, the opposite pattern prevails; the poor gain more than the rich, with the bottom quartile experiencing an average real income gain of 14.20% whereas the top quartile enjoys a 12.08% increase in their real incomes. Put differently, the impact of climate change is more pronounced for the poor.[19] Climate change exacerbates inequality in countries suffering income losses, but reduces inequality in countries experiencing gains.

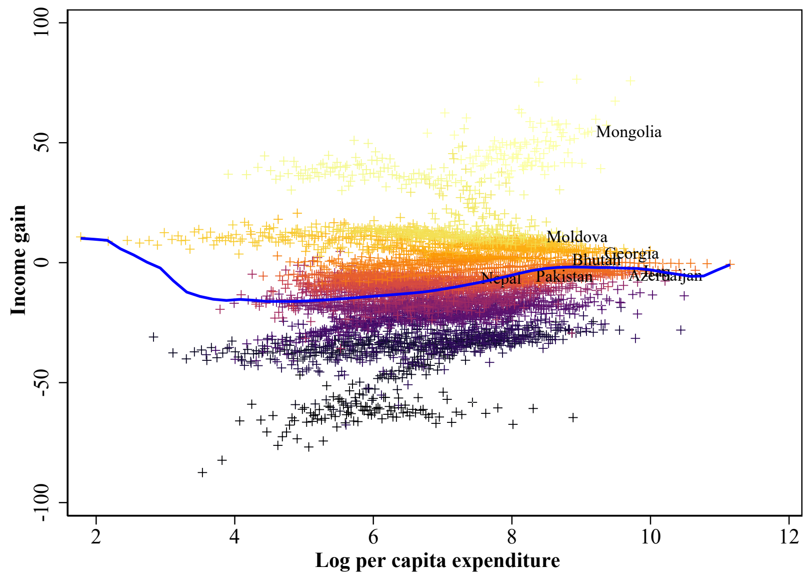
The biases in single-household models are bigger in the case of climate change (see column 4 of Table 4). Solving the model with only one household in each country, the average worldwide loss would be –8.64%, which is 11.11% smaller than our estimate (–9.72% in column 1). The reason is that the climate change shock is bigger and more widespread, with consequently more varied effects across countries and households. As expected, there are cases with big biases, such as Uganda, Mozambique, Comoros and Gambia.

5.2 Mechanisms

This section unpacks the mechanisms by which climate change impacts household welfare in developing countries. As before, we investigate the interrelationship between the direct productivity impacts of climate change and the choices of households. The primary driver of differences in the impact of climate change across countries are its projected productivity impacts. In panel a) of Figure 9, we inspect the correlation between the country-wide change in average incomes (blue dots) against the country-wide change in average productivity (measured with the simple average across crops). This association is clearly positive, as shown by the light blue solid line. Countries that become more productive in agriculture as a consequence of climate change tend to gain more, whereas those who suffer productivity losses tend to lose more too. We also plot, for each country, the kernel density of the distribution of welfare impacts against the country's productivity growth. This shows that the within-country variance in income gains widens as average impacts increase; countries exhibiting the

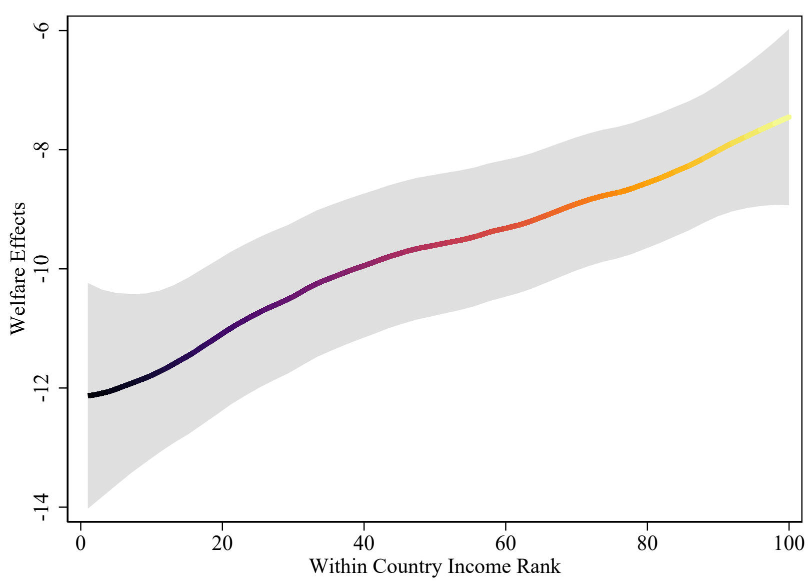
[19]Note that the variance in welfare impacts decreases moving from the left to the right of the graph.

Figure 7: Impact of climate change versus initial income - by country



Notes: The top graph depicts the kernel density distribution of the estimated welfare impacts of climate change, expressed in real income gains, across all countries in our sample against current log per capita expenditure. Each observation (denoted by a "+") represents an income percentile in a different country. Each country is demarcated by a different color - with lighter colors denoting higher average gains. The blue line is a fitted polynomial line.

Figure 8: Impact of climate change versus initial (within-country) income rank



Notes: The top graph depicts the kernel density distribution of the estimated welfare impacts of climate change, expressed in real income gains, across all countries in our sample against current log per capita expenditure. Each observation (denoted by a "+") represents an income percentile in a different country. Each country is demarcated by a different color - with lighter colors denoting higher average gains. The blue line is a fitted polynomial line.

largest gains and losses also tend to exhibit a larger variation in gains.

In particular, the productivity changes induced by climate change disproportionately impact the incomes of poor households: The incomes of households in the bottom quartile of their respective country's income distribution, as depicted by the blue short-dashed line, are more responsive to productivity changes compared to those of their counterparts in the richest quartile, represented by the dark blue long-dashed line. Countries in which climate change leads to improved productivity tend to enjoy pro-poor growth, characterized by rising average incomes and reduced income inequality. However, climate change more typically reduces agricultural productivity. The majority of countries therefore suffer income losses and exacerbated inequality as a consequence of global warming.

In panel b) of Figure 9 we study the role of household consumption and factor allocation choices. We plot land income changes, labor income changes and changes in the household-specific CPI against the projected productivity changes. These plots show that the productivity changes correlate positively with both household labor and land income changes. By contrast changes in productivity are not correlated with changes in the Consumer Price Index. This is because productivity shocks directly impact household incomes (via their impact on the household production function), while the price effect depends on the trade equilibrium, which is influenced by productivity shocks in all countries. Unlike the Ukraine conflict, climate change's welfare effects are mainly driven by income changes rather than expenditure effects.

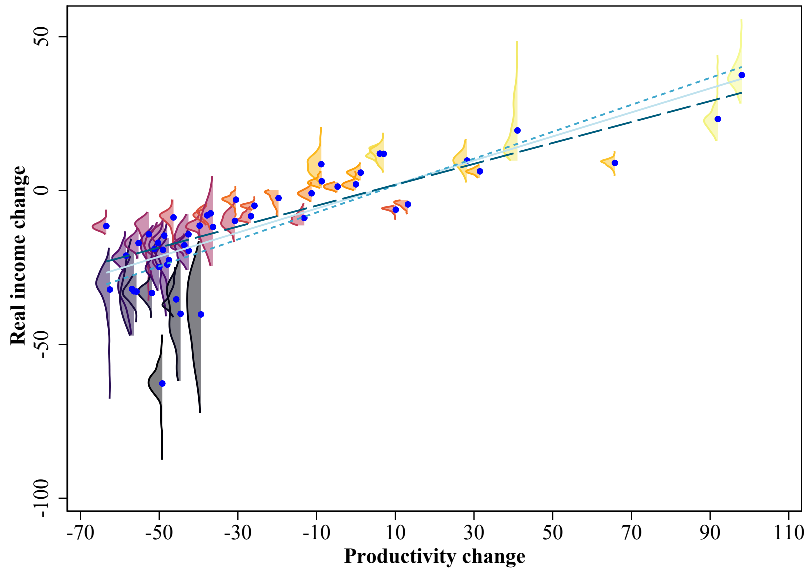
Climate change also induces substantial factor re-allocation, which partially mitigates its initial effects. On average 20.79% of households change their labor allocation and 21.12% their crop choice (i.e. land allocation). Without these adjustments climate change would have even worse impacts.[20]

As in the case of conflict, the welfare effects within countries depend of initial consumption and income choices. In Figure 10, we plot the three household choice mechanisms against initial within-country income rank. The graphs show that, within countries, the household CPI effect tends to be small across all income strata. Changes in CPI on average benefit the poorest households and hurt the richest ones, but their magnitude is very small. The dominant effects are the labor and land income effects. These income losses are bigger among the poor, because they depend more heavily on agricultural income generating activities.

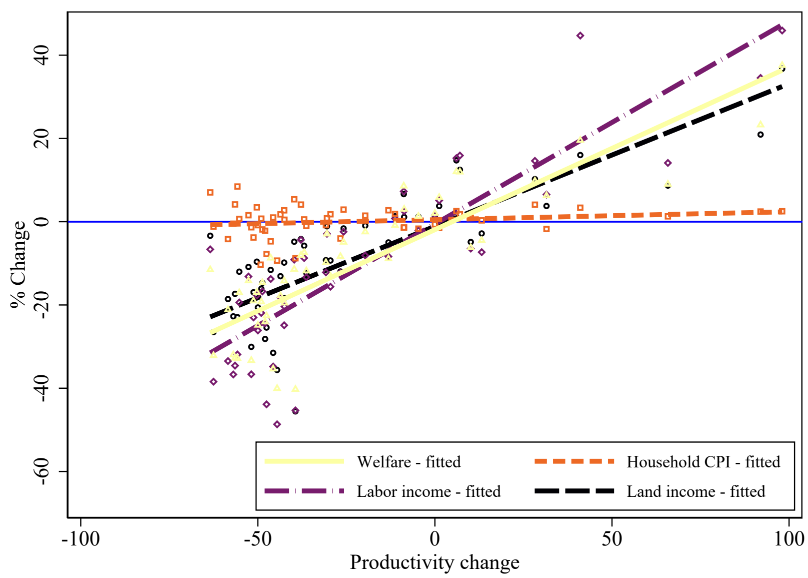
[20]This is shown in the Supplementary Material which presents the results of a scenario in which households are not allow to adjust their land and labor allocations. Losses are now –12.43% on average, i.e. 27.88% higher than in a scenario in which households are allowed to make adjustments. These adjustments are predominantly undertaken by low income households.

