Climate change, comparative advantages, and structural transformation in agriculture

Abstract

This paper quantifies the macro-level consequences of climate change under nonhomothetic preferences. Using a general equilibrium Ricardian trade model, we assess how climate-induced productivity shocks affect global welfare. Unlike standard models, we account for the role of income in shaping food demand and estimate the potential of international trade to mitigate welfare losses. Empirical estimates using a rich micro-level dataset on agricultural productivity suggest that climate change reduces global welfare by 4.6%, compared to just 0.26% when income effects are ignored. Low-income countries suffer the largest impacts due to higher food expenditure shares and limited adaptive capacity. Importantly, the analysis shows that price effects matter more than structural reallocation, and that trade—especially through tariff reductions—can partially offset welfare losses by improving food access and reallocating resources more efficiently.

JEL Classification: F13, F18, F40, Q11, Q17, Q54

Keywords: International Trade, Welfare, Trade and Environment, Agricultural Commodities, Farming, Climate Change.

1. Introduction

Climate change has the ability to increase average temperatures and the frequency of climate extremes, according to Leonard et al. (2014) , AghaKouchak et al. (2014) and AghaKouchak et al. (2020). The predictions of the Intergovernmental Panel on Climate Change (IPCC) warn against a worsening of the situation in the coming years. This result in an increase in the frequency, intensity, spatial extent, and duration of extreme and increasingly complex climatic events (Bathke et al., 2015; Tavakol et al., 2020) in all regions in the world. The impact of climate change on agriculture is particularly pronounced, showing substantial disparities in various geographical areas. Food security is affected by uncertainty over domestic production and production in foreign countries. The resilience of agri-food supply chains to climate change is also of great concern.

Due to its heterogeneous impacts, climate change affects the competitivity of firms and countries' comparative advantage inducing changes in specializations between countries and adjustments in trade flows (Costinot et al., 2016; Nath, 2020, 2025). As comparative advantages evolve over time (Gaigné and Gouel, 2022), climate change and shifting patterns of specialization are likely to have significant implications for welfare and consumption baskets. A key insight is that the effects of climate change will differ across regions. If climate change impacts all crops and countries uniformly, the resulting reduction in cross-country productivity differences may weaken trade incentives, leading to substantial welfare losses. By contrast, if climate change increases productivity disparities across regions, it could amplify trade opportunities and, in doing so, help mitigate some of the welfare losses.

This paper addresses these challenges by examining the macro-level consequences of climate change. Our main contribution to the existing literature is twofold : first, building on a ricardian model of international trade, we develop a theoretical framework to address the role of income in the impact of climate change on household welfare, while accounting for a demand system based on non-homothetic CES preferences. Second, by embedding changes in productivity into a general equilibrium trade model, we quantify macro-level impact of climate shocks, and the role of international trade in mitigating welfare losses. Third, we measure changes in consumer welfare using a money-metric utility approach (Baqaee and Burstein, 2023; Baqaee et al., 2024; Jaravel and Lashkari, 2024), which allows for consistent comparisons of income before and after climate change. We then decompose the total welfare effect into two components:

a structural effect, driven by changes in the share of agricultural goods in consumption across countries, and a price effect, reflecting the impact of relative price changes induced by climate shocks.

We do this by relying on a rich micro-level data, covering the entire globe, from the Global Agro-Ecological Zones (Fischer et al., 2021) project of the Food and Agricultural Organization (FAO), which combines agronomic modeling with detailed geospatial information—including soil type, elevation, and climate related variables to estimate potential yields for individual crops worldwide. Comparing yields under present and future climate scenarios allows us to infer changes in comparative advantage across space and time. Our results indicate that climate change has uneven effects on agri-food productivity and welfare, with low- and lower-middle-income economies especially vulnerable due to their reliance on climate-sensitive sectors. Exposure to climate shocks can have substantial effects on price variation compared to structural changes in demand shares for agricultural products.

This paper can be related to the recent literature evaluating the gains from trade using a large class of models delivering structural gravity equations (Gouel and Laborde (2021), Costinot et al. (2016)). Gouel and Laborde (2021) build a theoretical framework with quasi-linear preferences to investigate how international trade flows are adapting to climate change. By applying a similar approach using less restrictive assumptions, we quantify the consequences of climate change on productivity and welfare.

2. A Brief Literature Review

Key contributions on climate change, productivity and shifting comparative advantages include Costinot et al. (2012), Costinot et al. (2016), and Gouel and Laborde (2021). This literature link climate change to trade using Ricardian models models allowing for land heterogeneity with yields drawn from a frechet distribution (e.g., Huang et al. (2011); Costinot et al. (2012, 2016); Heerman (2020); Heerman and Sheldon (2022); Levchenko and Zhang (2013); Simonovska and Waugh (2014a,b); Caliendo and Parro (2015)). This paper builds on these insights and further explores the role of trade as a mechanism for climate adaptation, as seen in Cui (2020), Conte et al. (2021), Gouel and Laborde (2021) and more recently Nath (2025).

We rely on prior work that provided the tools to define comparative advantages at the individual product level, by defining technologies in global general equilibrium models following

Eaton and Kortum (2002) or Melitz (2003), with heterogeneous productivity across products. Allowing for intra-sector heterogeneity in productivity has important implications for empirical analysis (Chor (2010); Costinot et al. (2012); Caliendo and Parro (2015); Tombe (2015)). Chor (2010) sectioned productivity into two components: randomly generated, and another linearly determined by a combination of country and industry attributes. Heerman et al. (2015) and Heerman (2020) defined sectoral heterogeneity with a product-level parameter that can be used to represent product-specific preferences and linked to characteristics of varieties, implying that countries possessing the same product-characteristics are inclined to compete because they are more likely to produce similar varieties. When consumers "love variety" firms will avoid making the same varieties to exploit horizontal product differentiation.

Our paper contributes to the recent debate examining the economic impact of climate change using agro-ecological characteristics (Fezzi and Bateman, 2015; Chalise and Naranpanawa, 2016; Habtemariam et al., 2017; Hossain et al., 2019; Gebreegziabher et al., 2020; Kim, 2022; Emediegwu et al., 2022; Abeysekara et al., 2023). Gebreegziabher et al. (2020) report that climate change-induced reductions in agricultural productivity could decrease average income by approximately 20 percent relative to a no-climate-change scenario. On the other hand, Hossain et al. (2019) indicate that higher temperatures and increased rainfall can enhance income and welfare. Our results expand on this literature by showing the connection between climate change effects, income distribution, and per capita income.

