Climate change adaptation: Agricultural productivity shocks and trade policy responses

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Abstract

Climate change will cause productivity shocks that will be unevenly distributed across space. That will shift international comparative advantage. While for some countries productivity will increase, for others it will decrease. Some countries are more vulnerable to climate-induced productivity shocks than others, e.g. low-income countries. At the same time, these countries often have high barriers to trade, limiting their scope to adapt to external economic shocks.

This paper analyses how trade policy liberalization can off-set climate-induced welfare losses and how it affects climate change adaption. I use rich granular data to examine the impact of future climate change on agricultural crop productivity around the world. The productivity shocks are fed into a general equilibrium trade model with input-output linkages, land, and different labor categories as production factors. I develop a brute-force algorithm to compute each country's trade policy response to compensate climate-induced welfare losses.

JEL-Codes: F13; F14; F18; Q56
Keywords: Comparative advantage; international trade; gravity; climate change

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1 Introduction

Feeding the world is an expensive undertaking. Food production uses up half of the Earth's habitable land, and expending this land comes with considerable costs and externalities. Climate change poses a threat to productivities of currently used cropland in many places and therefore will shift international comparative advantage. But productivity shocks will be heterogeneous across space and sectors. One adaptation strategy lies in international trade. If productivity of some goods in country A decreases, but in country B increases, country A can import more of these goods from B and focus on the production of goods that are not negatively affected by climate change. This is possible if trade costs (e.g., tariffs, non-tariff barriers, costs of logistics) between A and B are sufficiently low. If trade costs are high, adverse productivity shocks can lead to a higher share of resources devoted to this sector to compensate production shortfalls in A. The relocation to a less productive sectors would rewind structural transformation and may cause significant welfare losses.

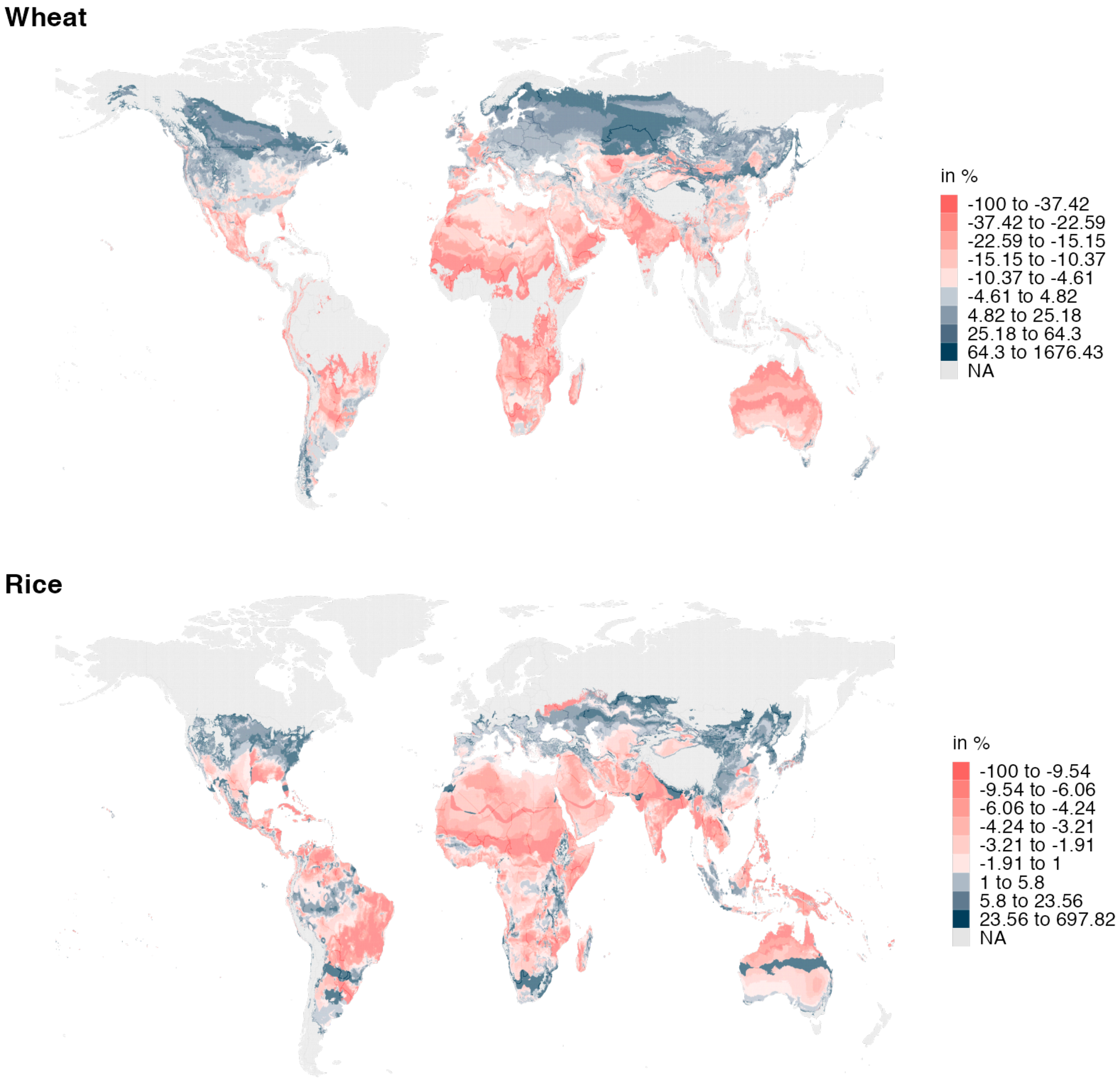
In this paper, I study how climate change affects agricultural productivity around the world and which trade policy response is necessary to compensate for climate-induced welfare losses. First, I derive productivity shocks from an extremely rich granular data set on agricultural yields – before and after climate change – for 71 different crops for each of 2.3 million fields covering the surface of the earth. Second, I use a Ricardian quantitative trade with input-output linkages and trade across 141 countries, covering 98 percent of World's GDP. I add *land* production factors and sectoral productivities to this model. Third, I develop a brute-force algorithm so calculate each country's necessary trade policy liberalization to compensate climate-induced welfare losses.

I contribute to several strands of the literatures. First, there is important work on climate change impacts on social welfare, going from micro-level shocks to macro-level consequences. For example, the impact of weather on economic growth (Kotz et al., 2021) through underlying channels including, e.g., human health (Barreca et al., 2016; Burgess et al., 2017; Burke et al., 2018), worker productivity (Somanathan et al., 2021), and houshold consumption (Lai et al., 2022). Second, I contribute to the literature on climate change adaptation through trade. Costinot et al. (2016) use micro-level shocks and study the welfare consequences of climate change. They find that adaptation depends on a country's ability to change its production patterns, rather than its trade patterns. In contrast, Gouel and Laborde (2021) show that trade substitution is evenly important than adjusting production patterns. Janssens et al. (2020) come to the same conclusion, but unlike Gouel and Laborde (2021), who examine climate-induced welfare effects, the authors analyse climate-induced hunger risks. Cruz and Rossi-Hansberg (2021) develop a dynamic intergrated assesment model in which individuals can adapt to global warming via trade, migration, innovations or natality rates. They focus on the climate damage function of temperature and find a relative small impact of trade as an adaptation mechanism. The work of Nath (2022) is closely related to my paper. The author uses a static general equilibrium trade model and analyse how sectoral reallocation between agriculture and non-agriculture production might help to adapt to climate change. In contrast to this paper, Nath (2022) uses local temperature projections to derive climate-induced sectoral productivity changes. Third, this paper relates to recent work enriching New Quanitative Trade (NQT) models with "natural" production factors: Going from one additional factor, such as crude oil (Farrokhi, 2020), to a few fossil resources (Mahlkow and Wanner, 2023), to multiple commodities (Fally and Sayre, 2018).

This paper makes three main contributions. (i) I contribute to a growing literature on the climate change impact on social welfare, taking micro-level shocks and deriving macro-level consequences (ii) I analyse how trade policy may help to adapt to climate change impacts. (iii) I enhance the seminal framework by Caliendo and Parro (2015) with land as an additional production factor that is used by agricultural production.

To analyse the impact of climate change on agriculture productivity, I take advantage of rich micro-level data from the Global Agro-Ecological Zones (GAEZ) data set, which was jointly developed by the UN Food and Agriculture Organization and the International Institute for Applied Systems Analysis (Fischer et al., 2021). GAEZ is based on agronomic models and high-resolution data on geographic characteristics such as soil, topography, elevation, and, crucially, climatic conditions. Using this data, GAEZ predicts the obtainable yield - crop by crop - at 2.3 million high-resolution grid cells (about 9 km by 9 km at the equator) covering the surface of the earth. GAEZ is available both under contemporary growing conditions and under climate change scenarios used by the UN's

Figure 1: Climate-induced yield changes.



Note: Yield changes from historical values in 1981-2010 to 2071-2100 under RCP 6.0. The latter is the mean value of two ESMs (*HadGEM2–ES* and *GFDL–ESM2M*) and among rain-fed and irrigated crops. Own calculation, based on GAEZ.

Intergovernmental Panel on Climate Change (IPCC).[1]

Using GAEZ, Figure 1 shows gridded yield changes under future climate change for rice and wheat under RCP 6.0.[2] Both crops show considerable spatial heterogeneity. In general, locations in the temperate zone will experience yield increases, while in the tropics and subtropics yields will decline. This pattern is more pronounced for wheat than rice. For rice, also some areas in Sub-Saharan Africa and in the Amazon will see yield increases. Yields will decrease in the majority of cells, 61.9 percent for wheat and 63.5 percent for rice. In 10 percent of cells rice yields will decrease more than 10.2 and for wheat more than 39.5 percent.

A potential adaptation strategy to mitigate negative climate change impacts is international trade. Trade can help countries diversify their economies and reduce their reliance on sectors that are vulnerable to climate change. Trade can also reduce risks associated with climate change by allowing a country to access a wider range of goods and services from different regions under heterogeneous climate change effects.[3] For example, if wheat yields in India will decrease substantially under climate change (see Figure 1), the country could import the quantity that is necessary to meet its domestic demand from countries that might experience a positive productivity shock, e.g. Germany. If workers can move out of wheat production into other sectors whose products can also be sold internationally, labour market impacts can even be positive.[4] On the other hand, besides the spatial correlation of climate change-induced productivity shocks (**?**), foreign shocks spread to other countries trough trade and GVCs, e.g. through foreign supply shocks (Eppinger et al., 2021). The most closely related study of climate change-induced shocks that transmit through trade and input-output linkages is by **?**. The authors extend the framework of Caliendo et al. (2019) and decompose the role of market-based adaptation to climate change. They show that input-output linkages matter for determining

[1]Climatic conditions are based on a time series of historical data of 1961-2010 and a selection of future climate simulations using recent IPCC AR5 Earth System Model (ESM) outputs for four Representative Concentration Pathways (RCPs). Hence, GAEZ results consistently quantify impacts on land productivity of historical climate conditions as well as of potential future climate change.

[2]Yield changes for other crops can be found in Figures 8 to 13 in the Appendix **??**.

[3]Burgess and Donaldson (2010) provide empirical evidence that trade mitigates economic costs associated with local weather shocks by enabling import substitution.

[4]This depends on the overall change in comparative advantage among the trading partners. The sign of the labour market impacts is not clear from a reduced-form perspective.

welfare effects of climate change and provide structural estimations of the temperature response function on sectoral productivities. In contrast, in this paper I use computed productivities from agronomic models under a global, more granular spatial coverage.