Figure 9: Impacts of climate change by its projected productivity impact

(a) Distributional and average impacts by productivity change

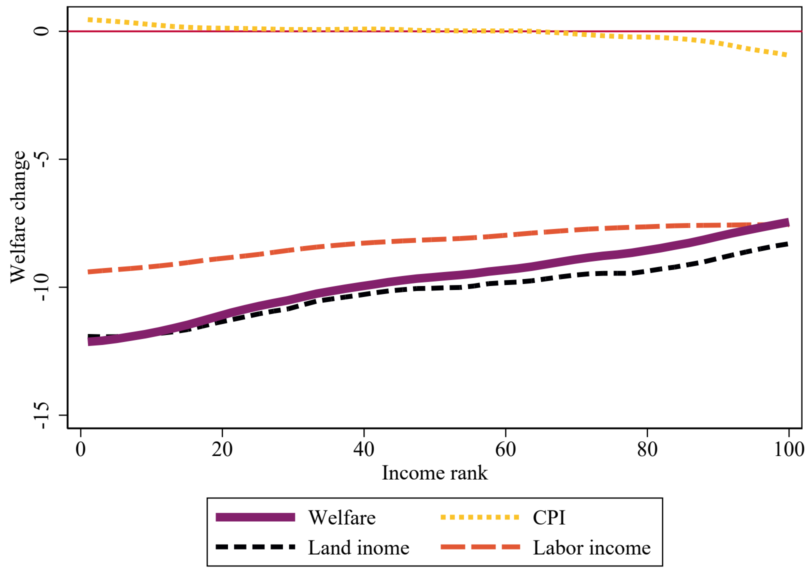


(b) Channels of impact



Notes: The top graph plots the estimated distribution of welfare impacts, proxied by real income changes, of climate change against the productivity change induced by agriculture. Blue dots denote average impacts by country. The bottom graph depicts average income effects, changes in the Consumer Price Index, changes in land income and changes in labor income against changes in productivity.

Figure 10: Impact of climate change versus initial within-country income rank



Notes: The graph presents the percentage change in welfare, measured as real income, associated with the Ukraine war against a household's rank in the initial per capita income distribution, with rank 100 denoting the richest percentile and rank 1 denoting the poorest percentile.

6 Conclusion

Agriculture is central to development but inherently subject to risk, which is being aggravated by conflict and climate change. Examining how agricultural shocks reverberate through the income distribution is challenging because agricultural products are traded globally and because households in different segments of the income distribution are impacted in multiple ways—as consumers, producers, and laborers—and have vastly different income and consumption patterns, which they can adjust.

This paper has introduced a discrete choice general equilibrium trade model of heterogeneous households making consumption, land, and labor allocation choices, designed to leverage household survey data. The model is distinctive in being able to generate both highly granular, income-percentile specific, and highly comprehensive assessments of the impact of agricultural shocks. It accounts for changes in land income, labor income and the cost of consumption, and accommodates factor adjustment.

Applying the model to the impacts of the Ukraine war on developing countries reveals that the agricultural trade disruptions associated with the war fuelled food price inflation, which our model accurately predicts. This inflation reduced average incomes across and increased inequality across the developing world. While almost all households (96.49%) lost real income due to the war, the magnitude of the losses varied enormously both across and within countries, ranging from a minimum of -12.78% of real household income to a maximum of 1.60%. The average income loss across countries was -2.06%. Models with a single representative household instead of heterogeneous households underestimate these losses by 7.77%. Countries most impacted were those with higher pre-war reliance on imports from Russia and the Ukraine. Within countries, the poor suffered the largest losses because they spend a larger share of their budget on food. On average households in the bottom income quartile in a country suffering losses that are 23.20% larger than households in the top income quartile.

Climate change was shown to have even more deleterious and more dispersed effects on the income distribution. Almost three-quarters of countries and households lose, but the remainder gain. The average change in real income due to climate change is -9.72% but the range of impacts spans from a minimum of -87.47% to a maximum 76.47% of real household income. These estimates of average welfare losses generated by our heterogeneous household model are larger than those obtained using a representative agent model, which underestimates average losses by 11.11%. The welfare effects of climate change are strongly correlated with its projected impacts on productivity; countries that witness rising productivity tend to be better off because of increased land and labor income. Intriguingly, in these countries the poor enjoy a disproportionate share of the gains as they derive a greater share of their income(s) from agricultural activities. Yet, the majority of countries lose productivity and suffer welfare losses. These losses are also disproportionately borne by the poor. Across all countries, the climate change shock leads to losses for the bottom income quartile that are 43.92% larger than those experienced by the top quartile.

Given the evolving nature of these shocks, there are inherent statistical and economic uncertainties surrounding the estimates of the impacts of the Ukraine war and climate change. Nevertheless, it is evident that the burden of these costs is primarily borne by already vulnerable households, which suffer losses that are considerably larger and much more dispersed than could be anticipated by models that do not feature household heterogeneity and rely exclusively on aggregate data.

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Supplemental Material for "Crops, Conflict and Climate Change"

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A1 Solution Method

The model is solved in changes using hat-algebra following Dekle, Eaton, and Kortum (2008) and Caliendo and Parro (2015), which utilizes factor allocation shares (i.e. $\pi_{T,j}^{n,h}$ and $\pi_{L,j}^{n,h}$) instead of productivity parameters (i.e. $A_{T,j}^{n,h}$ and $A_{T,j}^{n,h}$). Note that we perform the analysis using households grouped by their income as the units of observation, as opposed to plots. This prevents us from directly using the underlying plot-level productivity data of GAEZ in the solution. From Table 1 in the main text, the main inputs to solve the model are the initial shares and a set of key parameters. In particular, we need the labor and income allocation shares, $\overline{\pi}_{T,j}^{n,h}$ and $\overline{\pi}_{L,j}^{n,h}$; the household h's labor supply share in total effective labor allocated to j, $\eta_{L,j}^{n,h}$; the household h's land supply share in total effective land allocated to j in country n, $\eta_{T,j}^{n,h}$; and the shares of land and labor and income in household h's total income, $\kappa_T^{n,h}$ and $\kappa_L^{n,h}$. With respect to trade, we need the share of exports of m in n's imports, $\overline{x}_j^{n,m}$, and the share of imports of n in m's exports, $\widetilde{x}_j^{n,m}$. To characterize demand, we need the share of household h in total demand for j in country n, $\overline{D}_j^{n,h}$.

The set of calibrated or estimated parameters are: the Cobb-Douglas labor, land, and intermediate inputs production shares, $\beta_{L,j}$, $\beta_{T,j}$, and $\beta_{F,j}$; the household-specific Cobb-Douglas expenditure shares, $\alpha_j^{n,h}$; the labor and land elasticities (Frechet shape), θ_L and θ_T; and the implicit trade elasticity (negative), $1-\sigma$.

We introduce two different shocks in this system. In the case of the Ukraine war, we impose export bans on selected agricultural products from Ukraine and Russia. We model this as follows. In the case of Ukraine, we shut down imports and exports of all agricultural products and fertilizer. That is, we impose prohibitively high τ_H trade costs on imports

$$\widehat{\tau}_j^{U,m} = \tau_H, \forall j, F \& \forall m,$$

where U stand for Ukraine. We also set prohibitively high trade costs on Ukrainian exports

$$\widehat{\tau}_j^{n,U} = \tau_H, \forall j, F \& \forall n.$$

In addition, we impose bans on Russian exports of wheat, rice, corn, other cereals, sugar, other oilseeds, and fertilizers to the world. That is, we set

$$\widehat{\tau}_j^{n,R} = \tau_H, \forall n,$$

where R stands for Russian and j is wheat, rice, corn, other cereals, sugar, other oilseeds, and fertilizers.

To see how we solve the model with hat-algebra, let $\widehat{x}$ denote the proportional change in a variable x. We proceed as follows. First, start with a guess for the change in wages $\widehat{w}_j^n$, rental rates $\widehat{r}_j^n$ and input prices at origin $\widehat{p}_F^n$.

With these guesses, we calculate the change in input price index faced by producers

$$\widehat{P}_F^n = \left[\sum_m \overline{x}_F^{n,m} \left(\widehat{p}_M^m \widehat{\tau}_M^{n,m}\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}};$$

the change in consumer prices

$$\widehat{p}_j^n = \left(\widehat{P}_M^n\right)^{\beta_F} \left(\widehat{r}_j^n\right)^{\beta_T} \left(\widehat{w}_j^n\right)^{\beta_L};$$

and the change in price index faced by consumers

$$\widehat{P}_j^n = \left[\sum_m \overline{x}_j^{n,m} \left(\widehat{p}_j^m \widehat{\tau}_j^{n,m}\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}.$$

This allows to calculate the change in trade (import shares) for consumed goods and intermediate input

$$\widehat{x}_j^{n,m} = \frac{\left(\widehat{p}_j^m \widehat{\tau}_j^{n,m}\right)^{1-\sigma}}{\left(\widehat{P}_j^n\right)^{1-\sigma}}.$$

These trade shares plunge to zero for the shocked products and countries.

In the next step, we calculate the change in household labor supply, $L_j^{n,h}$, via (32), and we calculate L_j^n at national level by adding them across households

$$\widehat{\Phi}_L^{n,h} = \left(\sum_j \overline{\pi}_{L,j}^{n,h} \left(\widehat{w_j^n}\right)^{\theta_L}\right)^{\frac{1}{\theta_L}};$$

$$\widehat{L}_j^{n,h} = \frac{\left(\widehat{w}_j^n\right)^{\theta_L}}{\left(\widehat{\Phi}_L^{n,h}\right)^{\theta_L}} \frac{\widehat{\Phi}_L^{n,h}}{\widehat{w}_j^n};$$

$$\widehat{L}_j^n = \sum_h \widehat{L}_j^{n,h} \eta_{L,j}^{n,h},$$

where $\eta_{L,j}^{n,h}$ is the share of household h in total labor income of sector j, $\eta_{L,j}^{n,h} = \frac{L_j^{n,h}}{\sum_{h'} L_j^{n,h'}}$.

Similarly, we calculate household land supply, $T_j^{n,h}$, via (17), and then calculate T_j at national level by adding them up across households

$$\widehat{\Phi}_T^{n,h} = \left(\sum_j \overline{\pi}_{T,j}^{n,h} \left(\widehat{r}_j\right)^{\theta_T}\right)^{\frac{1}{\theta_T}};$$

$$\widehat{T}_j^{n,h} = \frac{(\widehat{r}_j^n)^{\theta_T}}{\left(\widehat{\Phi}_T^{n,h}\right)^{\theta_T}} \frac{\widehat{\Phi}_T^{n,h}}{\widehat{r}_j^n};$$

$$\widehat{T}_j^n = \sum_h \widehat{T}_j^{n,h} \eta_{T,j}^{n,h},$$

where $\eta_{T,j}^{n,h}$ is the share of household h in total return on land in sector k, $\eta_{T,j}^{n,h} = \frac{T_j^{n,h}}{\sum_{h'} T_j^{h'}}$

This permits the calculation of the change in household income

$$\widehat{\Phi}^{n,h} = \widehat{\Phi}_L^{n,h} \kappa_L^{n,h} + \widehat{\Phi}_T^{n,h} \kappa_T^{n,h}.$$

The change in total demand for each product by each country consumers is

$$\widehat{D}_j^n = \sum_h \widehat{\Phi}^{n,h} \overline{D}_j^{n,h},$$

the change in demand for each product produced by each country is

$$\widehat{\Delta}_j^m = \sum_n \widehat{D}_j^n \widehat{x}_j^{n,m} \widetilde{x}_j^{n,m},$$

and the change in demand for inputs produced by each country is

$$\widehat{\Delta}_F^m = \sum_n \widehat{\Delta}_j^n \widehat{x}_F^{n,m} \widetilde{x}_F^{n,m}.$$

These updated values are employed to refine our guesses of the changes in wages $\widehat{w}_j^n$, rental rates $\widehat{r}_j^n$, and input prices at origin $\widehat{p}_M^n$ based on

$$\widehat{w}_j^n = \widehat{\Delta}_j^n / \widehat{L}_j^n,$$

$$\widehat{r}_j^n = \widehat{\Delta}_j^n / \widehat{T}_j^n,$$

$$\widehat{p}_F^n = \widehat{\Delta}_F^n.$$

We keep iterating and adjusting these guesses until reaching equilibrium.