This paper is also related to the recent literature evaluating welfare gains from trade using a large class of models delivering structural changes with non-homothetic preferences equations. Gouel and Laborde (2021) build a theoretical framework with quasi-linear preferences to investigate how trade in agriculture are adapting to climate change. The authors investigate the role of international trade in adaptations to climate change, while assuming that income remains constant and agricultural demand is unrelated to income levels. We allow both income and preferences to vary, providing a richer understanding of trade's role in adaptation. In that respect, we build on recent research on the incidence of international shock propagation on production and welfare. We apply the framework and tools developped in Comin et al. (2021) and Lewis et al. (2022) to study how a substantial shift in consumption has affected trade in a general multi-country two-sector multi-factor model with intermediate goods.

Unlike Gouel and Laborde (2021), modeling the demand of goods with non-homothetic preferences is more appropriate when economies are undergoing structural changes (large-scale sectoral reallocation of employment as they develop), a gradual fall in the relative size of the agricultural sector and a corresponding increase in manufacturing. Assuming homothetic preferences for agrifood products is problematic due to (*i*) differences in the level of development between countries; (*ii*) the significance of income distribution and per capita income as determinants of trade and consumption of agrifood products (Uy et al., 2013; Chen and Juvenal, 2016) and (*iii*) the general high expectation of substantial income effects resulting from climate shocks. Non-homothetic CES preferences, by allowing for an arbitrary number agricultural products, have two interesting properties: (*iv*) they include good-specific non-homotheticity parameters that control the relative income elasticities, and (*v*) they exhibit a constant elasticity of substitution. Our counterfactuals simulate the welfare shocks in an environment with endogenous labor supply, allowing for propagation through intermediate inputs. Trade in intermediate inputs is a key component of global trade and its implications have been documented in recent contributions by Johnson and Noguera (2012, 2017); Caliendo and Parro (2015) and Eaton et al. (2016, 2022) among others.

The reminder of the paper proceeds as follows. The next section provides key takeaways from stylized facts. Section (4) outline a framework from which we derive the effect of climate change on household welfare. In section (5), we present the data to be used in the estimation and why it is well-suited for this analysis. Section (6) describes the empirical specification, and discuss the estimation of the income elasticities. Sections (7), (8) and (9) give the results, and section(10) conclude.

3. Stylized Facts

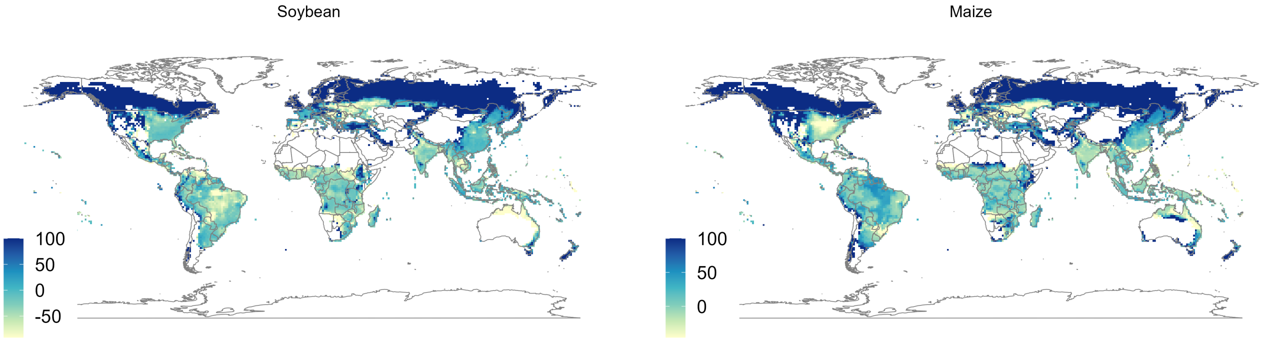
Our analysis is based on two key insights: (*i*) the observable and evolving nature of comparative advantages across countries and (*ii*) the fact that the impact of climate change vary with consumer income levels

3.1. Evolving comparative advantages

In a globalized world, the impact of micro-level shocks is determined not only by their average magnitude but also by their spatial dispersion, especially in agriculture. If climate change affects agricultural productivity, it will, in turn, influence specialization patterns and countries' ability to benefit from trade, ultimately impacting consumer welfare. We define comparative advantages by a country's ability to specialize in producing goods for which it has relatively higher productivity or lower opportunity cost, allowing more efficient global trade (Donaldson, 2019). In line with standard Ricardian frameworks, cross-country differences in productivity are the primary drivers of comparative advantage. Comparative advantages evolve over time and are highly dependent on climate change.

Figure (1) provides an overview of the productivity differences for the production of Maize and Soybean in different countries, using the detailed micro-level data from the FAO's Global Agro-Ecological Zones (GAEZ) database, and taking into account climatic conditions and yield (land productivity). In countries, there are large productivity disparities, and tropical countries are particularly suitable to these crops. The acknowledgment of such variations is a well-established principle in the literature, supporting the analysis of welfare gains from agricultural trade. In line with earlier research (e.g., Costinot et al. (2016); Donaldson (2019)), we conceptualize climate shocks as productivity shocks that have direct consequences for production, trade, consumption baskets and household welfare.

Figure 1: Within country heterogeneity in yield at the parcel level due to climate change in GAEZ model for Maize and Soybean. Areas shaded in lighter blue correspond to regions where cross-country productivity disparities are relatively small.



3.2. Structural Change, exposure to shocks, and income heterogeneity

To move beyond the analysis of comparative advantage and quantify the macroeconomic consequences of climate change, this paper connects the distributional impact of climate shocks on household welfare to income levels.

In Figure 2, we illustrate sectoral value-added shares relative to GDP per capita in 43 countries from 2000 to 2014, indicating three key patterns of structural change[1]: (1) a decline in agriculture's share as economies develop, (2) a hump-shaped trajectory of industry's share, and (3) an increasing dominance of the services sector. The increase in GDP per capita is associated with a decrease in the nominal value added share in agriculture. Previous research provided extensive documentation of these trends across different sets of countries and time horizons (e.g., Buera and Kaboski (2012); Herrendorf et al. (2014)). In many low-income countries, agriculture employs a large share of the population but contributes a small share of GDP. As a result, climate shocks to agriculture are expected to reduce both labor income and food availability for a substantial portion of households. This paper explores these issues and shows that accounting for preferences exacerbates the impact of climate shocks on welfare. Poor households spend a larger share of income on food compared to wealthier households, and climate-induced increases in food prices are expected to lead to a significant decline in real purchasing power. Thus, even small GDP losses can translate into large utility losses for low-income populations.

In addition to these facts, and using the World Input-Output Database (WIOD), we measure (a) the share of value added in gross output for each sector, and (b) the share of each sector's use of intermediate input in every other sector (including its own). Table 1 reports these shares for the five richest and five poorest countries in our sample-classified by GDP per capita—focusing on the most recent year available, 2024.