The adaptation potential of trade depends on the extent of barriers to trade, such as tariffs or non-tariff barriers, e.g., time-consuming administrative procedures, technical requirements, and differences in regulations. If trade barriers are low, countries can adapt to local production shocks by changing production patterns and trading different goods and quantities. Ederington and Ruta (2016) calculate trade restrictiveness, using the framework of Kee et al. (2009), and show that agriculture trade faces high restrictiveness both in developing and developed countries. Non-tariff barriers (NTBs) result in substantially more restrictiveness compared to tariffs. For a country with high trade barriers it is more difficult to substitute national production through imports, making the country more exposed to local productivity shocks. But the average numbers of Ederington and Ruta (2016) do not reveal counterfactual effects of future climate change impacts. For example, average agricultural NTBs in developing countries might be high, but NTBs on imports from large producers with low trade costs might be low. Then, import substitution might be feasible and less costly. But this also depends on how demand and supply will develop under climate change in the rest of the world. To account for those global circumstances I extend and apply a NQT model.

The remainder of the paper is structured as follows: In Section 2, I describe the NQT model of international trade that allows me to compute a counterfactual world with climate change impacts and trade policy responses. In Section 3 I describe the data and estimation procedure, before computing the counterfactual scenarios in Section 4. Section 5 concludes.

2 Model

For the analysis, I use the Ricardian trade model of Caliendo and Parro (2015), who provide a multi-sector version of the Eaton and Kortum (2002) gravity model with input-output linkages. I extend the model with the production factor *land* and decompose total factor productivity into *land* and *labour* productivity.

2.1 Preferences

There are N countries, indexed o and d, and J sectors, indexed j and k. In each sector, there is a continuum of goods $\omega^j \in [0, 1]$. Households in n obtain utility from consumption C according to a two-tier Cobb-Douglas utility function:

$$u(C_d) = \prod_{j=1}^{J} C_d^{j\ \alpha_d^j} \quad \text{with} \quad \sum_{j=1}^{J} \alpha_d^j = 1.$$

where α_d^j is the constant consumption share on industries j's goods. While the aggregation of utility from different varieties *within* one sector is the same for all countries, expenditures shares *across* sectors vary between countries, allowing for differently agricultural-intensive consumption patterns.

2.2 Production

Sectors j use two production factors: labour and intermediate inputs. Labour is fully mobile across sectors $L_n = \sum_j^J L_d^j$, but not across countries. It can be seen as an aggregate factor[5]. Each country is endowed with an exogenous quality-adjusted amount of land which is used across sectors $H_d = \sum_j^J H_d^j$. From the model perspective, land can also be considered as "mobile".[6]

All goods are produced using composite intermediate input bundles m from the own and other sectors. In all sectors, countries differ in their productivity for different goods from the continua and in the intermediate input cost shares γ. Total factor productivity is composed of two terms, a country-sector specific "fundamental productivity" A, and a variety-specific productivity z. The production technologies are Cobb-Douglas and hence given by:

$$q_d^j(\omega^j) = A_d^j z_d(\omega^j) \left[l_d^j(\omega^j)\right]^{\beta_d^j} \left[h_d^j(\omega^j)\right]^{\eta_d^j} \left[\prod_{k=1}^{J} m_d^{k,j}(\omega^j)^{\gamma_d^{k,j}}\right]^{1-\beta_d^j-\eta_d^j}$$

with $l_d^j + \eta_d^j + \sum_{k\in J} \gamma_d^{k,j} = 1$. l_d is the labour input, β_d the labour input share, h_d the

[5]The factor is a composite of many factors, e.g., labour, capital, and other natural resources (despite land), which are all non-tradeable in my framework.

[6]Mobile in a sense that the production on each field can switch among sectors.

land input, and η_d the land input share. With constant returns to scale and perfectly competitive markets, unit cost are given by

$$c_d^j = \frac{\Upsilon_d^j w_d^{\beta_d^j} r_d^{\eta_d^j}}{A_d^j z_d^j(\omega^j)} \left[\prod_{k=1}^{J} (P_d^k)^{\gamma_d^{k,j}} \right]^{1-\beta_d^j-\eta_d^j}$$

where $\Upsilon_d^j = (\beta_d^j)^{-\beta_d^j} (\eta_d^j)^{-\eta_d^j} \prod_{k\in\mathcal{J}} (\gamma_d^{k,j})^{-\gamma_d^{k,j}}$, w denotes the wage, r is the land rent, and P the price of a composite intermediate bundle. Hence, the cost of the input bundle depends on wages, land rents and the prices of *all* composite intermediate goods in the economy. Producers of composite intermediate goods supply Q_d^j at minimum costs by purchasing intermediate goods ω^j from the lowest cost supplier across countries, so that

$$Q_d^j = \left[\int d_d^j(\omega^j)^{1-1/\sigma^j} d\omega^j \right]^{\sigma^j/(\sigma^j-1)}.$$

$\sigma^j > 0$ is the elasticity of substitution across intermediate goods within sector j, and $d_d^j(\omega^j)$ the demand for intermediate goods ω^j from the lowest cost supplier such that

$$d_d^j(\omega^j) = \left(\frac{p_d^j(\omega^j)}{P_d^j} \right)^{-\sigma^j} Q_d^j$$

where P_d^j is the unit price of the composite intermediate good

$$P_d^j = \left[\int p_d^j(\omega^j)^{1-\sigma^j} d\omega^j \right]^{1/(1-\sigma^j)}$$

and $p_d^j(\omega^j)$ denotes the lowest price of intermediate good ω^j in n across all possible origin locations, i.e.

$$p_d^j = \min_o \left\{ p_{od}^j \right\}. \qquad (1)$$

Composite intermediate goods are used in the production of intermediate goods ω^j and as the final good in consumption as C_d^j, so that the market clearing condition is written as

$$Q_d^j = C_d^j + \sum_{k=1}^{J} \int m_d^{j,k}(\omega^j) d\omega^j \tag{2}$$

2.3 International trade

Trade in goods is costly, such that the offered price of ω^j from i in n is given by

$$p_{od}^j = \phi_{od}^j \cdot \frac{c_o^j}{z_o^j(\omega^j)} \tag{3}$$

where ϕ_{od}^j denote generic bilateral sector-specific trade frictions.[7] These can take a variety of forms — e.g., tariffs, non-tariff barriers, export taxes. In that case we can specify

$$\phi_{od}^j = \tau_{od}^j \cdot \kappa_{od}^j \cdot \zeta_{od}^j,$$

where τ_{od}^j represent sector-specific ad-valorem tariffs, $\kappa_{od}^j \geq 1$ iceberg trade costs, and ζ_{od}^j export taxes or subsidies. Tariff revenue $(\tau_{od}^j - 1)$ and export tax revenue (or subsidy cost) $(\zeta_{od}^j - 1)$ is collected (or spent) by the importing country and exporting country, respectively, and transferred lump-sum to its households.

Ricardian comparative advantage is induced à la Eaton and Kortum (2002) through a country-specific idiosyncratic productivity draw z^j from a Fréchet distribution.[8]

The price of the composite good is then given as

$$P_d^j = A^j \left[\sum_{o=1}^{d} \lambda_o^j (c_o^j \phi_{od}^j)^{-\theta^j} \right]^{-1/\theta^j} \tag{4}$$

[7] The "phiness" of trade à la Baldwin et al. (2003).

[8] The productivity distribution is characterized by a location parameter λ_o^j that varies by country and sector inducing *absolute* advantage, and a shape parameter θ^j that varies by sector determining *comparative* advantage. θ^j describes the elasticity of trade to trade costs

which, for the non-tradable sector or embargoed sector towards *all* non-domestic sources collapses to

$$P_d^j = A^j(\lambda_d^j)^{-1/\theta^j} c_d^j \tag{5}$$

where $A^j = \Gamma(\xi^j)^{1/(1-\sigma^j)}$ with $\Gamma(\xi^j)$ being a Gamma function evaluated at $\xi^j = 1 + (1-\sigma^j)/\theta^j$. Total expenditures on goods from sector j in country d are given by $X_d^j = P_d^j Q_d^j$. The expenditure on those goods originating from country o is called X_{od}^j, such that the share of j from o in d is $\pi_{od}^j = X_{od}^j / X_d^j$. In other words, it is the share of an exporter country in the total expenditure, by sector, of an importer country. This share can also be expressed as

$$\pi_{od}^j = \frac{\lambda_o^j (c_o^j \phi_{od}^j)^{-\theta^j}}{\sum_{h=1}^{d} \lambda_h^j (c_h^j \phi_{hd}^j)^{-\theta^j}} \tag{6}$$

2.4 General equilibrium

Total expenditures on goods from sector j are the sum of the firms' and households' expenditures on the composite intermediate good, either as input to production or for final consumption

$$X_d^j = \sum_{k=1}^{J} (1-\beta_d^k)\gamma_d^{j,k} \sum_{o=1}^{d} X_o^k \frac{\pi_{do}^k}{\tau_{do}^k \zeta_{do}^k} + \alpha_d^j I_d \tag{7}$$

with $I_d = w_d L_d + r_d H_d + R_d + D_d$, i.e., labour income, land resource rent, government revenue (tariff and export taxes minus export subsidies) and the aggregate trade balance. Sectoral trade balance is simply the difference between imports and exports

$$D_d^j = \sum_{o=1}^{d} X_{od}^j - X_{do}^j \tag{8}$$

and the aggregate trade balance $D_d = \sum_{j=1}^{J} D_d^j$, and $\sum_{d=1}^{d} D_d = 0$, with D_d being exogenously and D_d^j being endogenously determined. The trade balance can then be expressed as

$$\sum_{j=1}^{J}\sum_{o=1}^{d} X_d^j \frac{\pi_{od}^j}{\tau_{od}^j \zeta_{od}^j} - D_d = \sum_{j=1}^{J}\sum_{o=1}^{d} X_o^j \frac{\pi_{do}^j}{\tau_{do}^j \zeta_{do}^j}. \tag{9}$$

The goods market clearing (7) and trade balance (9) conditions close the model.