For the case of the climate change shock, we input changes in yields from GAEZ. These yield projection changes are country n and crop j specific. To implement this, let z_j^n be the GAEZ projection in country n referring to crop j. Then we set

$$\widehat{\overline{A}}_j^n = z_j^n,$$

for all h, where $\overline{A}_j^n$ is given by (42).

A2 Proofs for labor and land supply problems

For simplicity, we are only considering the labor allocation problem because the land allocation problem is isomorphic, and all proofs will hold for the land allocation problem if one replaces L with T, and w with r.

We define the following variables for convenience: $x_j \equiv A^{n,h}_{L,j} w^n_j$, and $B_j \equiv (x_j)^{\theta_L}/(\Phi^{n,h}_L)^{\theta_L}$. Recall that $\Phi^{n,h}_L = \left(\sum_{j=1}^J x_j^{\theta_L}\right)^{\frac{1}{\theta_L}}$. We use an additional random variable z_j with scale 1 and shape θ_L, instead of using the random variable $\xi_j(\omega_L)$ to make the algebra easier to follow. Define the pdf and cdf of z_j as $f(z_j) = \theta_L z_j^{-1-\theta_L} \exp\left(-(z_j)^{-\theta_L}\right)$ and $F(z_j) = \exp\left(-(z_j)^{-\theta_L}\right)$ respectively. Recall that $\xi_{L,j}(\omega_L)$ has scale $\widetilde{\gamma}_L A^{n,h}_{L,j}$ and shape θ_L, thus we are setting $\widetilde{\gamma}_L A^{n,h}_{L,j} z_j = \xi_{L,j}(\omega_L)$.

Proposition 1 *Subject to optimality, the probability of allocating labor to product j is equal to*

$$\pi^{n,h}_{L,j} = \frac{(x_j)^{\theta_L}}{(\Phi^{n,h}_L)^{\theta_L}}.$$

Proof. Optimality requires that $z_j x_j \geq z_k x_k$ for every $k \neq j$, if the labor is allocated to j. This means $z_k \leq z_j x_j / x_k$. For a given z_j, the probability of this outcome is $\prod_{k\neq j} F(\frac{x_j}{x_k} z_j)$. We need to integrate this probability over its domain after multiplying with $f(z_j)$, to calculate the unconditional probability:

$$\begin{aligned}
\pi^{n,h}_{L,j} &= \int_0^\infty f(z_j) \prod_{k\neq j} F(\frac{x_j}{x_k} z_j) dz_j, \\
&= \int_0^\infty \theta_L (z_j)^{-1-\theta_L} \exp\left(-z_j^{-\theta_L}\right) \prod_{k\neq j} \exp\left(-\left(\frac{x_j}{x_k} z_j\right)^{-\theta_L}\right) dz_j, \\
&= \int_0^\infty \theta_L (z_j)^{-1-\theta_L} \prod_{k=1}^{J} \exp\left(-\left(\frac{x_j}{x_k} z_j\right)^{-\theta_L}\right) dz_j, \\
&= \int_0^\infty \theta_L (z_j)^{-1-\theta_L} \exp\left(-\left(\frac{x_j}{\Phi^{n,h}_L} z_j\right)^{-\theta_L}\right) dz_j, \\
&= \int_0^\infty \theta_L (z_j)^{-1-\theta_L} \exp\left(-(B_j)^{-1} (z_j)^{-\theta_L}\right) dz_j,
\end{aligned}$$

define $u = \exp\left(-(B_j)^{-1}(z_j)^{-\theta_L}\right)$ then

$$\begin{aligned}
\pi^{n,h}_{L,j} &= \int_0^1 B_j \, du, \\
&= B_j.
\end{aligned}$$

■

Proposition 2 *Subject to optimality, the effective units of labor allocated to production j is equal to*

$$L_j^{n,h} = \frac{(x_j)^{\theta_L}}{(\Phi_L^{n,h})^{\theta_L}} \frac{\Phi_L^{n,h}}{w_j^n} L^{n,h}.$$

Proof. Note that effective units of labor is the sum of labor units when taking the productivity shock $\xi_{L,j}(\omega_L)$ into account. Based on the previous proof, we can express $L_j^{n,h}$ as

$$\begin{aligned} L_j^{n,h} &= L^{n,h}\tilde{\gamma}_L A_{L,j}^{n,h} \int_0^\infty z_j \theta_L (z_j)^{-1-\theta_L} \exp\left(-(B_j)^{-1}(z_j)^{-\theta_L}\right) dz_j, \\ &= L^{n,h}\tilde{\gamma}_L A_{L,j}^{n,h} \int_0^\infty z_j \theta_L (z_j)^{-1-\theta_L} \exp\left(-\left(\frac{z_j}{S}\right)^{-\theta_L}\right) dz_j, \end{aligned}$$

where $S \equiv B_j^{-\frac{1}{\theta}}$.

Note that the expression above closely resembles the expected value of a random Frechet variable with scale S and shape θ_L. In fact, consider a Frechet draw z' with scale S and shape θ_L, then

$$\begin{aligned} E(z') &= \int_0^\infty z' \frac{\theta_L}{S} \left(\frac{z'}{S}\right)^{-1-\theta_L} \exp\left(-\left(\frac{z'}{S}\right)^{-\theta_L}\right) dz', \\ &= \frac{L_j^{n,h}}{L^{n,h}\tilde{\gamma}_L A_{L,j}^{n,h}} \frac{1}{S}\left(\frac{1}{S}\right)^{-1-\theta_L}. \end{aligned}$$

Note that mean of Frechet drawn z' is $E(z') = \frac{S}{\tilde{\gamma}_L}$, therefore

$$\frac{S}{\tilde{\gamma}_L} = \frac{L_j^{n,h}}{L^{n,h}\tilde{\gamma}_L A_{L,j}^{n,h}} \frac{1}{S}\left(\frac{1}{S}\right)^{-1-\theta_L},$$

and

$$\begin{aligned} L_j^{n,h} &= L^{n,h} A_{L,j}^{n,h} (S)^{1-\theta_L}, \\ &= L^{n,h} A_{L,j}^{n,h} (B_j)^{\frac{\theta-1}{\theta_L}}, \\ &= \frac{(x_j)^{\theta_L}}{(\Phi_L^{n,h})^{\theta_L}} \frac{\Phi_L^{n,h}}{w_j^n} L^{n,h}. \end{aligned}$$

■

Proposition 3 *Return on labor allocated to production of j as a share of total return on labor is equal to the probability of allocating labor to production of j.*

Proof. The return on labor allocated to production of j is equal to $L_j^{n,h} w_j^n$, and the total return on labor is equal to $\sum_k L_k^{n,h} w_k^n$, therefore

$$
\begin{aligned}
\frac{L_j^{n,h} w_j^n}{\sum_k L_k^{n,h} w_k^n} &= \frac{\frac{(x_j)^{\theta_L}}{(\Phi_L^{n,h})^{\theta_L}} \Phi_L^{n,h} L^{n,h}}{\sum_k \frac{(x_k)^{\theta_L}}{(\Phi_L^{n,h})^{\theta_L}} \Phi_L^{n,h} L^{n,h}}, \\
&= \frac{\frac{(x_j)^{\theta_L}}{(\Phi_L^{n,h})^{\theta_L}} \Phi_L^{n,h} L^{n,h}}{\Phi_L^{n,h} L^{n,h}}, \\
&= \frac{(x_j)^{\theta}}{(\Phi_L^{n,h})^{\theta_L}}, \\
&= \pi_{L,j}^{n,h}.
\end{aligned}
$$

■

Proposition 4 *Expected average returns from labor allocated to each crop are equalized, such that* $L_j^{n,h} w_j^n / \pi_{L,j}^{n,h} = L_{j'}^{n,h} w_{j'}^n / \pi_{L,j'}^{n,h}$ *for any* j *and* j' *as long as both* $\pi_{L,j}^{n,h} > 0$ *and* $\pi_{L,j'}^{n,h} > 0$.

Proof. This directly follows from the expressions derived in previous propositions.

$$
\begin{aligned}
\frac{L_j^{n,h} w_j^n}{\pi_{L,j}^{n,h}} &= \Phi_L^{n,h} L^{n,h}, \\
&= \frac{L_{j'}^{n,h} w_{j'}^n}{\pi_{L,j'}^{n,h}},
\end{aligned}
$$

Hence it holds for to any j' as long as the expression is not divided by zero, i.e. $\pi_{L,j'}^{n,h} > 0$.

■

Proposition 5 *The total wage income (return on labor) of household* h *can be calculated as* $R_L^{n,h} = \Phi_L^{n,h} L^{n,h}$, *if labor is allocated optimally to crops.*

Proof.

$$
\begin{aligned}
R_L^{n,h} &= \sum_j L_j^{n,h} w_j^n, \\
&= \sum_j \pi_{L,j}^{n,h} \frac{\Phi_L^{n,h}}{w_j^n} L^{n,h} w_j^n, \\
&= \Phi_L^{n,h} L^{n,h} \sum_j \pi_{L,j}^{n,h}, \\
&= \Phi_L^{n,h} L^{n,h}.
\end{aligned}
$$

■

A3 A note on the upward-bias in factor income when using aggregate data

It is possible to show that the change in factor income caused by using aggregate data is biased upwards for a given vector of factor price changes. Therefore, if the aggregate welfare impact is negative, it will be underestimated; and if the impact is positive, it will be overestimated. However, it is important to note that this is only true for a given vector of factor price changes, and the direction of the overall bias will be ambiguous in a complex general equilibrium setting, such as our model. This is because factor prices (wages and rental rates), final good prices and intermediate input prices are subject to general equilibrium effects. Nevertheless, the proposition below is useful for demonstrating the existence of a bias and for understanding its underlying mechanisms.

Proposition 6 *When an aggregate version of our model is used with aggregate factor allocations, instead of household factor allocations, the change in total factor income is biased upwards for a given vector of factor price changes (i.e. wage or land rental rate changes) when* $\theta_L > 1$ *and* $\theta_T > 1$.

Proof.