For agriculture, our results indicate a higher share of value-added in gross output for poor countries, which implies that rich countries use intermediate inputs more intensively than poor countries. However, within the agricultural sector, poor countries rely more on agricultural inputs (for e.g, seeds and animal feed), whereas rich countries incorporate a larger share of service-based inputs. The key takeaways from this fact are: (i) the share of value added in agricultural output tends to be higher in poor countries than in rich countries, and (ii) poor

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[1] As in Buera and Kaboski (2012); Herrendorf et al. (2014), we define structural change as the reallocation of economic activity across three broad sectors (agriculture, manufacturing, and services) following the process of modern economic growth.

Figure 2: Sectoral shares in value added

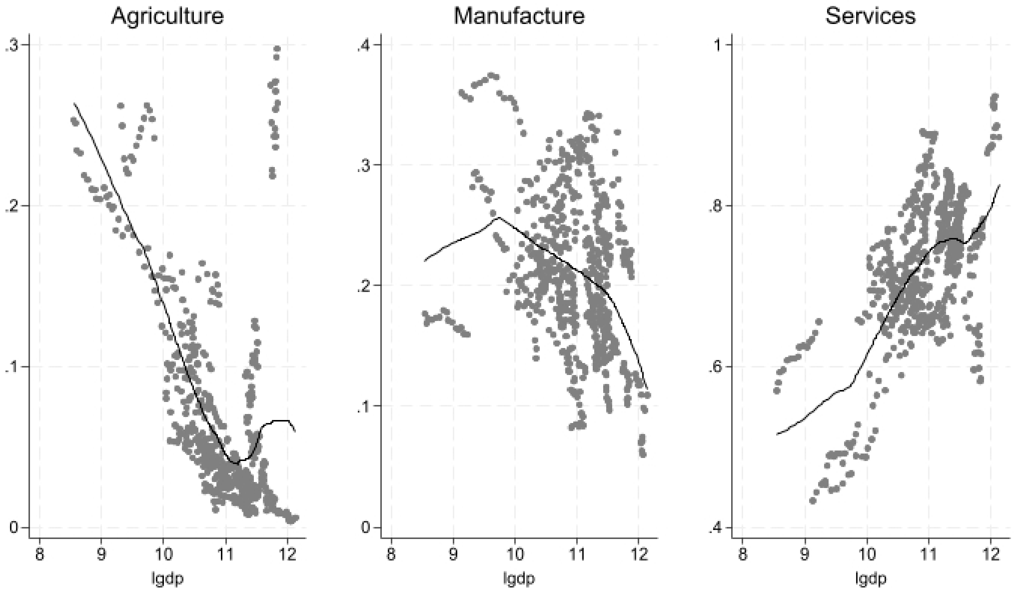

Table 1: Input intensities for Rich and Poor Countries

	Poor Countries (Rich Countries)		
	Output sector		
Input Sector	**Agriculture**	**Manufacturing**	**Services**
Agriculture	0.35 (0.30)	0.12 (0.07)	0.02 (0.07)
Manufacturing	0.41 (0.33)	0.49 (0.48)	0.14 (0.27)
Services	0.24 (0.37)	0.39 (0.45)	0.84 (0.66)
Value Added Shares	0.68 (0.46)	0.32 (0.33)	0.59 (0.57)

countries are more exposed to micro-shocks affecting the use of inputs in agriculture.

4. Theoretical framework

We describe a trade model in which the World is comprised of multi importing (j) and exporting (i) countries that are endowed with consumers who supply labor L and land N. Similar to Eaton and Kortum (2002), we assume that countries produce and trade multiple crops indexed by $k \in \{1, ..., K\}$ and an outside good (which we think of as a composite of manufactured goods and services). Labor can be freely allocated between crops, perfectly mobile within a country, and immobile across countries. Land consists of various fields, indexed by $f \in 1, ..., F_i$, and each field includes a continuum of diverse parcels, indexed by $\omega \in [0, 1]$. All fields in our data set correspond to 5-arcminute grid cells as in Costinot et al. (2016). Land is fully allocated to intermediate input production. We further assume that countries' comparative advantage is determined not only by their technological productivity (Heerman, 2020), but also by their agroecological characteristics and their trade costs. Trade flows from countries with the lowest prices (exporters) to the ones with the highest prices (importers). Following Matsuyama (2019) and Comin et al. (2021), we assume that consumers have non-homothetic preferences, such that the demand for agricultural goods varies with the level of income at given prices.

4.1. Demand side

—The demand side is modeled with a three-stage budgeting framework. The first stage splits national expenditure between a composite good and an agricultural good that aggregates crops.

In each country, we define a non-homothetic CES utility function for a representative agent, deriving utility from the consumption of an outside good C_j^0 and an aggregator of all crops, C_j^a.

$$\sum_{b=\{o,a\}} (\beta_b)^{\frac{1}{\alpha}} \left(\frac{C_j}{L_j} \right)^{\varepsilon_b \frac{(1-\alpha)}{\alpha}} \left(\frac{C_j^b}{L_j} \right)^{\frac{\alpha-1}{\alpha}} = 1 \qquad \dot{\forall} k, \tag{1}$$

where $U_j = \frac{E_j}{P_j} = \frac{C_j}{L_j}$ is the aggregate consumption (or utility) in country j, C_j^o and C_j^a indicate the consumption of either the outside good or the agricultural good in country j. E_j is the total consumption expenditure in country j. The parameters β_o and β_a determine the relative importance of each in the aggregate consumption, such that: $\beta_o + \beta_a = 1$. The term $\alpha > 0$ represents the substitution elasticity between goods, and L_j the total labor endowment in country j. These preferences, known as Non-Homothetic CES, are discussed by Hanoch (1975) and Comin et al. (2021). $\varepsilon \equiv (\varepsilon_o, \ \varepsilon_a)$ controls the relative income (expenditure) elasticity of demand for goods. The preference parameters are constant across countries.

In general, the representative household maximizes U_j subject to budget constraints:

$$E_j = \sum_b P_j^b C_j^b = \Phi_j(w_j, .) \quad , \tag{2}$$

where $\Phi_j(w_j, .) = w_j \ L_j + r_j \ N_j + D_j$ is total income in country j, expressed as a sum of labor income, land rent, and the national deficit D_j (Dekle et al., 2008; Antràs and Chor, 2018; Caliendo et al., 2018) such that $\sum_j D_j = 0$. The household's optimization problem implies that consumers select each good C_j^b, $b = \{a, 0\}$ that maximize aggregate consumption. The representative household's Lagrangian is:

$$\mathcal{L} = U_j + \rho\Bigg[1 - \sum_b (\beta_b)^{\frac{1}{\alpha}} \left(\frac{C_j}{L_j}\right)^{\varepsilon_b \frac{(1-\alpha)}{\alpha}} \left(\frac{C_j^b}{L_j}\right)^{\frac{\alpha-1}{\alpha}}\Bigg] + \Lambda\Bigg[w_j L_j + r_j N_j + D_j - \sum_b P_j^b C_j^b\Bigg]$$

with ρ and Λ the appropriate Lagrange multipliers. The first-order condition for C_j^b is:

$$0 = -\rho\,(\beta_b)^{\frac{1}{\alpha}} \left(\frac{C_j}{L_j}\right)^{\varepsilon_b \frac{(1-\alpha)}{\alpha}} \left(\frac{\alpha-1}{\alpha}\right) \left(\frac{C_j^b}{L_j}\right)^{\frac{\alpha-1}{\alpha}} \left(\frac{L_j}{C_j^b}\right) \left(\frac{1}{L_j}\right) - \Lambda\ P_j^b$$

$$\Rightarrow (\beta_b)^{\frac{1}{\alpha}} \left(\frac{C_j}{L_j}\right)^{\varepsilon_b \frac{(1-\alpha)}{\alpha}} \left(\frac{C_j^b}{L_j}\right)^{\frac{\alpha-1}{\alpha}} = \frac{\Lambda\alpha}{\rho(1-\alpha)} P_j^b\ C_j^b$$

using constraints 1 and 2 we get:

$$\frac{\rho(1-\alpha)}{\Lambda\alpha} = \sum_b P_j^b C_j^b = E_j \tag{3}$$

which further implies that :

$$(\beta_b)^{\frac{1}{\alpha}} \left(\frac{C_j}{L_j}\right)^{\varepsilon_b \frac{(1-\alpha)}{\alpha}} \left(\frac{C_j^b}{L_j}\right)^{\frac{\alpha-1}{\alpha}} = \frac{P_j^b C_j^b}{E_j} \tag{4}$$

Therefore, the optimal consumption of good C_j^b can be written as :

$$C_j^b = \beta_b\ L_j \left(\frac{P_j^b}{E_j}\right)^{-\alpha} \left(\frac{C_j}{L_j}\right)^{\epsilon_b(1-\alpha)} \tag{5}$$

If we define P_j as the ideal consumer price index for the aggregate consumption of goods C_j, such that $E_j = P_j\ U_j$, then we have:

$$C_j^b = \beta_b\ L_j \left(\frac{P_j^b}{P_j}\right)^{-\alpha} \left(\frac{C_j}{L_j}\right)^{(1-\alpha)\epsilon_b+\alpha} \tag{6}$$

For agri-food products, we have :

$$C_j^a = \beta_a\ L_j \left(\frac{P_j^b}{P_j}\right)^{-\alpha} \left(\frac{C_j}{L_j}\right)^{(1-\alpha)\epsilon_a+\alpha}$$

Multiplying both sides by $\frac{P_j^a}{P_j}$ results in an Engel equation that characterizes the share of spending allocated to agri-food products:

$$\frac{P_j^a C_j^a}{P_j} = \beta_a \left(\frac{P_j^a}{P_j}\right)^{1-\alpha} \left(\frac{C_j}{L_j}\right)^{(1-\alpha)(\epsilon_a-1)} (C_j) \tag{7}$$

$$\frac{P_j^a\ C_j^a}{P_j\ C_j} = \mathbf{s}_j^a = \beta_a \left(\frac{P_j^a}{P_j} \right)^{1-\alpha} \left(\frac{C_j}{L_j} \right)^{(1-\alpha)(\epsilon_a - 1)} \tag{8}$$

The average cost of real consumption at the country level P_j measures changes in the cost of living in term of price and expenditure share and is given by :

$$P_j = \left[\sum_{b=\{o,a\}} \beta_b \left(P_j^b \right)^{1-\alpha} \left(\frac{C_j}{L_j} \right)^{(\alpha-1)(\varepsilon_b-1)} \right]^{\frac{1}{1-\alpha}} \tag{9}$$

As in Comin et al. (2021), we also express the price index P_j in terms of observables and demand parameters (proof in the Appendix). The homothetic CES specification corresponds to the special case of equation (9) in which $\varepsilon_b = 1 \quad \forall b \in \{o, a\}$.

— The decision-making aspect of agricultural goods consumption in the second stage is subject to a crop aggregator (CES) such that:

$$C_j^a = \left[\sum_k \left(\beta_{jk}\right)^{\frac{1}{\kappa}} \ \left(C_{jk}\right)^{\frac{\kappa-1}{\kappa}} \right]^{\frac{\kappa}{\kappa-1}} \qquad \dot{\forall} k, \tag{10}$$

where C_{jk} is the consumed quantity of crop k in country j, $\beta_{jk} \geq 0$ indicates the relative weight of each crop k in the aggregate consumption bundle, $\kappa > 0$ is the elasticity of substitution between different crops. The optimal demand for each crop can be written as:

$$C_{jk} = \beta_{jk}\ P_{jk}^{-\kappa}\ \left(P_j^a\right)^{\kappa}\ C_j^a \qquad \dot{\forall} k, \tag{11}$$

where P_{jk} denotes the CES price index associated with crop k in country j, and $P_j^a = \left[\sum_k \beta_{jk}\ P_{jk}^{1-\kappa} \right]^{\frac{1}{1-\kappa}}$ is a price index in the agricultural sector.

— The aggregate crop consumption, C_j^a depend on the consumption of each crop, C_{jk}, which itself depend on the consumption of varieties from different origins C_{ijk}. Consumption of varieties is characterized by a CES crop aggregator:

$$C_{jk} = \left[\sum_j (\beta_{ijk})^{\frac{1}{\sigma}} \left(\ C_{ijk}\right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \qquad \dot{\forall} j, \tag{12}$$

where σ indicates the substitution elasticity between different varieties for all crops as in Costinot et al. (2016), and $\beta_{ijk} > 0$ the relative weight of the varieties. Given the CES form of equation 12 , the optimal level of consumption for a variety is :

$$C_{ijk} = \beta_{ijk}\ p_{ijk}^{-\sigma}\ P_{jk}^{\sigma}\ C_{jk} \qquad\qquad \forall j, \tag{13}$$

With p_{ijk} the cost for each variety of product consumed, and $P_{jk} = \left[\sum_i \beta_{ijk}\ p_{ijk}^{1-\sigma}\right]^{\frac{1}{1-\sigma}}$.

— **Demand-side equilibrium** Given equations 7, 11, and 13, utility maximization by the representative agent in each country requires that the consumption of variety is determined by the level of income per capita.

$$C_{ijk} = \beta_a \left[\frac{\beta_{ijk}\ p_{ijk}^{-\sigma}}{P_{jk}^{1-\sigma}}\right] \left[\frac{\beta_{j,k}\ P_{jk}^{1-\kappa}}{P_j^{a\,1-\kappa}}\right] \left[\frac{P_j^a}{P_j}\right]^{1-\alpha} \left[\frac{C_j}{L_j}\right]^{(1-\alpha)(\varepsilon_a-1)} \left[P_j C_j\right] \tag{14}$$

The substitution elasticities κ and σ are taken from the literature, while the remaining preference parameters —$\beta_a, \beta_{jk}, \beta_{ijk}, \alpha, \varepsilon_a$—are estimated from the model.