2.5 Solving for counterfactual equilibria

As suggested by Dekle et al. (2007, 2008), a counterfactual general equilibrium for alternative trade costs in the form of $\hat{\phi}_{od}^j = \phi_{od}^{j\prime}/\phi_{od}^j$ — i.e., where any variable $\hat{x}$ denotes the relative change from a previous value x to a new one x' — can be solved for in changes such that

Input costs
$$\hat{c}_d^j = \hat{w}_d^{\beta_d^j} \left[\frac{\hat{r}_d}{\hat{A}_d^j}\right]^{\eta_d^j} \left(\prod_{k=1}^{J} [\hat{P}_d^k]^{\gamma_d^{k,j}}\right)^{1-\beta_d^j-\eta_d^j} \tag{10}$$

Prices
$$\hat{P}_d^j = \left(\sum_{o=1}^{d} \pi_{od}^j [\hat{\phi}_{od}^j \hat{c}_o^j]^{-1/\theta^j}\right)^{-\theta^j} \tag{11}$$

Trade shares
$$\pi_{od}^{j\prime} = \pi_{od}^j \left(\frac{\hat{c}_o^j}{\hat{P}_d^j}\hat{\phi}_{od}^j\right)^{-1/\theta^j} \tag{12}$$

Expenditures
$$X_d^{j\prime} = \sum_{k=1}^{J} (1-\beta_d^k)\gamma_d^{j,k} \left(\sum_{o=1}^{d} \frac{\pi_{do}^{k\prime}}{\tau_{do}^{k\prime}\zeta_{do}^{k\prime}} X_o^{k\prime}\right) + \alpha_d^j I_d' \quad \text{with} \tag{13}$$

Income
$$I_d' = \hat{w}_d w_d L_d + \hat{r}_d r_d H_d$$

Tariff revenue
$$+ \sum_{k=1}^{J}\sum_{o=1}^{d} (\tau_{od}^{k\prime} - 1) \left(\frac{\pi_{od}^{k\prime}}{\tau_{od}^{k\prime}}\right) X_d^{k\prime}$$

Export tax revenue
$$+ \sum_{k=1}^{J}\sum_{o=1}^{d} (\zeta_{do}^{k\prime} - 1) \left(\frac{\pi_{do}^{k\prime}}{\tau_{do}^{k\prime}\zeta_{do}^{k\prime}}\right) X_o^{k\prime}$$

Trade balance
$$- D_d'$$

Trade balance
$$D_d = \sum_{j=1}^{J}\sum_{o=1}^{d} \frac{\pi_{od}^{j\prime}}{\tau_{od}^{j\prime}\zeta_{od}^{j\prime}} X_d^{j\prime} - \sum_{j=1}^{J}\sum_{o=1}^{d} \frac{\pi_{do}^{j\prime}}{\tau_{do}^{j\prime}\zeta_{do}^{j\prime}} X_o^{j\prime}. \tag{14}$$

As a measure of welfare changes I use changes in real income, obtained as

$$\hat{W}_d = \frac{\hat{I}_d}{\prod_{j=1}^{J}(\hat{P}_d^j)^{\alpha_d^j}}. \tag{15}$$

The model provides static level effects on real income and trade. As dynamic effects of trade integration are not taken into account, it provides a lower bound for the potential effects of climate adaptation through trade.

3 Data

3.1 Model parameters

The core data for this study are taken from the Global Trade Analysis Project (GTAP) database (Aguiar et al., 2019). The data provide a snapshot of the global economy in 2014, including domestic inter-industry flows and bilateral trade flows. The full database covers 141 regions, of which 121 are individual countries, and 65 sectors. The GTAP data are based on official trade flows. The backbone of the data are national input-output (I-O) tables.

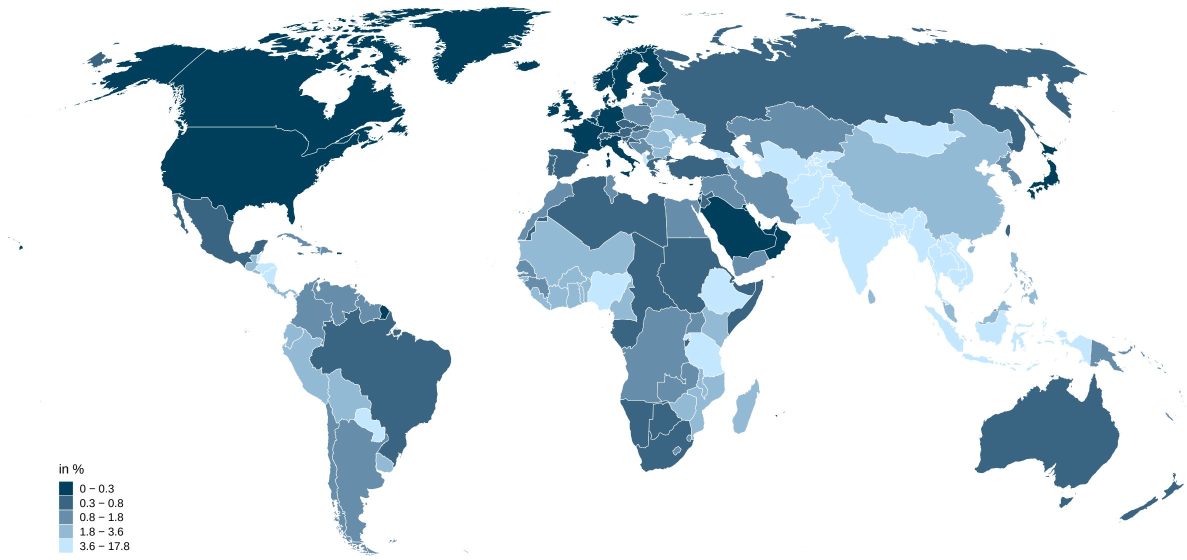
GTAP combines multiple I-O tables in a consistent manner. The complex process requires a high level of expertise and attention to detail, otherwise small inconsistencies and measurement errors of individual I-O tables would add up significantly.

From GTAP, I derive all model parameters[9], such as production factor shares of labour β, land η, intermediate input costs γ, trade shares π, consumption shares α, tariffs τ, export subsidies ζ, labour income wL, and land rents rH.

The extent to which climate-induced yield changes affect the economy and social welfare depends on the importance of agriculture on total value added. More specifically, GAEZ's obtainable yield predictions depend on the crop production suitability of a location, e.g. the soil and local weather pattern. I assume that this location specific characteristics is captured by the land rent a landowner receives. Figure 2 shows land

[9]Despite the trade elasticities θ^j, which I take from Fontagné et al. (2018), who use a gravity framework to estimate trade elasticites for all GTAP sectors despite services. Service flows do not face tariffs. Therefore, I rely on an estimate for the aggregate service sector provided by Egger et al. (2012).

Figure 2: Land rents in percent of total value added.



Note: Source: GTAP 10, own calculations.

rents ($r_d H_d$) in percent of total value added per country.

3.2 Climate impacts on crop yields

I focus on agricultural crop sectors to model the impact of climate change because (i) the link between climate conditions and agricultural productivities is well established, and (ii) future climate conditions under different RCPs are modeled extensively. I use the micro-level GAEZ data set (Fischer et al., 2021), which provides yields for 72 crops under temporary climate conditions and under future climate change. GAEZ is based on detailed data from a range of sources, including satellite imagery, ground observations, and computer models. The spatial resolution is about 9 km by 9 km at the equator[10], 2.3 million grid cells on the earth's surface. Primarily, GAEZ is used by farmers and government agencies to asses the production *potential* for different crops in any given location on earth.

GAEZ productivity estimates are available for each cell, regardless a crop actually growing there. GAEZ uses state-of-the-art agronomic models, combining a vector of (i)

[10]Owing to the curvature of the earth, grid cells at different latitudes cover different areas.

attributes describing the growing characteristics in each cell, (ii) multiple parameters that govern how a given set of growing characteristics map into the yield of a specific crop, (iii) assumptions about farming techniques and inputs, such as irrigation, fertilizers, machinery, and labour, that might influence crop yields at each cell.

GAEZ provides pre–climate change estimates of average agricultural productivity A_g^c over a period from 1981 to 2010 for crop c and grid-cell $g \in \mathcal{G}_d \equiv [1, ..., \mathcal{G}_d]$ in country d. For the pre-climate change estimates GAEZ uses an average of model runs on past daily weather realizations. This average takes into account the idiosyncratic variability of weather patterns from year to year in a coherent manner. I use this *historical* values as a "baseline" to calculate yield changes under future climate conditions.

Future climatic conditions are based on simulations from recent IPCC AR5 earth system model (ESM) outputs for four representative concentration pathways (RCPs). I use two ESMs, *HadGEM2-ES* (Collins et al., 2011) and *GFDL-ESM2M* (Dunne et al., 2013), to account for model uncertainty, and four RCPs to account for future greenhouse gas concentration uncertainty. RCPs are based on a range of assumptions about future social, economic, and technological developments, and provide a common framework for evaluating the potential impacts of different emission pathways on the climate. There are four RCPs, each representing a different level of future greenhouse gas concentrations.[11] The only difference to the "baseline" estimates, instead of past weather realizations GAEZ uses predicted future daily stream of weather from 2071 to 2100 to estimate future crop yields $A_g'^c$.

The change in productivity of agricultural sector j is then calculated the following

$$\hat{A}_d^j = \frac{\sum_{c \in \mathcal{J}_c} \sum_{g \in \mathcal{G}_d} s_g A_g'^c}{\sum_{c \in \mathcal{J}_c} \sum_{g \in \mathcal{G}_d} s_g A_g^c}, \tag{16}$$

where $c \in \mathcal{J}_c \equiv [1, ..., \mathcal{J}_c]$.[12] This approach assumes a certain within-sector substitutability

[11]RCP 2.6: This scenario represents a rapid and deep reduction in greenhouse gas emissions, resulting in atmospheric concentrations of around 430 parts per million (ppm) of CO2-equivalent by the year 2100. RCP 4.5: This scenario represents a moderate reduction in greenhouse gas emissions, resulting in atmospheric concentrations of around 640 ppm CO2-equivalent by 2100. RCP 6.0: This scenario represents a stabilization of greenhouse gas concentrations at around 710 ppm CO2-equivalent by 2100. RCP 8.5: This scenario represents a continuation of high levels of greenhouse gas emissions, resulting in atmospheric concentrations of around 970 ppm CO2-equivalent by 2100.

[12]For a sector-crop concordance see Table 5.

that isn't modeled directly. If two crops within $\mathcal{J}_c$ face opposite climate impacts in the same absolute amount this would be leveled out in the aggregate, $\hat{A}_d^j$ would be one.[13] Alternatively, I could calculate $\hat{A}_g^j$ for each grid cell and average the changes over all cells $g \in \mathcal{G}_d$ in each country d. But this would add additional degrees of freedom because I have to decide how to treat infinite changes, if $A_g^c = 0$ and $A_g'^c > 0$.

I assume that only current fields can be used for crop production. The share of current cropland per cell is s_g and is derived from the GAEZ data set, see Figure 7 in the Appendix **??**. The approach permits within-field crop substitution, but prohibits substitution at the extensive margin. Cropland expansion is a potential adaptation strategy to decreasing yields, but exogenous land use change requires a different model framework[14] which goes beyond the scope of this paper.

Figure 3 shows the values of $\hat{A}_d^j$ for $j =$ *wheat*[15] and *rice* under RCP 6.0. The across-country heterogeneity of climate impacts for both crops is striking. For wheat, especially countries around the equator lose productivity, while countries in higher latitudes gain productivity. Productivity changes range from minus 100 percent in Burkina Faso, Puerto Rico, Rest of Central America, and Senegal, to plus 75.4 in Finland and 85.9 percent in Norway. For rice, the within-region heterogeneity is higher. Productivity changes range from minus 50.5 and 50.4 percent in Tunisia and Rest of North Africa to plus 5,197 in Netherlands and 624,366 percent in Canada. For the latter, productivity changes are so high because initial productivities A are very low under a historical climate.

4 Results

I consider three different trade policy scenarios to deal with climate-induced productivity changes: (1) business as usual with current trade policies; (2) "sufficient" unilateral trade liberalization; and (3) multilateral trade liberalization.

Each scenario is computed for each of the four RCPs, to account for uncertainty about future climate change. Productivity shocks for each RCP are the ensemble mean of two

[13]Even though this consideration is highly unlikely given the narrow sector-crop matching.

[14]To model land use change properly, dynamic feedback loops with market prices and emissions are required, see e.g. Domınguez-Iino (2022).

[15]GTAP sector "wht", see Table 5 in the Appendix **??** for the concordance of GAEZ crops c to GTAP sector j.

Table 1: Scenario 1, production change in billion USD.