The initial return on labor for household h is denoted as $\overline{R}_L^{n,h}$, the share of labor income from crop j is $\overline{\pi}_j^{n,h}$.The share of household h in total labor income of the economy is denoted with $\tilde{\eta}_L^{n,h} = \overline{R}_L^{n,h}/(\sum \overline{R}_L^{n,h'})$. The new labor income for household h after a change in wages is

$$R_L^{n,h} = \overline{R}_L^{n,h} \left(\sum_j \overline{\pi}_j^{n,h} \left(\widehat{w_j^n} \right)^{\theta_L} \right)^{\frac{1}{\theta_L}}.$$

Note that $\theta_L > 1$ by assumption and $\widehat{w_j^n} > 0$ by construction (i.e. $0 < \widehat{w_j^n} < 1$ when price change is negative and $\widehat{w_j^n} \geq 1$ otherwise). The function above is strictly concave in $\overline{\pi}_j^{n,h}$, as all elements of the Hessian are negative such that

$$H_{jk} = \overline{R}_L^{n,h} \frac{1}{\theta_L} \frac{1-\theta}{\theta_L} \widehat{w_j^n} \widehat{w_k^n} \left(\sum_l \overline{\pi}_l^{n,h} \left(\widehat{w_l^n} \right)^{\theta_L} \right)^{\left(\frac{1}{\theta_L} - 2\right)} < 0, \forall j, k.$$

Recall that the change in total labor income is

$$R_L^n = \left(\sum_h \overline{R}_L^{n,h} \right) \left[\sum_h \tilde{\eta}_L^{n,h} \left(\sum_j \overline{\pi}_j^{n,h} \left(\widehat{w_j^n} \right)^{\theta_L} \right)^{\frac{1}{\theta_L}} \right].$$

If we were to use aggregate data, i.e. economy-wide allocations rather than household specific allocations, shares would be $\overline{\pi_j^n} = \sum_h \tilde{\eta}_L^{n,h} \overline{\pi}_j^{n,h}$, then we could write the change in labor income using aggregate labor income data as

$$R_L^{n*} = \left(\sum_h \overline{R}_L^{n,h} \right) \left[\left(\sum_j \left(\sum_h \tilde{\eta}_L^{n,h} \overline{\pi}_j^{n,h} \right) \left(\widehat{w_j^n} \right)^{\theta_L} \right)^{\frac{1}{\theta_L}} \right].$$

Note that $R_L^{n*} \geq R_L^n$ due to Jensen's inequality, or more precisely $R_L^{n*} > R_L^n$ as the function is strictly concave. The proof for land income is identical.

■

A4 Alternative characterization of the equilibrium

The equilibrium can alternatively be characterized without using the return on land. We preferred to use the version that uses the return on land in the main text because it simplifies the equations and the solution method significantly and makes the exposition easier to follow. The alternative characterization is provided below.

Definition. The international trade equilibrium is given by a vector of crop prices for each crop variety in each country, p_j^n; a vector of manufacturing prices for each country variety, p_M^n; a vector of services in each country, p_S^n; a vector of intermediate input prices for each country variety, p_F^n; a vector of wages for each product (crops, manufacturing and services), for each country w_j^n; and rental rates for the specific factors in manufacturing r_M^n, services r_S^n and intermediate inputs r_F^n, such that:

Goods Market. For each product, global demand equals national supply. For crops j, we combine total household expenditures (6) and the value of national output (24) to express the equilibrium condition as

$$\sum_n \sum_h x_j^{n,m} \alpha_j^{n,h} \left(R_T^{n,h} + R_M^{n,h} + R_S^{n,h} + R_L^{n,h} \right) = y_j^m, \tag{44}$$

where $x_j^{n,m}$ is the import share based on the price vector p_j^n defined by (4) and (5), $R_M^{n,h}$ and $R_S^{n,h}$ are the fixed factor revenues in sectors M and S (defined by (28)) accruing to household h, $R_T^{n,h}$ and $R_L^{n,h}$ are given by (18) and (33) and $R_T^{n,h} + R_M^{n,h} + R_S^{n,h} + R_L^{n,h} = E^{n,h}$ is total household expenditure.

The equilibrium for manufactures is the same as (44) with $j = M$

$$\sum_n \sum_h x_M^{n,m} \alpha_M^{n,h} \left(R_T^{n,h} + R_M^{n,h} + R_S^{n,h} + R_L^{n,h} \right) = y_M^m. \tag{45}$$

Supply and demand of the non-traded good requires that

$$\sum_h \alpha_S^{n,h} \left(R_T^{n,h} + R_M^{n,h} + R_S^{n,h} + R_L^{n,h} \right) = y_S^n. \tag{46}$$

For the intermediate input F, we have that

$$\sum_n \sum_h \sum_j x_F^{n,m} \beta_F y_j^{n,h} = y_F^m. \tag{47}$$

Factor Markets. The equilibrium wage in sector j equates labor supply with labor demand

$$\sum_h \left(\pi_{L,j}^{n,h}\right)^{\frac{\theta_L - 1}{\theta_L}} \frac{\overline{L}^{n,h}}{A_{L,j}^{n,h}} = \sum_h \left(p_j^n\right)^{\frac{1}{\beta_T}} \left(\frac{\beta_F}{P_F^n}\right)^{\frac{\beta_F}{\beta_T}} \left(\frac{\beta_L}{w_j^n}\right)^{\frac{\beta_L + \beta_T}{\beta_T}} \left(\pi_{T,j}^{n,h}\right)^{\frac{\theta_T - 1}{\theta_T}} \frac{\overline{T}^{n,h}}{A_{T,j}^{n,h}}. \tag{48}$$

For manufactures and services, we have

$$\left(\pi_{L,k}^{n,h}\right)^{\frac{\theta_L - 1}{\theta_L}} \frac{\overline{L}^{n,h}}{A_{L,k}^{n,h}} = \left(\frac{p_k^n \beta_{L,k}}{w_k^n}\right)^{\frac{1}{\beta_{K,k}}} K_k^n, \tag{49}$$

for $k = M, S$. Given prices, the rental rates for the specific factors can be recovered from (28). Finally, while land is not traded, households allocate their own plots to different crops and, given crop prices, there is an equilibrium return for land given by (18).

Note. The equilibrium outlined in the main text, in section 2.4, and the alternative characterization of equilibrium given above are isomorphic, and therefore give the same outcome. **Proof**. We can substitute out the return on land, by combining equations (39), (37) and (38) from the main definition of the equilibrium, then obtain precisely the same conditions described in the alternative definition.

A5 Supplementary Simulations

This section presents the results of supplementary simulations that serve to assess the robustness of our findings and shed light on the mechanisms that drive the results.

Inputs channel (Ukraine war). This scenario is similar to the export ban simulation in the main text, but only fertilizers are considered: (i) Ukraine cannot import or export fertilizers; (ii) Russia bans exporting fertilizers.

Final goods channel (Ukraine war). This scenario is similar to the main simulation, but fertilizers are excluded: (i) Ukraine cannot import or export any agricultural products, but not fertilizers; (ii) Russia bans exporting wheat, corn, other cereals, sugar, other oilseeds, but not fertilizers.

Retaliatory protectionism (Ukraine war). In an additional simulation we consider the policy responses by other countries based on the news and policy reports (see CNBC (2022), The Wall Street Journal (2022), Reuters (2022) and Agri-Pulse (2022): (i) Ukraine cannot import or export any agricultural products, or fertilizers; (ii) Russia bans exporting wheat, rice, corn, other cereals, sugar, other oilseeds, and fertilizers; (iii) Other countries respond (as documented in the news): Argentina bans exporting soya, Georgia bans exporting wheat, Ghana bans exporting corn, India bans exporting wheat and rice, Indonesia bans exporting oils, Japan bans exporting rice, Kazakhstan bans exporting wheat, Kyrgyzstan bans exporting wheat, Moldova bans exporting wheat, Tanzania bans exporting corn, Tunisia bans exporting fruits and vegetables, Turkey bans exporting corn, meats, and oils.

Limited adjustment (climate change). In this scenario we assess the impact of the climate change scenario used in Costinot, Donaldson, and Smith (2016) (i.e. their main climate change scenario), which is based on Hadley CM3 A1fi model. This scenario is the same as the climate change scenario in the main text, except we limit reallocation of land and labor to production of different crops by setting elasticities close to zero.

Table A1: Impact of the Ukraine war - Robustness
Inputs channel

	ΔWelfare				ΔIncome			ΔCPI	Exposure
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Imports
				Panel A: All countries (pooled)					
Average	-1.67	-1.77	-1.52	-1.57	-0.40	-0.31	-0.57	1.30	5.42
Pop w. average	-1.24	-1.37	-1.02	-1.08	-0.01	-0.02	-0.02	1.25	4.30
SD	1.61	1.74	1.55	1.60	1.57	1.17	2.19	0.37	5.35
Minimum	-9.25	-10.18	-8.30	-8.94	-7.59	-5.43	-9.28	-0.13	0.30
Median	-1.21	-1.26	-1.09	-1.16	0.11	0.10	0.13	1.28	3.66
Maximum	0.05	0.13	0.15	0.13	1.02	0.90	1.26	2.08	19.97
				Panel B: By country					
Azerbaijan	-9.25	-10.18	-8.30	-8.94	-7.59	-5.43	-9.28	1.84	18.25
Mongolia	-7.27	-7.25	-7.65	-7.33	-5.34	-3.64	-8.56	2.08	6.10
Moldova	-4.54	-4.97	-3.86	-4.45	-4.14	-2.94	-7.65	0.42	17.72
Cent. Afr. R	-3.68	-3.58	-3.65	-3.66	-2.05	-2.05	-2.05	1.69	1.12
Nicaragua	-2.85	-3.20	-2.45	-2.64	-1.69	-1.51	-1.92	1.19	1.42
Cameroon	-2.80	-3.04	-2.45	-2.55	-1.21	-1.19	-1.22	1.64	0.63
Georgia	-2.76	-3.10	-2.43	-2.60	-1.88	-1.55	-2.37	0.91	19.97
Armenia	-2.61	-2.59	-2.52	-2.59	-0.93	-0.76	-1.30	1.72	17.85
Ecuador	-2.52	-3.01	-1.89	-2.19	-1.16	-1.03	-1.40	1.39	14.18
Burkina Faso	-2.37	-2.46	-2.25	-2.24	-1.31	-1.22	-1.34	1.08	1.36
Cote d'Ivoire	-2.34	-2.56	-2.05	-2.14	-1.22	-0.98	-1.29	1.14	4.09
Kyrgyzstan	-2.32	-2.48	-2.18	-2.25	-1.13	-0.90	-1.50	1.22	11.60
Gambia	-1.80	-1.54	-1.81	-1.81	-0.10	-0.09	-0.10	1.74	2.13
Mauritania	-1.63	-1.97	-1.17	-1.35	0.01	-0.00	0.01	1.67	2.85
Tanzania	-1.59	-1.78	-1.30	-1.32	-0.55	-0.50	-0.62	1.05	5.04
Bolivia	-1.55	-1.63	-1.26	-1.32	-0.02	-0.03	-0.01	1.56	1.54
Liberia	-1.43	-1.30	-1.47	-1.46	0.21	0.18	0.22	1.66	1.70
Indonesia	-1.38	-1.65	-1.05	-1.16	-0.18	-0.16	-0.32	1.21	2.62

Notes: This table presents the results of a simulation in which (i) the Ukraine cannot import or export any fertilizers and (ii) Russia bans exporting fertilizers. Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the (pre-war) status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single HH. denotes a representative household and presents the results of a single agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption. Exposure measures what share of imports of a given country were accounted for by imports from the Ukraine and Russia before the war. Countries are ordered in terms of average real income gains (from lowest to highest).