4.2. Supply side

Technology —We assume that production of the outside good relies exclusively on labor and operates under constant returns to scale. In each country i, we define A_{0i} as labor productivity in the outside sector. Crop production use land N_i and labor L_i as inputs. Land in country i consists of f heterogeneous fields of surface s_{if}, each being composed of a continuum of parcels indexed by ω. There is a finite number of fields, and farmers profitability depends on the value of the marginal product. We assume that farmers are certain about the marginal product value $p_{ik}\ A_{ifk(\omega)}$ of every parcel of land. Since labor and land are complementary, the production per unit of land on each parcel ω, when the crop is planted, is given by:

$$q_{ik}(\omega) = \min\left\{A_{ifk}(\omega)\ ,\ \frac{L_{ifk}(\omega)}{\nu_{ik}}\right\}\ , A_{ifk}(\omega)\ ,\ \nu_{ik} > 0 \tag{15}$$

where $A_{ifk}(\omega)$ indicates land productivity (yield) of a parcel ω in field f if allocated to crop k in country i, and ν_{if} is the labor requirement per unit of output. For each parcel, the marginal product of land is $A_{ifk}(\omega)$ if $N_{ifk}(\omega) < \frac{L_{ifk}}{\nu_{if}}(\omega)$ (which means land is the constraining factor), and 0 otherwise. The Leontief structure of crop production implies for parcel ω that $q_{ifk}(\omega) = A_{ifk}(\omega) = \frac{L_{ifk}(\omega)}{\nu_{if(\omega)}}$.

As in Costinot et al. (2016), we assume that productivity and labor requirements are independently drawn from a Fréchet distribution with shape parameter $\theta > 1$ and scale $\gamma \equiv \Gamma((\theta{-}1/\theta))^{\theta}$ where $\Gamma(.)$ denote the gamma function set with unconditional average productivity A_{ifk} quantifying comparative advantages. $A_{ifk} = E[A_{ifk}(\omega)]$, and higher values of A_{ifk} imply that a country is more productive on average. θ describes the dispersion of agricultural productivity, and a smaller value implies a larger dispersion of differences in technological productivity. Comparative advantages is more important when θ is small.

Price —Perfect competition is assumed and the outside good (used as the numeraire) is freely tradable. In addition, international trade entails iceberg trade costs $\tau_{ij}^{k} \geq 1$ for goods originating in country i and exported to country j. The price of a crop k produced in country i and sold in country j is equal to:

$$p_{ij}^{k} = \tau_{ijk}\ p_{ik} \qquad ,\forall k \tag{16}$$

where p_{ik} is the exporter's price. In the outside sector, profit maximization imply equality of labor productivity $A_{i,0}$ to wage w_i : $A_{i,0} = w_i$, which will be used to substitute w_i away.

In order to ensure the greatest returns from lands, landowners maximize their profits by allocating parcels of land to the crop with the highest marginal product value. Let denote π_{ifk} the share of field f located in country i that are allocated to a crop k. Given our equation 15, and that $A_{ifk}(\omega)$ and ν_{if} follow type II extreme value distributions, we therefore have :

$$\begin{aligned} \pi_{ifk} &= \Pr\left(p_{ik}A_{ifk}(\omega) > p_{i\ell}A_{if\ell}(\omega),\ \forall \ell \neq\ k\right) \qquad (17)\\ &= \frac{(\tau_{ijk}\ p_{ik})^{\theta}}{\alpha_i^{\theta} + \sum_i (\tau_{ijk}\ p_{ik})^{\theta}}\ , \qquad (18) \end{aligned}$$

Where $\alpha_i = A_{0i}\nu_{0i}$ indicates country differences in labor costs.

Supply of crops —The total production of crop k from field f, $q_i^k = \sum_f \int_0^1 q_{ifk}(\omega)d\omega$ is determined by the field's area, the proportion of parcels allocated to the crop (π_{ifk}), and the average productivity A_{ifk} given that the crop is selected for production.

$$q_i^k = \sum_f s_i^f\ \pi_{ifk}\ E\left[A_{ifk}(\omega) \mid p_{ik}A_{ifk}(\omega)\right] \tag{19}$$

Given our distributional assumptions, we have :

$$\begin{aligned} E\left[A_{ifk}(\omega) \mid p_{ik}A_{ifk}(\omega)\right] &= \max\left\{A_{i0}\ \nu_{if}(\omega), p_{i1}\ A_{if1}(\omega), \ldots, p_{ik}\ A_{ifk}(\omega)\right\} \\ &= A_{ifk} \times \left(\pi_{ifk}\right)^{-1/\theta}. \end{aligned} \tag{20}$$

Combining the two previous expressions with equation 17, gives an expression for the supply of crops k in country i :

$$q_{ik} = \sum_f s_{if} A_{ifk} \left[\frac{\left(p_{ik}A_{ifk}\right)^{\theta}}{\left(\alpha_i\right)^{\theta} + \sum_k \left(p_{ik}A_{ik}\right)^{\theta}}\right]^{(\theta-1)/\theta} \qquad \forall i, \quad \text{and } \forall\ k \tag{21}$$

Market clearing —Full employment conditions imply that :

$$\sum_{f,k} L_{ifk}(\omega) = L_i \quad \forall i \text{ and } \forall\ f. \tag{22}$$

$$\sum_{f,k} N_{ifk}(\omega) = N_i \quad \forall i \text{ and } \forall\ f. \tag{23}$$

In addition, the market clearing for all varieties of crops also require:

$$q_i^k = \sum_j \tau_{ijk}\ C_{ijk}, \quad \forall i \text{ and} \forall k. \tag{24}$$

In addition, under the assumption that Labor cost equal 1 and that the outside good is produced in all countries, the amount of labor demanded by the outside sector adjusts to ensure that the labor market clears with a wage of A_{0i} :

$$A_{0i} = w_i = 1 \tag{25}$$

Trade equilibrium —The total value of export of crop k from country i to country j is given by : $X_{ijk} = (\tau_{ijk}\ p_{ik})\ C_{ijk}$. Using equation 14, we can write :

$$X_{ijk} = \beta_a \left[\frac{\beta_{ijk}\ p_{ijk}^{1-\sigma}}{P_{jk}^{1-\sigma}}\right] \left[\frac{\beta_{j,k}\ P_{jk}^{1-\kappa}}{P_j^{a\,1-\kappa}}\right] \left[\frac{P_j^a}{P_j}\right]^{1-\alpha} \left[\frac{C_j}{L_j}\right]^{(1-\alpha)(\varepsilon_a-1)} \left[P_j C_j\right] \tag{26}$$

In the presence of trade and following Eaton and Kortum (2002), The price of a crop P_{ik} that a country j actually buys from any country i can also be written as :

$$P_{jk} = \gamma\ \Phi_{jk}{}^{-1/\theta} \quad , \tag{27}$$

with $\gamma = \left[\Gamma((\theta + 1 - \sigma)/\theta)\right]^{1/(1-\sigma)}$ a Gamma function.