	RCP 2.6		RCP 4.0		RCP 6.0		RCP 8.5	
	L	G	L	G	L	G	L	G
Ag. Products	-7.0	7.3	-13.9	12.9	-17.0	14.9	-27.9	25.9
Crops	-16.1	15.8	-31.0	27.6	-36.8	31.3	-57.9	49.1
Fossils & Energy	1.6	-2.7	2.5	-4.0	1.9	-3.3	3.2	-5.9
Manufacturing	5.4	1.0	9.3	-1.3	10.7	-2.7	16.7	-7.2
Services	-7.2	7.5	-13.1	19.8	-15.3	25.6	-25.0	41.7
N	40	101	61	80	73	68	74	67

Note: Change in production in bil. USD for countries who lose welfare (*L*) and gain welfare (*G*) per RCP. See Table 4 for the aggregation of GTAP sectors.

ESMs, and for irrigated and rain-fed yields.

Scenario 1: Business as usual.

Under the "business as usual" countries adjust their trade and production patterns to climate-induced productivity changes under current trade policies. Not surprisingly, under increasing greenhouse gas concentrations more and more countries lose welfare as more productivity changes become negative (compare Figure 4 to Figures 14, 15, and 16 in the Appendix **??**). Under RCP 6.0, welfare in Pakistan (minus 1.71 percent), Cambodia (minus 1.5), and Nigeria (minus 1.19) declines the most. The highest increases happen in Rest of South Asia (1.74 percent), Belarus (1.52), and Tajikistan (1.31). Under RCP 2.6 and 4.0, the majority of countries experience welfare gains, while it is opposite under RCP 6.0 and 8.5.

Table 1 presents the production changes for countries who lose (*L*) and gain welfare (*G*) under different RCP scenarios. Because climate-induced productivity changes directly affect crop sectors, aggregate crop production is most affected by cross-country reallocations. For countries who lose welfare, crop production decreases by 36.8 bn USD under RCP 6.0. That accounts for 2.5 percent of total crop production in that country group. Crop production in countries that gain welfare increases by 31.3 bn USD. But the increase is not sufficient to compensate all losses. That pattern is similar for all RCP scenarios. Sectors further down in the agriculture supply chain also suffer losses. Production of agricultural products, which include processed commodities such as crops and animal products, decreases in countries that lose welfare. The same happens to service sectors whose input for crop and food production is less needed in that country group anymore, e.g. transport and warehousing. As a response to the climate shock, workers move out of agriculture and service sectors into manufacturing, fossil fuels and energy production. Under RCP 6.0, production in manufacturing and fossil fuels increases by 10.7 and 1.9 bn USD in the country group that loses welfare. But these production gains cannot compensate the bigger losses in the three other categories (see Table 1).

Table 2 shows trade flow changes for both countries groups under RCP 6.0.[16] Country group *L* substitutes diminishing crop production by imports from country group *W*. Crop imports increase by 8.83, agricultural products by 1.1 percent. Although manufacturing production increases in *L* (see Table 1), total exports only increase by 0.3 percent. Meanwhile, crop and agricultural exports decrease by 7.94 and 1.32 percent.

Table 2: Scenario 1, trade flow changes in RCP 6.0, in percent.

	Δ Bilateral imports		Δ Internal trade		Δ Total exports	
	L	W	L	W	L	W
Ag. Products	1.10	-1.56	-0.97	0.72	-1.32	0.84
Crops	8.83	-9.28	-4.85	5.41	-7.94	6.53
Fossils & Energy	-0.41	0.45	-0.26	-0.25	0.25	-0.29
Manufacturing	-0.24	0.36	0.13	-0.01	0.30	-0.08
Services	-0.39	0.59	0.21	0.04	0.49	-0.08

Note: Change in trade flows in percent for countries that lose welfare (*L*) and gain welfare (*G*) in Scenario 1 under RCP 6.0. Bilateral imports refer to imports between both country groups. Internal trade refers to trade within each country group. See Table 4 for the aggregation of GTAP sectors.

Table 3 shows the drivers behind the welfare changes of Scenario 1. In Column (1) welfare change is regressed on the import share of agricultural goods and the average productivity change, weighted by initial production, for all countries under RCP 8.5.

[16] See Table 6, 7, and 8 in the Appedix **??** for other RCPs.

Unsurprisingly, the climate-induced change in productivity is positive associated with welfare change. A one percent increase in productivity is associated with a 0.003 percent increase in welfare, holding all else equal. Columns 2 to 4 only use the subset of welfare losers, 74 countries out of 141, because theory lets us suspect counteracting effects of the independent variables. For example, a high agricultural import share might have a dampening effect on welfare for the winners, because it indicates a higher level of specialization (within agriculture and/or across sectors). Indeed, for welfare losers a one percent increase in the import share is associated with an increase in welfare by 0.012 percent. Adding trade exposure, the average productivity change of trading partners weighted by their respective import share for each destination, to the regression does not lead to a significant result. This indicates that the primarily effect on welfare change comes from the productivity change and the importance of local agricultural production. That point is further highlighted in Column (4). A one percent increase in the share of total production from agriculture is associated with a welfare decrease of 0.047 percent. Adding the agriculture share to the regression also drops the significance level of the import share. This result is in line with Costinot et al. (2016), who found that the adjustment of production patterns within country is more important than the adjustment of trade patterns across countries.

Table 3: Change in welfare.

	(1)	(2)	(3)	(4)
Import share	0.004+	0.012***	0.012***	0.004
	(0.002)	(0.003)	(0.003)	(0.004)
Δ Productivity	0.003**	0.018***	0.015**	0.015**
	(0.001)	(0.005)	(0.005)	(0.005)
Trade exposure			0.005+	0.004
			(0.003)	(0.003)
Agriculture share				-0.047***
				(0.013)
Num.Obs.	141	74	74	74
Adj. R2	0.128	0.321	0.349	0.460

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: Dependent variable is welfare change in percent in Scenario 1 under RCP 8.5. Import share is the share of imported over total agricultural goods. Change in productivity is the mean of $\hat{A}_d^j$ weighted by the baseline production value of j. Trade exposure is the average productivity change of trading partners weighted by the import share. Agriculture share is the share of agricultural production over total production. Column (1) contains all countries, while Columns (2) to (4) only considers countries that loose welfare.

Scenario 2: "Sufficient" unilateral trade liberalization

Scenario 2 models an "sufficient" unilateral trade policy response to counteract the welfare decrease for each country that loses welfare under Scenario 1. Therefore, I reduce NTBs on imports for country d till $\hat{W}_d = 0$ (see Eq. 15) individually, all else being equal. Figure 5 displays the necessary reduction in import barriers to compensate climate-induced welfare losses under RCP 6.0. Each country's number indicates an "sufficient" trade liberalization, only if that country reduces their NTBs under climate change and all other countries do not change their trade policies. Highest NTB reductions have to occur in Pakistan (8.5 percent), Nigeria (6.5), and India (2.9). Pakistan and Nigeria also experience the highest welfare losses in Scenario 1. With increasing greenhouse gas concentrations and more severe yield losses, necessary NTB reductions also have to get bigger.[17] Under RCP 8.5, Nigeria needs to reduce import NTBs by 11.8 percent to compensate climate-induced welfare losses.

Scenario 3: Multilateral trade liberalization

Scenario 3 models all unilateral NTB reductions of Scenario 2 simultaneously. Figure 6 shows welfare changes under RCP 6.0. Countries that lose welfare under Scenario 1 experience high welfare gains. The biggest increases happen in Pakistan (16.67 percent), Nigeria (7.48), and India (5.77). It shows that the NTB reduction necessary to compensate a single country's climate-induced welfare loss, all else being equal, leads to high welfare gains when they are executed multilaterally. But also countries outside the group that liberalizes trade benefit, e.g., Nepal's welfare increases by 0.44, rest of South Asia by 0.43, and Rwanda by 0.14 percentage points from Scenario 1 to 3. That shows important spill-over effects from countries that liberalize trade policies to the countries that do not. Unsurprisingly, since this massive policy change shifts global production and trade patterns, there are some countries that are worse off. Countries that lose the most welfare from Scenario 1 to 3 are Kyrgyzstan (0.05 percentage points), South Korea (0.03 percentage points), and Belarus (0.02 percentage points), but they still experience welfare gains. In contrast to Taiwan and Japan, that have small welfare gains under Scenario 1 (0.004 and 0.01 percent) and lose welfare under Scenario 3 (minus 0.006 and 0.002 percent).

5 Conclusion

In this paper I carry out a quantitative assessment of the trade and welfare effects of future climate change globally. I use a Ricadian NQT trade model to simulate the general equilibrium effects of trade liberalization along the whole value chain in response to climate-induced productivity changes in agriculture.

I show that climate change affects agricultural productivities differently around the world. In particular, countries who experience welfare losses are predominantly located in the global south. These countries cannot compensate climate-induced productivity

[17] Compare Figure 17, 18, and 19 in the Appedix for other RCPs.

losses by (i) switching their production to more productive sectors, and (ii) import those crops whose local productivity declines, because they face high trade barrieres. I show for each country which reduction in non-tariff barriers on imports is necessary to compensate welfare losses. Usually, the largest NTB reductions have to happen in countries with the highest initial losses. But this relation is not linear.

Trade liberalization is an important adaptation policy to mitigate climate-induced welfare losses. If no coordination happens among countries who lose welfare, unilateral trade policy liberalization has to be higher. In contrast, if all countries, that experience climate-induced welfare losses, reduce their import NTBs simultaneously, positive spill-over effects occur globally. Also the country group that already gains from climate change increases their welfare even further.

Mitigating future climate change is a rewarding endeavour. Under a low concentration pathway (RCP 2.6) almost all countries benefit from crop productivity increases, while for higher RCPs welfare costs get tremendous. The international community should therefore make every effort to cut carbon emissions.