Table A1: Impact of the Ukraine war - Robustness (continued)
Inputs channel

	ΔWelfare				**ΔIncome**			**ΔCPI**	**Exposure**
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Imports
Ghana	-1.37	-1.76	-1.10	-1.17	-1.50	-1.31	-2.29	-0.13	3.23
Mozambique	-1.34	-0.78	-1.87	-1.65	0.11	0.05	0.13	1.47	6.77
Vietnam	-1.30	-1.29	-1.20	-1.25	-0.04	-0.04	-0.04	1.28	2.72
Sierra Leone	-1.28	-1.45	-1.16	-1.20	0.37	0.30	0.38	1.67	4.12
Togo	-1.27	-1.18	-1.24	-1.24	0.09	0.11	0.08	1.38	2.90
Jordan	-1.26	-1.39	-1.09	-1.18	0.16	0.13	0.27	1.44	0.76
Nigeria	-1.25	-1.02	-1.27	-1.27	0.18	0.14	0.23	1.45	2.11
Guatemala	-1.21	-1.21	-1.12	-1.16	0.01	0.01	0.03	1.24	1.02
Yemen	-1.19	-1.25	-1.04	-1.07	0.47	0.41	0.56	1.68	3.76
Kenya	-1.19	-1.33	-0.97	-0.96	-0.06	-0.06	-0.06	1.14	4.81
South Africa	-1.18	-1.72	-0.52	-0.63	-0.05	-0.05	-0.11	1.15	3.66
Zambia	-1.18	-1.26	-1.13	-1.15	0.46	0.34	0.61	1.66	2.96
Comoros	-1.11	-1.16	-1.04	-1.06	0.56	0.50	0.60	1.69	0.30
Egypt	-1.09	-1.10	-1.03	-1.04	0.37	0.29	0.49	1.48	6.91
Burundi	-1.03	-1.02	-0.89	-0.94	0.45	0.29	0.47	1.50	4.74
Bangladesh	-1.02	-1.16	-0.84	-0.93	0.46	0.34	0.54	1.50	4.65
Rwanda	-0.89	-1.11	-0.65	-0.74	-0.07	-0.08	-0.07	0.82	1.77
Iraq	-0.87	-1.06	-0.55	-0.68	0.28	0.18	0.49	1.15	4.14
Guinea	-0.86	-0.75	-0.95	-0.89	0.50	0.39	0.51	1.38	0.96
Sri Lanka	-0.86	-1.28	-0.36	-0.52	0.25	0.19	0.34	1.13	15.57
Guinea-Bissau	-0.86	-0.98	-0.55	-0.56	0.82	0.80	0.84	1.70	3.65
Niger	-0.82	-0.57	-1.02	-0.90	0.48	0.38	0.50	1.32	5.40
Uganda	-0.82	-0.89	-0.85	-0.82	0.11	0.10	0.12	0.94	2.13
Papua N.G.	-0.72	-0.67	-0.70	-0.68	0.64	0.46	0.73	1.37	1.29
Benin	-0.70	-0.45	-0.90	-0.82	0.44	0.37	0.47	1.14	1.75
Uzbekistan	-0.69	-0.57	-0.92	-0.78	0.34	-0.05	0.76	1.04	17.31
Pakistan	-0.61	-1.11	0.03	-0.17	0.37	0.33	0.50	0.99	3.77
Tajikistan	-0.61	-0.53	-0.72	-0.63	0.46	0.45	0.49	1.07	9.41
Cambodia	-0.59	-0.61	-0.50	-0.50	0.68	0.47	0.83	1.28	3.32
Madagascar	-0.53	-0.47	-0.61	-0.53	0.67	0.56	0.73	1.21	0.59
Malawi	-0.41	-0.28	-0.67	-0.54	0.47	0.37	0.53	0.89	8.34
Nepal	-0.41	-0.53	-0.28	-0.33	0.57	0.57	0.58	0.98	7.72
Bhutan	0.05	0.13	0.15	0.13	1.02	0.90	1.26	0.97	3.80

Notes: This table is a continuation from the table on the previous page. It presents the results of a simulation in which (i) the Ukraine cannot import or export any fertilizers and (ii) Russia bans exporting fertilizers. Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the (pre-war) status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single HH. denotes a representative household and presents the results of a single agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption. Exposure measures what share of imports of a given country were accounted for by imports from the Ukraine and Russia before the war. Countries are ordered in terms of average real income gains (from lowest to highest).

Table A2: Impact of the Ukraine war - Robustness
Final goods channel

	ΔWelfare				ΔIncome			ΔCPI	Exposure
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Imports
Panel A: All countries (pooled)									
Average	-0.31	-0.37	-0.23	-0.26	0.45	0.36	0.58	0.77	5.42
Pop w. average	-0.05	-0.11	0.03	0.00	0.46	0.38	0.59	0.52	4.30
SD	0.88	1.12	0.67	0.78	0.48	0.41	0.68	1.11	5.35
Minimum	-4.17	-5.06	-2.74	-3.47	-0.11	-0.11	-0.13	0.02	0.30
Median	-0.10	-0.06	-0.09	-0.08	0.25	0.20	0.32	0.39	3.66
Maximum	0.76	0.88	1.35	1.09	2.28	1.80	3.29	6.27	19.97
Panel B: By country									
Georgia	-4.17	-5.01	-2.74	-3.47	0.61	0.47	0.81	5.00	19.97
Armenia	-3.74	-5.06	-2.67	-3.25	2.28	1.80	3.29	6.27	17.85
Mongolia	-1.88	-2.27	-1.47	-1.71	-0.00	-0.01	0.02	1.92	6.10
Egypt	-1.30	-1.55	-0.98	-1.13	0.60	0.48	0.77	1.92	6.91
Azerbaijan	-1.03	-1.54	-0.41	-0.82	0.83	0.57	1.03	1.88	18.25
Mauritania	-0.90	-1.14	-0.61	-0.72	0.09	0.06	0.10	1.01	2.85
Yemen	-0.78	-1.18	-0.36	-0.54	0.09	0.07	0.12	0.88	3.76
Jordan	-0.73	-1.05	-0.46	-0.59	0.17	0.14	0.27	0.91	0.76
Zambia	-0.64	-0.70	-0.58	-0.61	0.20	0.15	0.26	0.84	2.96
South Africa	-0.62	-0.89	-0.21	-0.28	0.01	0.01	0.16	0.63	3.66
Kyrgyzstan	-0.55	-0.66	-0.38	-0.48	0.86	0.68	1.16	1.41	11.60
Mozambique	-0.52	0.05	-1.36	-1.05	0.18	0.10	0.21	0.71	6.77
Tajikistan	-0.48	-0.42	-0.52	-0.47	0.55	0.54	0.60	1.04	9.41
Uzbekistan	-0.34	-0.21	-0.61	-0.44	0.96	0.16	1.82	1.31	17.31
Bolivia	-0.33	-0.46	-0.18	-0.23	0.10	0.08	0.12	0.44	1.54
Guinea-Bissau	-0.26	-0.28	-0.19	-0.18	0.19	0.17	0.20	0.45	3.65
Ecuador	-0.26	-0.33	-0.18	-0.21	-0.11	-0.11	-0.13	0.14	14.18
Guatemala	-0.24	-0.24	-0.19	-0.21	0.08	0.06	0.10	0.32	1.02
Niger	-0.23	-0.15	-0.29	-0.26	0.04	0.05	0.04	0.27	5.40

Notes: This table presents the results of a simulation in which (i) the Ukraine cannot import or export any agricultural product and (ii) Russia bans exporting wheat, rice, corn, other cereals, sugar, and other oilseeds. Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the (pre-war) status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single HH. denotes a representative household and presents the results of a single agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption. Exposure measures what share of imports of a given country were accounted for by imports from the Ukraine and Russia before the war. Countries are ordered in terms of average real income gains (from lowest to highest).

Table A2: Impact of the Ukraine war - Robustness (continued)
Final goods channel

	ΔWelfare				**ΔIncome**			**ΔCPI**	**Exposure**
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Imports
Nicaragua	-0.14	-0.14	-0.10	-0.11	0.25	0.19	0.32	0.39	1.42
Burundi	-0.14	-0.17	-0.05	-0.08	0.11	0.13	0.12	0.25	4.74
Gambia	-0.13	-0.10	-0.12	-0.12	0.07	0.06	0.07	0.19	2.13
Liberia	-0.13	-0.02	-0.18	-0.16	0.24	0.20	0.26	0.36	1.70
Malawi	-0.11	0.02	-0.27	-0.20	0.16	0.13	0.18	0.27	8.34
Bhutan	-0.11	-0.13	-0.02	-0.05	0.31	0.28	0.37	0.43	3.80
Cambodia	-0.10	-0.11	-0.09	-0.09	-0.08	-0.06	-0.10	0.02	3.32
Sri Lanka	-0.09	-0.13	-0.03	-0.05	0.02	0.00	0.05	0.10	15.57
Papua N.G.	-0.08	-0.06	-0.11	-0.07	0.39	0.29	0.44	0.48	1.29
Togo	-0.07	-0.00	-0.09	-0.08	0.24	0.24	0.24	0.31	2.90
Nigeria	-0.06	-0.06	-0.09	-0.06	0.32	0.27	0.38	0.38	2.11
Vietnam	-0.06	-0.05	-0.05	-0.05	0.02	-0.00	0.03	0.07	2.72
Indonesia	-0.02	-0.02	-0.02	-0.02	0.04	0.03	0.11	0.06	2.62
Burkina Faso	-0.01	-0.01	-0.01	0.01	0.21	0.18	0.22	0.21	1.36
Cote d'Ivoire	0.01	0.03	-0.00	0.00	0.09	0.06	0.09	0.08	4.09
Bangladesh	0.02	0.02	0.02	0.02	0.35	0.25	0.41	0.33	4.65
Rwanda	0.05	0.06	0.02	0.02	0.22	0.17	0.29	0.17	1.77
Madagascar	0.06	0.08	0.01	0.05	0.23	0.18	0.25	0.17	0.59
Cameroon	0.10	0.11	0.08	0.09	0.35	0.34	0.36	0.25	0.63
Uganda	0.11	0.13	0.02	0.07	0.45	0.41	0.47	0.33	2.13
Moldova	0.13	0.03	0.09	0.17	1.06	0.72	2.08	0.93	17.72
Tanzania	0.13	0.13	0.11	0.13	0.35	0.30	0.40	0.22	5.04
Sierra Leone	0.19	0.37	0.02	0.12	0.53	0.40	0.55	0.34	4.12
Guinea	0.20	0.30	0.13	0.17	0.53	0.42	0.54	0.32	0.96
Kenya	0.22	0.42	0.14	0.22	1.24	1.11	1.40	1.02	4.81
Benin	0.28	0.42	0.14	0.23	0.62	0.53	0.67	0.34	1.75
Ghana	0.32	0.37	0.26	0.28	0.54	0.46	0.90	0.22	3.23
Cent. Afr. R	0.33	0.54	0.21	0.23	1.13	1.09	1.13	0.80	1.12
Comoros	0.34	0.33	0.27	0.32	0.95	0.86	1.00	0.61	0.30
Nepal	0.59	0.64	0.52	0.55	1.36	1.35	1.39	0.76	7.72
Iraq	0.69	0.88	0.61	0.64	1.25	0.86	2.16	0.56	4.14
Pakistan	0.76	0.28	1.35	1.09	1.51	1.38	1.82	0.75	3.77

Notes: This table is a continuation from the table on the previous page. It presents the results of a simulation in which (i) the Ukraine cannot import or export any agricultural product and (ii) Russia bans exporting wheat, rice, corn, other cereals, sugar, and other oilseeds. Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the (pre-war) status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single. HH. denotes a representative household and presents the results of a single agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption. Exposure measures what share of imports of a given country were accounted for by imports from the Ukraine and Russia before the war. Countries are ordered in terms of average real income gains (from lowest to highest).