An equilibrium in the model is defined by the values of consumption C_{ijk}, output q_i^k and domestic price p_i^k that satisfy the above equilibrium conditions given all structural parameters $\{\sigma, \kappa, \alpha, \varepsilon_k, \theta\}$, and worker endowments L_i.

5. Data

5.1. Output, Price, and Trade Flow Data

Bilateral market shares of agrifood products are constructed from the FAO website using data on bilateral trade flows and the values of production for each variety in crops. Our sample includes 50 countries and 10 crops with the highest share of global crop production. Crops include banana, soybean, cotton, sugarcane, maize, tomato, oil palm, wheat, rice, and white potato. Data on trade costs variables are collected from CEPII, and data on GDP are obtained from the World Bank database. Data on trade flows and tariffs come from COMTRADE and TRAINS respectively.

5.2. Agricultural productivity

Our counterfactual simulations consider two scenarios in year 2010: the pre-climate change estimates of agricultural productivity, and post climate change estimates. Information on the distribution of each country's total land area across climate zones comes from the GAEZ project (FAO et al., 2012), which also provides information on potential yields under current climate and under climate change. The current version of the GAEZ has generated large spatial databases of (i) natural resources endowments relevant for agricultural uses (ii) assessments of suitability and attainable yields, (iii) harvested area, yields and production of main food and fiber commodities for rain-fed and irrigated cultivated land areas in 2010. Each of the crops in the FAO data are assigned to one the GAEZ aggregates.

6. Estimation of preference Parameters

To simulate the model described in section 4, we require estimates of the following parameters: (i) the preference parameters that are common across countries—β_a, β_0, ε_a, ε_0, (ii) substitution elasticities α, κ, and σ ; (iii) the within field heterogeneity parameter —θ; The parameter values are listed in Table 2.

The preference parameters are estimated by exploiting cross-sectional variations and by min-

Table 2: Parameter estimates

Relative weights in utility
$\beta_0 = 0.51$
$\beta_a = 0.49$
Income elasticities of demand
$\varepsilon_0 = 1$
$\varepsilon_a = 0.79$
Substitution parameters
$\alpha = 0.5$
$\kappa = 2.82$
$\sigma = 5.4$
Supply side parameter
$\theta = 2.46$

imizing the squared distance between the sectoral expenditures observed in GTAP and those implied by the model's first-order conditions, using data on sectoral prices and aggregate consumption.

$$\min_{\alpha,\beta_0,\beta_a,\varepsilon_0,\varepsilon_a} \sum_i \sum_{b\in\{0,a\}} \left[\left(\frac{\beta_a}{\beta_0}\right)^{\alpha} \left(\frac{P_i^a}{P_{0i}}\right)^{1-\alpha} \left(\frac{C_i}{L_i}\right)^{\varepsilon_a-1} - \left(\frac{E_{ai}}{E_{0i}}\right)\right]^2$$

$s.t. \quad \alpha, \beta_a, \beta_0, \varepsilon_a \geq 0 \quad$ and $\quad \beta_a + \beta_0 = 1$, with consumption $C_i = \frac{E_i}{P_i}$

Following Comin et al. (2021), income elasticities are estimated in relative terms (i.e., in relation to a base value, $\varepsilon_a - 1$), and we found a higher elasticity ($\varepsilon_a = 0.79$) than the benchmark value reported in Comin et al. (2021) for the agricultural sector.

For the elasticity of substitution between agricultural products κ, the elasticity of substitution between varieties σ and the supply side parameter θ, we follow Costinot et al. (2016) and set $\kappa = 2.82$, $\sigma = 5.4$, and $\theta = 2.46$ respectively.

7. Results

We use the estimated parameter to simulate our model and quantify the various channels through which climate change affects agricultural markets in a global economy. Climate change is quantified as a shock to crop productivity from A_{ifk} (productivity under the baseline scenario) to A'_{ifk} (productivity under climate change scenario). All other parameters are held fixed at the value estimated in the previous section.

To measure the aggregate consequences of climate change, we first compute for each country in our dataset a first order approximation ΔA_i to the welfare impact of climate change. We then use ΔA_i to measure the welfare consequence of climate change under the full adjustment of production and trade. Climate change is measured as :

$$\Delta A_i \equiv \sum_{k,f} \rho_{ifk} \; \Delta A_{ifk} \ ,$$

where $\rho_{ifk} = \frac{p_{ik} \cdot q_{ifk}}{Y_i}$ represents the share of the production value of crop k in field f as a proportion of country i's GDP, and $\Delta A_{ifk} = A'_{ifk} - A_{ifk}/A_{ifk}$, reflects the percentage change in productivity compared to the reference scenario.

To measure the overall welfare consequences of climate change, we solve for competitive equilibrium before and after climate change. To match the literature on welfare measures under non-homothetic preferences (Baqaee and Burstein, 2023; Baqaee et al., 2024; Jaravel and Lashkari, 2024), our baseline measure is the equivalent variation (EV) in fixed final preferences that measures changes in the level of income cost or gain when moving from the baseline to the counterfactual equilibrium.

$$\Delta W = \frac{e(P,u) - e(P',u)}{e(P,u)}, \tag{28}$$

where $e(\cdot)$ is the expenditure function, with P and P' denoting demand shifters and prices evaluated at the two equilibria[2]. By rearranging the terms, we can decompose the welfare effect into a structural change effect and a price effect:

$$\Delta W = 1 - \frac{e(P'(\mathbf{s}',.),u)}{e(P^h,u)} \times \frac{e(P^h,u)}{e(P(\mathbf{s},.),u)} \ , \tag{29}$$

with $P(\mathbf{s},.)$ the cost of aggregate real consumption (i.e., the price of one utility unit when expenditures are optimally allocated across goods and services) under constant expenditure share, $P'(\mathbf{s}',.)$ the cost of aggregate real consumption expressed under variable expenditure share, and P^h the CES Price index that holds expenditure shares constant in the counterfactual scenario; The first ratio of equation (29) measures the impact of structural change, and the second, the welfare effect of price variation because of climate change. Column (4) and (5) of table (3) report our estimates of ΔW for the 50 countries in our dataset. According to our results, the decrease in global welfare is underestimated when income effects are not considered. Climate change induces a global welfare decrease of 4.6 %, versus a 0.26 percent decrease when income effects are ignored. Our result indicates that low- and lower-middle-income countries such as

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[2] As in (Comin et al., 2021), we derive $e(\beta, P, u) = \left(\sum_b \beta_b P_{ib}^{1-\alpha} u^{(1-\alpha)\varepsilon_b}\right)^{\frac{1}{1-\alpha}}$

Malawi, Ghana, and Sudan, experience the most severe negative effects, especially when accounting for demand-side changes in consumption patterns. The findings suggest that these economies are highly vulnerable due to their reliance on agriculture, which is more sensitive to climate shocks. In contrast, some countries, for example, Germany, Canada, United kingdom, Netherland and Russia, experience considerable benefits from climate change, reflecting their economic diversification and greater adaptive capacity. When adjusting for non-homothetic preferences—acknowledging that income influences spending patterns—the economic losses become even more pronounced for developing countries, indicating a disproportionate burden on poorer nations.