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Appendix

A Tables

Table 4: GTAP 10 sectorlist and production values, scenario 1

Category	Code	Sector	Production in Bn. USD				
			Initial	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Ag. Products	b_t	Beverages & tobacco products	1274.5	1278.5	1278.7	1278.0	1277.4
	cmt	Bovine meat products	609.0	610.0	609.9	609.8	609.4
	ctl	Bovine cattle, sheep & goats, horses	430.3	431.7	431.3	431.0	430.3
	frs	Forestry	345.4	345.5	345.5	345.4	345.4
	fsh	Fishing	389.7	390.5	390.4	390.1	390.2
	mil	Dairy products	801.4	803.1	802.8	802.5	801.9
	oap	Animal products nec	737.4	739.8	739.2	738.4	737.7
	ofd	Food products nec	2929.2	2939.7	2935.0	2931.6	2924.5
	omt	Meat products nec	711.2	712.7	712.5	712.1	712.0
	pcr	Processed rice	391.3	399.7	398.8	394.9	394.5
	rmk	Raw milk	373.4	374.7	374.5	374.3	374.0
	sgr	Sugar	208.8	208.6	207.5	206.8	203.7
	vol	Vegetable oils & fats	460.2	463.6	462.3	461.5	457.7
	wol	Wool, silk-worm cocoons	39.9	40.0	40.1	40.0	39.9
Crops	c_b	Sugar cane, sugar beet	148.2	148.2	146.8	146.0	141.6
	gro	Cereal grains nec	382.1	387.9	386.1	384.0	383.8
	ocr	Crops nec	297.5	310.2	314.9	314.8	316.2
	osd	Oilseeds	340.2	343.4	341.2	340.5	334.5
	pdr	Paddy rice	313.7	324.6	322.9	317.7	316.2
	pfb	Plant-based fibers	101.0	102.3	101.1	99.6	99.4
	v_f	Vegetables, fruits, nuts	1385.7	1396.5	1381.1	1372.6	1355.3
	wht	Wheat	233.1	232.7	227.4	226.7	219.7
Fossils & Energy	coa	Coal	555.2	555.2	555.2	555.2	555.1
	ely	Electricity	2916.5	2916.4	2916.1	2916.1	2915.4
	gas	Gas	622.7	622.6	622.8	622.9	623.1
	gdt	Gas manufacture, distribution	289.5	289.5	289.5	289.5	289.6
	oil	Oil	2526.4	2526.2	2526.5	2526.8	2526.6
	p_c	Petroleum, coal products	4027.7	4027.4	4027.6	4027.9	4027.6
Manufacturing	bph	Basic pharmaceutical products	1115.7	1116.4	1116.3	1116.1	1115.9
	chm	Chemical products	4311.6	4314.0	4313.6	4313.1	4312.3
	eeq	Electrical equipment	2157.6	2157.9	2157.8	2157.8	2157.6
	ele	Computer, electronic & optical products	4678.7	4678.5	4678.4	4678.4	4677.8
	fmp	Metal products	2524.9	2525.0	2524.9	2524.7	2524.4
	i_s	Ferrous metals	3233.3	3233.6	3233.6	3233.4	3233.2
	lea	Leather products	491.2	491.6	491.6	491.5	491.4
	lum	Wood products	1012.9	1013.2	1013.3	1013.2	1013.2
	mvh	Motor vehicles & parts	4145.4	4145.9	4145.8	4145.5	4145.3
	nfm	Metals nec	2069.7	2069.2	2068.9	2068.8	2068.1
	nmm	Mineral products nec	2030.4	2030.8	2030.7	2030.6	2030.5
	ome	Machinery & equipment nec	4156.2	4156.8	4156.7	4156.6	4156.2
	omf	Manufactures nec	1817.6	1818.3	1818.5	1818.4	1818.5
	otn	Transport equipment nec	1312.6	1312.9	1312.8	1312.7	1312.7
	oxt	Other Extraction	1123.4	1123.7	1123.7	1123.7	1123.8
	ppp	Paper products, publishing	1788.3	1789.0	1789.2	1789.1	1789.2
	rpp	Rubber & plastic products	2240.7	2242.6	2242.9	2242.6	2242.9
	tex	Textiles	1617.8	1622.8	1622.6	1621.1	1621.6
	wap	Wearing apparel	1173.7	1175.2	1175.1	1174.7	1174.9
Services	afs	Accommodation, Food & service activities	3892.7	3896.0	3895.0	3894.0	3891.7
	atp	Air transport	959.8	959.9	959.9	959.9	959.9
	cmn	Communication	5741.3	5742.2	5742.3	5742.2	5742.4
	cns	Construction	12228.3	12231.1	12231.0	12230.3	12230.2
	dwe	Dwellings	5359.5	5359.5	5359.5	5359.5	5359.3
	edu	Education	4363.6	4364.0	4364.0	4363.9	4363.8

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Table 4 – *Continued from previous page*

Category	Code	Sector	Production in Bn. USD				
			Initial	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
	hht	Human health & social work activities	7649.6	7651.6	7651.4	7651.0	7650.7
	ins	Insurance (formerly isr)	1825.2	1825.5	1825.5	1825.5	1825.5
	obs	Business services nec	8383.9	8386.0	8386.6	8386.6	8387.4
	ofi	Financial services nec	5788.8	5789.2	5789.1	5789.0	5788.8
	osg	Public Administration & defense	5834.8	5835.6	5835.5	5835.3	5835.1
	otp	Transport nec	4261.7	4262.5	4262.3	4262.1	4262.1
	ros	Recreational & other services	4329.7	4330.5	4330.4	4330.2	4329.6
	rsa	Real estate activities	3149.4	3149.6	3149.6	3149.6	3149.6
	trd	Trade	12022.2	12023.7	12023.6	12023.2	12022.7
	whs	Warehousing & support activities	1520.9	1521.5	1521.5	1521.4	1521.4
	wtp	Water transport	488.1	488.1	488.1	488.1	488.0
	wtr	Water	1416.7	1416.7	1416.7	1416.7	1416.6

Table 5: GAEZ to GTAP concordance

GAEZ crop	Unit	GTAP sector
Sugarbeet	kg sugar/ha	c_b
Sugarcane	kg sugar/ha	
Barley	kg DW/ha	gro
Buckwheat	kg DW/ha	
Foxtail millet	kg DW/ha	
Highland maize	kg DW/ha	
Highland sorghum	kg DW/ha	
Lowland maize	kg DW/ha	
Lowland sorghum	kg DW/ha	
Maize	kg DW/ha	
Millet	kg DW/ha	
Oat	kg DW/ha	
Pearl millet	kg DW/ha	
Rye	kg DW/ha	
Silage maize	kg DW/ha	
Sorghum	kg DW/ha	
Spring barley	kg DW/ha	
Spring rye	kg DW/ha	
Temperate maize	kg DW/ha	
Temperate sorghum	kg DW/ha	
Winter barley	kg DW/ha	
Winter rye	kg DW/ha	
Cocoa	kg DW/ha	ocr
Cocoyam	kg DW/ha	
Coffee	kg DW/ha	
Coffee arabica	kg DW/ha	
Coffee robusta	kg DW/ha	
Greater yam	kg DW/ha	
Para rubber	kg DW/ha	

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Table 5 – *Continued from previous page*

GAEZ crop	Unit	GTAP sector
Tea	kg DW/ha	
Tobacco	kg DW/ha	
White yam	kg DW/ha	
Yam	kg DW/ha	
Yellow yam	kg DW/ha	
Coconut	kg DW/ha	osd
Groundnut	kg DW/ha	
Jatropha	kg DW/ha	
Rapeseed	kg DW/ha	
Soybean	kg DW/ha	
Sunflower	kg DW/ha	
Dryland rice	kg DW/ha	pdr
Wetland rice	kg DW/ha	
Alfalfa	10kg DW/ha	pfb
Biomass highland sorghum	kg DW/ha	
Biomass lowland sorghum	kg DW/ha	
Biomass sorghum	kg DW/ha	
Biomass temperate sorghum	kg DW/ha	
Flax	kg DW/ha	
Grass	10kg DW/ha	
Miscanthus	10kg DW/ha	
Napier grass	10kg DW/ha	
Pasture legumes	10kg DW/ha	
Reed canary grass	10kg DW/ha	
Switchgrass	10kg DW/ha	
Banana	kg DW/ha	v_f
Cabbage	kg DW/ha	
Carrot	kg DW/ha	
Cassava	kg DW/ha	
Chickpea	kg DW/ha	
Citrus	kg DW/ha	
Cowpea	kg DW/ha	
Dry pea	kg DW/ha	
Gram	kg DW/ha	
Onion	kg DW/ha	
Phaseolus bean	kg DW/ha	
Pigeonpea	kg DW/ha	
Sweet potato	kg DW/ha	
Tomato	kg DW/ha	
White potato	kg DW/ha	
Spring wheat	kg DW/ha	wht

Continued on next page

Table 5 – *Continued from previous page*

GAEZ crop	Unit	GTAP sector
Wheat	kg DW/ha	
Winter wheat	kg DW/ha	

Table 6: Scenario 1, trade flow changes in RCP 2.6, in percent.

	Δ Bilateral imports		Δ Internal trade		Δ Total exports	
	L	W	L	W	L	W
Ag. Products	0.99	-1.19	-0.41	0.54	-1.03	0.59
Crops	6.35	-5.79	-1.86	2.92	-5.33	3.24
Fossils & Energy	-0.43	0.60	0.03	-0.06	0.47	-0.11
Manufacturing	-0.21	0.52	0.25	0.01	0.48	-0.01
Services	-0.40	0.61	0.19	0.04	0.58	0.01

Table 7: Scenario 1, trade flow changes in RCP 4.5, in percent.

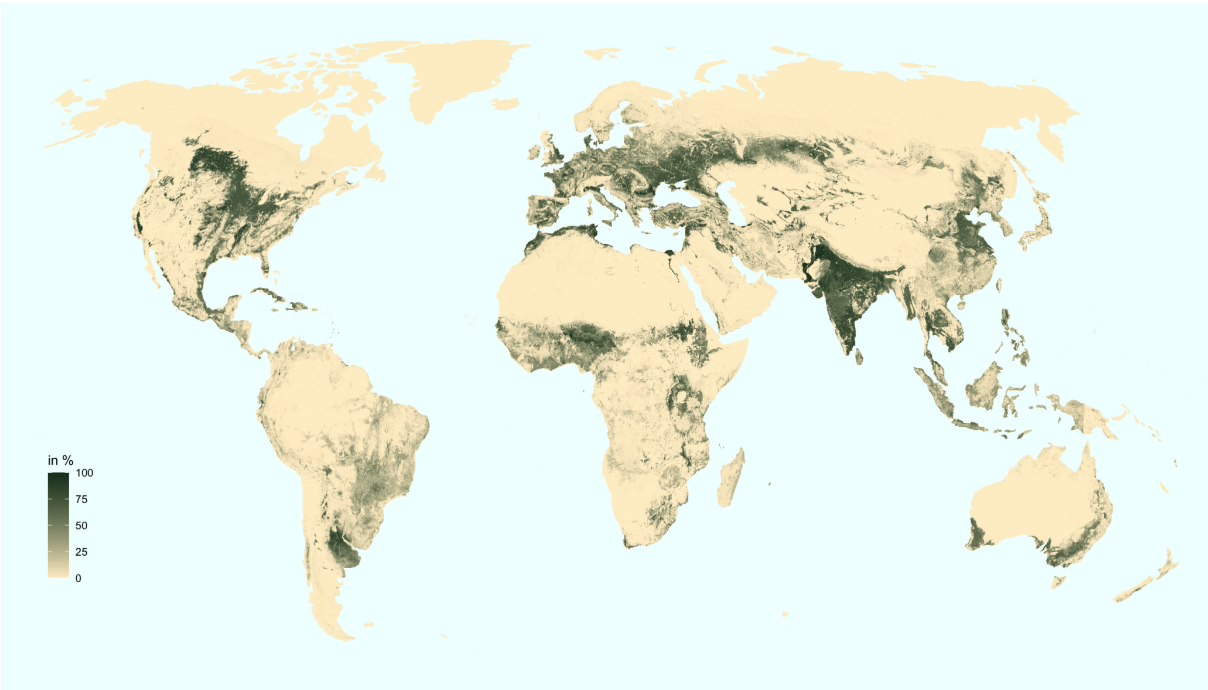
	Δ Bilateral imports		Δ Internal trade		Δ Total exports	
	L	W	L	W	L	W
Ag. Products	1.14	-2.02	-0.86	0.63	-1.61	0.72
Crops	7.70	-9.16	-3.58	4.70	-7.94	5.36
Fossils & Energy	-0.47	0.56	-0.29	-0.17	0.36	-0.22
Manufacturing	-0.27	0.53	0.28	-0.00	0.48	-0.05
Services	-0.51	0.90	0.40	0.04	0.84	-0.03

Table 8: Scenario 1, trade flow changes in RCP 8.5, in percent.