Table A3: Impact of the Ukraine war - Robustness
Retaliatory protectionism

	ΔWelfare				**ΔIncome**			**ΔCPI**	**Exposure**
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Imports
	Panel A: All countries (pooled)								
Average	-2.24	-2.43	-1.95	-2.05	0.23	0.18	0.22	2.55	5.42
Pop w. average	-1.43	-1.68	-1.06	-1.18	0.67	0.53	0.85	2.13	4.30
SD	2.30	2.66	2.03	2.20	1.90	1.48	2.67	1.68	5.35
Minimum	-10.87	-12.56	-9.55	-10.25	-6.32	-4.56	-8.65	-0.60	0.30
Median	-1.79	-1.61	-1.61	-1.60	0.49	0.35	0.51	2.36	3.66
Maximum	0.99	0.98	1.77	1.08	4.21	3.88	7.26	10.04	19.97
	Panel B: By country								
Azerbaijan	-10.87	-12.56	-8.97	-10.25	-6.32	-4.56	-7.69	5.14	18.25
Mongolia	-9.72	-10.28	-9.55	-9.55	-5.42	-3.72	-8.65	4.76	6.10
Georgia	-8.50	-9.91	-6.25	-7.42	-1.24	-1.08	-1.50	7.98	19.97
Armenia	-7.33	-9.06	-5.82	-6.68	1.95	1.51	2.87	10.04	17.85
Moldova	-4.24	-4.58	-3.71	-4.18	-3.85	-2.76	-7.03	0.40	17.72
Cent. Afr. R	-3.70	-3.43	-3.67	-3.70	-0.82	-0.81	-0.82	2.98	1.12
Kyrgyzstan	-3.26	-3.55	-2.93	-3.11	-0.72	-0.61	-0.89	2.63	11.60
Mauritania	-3.18	-3.89	-2.25	-2.61	-0.04	-0.08	-0.04	3.24	2.85
Nicaragua	-3.13	-3.51	-2.65	-2.87	-1.42	-1.32	-1.56	1.76	1.42
Ecuador	-2.92	-3.51	-2.17	-2.51	-1.37	-1.23	-1.62	1.59	14.18
Egypt	-2.84	-3.17	-2.39	-2.59	0.95	0.74	1.24	3.90	6.91
Cameroon	-2.77	-3.01	-2.47	-2.53	-0.47	-0.46	-0.48	2.36	0.63
Ghana	-2.62	-3.23	-2.15	-2.27	-3.21	-2.79	-5.03	-0.60	3.23
Cote d'Ivoire	-2.54	-2.79	-2.21	-2.31	-1.12	-0.91	-1.18	1.45	4.09
Yemen	-2.44	-3.12	-1.64	-1.95	0.65	0.54	0.81	3.18	3.76
Burkina Faso	-2.32	-2.33	-2.23	-2.19	-0.92	-0.90	-0.93	1.43	1.36
Tajikistan	-2.25	-1.94	-2.47	-2.27	1.40	1.37	1.55	3.74	9.41
Mozambique	-2.23	-0.91	-3.82	-3.20	0.29	0.13	0.35	2.60	6.77
Jordan	-2.20	-2.65	-1.73	-1.96	0.71	0.59	1.14	2.98	0.76

Notes: This table presents the results of a simulation in which (i) the Ukraine cannot import or export any agricultural products, or fertilizers and (ii) Russia bans exporting wheat, rice, corn, other cereals, sugar, other oilseeds, and fertilizers. Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the (pre-war) status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single HH. denotes a representative household and presents the results of a single agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption.Exposure measures what share of imports of a given country were accounted for by imports from the Ukraine and Russia before the war. Countries are ordered in terms of average real income gains (from lowest to highest).

Table A3: Impact of the Ukraine war - Robustness (continued)
Retaliatory protectionism

	ΔWelfare				**ΔIncome**			**ΔCPI**	**Exposure**
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Imports
Gambia	-2.19	-1.86	-2.16	-2.18	-0.10	-0.11	-0.07	2.14	2.13
Bolivia	-2.10	-2.35	-1.57	-1.71	-0.01	-0.07	0.04	2.13	1.54
Zambia	-2.08	-2.22	-1.97	-2.01	0.67	0.50	0.92	2.82	2.96
South Africa	-2.04	-2.93	-0.84	-1.05	-0.09	-0.09	0.03	2.00	3.66
Liberia	-1.97	-1.51	-2.12	-2.05	0.91	0.76	0.98	2.93	1.70
Tanzania	-1.92	-2.04	-1.61	-1.60	-0.63	-0.56	-0.71	1.31	5.04
Nigeria	-1.79	-1.55	-1.79	-1.79	0.61	0.50	0.73	2.44	2.11
Togo	-1.75	-1.68	-1.64	-1.66	0.32	0.34	0.32	2.11	2.90
Guatemala	-1.58	-1.57	-1.41	-1.48	0.09	0.06	0.14	1.69	1.02
Guinea-Bissau	-1.56	-1.78	-1.07	-1.07	0.97	0.91	1.01	2.57	3.65
Burundi	-1.50	-1.54	-1.17	-1.25	0.49	0.39	0.51	2.03	4.74
Vietnam	-1.43	-1.44	-1.29	-1.36	0.02	-0.02	0.05	1.47	2.72
Bangladesh	-1.37	-1.58	-1.10	-1.23	1.08	0.77	1.27	2.49	4.65
Niger	-1.32	-0.96	-1.57	-1.41	0.40	0.35	0.42	1.75	5.40
Uzbekistan	-1.13	-0.86	-1.64	-1.33	1.81	0.31	3.42	2.98	17.31
Sri Lanka	-1.06	-1.60	-0.44	-0.63	0.28	0.19	0.44	1.36	15.57
Kenya	-0.99	-0.89	-0.80	-0.71	1.82	1.57	2.09	2.84	4.81
Rwanda	-0.99	-1.20	-0.74	-0.84	0.11	0.06	0.20	1.11	1.77
Comoros	-0.96	-1.12	-0.90	-0.88	1.82	1.62	1.93	2.80	0.30
Uganda	-0.92	-1.06	-1.02	-0.94	0.68	0.61	0.72	1.62	2.13
Papua N.G.	-0.85	-0.78	-0.85	-0.78	1.24	0.88	1.40	2.10	1.29
Indonesia	-0.82	-0.90	-0.74	-0.75	-0.13	-0.13	-0.15	0.69	2.62
Cambodia	-0.71	-0.76	-0.59	-0.60	0.68	0.45	0.82	1.40	3.32
Malawi	-0.71	-0.38	-1.21	-0.98	0.57	0.44	0.65	1.29	8.34
Madagascar	-0.61	-0.53	-0.75	-0.61	1.05	0.86	1.16	1.68	0.59
Benin	-0.50	-0.05	-0.88	-0.69	1.24	1.04	1.33	1.74	1.75
Sierra Leone	-0.49	-0.29	-0.72	-0.51	2.46	1.96	2.52	2.97	4.12
Bhutan	-0.49	-0.59	-0.09	-0.20	1.50	1.32	1.83	1.99	3.80
Guinea	-0.43	0.00	-0.73	-0.54	1.96	1.52	2.02	2.40	0.96
Pakistan	-0.09	-1.61	1.77	1.08	2.57	2.32	3.21	2.67	3.77
Iraq	0.06	0.20	0.51	0.31	4.21	2.88	7.26	4.15	4.14
Nepal	0.99	0.98	0.95	0.96	3.91	3.88	3.97	2.89	7.72

Notes: This table is a continuation from the table on the previous page. It presents the results of a simulation in which (i) the Ukraine cannot import or export any agricultural products, or fertilizers and (ii) Russia bans exporting wheat, rice, corn, other cereals, sugar, other oilseeds, and fertilizers. Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the (pre-war) status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single HH. denotes a representative household and presents the results of a single agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption. Exposure measures what share of imports of a given country were accounted for by imports from the Ukraine and Russia before the war. Countries are ordered in terms of average real income gains (from lowest to highest).

Table A4: Impact of Climate Change - Robustness
Limited adjustment

	ΔWelfare				ΔIncome			ΔCPI	Exposure
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Yield
Panel A: All countries (pooled)									
Average	-12.43	-14.45	-10.70	-11.41	-12.91	-11.71	-13.70	-0.94	-17.41
Pop w. average	-14.43	-16.58	-12.25	-13.24	-13.59	-11.70	-16.93	1.05	-29.48
SD	20.40	23.01	18.34	19.27	21.47	19.65	23.73	4.22	54.81
Minimum	-72.98	-76.58	-72.52	-72.34	-76.52	-75.20	-77.46	-13.13	-63.43
Median	-11.54	-11.98	-10.32	-10.99	-12.09	-11.18	-13.17	-0.19	-37.81
Maximum	34.28	33.81	36.22	35.42	34.61	31.54	41.32	7.18	259.88
Panel B: By country									
Guinea-Bissau	-72.98	-76.58	-72.52	-72.34	-76.52	-75.20	-77.46	-13.13	-49.20
Gambia	-49.06	-64.27	-36.53	-42.42	-54.03	-55.53	-52.26	-9.72	-39.38
Cote d'Ivoire	-45.97	-57.25	-36.48	-40.47	-52.58	-45.06	-54.89	-11.91	-44.56
Cent. Afr. R.	-38.45	-40.70	-33.99	-35.49	-38.40	-35.21	-38.46	0.13	-45.67
Bolivia	-37.44	-46.64	-32.02	-33.85	-39.89	-33.82	-44.65	-3.47	-62.51
Benin	-36.18	-36.52	-34.70	-34.75	-37.60	-34.42	-39.54	-2.22	-51.84
Papua N.G.	-35.78	-41.04	-31.01	-33.32	-36.41	-27.89	-40.20	-0.93	-56.92
Nigeria	-34.99	-37.25	-32.15	-33.38	-30.38	-27.08	-34.08	7.18	-55.76
Mozambique	-34.55	-40.38	-24.35	-30.50	-32.07	-21.90	-35.94	3.80	-56.44
Togo	-29.81	-40.12	-21.30	-24.69	-32.51	-35.81	-30.65	-3.80	-47.94
Ghana	-28.03	-32.96	-24.77	-25.69	-36.15	-34.09	-47.72	-11.21	-47.54
Guinea	-26.78	-30.19	-22.68	-25.28	-28.16	-24.63	-28.65	-1.85	-49.97
Guatemala	-23.95	-28.39	-20.29	-22.36	-25.04	-24.76	-24.96	-1.35	-42.48
Sri Lanka	-23.88	-26.49	-20.30	-21.55	-28.00	-23.00	-35.52	-5.37	-58.42
Nicaragua	-23.21	-27.51	-19.43	-21.27	-24.00	-21.58	-26.89	-0.94	-49.02
Sierra Leone	-21.98	-23.78	-18.21	-20.60	-25.79	-20.37	-26.75	-4.89	-51.21
Malawi	-18.65	-17.61	-18.86	-18.72	-17.52	-15.01	-18.96	1.40	-43.61
Niger	-18.15	-19.58	-22.68	-20.08	-20.47	-20.82	-21.17	-2.81	-36.30
Burkina Faso	-17.84	-17.10	-16.57	-17.14	-19.88	-18.35	-20.42	-2.46	-48.71

Notes: This table presents the results of a simulation of the impacts of climate change based on the FAO GAEZ Hadley CM3 A1 model but in which households are not allowed to change their income earning portfolio.Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single HH. denotes a representative household and presents the results of a single agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption. Exposure refers to the change in agricultural productivity (i.e. crop yields) relative to the status quo. Countries are ordered in terms of average real income gains (from lowest to highest).