The results presented in table (4) highlight the disproportionate impact of climate change on welfare across income groups. Specifically, low-income countries are projected to experience an aggregate welfare loss of approximately 15.2%, followed by a 7.4% loss in lower-middle-income countries. In contrast, upper-middle-income and high-income countries face significantly smaller losses of 3.1% and 0.3%, respectively. Low-income economies are more reliant on climate-sensitive sectors such as agriculture, and have limited access to trade and technological adaptation mechanisms. As a result, climate shocks directly undermine both production and consumption in these regions, exacerbating existing vulnerabilities.

To conclude our quantitative analysis, we also investigate the role played by trade. We consider a world economy in which preferences and technology are described as in section (4), and simulate a policy change from a positive export tax to full liberalization (i.e., zero tariffs). Column (2) of table (4) reports the result. We see that removing tariffs has a positive effect as it reduces the loss in welfare (-2.8%). Specifically, welfare losses in low-income countries decrease from -15.2% to -14.8% , and from -7.4% to -6.9% in lower-middle-income countries. Although the magnitude of the reduction is modest, it signals that trade liberalization can improve resource allocation and ease market access, allowing to adjust to productivity shocks induced by climate change.

8. Sensitivity analysis

In this section, we explore the sensitivity analysis using the same data sets as in our baseline specifications. We assess the stability of the results when using different income elasticities, which helps us better understand how country groups respond to these shocks. We do this by varying the income elasticity of demand, which shifts a larger share of consumer spending toward

Table 3: Baseline Counterfactual Results

Country	Classification		Welfare Change	
		Crop output as % of total GDP (3)	Full Adjustment (homothetic preferences) (4)	Full Adjustment non - homothetic preference (5)
Ghana	Lower-middle-income	10.72	-0.106	-0.685
Sudan	Lower-middle-income	3.89	-0.068	-0.234
Canada	High-income	0.6	0.006	0.711
Congo	Low-income	15.35	-0.107	-0.558
Malawi	Low-income	74.92	-0.491	-0.561
Venezuela	Upper-middle-income	2.5	-0.038	-0.901
Thailand	Upper-middle-income	6.05	-0.073	-0.020
Nigeria	Lower-middle-income	7.92	-0.053	-0.436
Brazil	Upper-middle-income	3.19	-0.015	-0.324
South Africa	Upper-middle-income	1.24	-0.005	-0.368
Bangladesh	Lower-middle-income	12.36	-0.082	-0.295
Cameroon	Lower-middle-income	9.38	-0.032	-0.284
Australia	High-income	0.79	-0.001	-0.517
Indonesia	Lower-middle-income	8.12	-0.025	-0.212
Pakistan	Lower-middle-income	8.51	-0.013	-0.395
Kazakhstan	Upper-middle-income	3.48	-0.008	-0.266
Tanzania	Low-income	19.56	-0.054	-0.213
Ecuador	Upper-middle-income	8.26	-0.002	-0.556
Algeria	Upper-middle-income	2.51	-0.009	-0.252
Netherlands	High-income	0.33	0.001	0.978
India	Lower-middle-income	7.41	-0.016	-0.166
Colombia	Upper-middle-income	2.36	-0.018	0.132
Burma	Lower-middle-income	49.81	-0.112	-0.166
Argentina	Upper-middle-income	4.24	0.005	-0.392
Germany	High-income	0.17	0.001	0.976
Malaysia	Upper-middle-income	4.78	-0.005	-0.062
United Kingdom	High-income	0.16	0.002	0.927
Cote d'Ivoire	Lower-middle-income	7.3	-0.028	-0.002
Mexico	Upper-middle-income	1.06	-0.004	-0.215
Vietnam	Lower-middle-income	22.5	-0.065	-0.082
Romania	Upper-middle-income	2.8	-0.005	-0.133
Korea Republic of	High-income	1.4	-0.003	-0.091
United States	High-income	0.83	-0.001	-0.216
Uganda	Low-income	33.83	-0.039	-0.150
Philippines	Lower-middle-income	5.65	-0.018	0.070
Iran	Upper-middle-income	2.46	-0.005	-0.114
Morocco	Lower-middle-income	3.27	-0.019	-0.179
Ethiopia	Low-income	11.93	-0.007	-0.140
Ukraine	Lower-middle-income	5.58	-0.002	-0.167
Japan	High-income	0.62	0.001	-0.123
France	High-income	0.33	-0.001	-0.489
Greece	High-income	1.19	-0.001	-0.204
China	Upper-middle-income	4.56	0.002	-0.037
Turkey	Upper-middle-income	2.85	0.001	-0.020
Poland	High-income	0.66	0.001	-0.952
Italy	High-income	0.38	-0.001	-0.254
Uzbekistan	Lower-middle-income	20.76	0.014	0.052
Spain	High-income	0.43	0.001	-0.695
Russia	Upper-middle-income	1.62	0.011	0.185
Egypt	Lower-middle-income	5.25	-0.004	0.865
World		1.8	-0.0025	-0.046

agricultural goods. The table shows that as the income elasticity of demand for agricultural goods increases, aggregate welfare losses increase, particularly for low- and lower-middle-income countries. When the income elasticity of the demand for agrifood products increases, households, especially in poorer countries, allocate a larger share of income to food. Given Engel's Law and nonhomothetic preferences, food become more essential in utility and more expensive, and households suffer a larger utility loss.

Our findings also suggest that the welfare loss induced by climate-driven price changes exceeds the loss induced by structural changes in demand shares. The impact of climate change on relative prices plays a dominant role in explaining welfare losses. In contrast, the structural effect—which captures how climate change shifts demand shares across sectors—has a smaller impact.

The implication of these results is that relative price changes matter more than sectoral reallocation. The primary welfare channel of climate change is not how much the economy restructures, but how much consumers pay for essential goods—especially in countries where food makes up a large share of consumption. Consequently, policy efforts that address price volatility and improve access to affordable food may be more effective in protecting household welfare than those focused solely on long-run structural adjustments.

Moreover, the price effect is more severe for poorer households than for richer ones. The welfare loss is not uniform and is greater in countries where food still dominates the consumption basket. These effects are consistent with findings from Hottman and Monarch (2018) and Atkin et al. (2020), who show that lower-income households tend to experience the highest price inflation, while higher-income households are least affected.