	Δ Bilateral imports		Δ Internal trade		Δ Total exports	
	L	W	L	W	L	W
Ag. Products	1.79	-3.87	-2.35	0.78	-3.27	1.02
Crops	12.46	-14.14	-6.89	7.42	-12.21	8.94
Fossils & Energy	-0.71	0.90	-0.44	-0.36	0.45	-0.44
Manufacturing	-0.43	0.66	0.32	-0.03	0.58	-0.14
Services	-0.78	1.35	0.54	0.04	1.20	-0.12

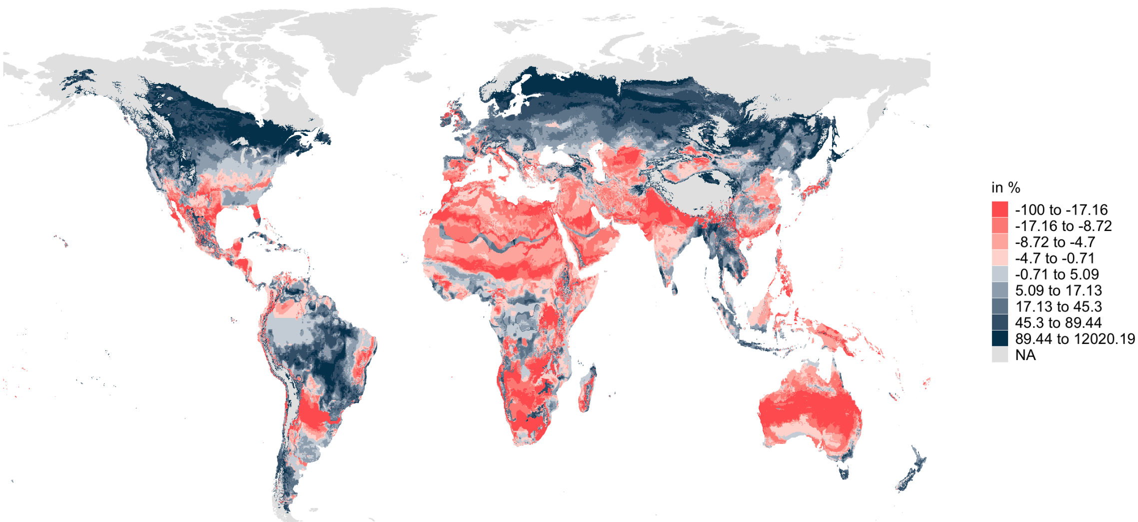
B Figures

Figure 7: Cropland share, 2014.



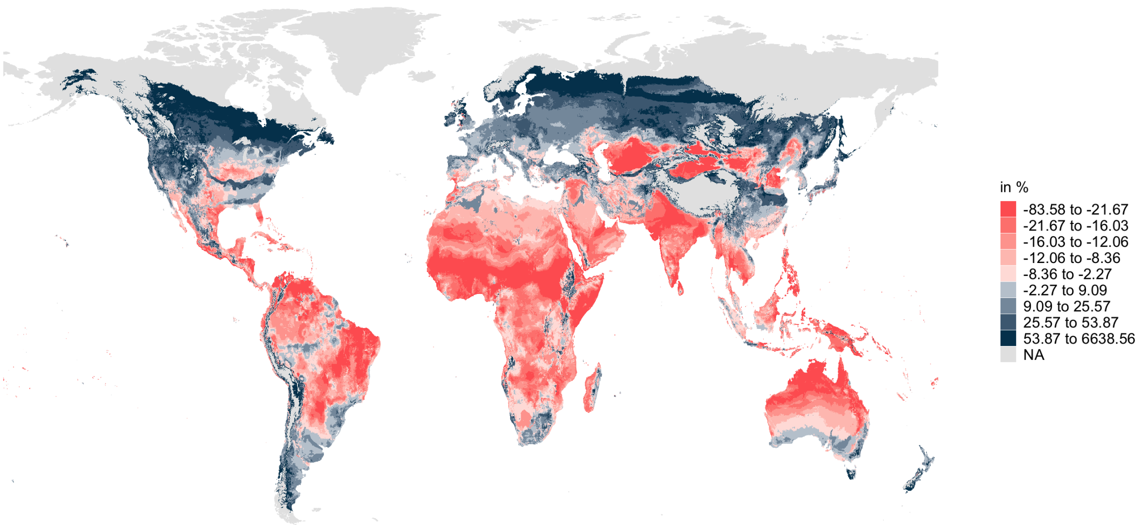
Note: Cropland share per grid cell in 2014 based on GAEZ, own calculation.

Figure 8: *Cereal grains nec*, yield changes in 2071-2100 under RCP 6.0.



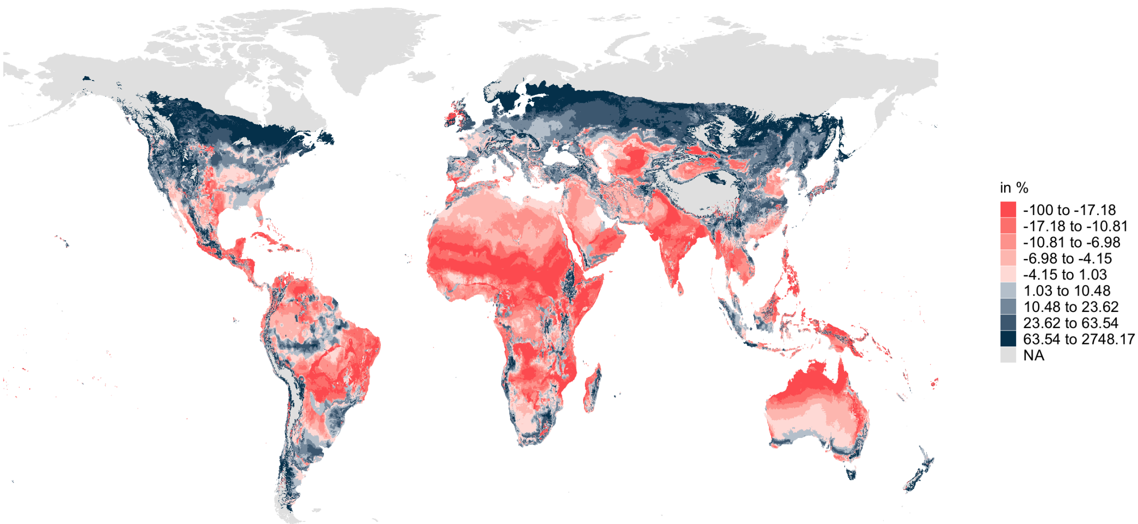
Note: GTAP sector *gro*, for mapping see Table 5, based on GAEZ, own calculation.

Figure 9: *Vegetables, fruits, nuts*, yield changes in 2071-2100 under RCP 6.0.



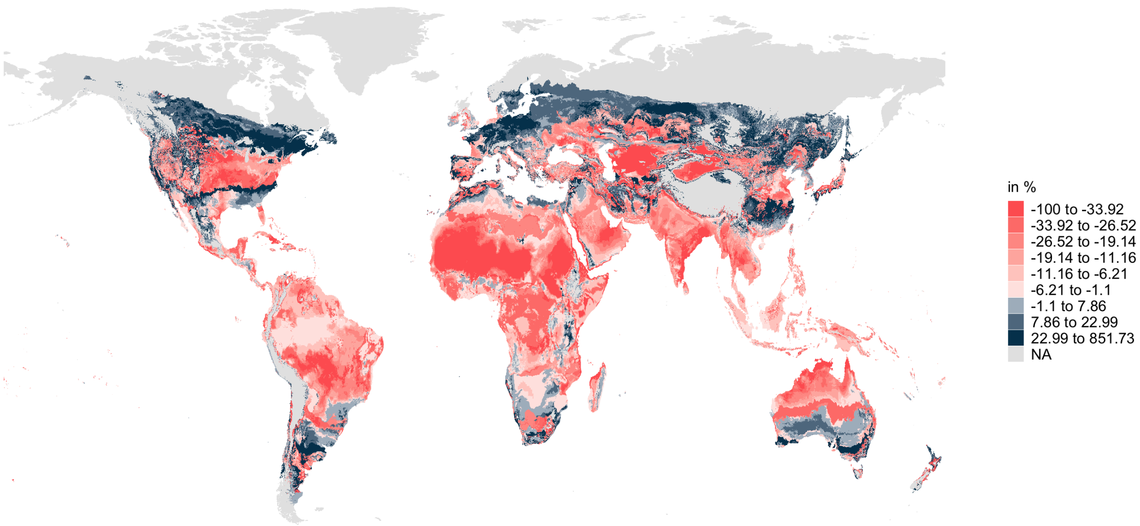
Note: GTAP sector *v_f*, for mapping see Table 5, based on GAEZ, own calculation.

Figure 10: *Oilseeds*, yield changes in 2071-2100 under RCP 6.0.



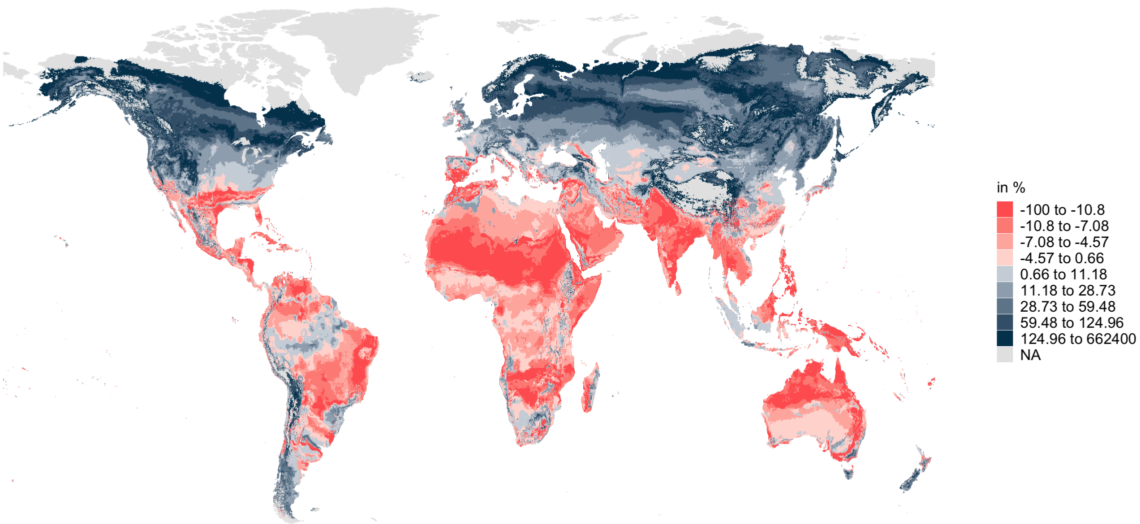
Note: GTAP sector *osd*, for mapping see Table 5, based on GAEZ, own calculation.

Figure 11: *Sugar cane, sugar beet*, yield changes in 2071-2100 under RCP 6.0.