Table A4: Impact of Climate Change (continued)
Limited adjustment

	ΔWelfare				ΔIncome			ΔCPI	Exposure
	Average	Bottom 25%	Top 25%	Single HH.	Total	Labor	Land	HH.	Yield
Mauritania	-17.81	-22.77	-17.32	-17.46	-16.68	-14.70	-16.98	1.40	-52.64
Bangladesh	-17.79	-20.36	-15.34	-16.92	-17.97	-14.04	-20.46	-0.19	-55.24
Vietnam	-17.25	-19.64	-14.47	-16.10	-14.93	-11.41	-17.73	2.84	-50.27
Indonesia	-15.09	-18.55	-11.09	-12.85	-13.17	-11.46	-24.23	2.30	-42.56
Cambodia	-12.53	-13.07	-11.52	-11.87	-6.85	-4.92	-8.18	6.51	-63.43
Liberia	-12.22	-14.06	-11.08	-11.33	-17.03	-15.63	-17.75	-5.49	-46.36
Zambia	-11.54	-11.98	-10.32	-10.99	-7.50	-5.86	-9.67	4.58	-39.72
Tanzania	-11.13	-11.87	-9.01	-9.84	-12.09	-11.18	-13.17	-1.07	-30.77
Nepal	-10.12	-11.55	-8.21	-8.88	-14.65	-14.59	-14.84	-5.02	-26.67
Cameroon	-8.60	-9.24	-7.22	-7.60	-5.33	-5.39	-5.30	3.59	-37.81
Egypt	-8.44	-10.02	-6.39	-7.67	-6.71	-5.54	-8.33	1.91	-13.12
Ecuador	-8.07	-10.85	-5.83	-7.08	-8.09	-7.06	-9.76	-0.00	-36.91
Pakistan	-6.56	-7.73	-6.33	-5.86	-5.69	-5.37	-6.26	0.94	10.12
Madagascar	-5.37	-5.79	-4.54	-5.28	-3.07	-2.63	-3.31	2.43	-25.79
Iraq	-4.36	-5.71	-3.48	-3.91	-4.23	-3.12	-6.77	0.14	13.21
Uganda	-3.71	-3.56	-3.26	-3.32	-2.96	-2.55	-3.18	0.78	-11.27
Azerbaijan	-3.04	-4.04	-3.65	-2.93	-2.98	-1.91	-3.79	0.06	-30.48
South Africa	-2.05	-5.03	-0.04	-0.61	-1.34	-1.26	-7.31	0.76	-19.67
Bhutan	1.29	2.36	0.36	1.22	-0.18	-0.35	0.24	-1.44	-8.69
Uzbekistan	1.42	1.30	2.10	1.52	-0.43	1.06	-2.02	-1.83	-4.65
Yemen	1.91	1.53	2.22	2.10	1.24	1.13	1.34	-0.66	0.00
Georgia	5.62	6.56	4.39	4.98	3.69	3.43	4.21	-1.82	1.21
Jordan	6.13	7.16	4.95	5.39	3.83	3.43	5.22	-2.16	31.51
Comoros	6.93	9.46	4.69	6.50	4.55	4.53	4.67	-2.17	-8.79
Burundi	7.04	7.03	6.68	6.63	10.96	8.14	11.20	3.68	28.24
Armenia	8.13	8.47	7.07	7.67	8.87	7.80	11.25	0.69	65.79
Kenya	8.96	9.84	6.81	7.27	9.74	9.14	10.77	0.72	7.06
Tajikistan	11.16	12.50	9.74	9.78	13.44	13.39	13.51	2.06	6.07
Moldova	14.29	17.86	10.22	14.02	16.89	12.15	30.14	2.28	41.05
Kyrgyzstan	20.06	22.45	17.33	19.53	22.40	18.76	28.06	1.96	91.96
Rwanda	31.97	32.89	29.57	30.52	34.61	31.54	37.81	2.02	98.05
Mongolia	34.28	33.81	36.22	35.42	28.82	22.01	41.32	-4.07	259.88

Notes: This table is a continuation from the table on the previous page.It presents the results of a simulation of the impacts of climate change based on the FAO GAEZ Hadley CM3 A1 model but in which households are not allowed to change their income earning portfolio. Welfare changes and changes in income are expressed as percentage changes in real household income relative to the status quo. Welfare changes (ΔWelfare) and changes in income (ΔIncome) are expressed as percentage changes in real household income relative to the status quo. Bottom 25% (top 25%) refers to the poorest (richest) 25% of the population within a given country. Single HH. denotes a representative household and presents the results of a single agent model in which all households are aggregated into one representative household. ΔCPI measures the increase in the cost of consumption. Exposure refers to the change in agricultural productivity (i.e. crop yields) relative to the status quo. Countries are ordered in terms of average real income gains (from lowest to highest).

A6 Concordance

Table A5: Concordance ITPDE-HIT (1/2)

Code	Description	ITPD-E Product(s)
1	Wheat	Wheat
2	Rice	Rice (raw)
3	Corn	Corn
4	Other cereals	Other cereals, Cereal products, Grain mill products
5	Soya	Soybeans
6	Other oilseeds	Other oilseeds (exc. peanuts)
7	Sugar	Raw, Refined sugar, Sugar crops, Other sweeteners, Sugar
8	Legumes	Pulses, Legumes(dried, preserved)
9	Fruits and vegetables	Fresh fruit, Fresh vegetables, Processing/preserving of fruit and vegetables
10	Nuts	Nuts
11	Eggs/Meat/Dairy	Live Cattle, Live Swine, Other meats, livest. pr. live animals, Processing/preserving of meat, Eggs, Dairy products
12	Cocoa	Cocoa and cocoa products, Cocoa chocolate and sugar confectionery
13	Oils/Fats	Vegetable and animal oils and fats
14	Other staple food	Animal feed ingredients and pet foods, Prepared fruits, fruit juices, Prepared vegetables, Other ag. products, nec, Starches and starch products, Prepared animal feeds, Bakery products, Macaroni noodles and similar products, Other food products n.e.c.
15	Beverages, nec	Beverages (nec), Soft drinks, mineral waters
16	Cotton	Cotton
17	Tobacco	Tobacco leaves and cigarettes, Tobacco products
18	Spices/herbs	Spices
19	Alcohol	Wines, Malt liquors and malt, Distilling rectifying and blending of spirits
20	Fish	Processing/preserving of fish
21	Manufacturing (continues on next page)	Mining of hard coal, Mining of lignite, Extraction crude oil and gas, Mining of iron ores, Other mining and quarring, Electricity prodcn, collcn, and distr., Gas production and distribution, Coke oven products, Refined petroleum products, Processing of nuclear fuel, Textile fibre preparation; textile weaving, Made-up textile articles except apparel, Carpets and rugs, Cordage rope twine and netting, Other textiles n.e.c., Knitted and crocheted fabrics and articles, Wearing apparel except fur apparel, Dressing and dyeing of fur, processing of fur, Tanning and dressing of leather, Luggage handbags etc., saddlery and harness, Footwear, Sawmilling and planing of wood, Veneer sheets plywood particle board etc., Builders' carpentry and joinery, Wooden containers, Other wood products; articles of cork/straw, Furniture, Domestic appliances n.e.c., Office accounting and computing machinery, Electric motors generators and transformers, Electricity distribution and control apparatus, Insulated wire and cable, Accumulators primary cells and batteries, Lighting equipment and electric lamps, Other electrical equipment n.e.c., Electronic valves tubes etc., TV/radio transmitters; line comm. apparatus, TV and radio receivers and associated goods, Medical surgical and orthopedic equipment, Measuring/testing/navigating appliances and equipment, Optical instruments and photographic equipment, Watches and clocks, Pulp paper and paperboard, Corrugated paper, and paperboard, Other articles of paper and paperboard,

Table A5: Concordance between HIT and ITPDE (2/2)

Code	Description	ITPD-E Product(s)
21	Manufacturing (continued)	Publishing of books and other publications, Publishing of newspapers journals etc., Publishing of recorded media, Other publishing, Printing, Service activities related to printing, Reproduction of recorded media, Basic chemicals except fertilizers, Fertilizers and nitrogen compounds, Plastics in primary forms; synthetic rubber, Pesticides and other agro-chemical products, Paints varnishes printing ink and mastics, Pharmaceuticals medicinal chemicals etc., Soap cleaning and cosmetic preparations, Other chemical products n.e.c., Man-made fibers, Rubber tires and tubes, Other rubber products, Plastic products, Glass and glass products, Pottery china and earthenware, Refractory ceramic products, Struct.non-refractory clay; ceramic products, Cement lime and plaster, Articles of concrete cement and plaster, Cutting shaping and finishing of stone, Other non-metallic mineral products n.e.c., Basic iron and steel, Basic precious and non-ferrous metals, Casting of iron and steel, Structural metal products, Tanks reservoirs and containers of metal, Steam generators, Cutlery hand tools and general hardware, Other fabricated metal products n.e.c., Engines and turbines (not for transport equipment), Pumps compressors taps and valves, Bearings gears gearing and driving elements, Ovens furnaces and furnace burners, Lifting and handling equipment, Other general purpose machinery, Agricultural and forestry machinery, Machine tools, Machinery for metallurgy, Machinery for mining and construction, Food/beverage/tobacco processing machinery, Machinery for textile apparel and leather, Weapons and ammunition, Other special purpose machinery, Motor vehicles, Automobile bodies trailers and semi-trailers, Parts/accessories for automobiles, Building and repairing of ships, Building/repairing of pleasure/sport. boats, Railway/tramway locomotives and rolling stock, Aircraft and spacecraft, Motorcycles, Bicycles and invalid carriages, Other transport equipment n.e.c., Jewelery and related articles, Musical instruments, Sports goods, Games and toys,
22	Services	Transport, Travel, Health services, Education services, Telecommunications, computer and information services, Manufacturing services on physical inputs owned by others, Maintenance and repair services n.i.e., Construction, Insurance and pension services, Financial services, Charges for the use of intellectual property n.i.e., Other business services, Heritage and recreational services, Government goods and services n.i.e., Services not allocated, Trade-related services, Other personal services
23	Fertilizers	Fertilizers and nitrogen compounds

Table A6: Concordance between HIT-ITPDE and WFP food prices data (1/3)