Table 4: Aggregate Welfare Loss by Income Group

Income Group	Tariff removal (2)	Income elasticities				
		$\varepsilon_a = 0.79$ (3)	$\varepsilon_a = 0.83$ (4)	$\varepsilon_a = 0.86$ (5)	$\varepsilon_a = 0.91$ (6)	$\varepsilon_a = 0.95$ (7)
Low	-0.148	-0.152	-0.163	-0.181	-0.211	-0.253
Lower-middle	-0.069	-0.074	-0.081	-0.092	-0.111	-0.138
Upper-middle	-0.036	-0.031	-0.033	-0.036	-0.041	-0.049
High	-0.002	-0.003	-0.003	-0.003	-0.004	-0.004
ΔW	-0.028	-0.046	-0.052	-0.064	-0.084	-0.115

Table 5: Welfare Effects of Price Variation and Structural Change

		Income elasticities				
		$\varepsilon_a = 0.79$ (3)	$\varepsilon_a = 0.83$ (4)	$\varepsilon_a = 0.86$ (5)	$\varepsilon_a = 0.91$ (6)	$\varepsilon_a = 0.95$ (7)
Price Effect, ***of which***	Low income	-0.024	-0.037	-0.055	-0.085	-0.127
	Lower-middle	-0.019	-0.029	-0.045	-0.071	-0.108
	Upper-middle	-0.006	-0.009	-0.014	-0.022	-0.033
	High	0.000	-0.001	-0.001	-0.001	-0.002
	World	-0.022	-0.033	-0.052	-0.082	-0.110
Structural change effect		-0.024	-0.018	-0.012	-0.002	-0.004

9. Policy implications

Our study highlights key policy considerations. First, the findings underscore the need for policies that promote climate adaptation in agricultural practices and supply chain resilience. Our findings suggest that climate shocks reduce global welfare by 4.6%, with disproportionate effects on low-income households due to their consumption patterns and income elasticity. Low-income countries often exhibit high income elasticity of demand for agri-food products, meaning that as incomes rise, their demand for these products increases more than proportionally. However, if a climate shock disrupts supply and cannot meet growing demand, there may be a shift away from agriculture toward more resilient or less climate-sensitive sectors. Our results suggest that to minimize welfare losses, it is critical to target these vulnerable sectors and invest in resilient agricultural practices to stabilize supply and ensure food security.

Second, countries need to continue reforming in terms of access to trade. Given that climate change shape comparative advantages, our results underscore the importance of international trade policies that account for shifting production patterns. For instance, reducing trade barriers on climate-resilient crops can help stabilize food supplies and mitigate price shocks.

Third, the differentiated impact of climate shocks on household welfare calls for strengthening social protection systems, such as conditional cash transfers and food assistance programs, to shield the most affected populations from food insecurity and income volatility.

10. Conclusion

Given the increasing significance of climate change in shaping the international activities of developing and emerging markets, and the scarcity of empirical research focused focused on trade flows shaped by demand patterns through non-homothetic preferences, we use a general equilibrium model with 50 economies to investigate the relationship between climate, global trade, and comparative advantages. Our result indicates that, when the consumption of agricultural goods is inelastic to income, climate change for the world as a whole amounts 4.6% percent decrease in the global welfare, compared to 0.26% decrease when there is no income effect. The welfare loss that occurred through price changes exceeds that resulting from structural changes in demand shares. Price variation due to climate change was greater for poor households than for rich households. While our analysis centers on a two-sector model, the proposed framework is readily applicable to broader contexts. It is particularly useful in multi-sector models where labor mobility between sectors is imperfect.

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11. Appendix

Price index with Non-homothetic CES preferences

The non-homothetic CES price index depends on the consumer's utility level, which is generally unobservable. To address this challenge, we rely on expenditure shares, which are observable at the country level. The consumer's utility level is implicitly derived from the following equation:

$$\sum_{b=\{o,a\}} (\beta_b)^{\frac{1}{\alpha}} \left(\frac{C_j}{L_j}\right)^{\varepsilon_b \frac{(1-\alpha)}{\alpha}} \left(\frac{C_j^b}{L_j}\right)^{\frac{\alpha-1}{\alpha}} = 1 \qquad \forall \dot{k}, \tag{30}$$

Such that:

$$\mathbf{s}_j^b = \beta_b \left(\frac{P_j^b}{P_j}\right)^{1-\alpha} \left(\frac{C_j}{L_j}\right)^{(1-\alpha)(\epsilon_b-1)} \quad , \tag{31}$$

and

$$P_j^{1-\alpha} = \frac{\beta_b}{\mathbf{s}_j^b} \left(P_j^b\right)^{1-\alpha} \left(\frac{C_j}{L_j}\right)^{(1-\alpha)(\epsilon_b-1)} \tag{32}$$

Taking logarithms yield:

$$\log P_j = \frac{1}{1-\alpha}\left[\log \beta_b - \log \mathbf{s}_j^b\right] + \log P_j^b + (\epsilon_b - 1)\ \log\left(\frac{E_j}{P_j\ L_j}\right) \tag{33}$$

Applying the sum, we have:

$$\sum_b \log P_j = \frac{1}{1-\alpha}\sum_b \left[\log \beta_b - \log \mathbf{s}_j^b\right] + \sum_b \log P_j^b + \sum_b (\epsilon_b - 1)\log\left(\frac{E_j}{P_j\ L_j}\right) \tag{34}$$

Averaging across sectors gives:

$$\log P_j = \frac{1}{1-\alpha}\ \log \tilde{\beta} - \frac{1}{1-\alpha}\ \log \tilde{\mathbf{s}}_j + \log \tilde{P}_j + \psi\ \log\left(\frac{E_j}{P_j\ L_j}\right) \ , \tag{35}$$

where a tilde above each variable denotes an average across sectors such that $\tilde{P}_j = \left(\prod_{b\in B} P_j^b\right)^{\frac{1}{\texttt{Card}(\mathbf{B})}}$, $\psi = \frac{1}{\texttt{Card}(\mathbf{B})}\sum_b(\epsilon_b - 1)$, and **B** is the set of elements indexed by b, or the total number of sectors. Therefore:

$$(1+\psi)\log P_j = \frac{1}{1-\alpha}\ \log \tilde{\beta} - \frac{1}{1-\alpha}\ \log \tilde{\mathbf{s}}_j + \log \tilde{P}_j + \psi\ \log\left(\frac{E_j}{L_j}\right) \tag{36}$$

Finally, we have :

$$P_j = \tilde{\beta}^{\frac{1}{(1+\psi)(1-\alpha)}} \; \tilde{P}_j^{\frac{1}{(1+\psi)}} \; \tilde{\mathbf{s}}_j^{\frac{1}{(1+\psi)(1-\alpha)}} \; \left(\frac{E_j}{L_j}\right)^{\frac{\psi}{1+\psi}} \; , \tag{37}$$