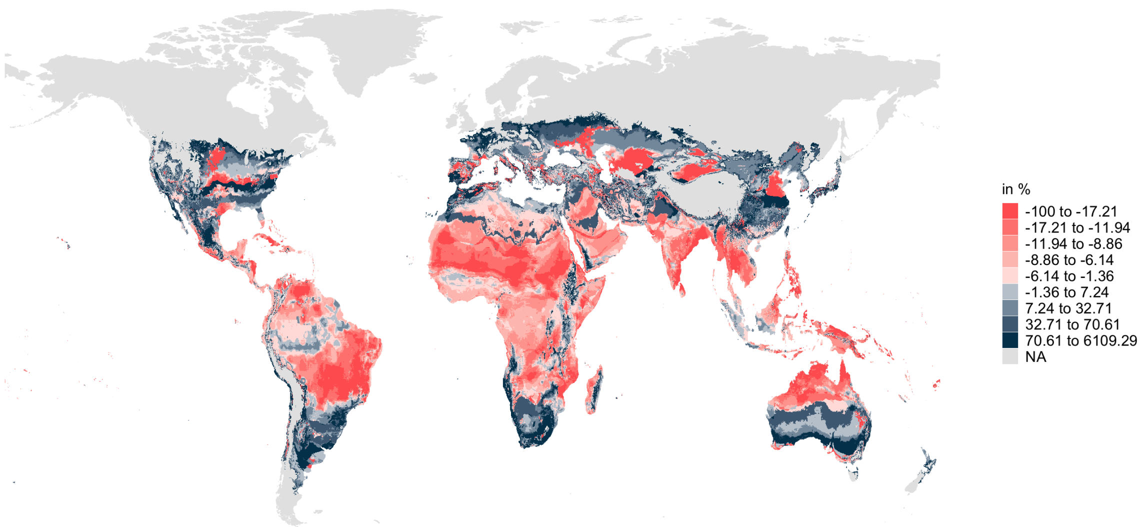
Note: GTAP sector *c_b*, for mapping see Table 5, based on GAEZ, own calculation.

Figure 12: *Plant-based fibers*, yield changes in 2071-2100 under RCP 6.0.



Note: GTAP sector *pfb* for mapping see Table 5, based on GAEZ, own calculation.

Figure 13: *Crops nec*, yield changes in 2071-2100 under RCP 6.0.



Note: GTAP sector *ocr*, for mapping see Table 5, based on GAEZ, own calculation.

Figure 14: Welfare change in scenario 1 under RCP 2.6.

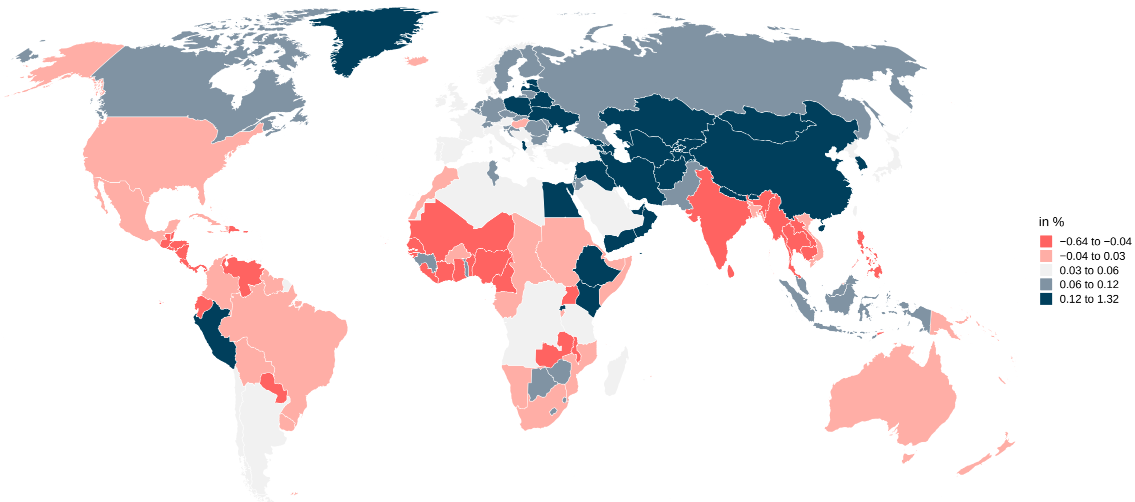


Figure 15: Welfare change in scenario 1 under RCP 4.5.

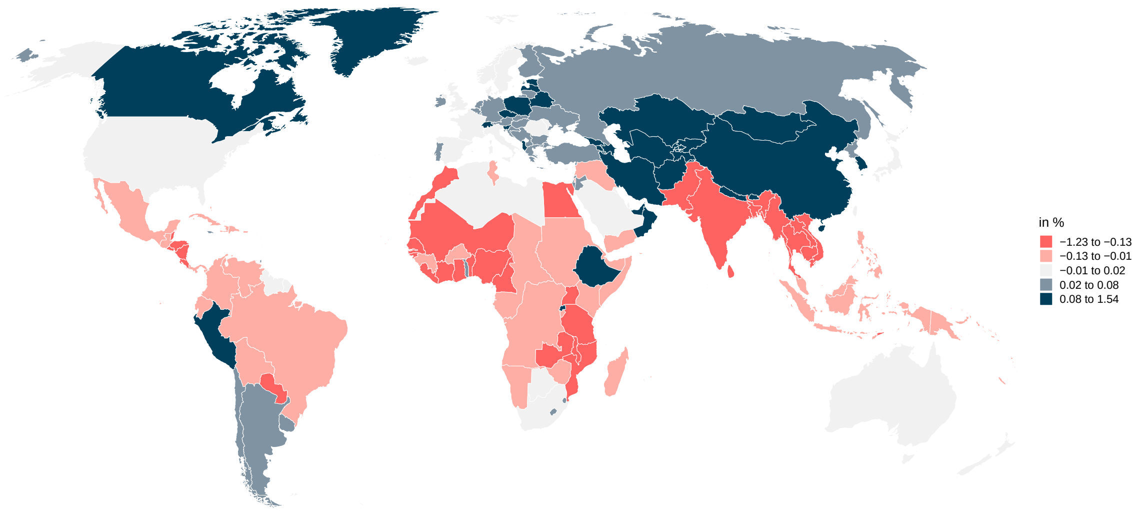


Figure 16: Welfare change in scenario 1 under RCP 8.5.

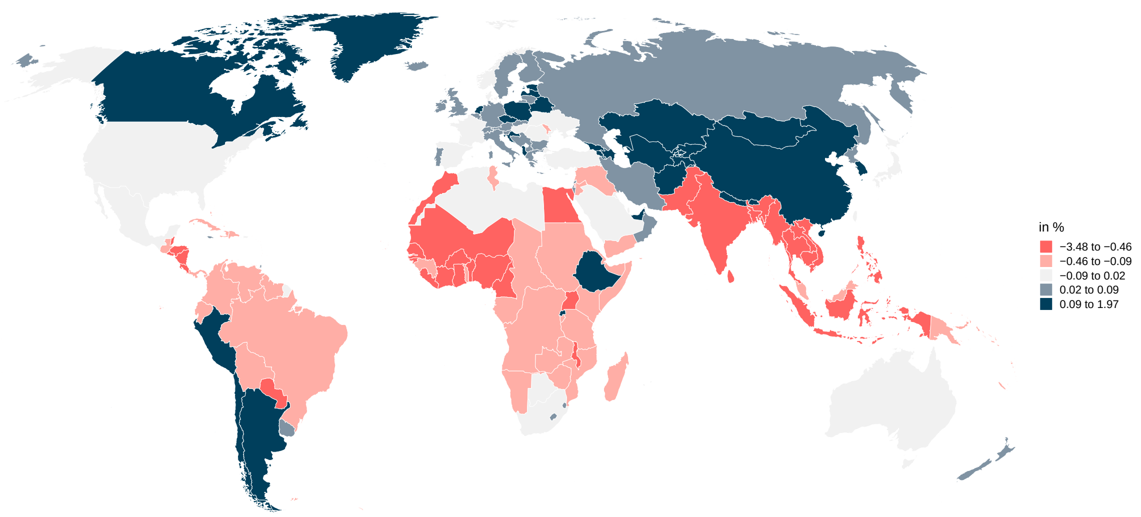


Figure 17: NTB changes in scenario 2 under RCP 2.6.

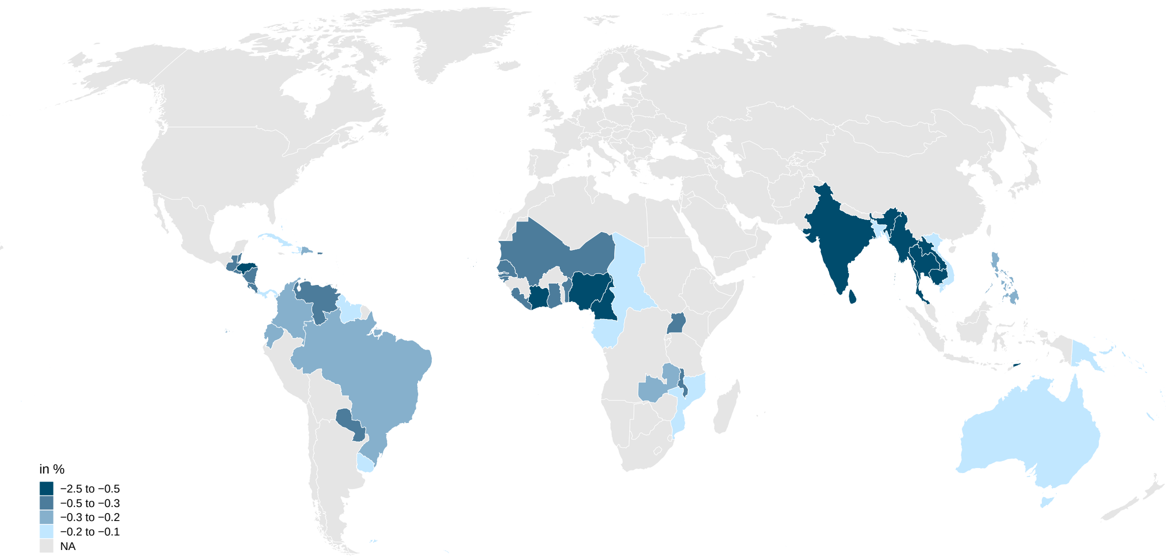


Figure 18: NTB changes in Scenario 2 under RCP 4.5.

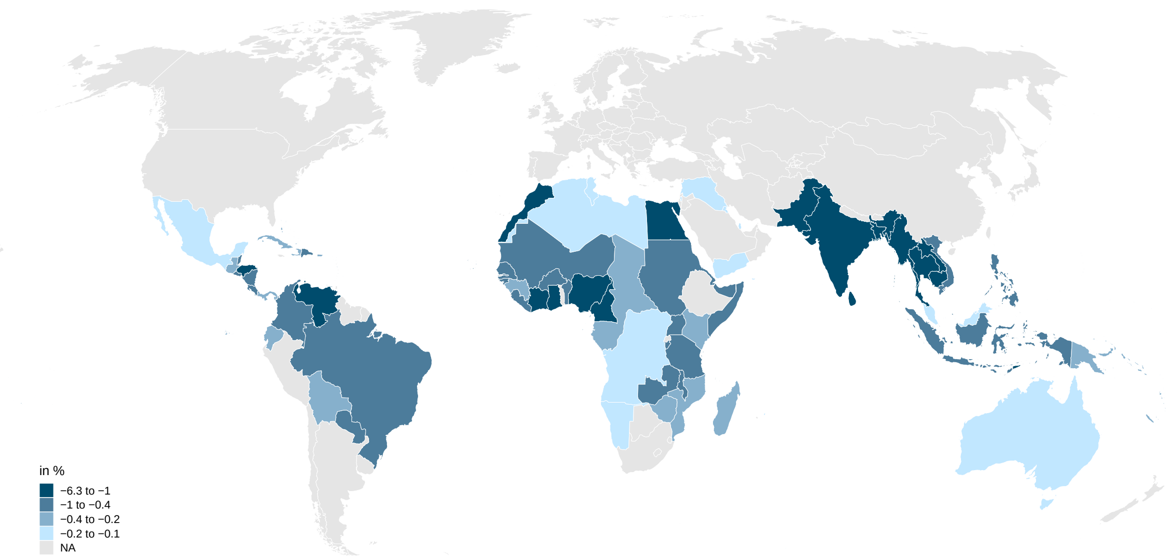


Figure 19: NTB changes in scenario 2 under RCP 8.5.