Code	Description	WFP Commodity
1	Wheat	Buckwheat, Buckwheat grits, Bulgur, Couscous, Feed (flour), Feed (rakhel), Feed (wheat bran), Noodles (short), Pasta, Pasta (macaroni), Pasta (spaghetti), Semolina, Wheat, Wheat (food aid), Wheat (imported), Wheat (mixed), Wheat (white), Wheat flour, Wheat flour (first grade), Wheat flour (high quality), Wheat flour (imported), Wheat flour (local), Wheat flour (Turkey), Wheat meal
2	Rice	Rice, Rice (aromatic), Rice (basmati broken), Rice (basmati), Rice (broken imported), Rice (carolina 1st), Rice (carolina 2da), Rice (coarse BR-8/ 11/ Guti Sharna), Rice (coarse Guti Sharna), Rice (coarse), Rice (denikassia imported), Rice (estaquilla), Rice (good quality), Rice (Grano de Oro), Rice (high quality local), Rice (high quality), Rice (imported Pakistan), Rice (imported Tanzanian), Rice (imported), Rice (local), Rice (long grain high quality local), Rice (long grain imported), Rice (long grain), Rice (low quality local), Rice (low quality), Rice (medium grain imported), Rice (medium grain), Rice (medium quality), Rice (milled local), Rice (mixed low quality), Rice (ordinary first quality), Rice (ordinary second quality), Rice (paddy long grain local), Rice (paddy), Rice (red nadu), Rice (red), Rice (short grain low quality local), Rice (small grain imported), Rice (white imported 551), Rice (white imported JPC SK Gold), Rice (white imported), Rice (white), Rice (milled 80-20)
3	Corn	Corn Soy Blend (CSB++ food aid), Cornstarch, Maize, Maize (crushed), Maize (food aid), Maize (local), Maize (white biofortified), Maize (white dry), Maize (white East), Maize (white North), Maize (white), Maize (yellow biofortified), Maize (yellow), Maize flour, Maize flour (imported), Maize flour (white), Maize meal, Maize meal (white breakfast), Maize meal (white first grade), Maize meal (white roller), Maize meal (white with bran), Maize meal (white without bran), Tortilla (maize)
4	Other cereals	Barley, Barley (mixed), Barley (white), Fonio, Millet, Millet (bulrush), Millet (finger), Millet flour, Oat flakes, Quinoa, Sorghum, Sorghum (brown), Sorghum (food aid), Sorghum (local), Sorghum (mixed), Sorghum (red), Sorghum (r'haya), Sorghum (taghalit), Sorghum (white), Teff, Teff (mixed), Teff (red), Teff (Sergegna), Teff (white)
5	Soya	Soybeans
6	Other oilseeds	Lin seed, Rape seed, Sesame
7	Sugar	Cane juice (light), Cane juice (strong), Honey, Sugar, Sugar (brown imported), Sugar (brown local), Sugar (local), Sugar (premium), Sugar (white)
8	Legumes	Beans, Beans (black East) Beans (black North) Beans (black) Beans (butter) Beans (catarino) Beans (dolichos) Beans (dry) Beans (fava dry) Beans (fava) Beans (green fresh) Beans (green) Beans (haricot red) Beans (haricot white) Beans (haricot) Beans (kidney red) Beans (kidney pinto) Beans (kidney), Beans (magnum), Beans (mung), Beans (niebe white), Beans (niebe), Beans (pod), Beans (red East), Beans (red North), Beans (red), Beans (rosecoco), Beans (spotted), Beans (white East), Beans (white North), Beans (white), Beans (yardlong green), Beans (yellow), Beans(mash), Chickpeas, Cowpea leaves, Cowpeas, Cowpeas (brown), Cowpeas (Red), Cowpeas (white), Cowpeas (whole average), Lentils, Lentils (masur), Lentils (moong), Peas, Peas (fresh), Peas (green dry), Peas (mixed), Peas (split dry), Peas (yellow split), Peas (yellow), Pigeon peas, Pulses (Diamond Masoor Dal), Lentils (broken)

Table A6: Concordance between HIT-ITPDE and WFP food prices data (2/3)

Code	Description	WFP Commodity
9	Fruits and vegetables	Apples, Apples (dried), Apples (red), Avocados, Avocados (Hass medium size), Bananas, Bananas (imported), Bananas (local), Bananas (medium size), Beetroots, Blackberry, Broccoli, Cabbage, Cabbage (chinese flowering), Carrots, Cashew fruit, Cassava, Cassava (cossette), Cassava (dry), Cassava (fresh), Cassava flour, Cassava leaves, Cassava meal, Cassava meal (attieke), Cassava meal (gari fine), Cassava meal (gari yellow), Cassava meal (gari), Cassava meal (tapioca), Cauliflower (medium size), Coconut, Coconut (dried), Cocoyam (macabo), Cucumbers, Cucumbers (greenhouse), Dates, Eggplants, Garlic, Garlic (medium), Grapes (black), Grapes (pink), Guava, Kale, Leafy vegetables, Lemons, Lemons (Criollo medium size), Lemons (Persa medium size), Lentils (red), Lettuce, Mandarins, Mangoes, Melons (cantaloupe), Naranjilla (hybrid), Okra (dry), Okra (fresh), Onions, Onions (dry), Onions (imported), Onions (red dry), Onions (red imported), Onions (red local), Onions (red), Onions (shallot medium), Onions (shallot), Onions (white dry), Onions (white), Oranges, Oranges (big size), Oranges (Piña), Oranges (Valencia medium size), Papaya, Passion fruit, Peach (medium size), Pineapples, Plantains, Plantains (apem), Plantains (apentu), Plantains (barraganete green), Plantains (barraganete mature), Plantains (big size), Plantains (dominico green), Plantains (dominico mature), Plantains (medium size), Potatoes, Potatoes (imported), Potatoes (Irish imilla), Potatoes (Irish red), Potatoes (Irish white), Potatoes (Irish), Potatoes (local), Potatoes (red), Potatoes (super chola), Potatoes (unica), Pumpkin, Radish, Spinach, Squashes, Strawberries, Sweet potatoes, Swiss chard, Taro, Tomatoes, Tomatoes (big size), Tomatoes (bitter), Tomatoes (greenhouse), Tomatoes (local), Tomatoes (medium size), Tomatoes (navrongo), Tomatoes (paste), Tree tomatoes, Watermelons, Wax gourd, Yam, Yam (Abuja), Yam (dry), Yam (florido), Yam (flour), Yam (puna), Yam (white), Yam (yellow)
10	Nuts	Cashew nut, Groundnuts, Groundnuts (Bambara), Groundnuts (large shelled), Groundnuts (paste), Groundnuts (shelled), Groundnuts (small shelled), Groundnuts (small unshelled), Groundnuts (unshelled), Peanut, Walnuts
11	Eggs/Meat/Dairy	Butter, Butter (cow milk), Butter (goat milk), Cheese, Cheese (dry), Cheese (fat), Cheese (local), Cheese (low-fat), Cheese (picon), Cheese (white boiled), Chicken, Eggs, Eggs (broiler), Eggs (duck fermented), Eggs (duck), Ghee (artificial), Ghee (natural), Kefir, Meat, Meat (antelope smoked), Meat (beef canned), Meat (beef chops with bones), Meat (beef first quality), Meat (beef second quality), Meat (beef with bones), Meat (beef without bones), Meat (beef), Meat (camel), Meat (chicken broiler), Meat (chicken fillet), Meat (chicken fresh), Meat (chicken frozen imported) -, Meat (chicken frozen), Meat (chicken local), Meat (chicken whole), Meat (chicken), Meat (gazelle smoked), Meat (goat), Meat (lamb), Meat (mixed sausage), Meat (mutton), Meat (pork first quality), Meat (pork second quality), Meat (pork with fat), Meat (pork), Meat (sheep second quality), Meat (sheep), Milk, Milk (camel fresh), Milk (camel), Milk (condensed), Milk (cow fresh), Milk (cow pasteurized), Milk (fresh), Milk (non-pasteurized), Milk (pasteurized), Milk (powder), Milk (UHT), Poultry, Sour cream, Yogurt

Table A6: Concordance between HIT-ITPDE and WFP food prices data (3/3)

Code	Description	WFP Commodity
12	Confectionery/Cocoa	Cocoa, Cocoa (powder)
13	Oils/Fats	Cooking fat, Fat (salo), Oil, Oil (coconut), Oil (cooking), Oil (cotton), Oil (groundnut), Oil (maize), Oil (mixed), Oil (olive), Oil (palm nut), Oil (palm refined), Oil (palm), Oil (sunflower), Oil (vegetable bulk), Oil (vegetable Himani Best Choice), Oil (vegetable imported), Oil (vegetable local), Oil (vegetable Mahakosh), Oil (vegetable packaged), Oil (vegetable), Oil (mustard), Oil (soybean)
14	Other staple food	Bitterball, Bread, Bread (first grade flour), Bread (high grade flour), Bread (khoboz), Bread (pita), Bread (rye), Bread (wheat), Curd, Gari, Gari (white)
15	Beverages, nec	Coffee, Coffee (instant), Tea, Tea (black), Tea (green), Water (drinking), Water spinach
16	Cotton	Cotton
18	Spices/herbs	Chili (bird's eye green), Chili (bird's eye red), Chili (bird's eye), Chili (red curly), Chili (red dry raw), Chili (red large), Chili (red), Jalapeño pepper (big size), Jalapeño pepper (medium size), Niger seed, Peppers (dried), Peppers (fresh), Peppers (green), Peppers (red dry), Peppers (red), Salt, Salt (iodised), Peppers (sweet)
20	Fish	Fish, Fish (appolo), Fish (barbel sole), Fish (bonga), Fish (catfish), Fish (dry katta), Fish (dry sprats), Fish (dry), Fish (fresh silvi), Fish (fresh), Fish (frozen), Fish (goldstripe sardinella), Fish (herring), Fish (jack), Fish (latesdryimported) -, Fish (latesdrylocal) -, Fish (mackerel fresh), Fish (mullet catfish), Fish (omena dry), Fish (sail fish), Fish (sardine canned), Fish (skipjack tuna), Fish (smoked), Fish (snake head dry), Fish (snake head), Fish (striped catfish), Fish (tilapia salted dried) -, Fish (tilapia), Fish (trenched sardinella), Fish (tuna canned), Fish (yellowfin tuna), Panga, Prawn, Shrimps
21	Manufacturing	Antibacterial wipes, Antibiotics (imported), Antibiotics (local), Antipyretic (imported), Antipyretic (local), Basin, Batteries, Batteries (big), Batteries (small), Candles (big), Candles (small), Disinfecting solution, Hand sanitizer (gel), Handwash soap, Hoe, Jerrycan (20 L), Jerrycan (5 L), Laundry detergent, Laundry soap, Mug (plastic), Nails, Pen, Pencil, Plate (plastic), Rope, Sanitary pads, Shampoo, Surgical mask, Toothbrush, Toothpaste, Torch, Underwear
23	Fertilizers	Fuel (diesel), Fuel (gas), Fuel (kerosene paraffin), Fuel (kerosene), Fuel (LPG), Fuel (petrol), Fuel (petrol-gasoline 92 octane), Fuel (petrol-gasoline 95 octane), Fuel (petrol-gasoline), Fuel (Super Petrol)