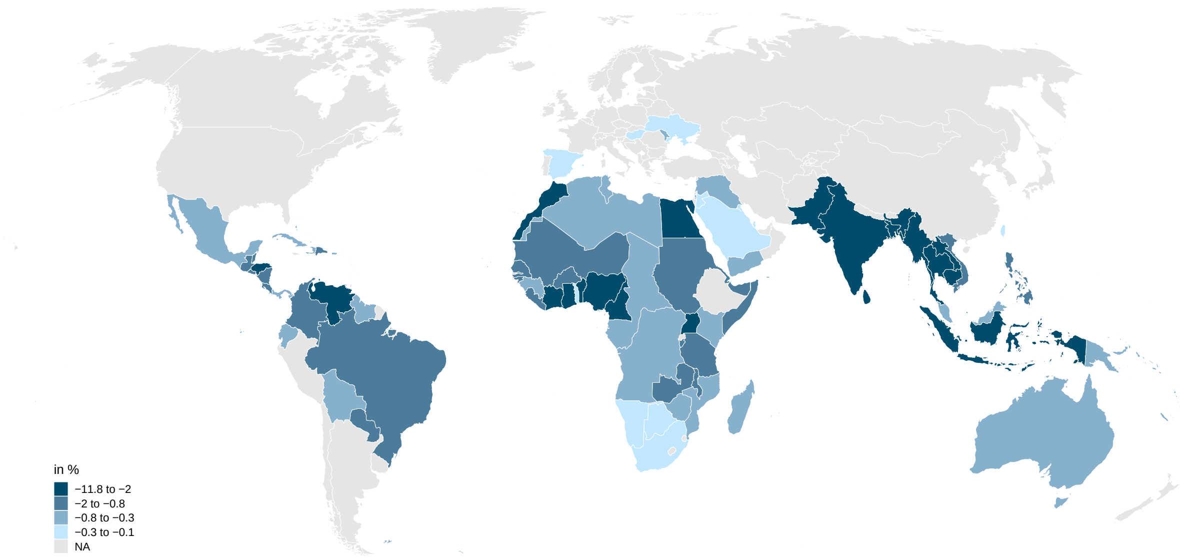
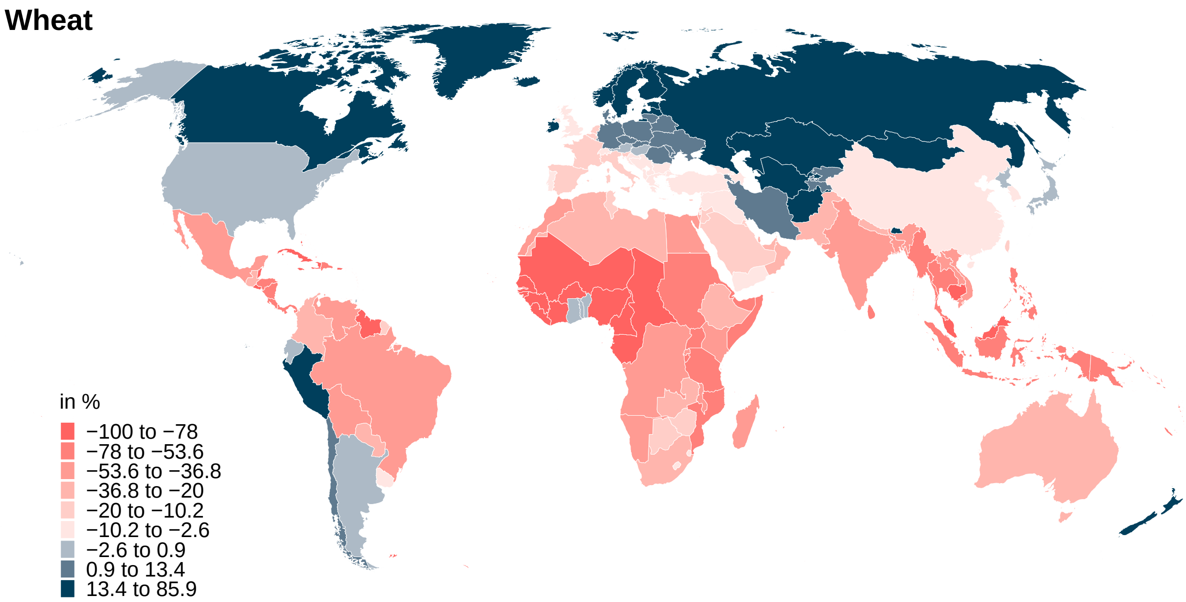


Figure 3: Productivity changes under RCP 6.0.



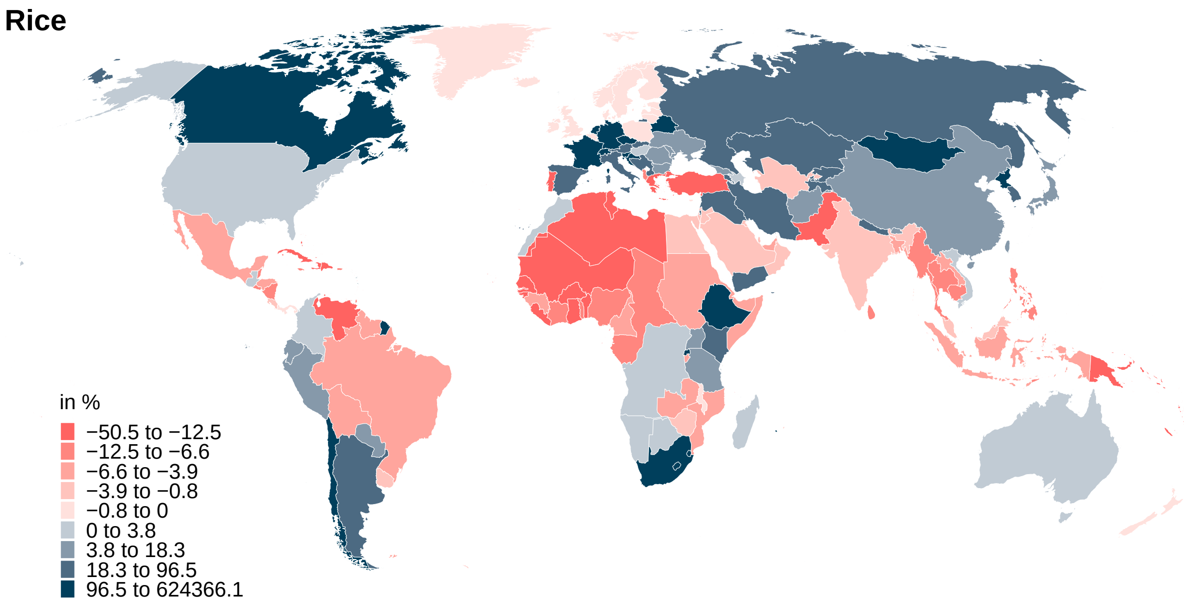


Figure 4: Welfare change in Scenario 1 “business as usual” under RCP 6.0.

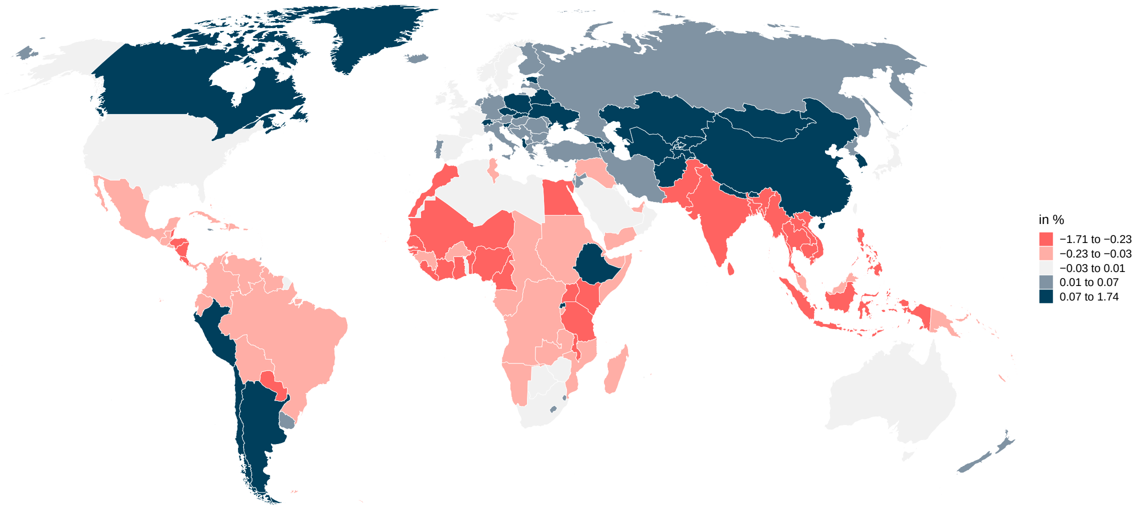
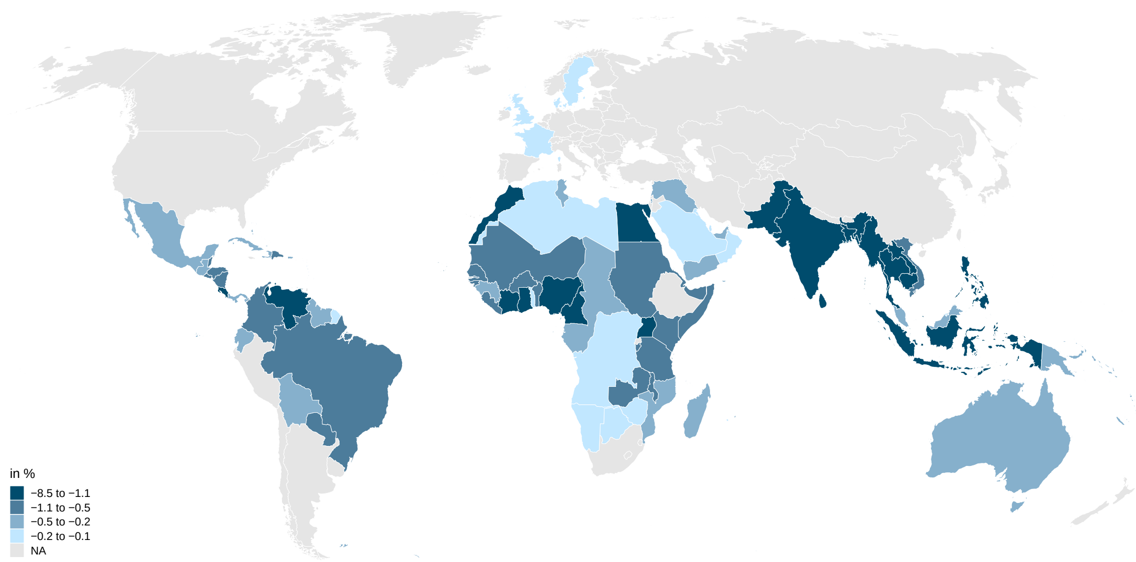


Figure 5: NTB changes in Scenario 2 under RCP 6.0.



Note: NTB change necessary to compensate climate-induced welfare losses (Scenario 1) per country. NA values indicate countries that gain welfare in Scenario 1.

Figure 6: Welfare change in Scenario 3 under RCP 6.0.