Global hunger and climate change adaptation through international trade

[manuscript accepted for publication in Nature Climate Change pending on editorial adjustments]

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Abstract

International trade allows to exploit regional differences in climate change impacts and is increasingly regarded as a potential adaptation mechanism. Here we focus on hunger reduction through international trade under alternative trade scenarios for a wide range of climate futures. Under current level of trade integration climate change would lead to up to 55 million people undernourished in 2050. Without adaptation through trade, global climate change impacts would increase to 73 million additional people undernourished (+33%). Reduction of tariffs, and institutional and infrastructural barriers would decrease the negative impact to 20 million (-64%). We assess trade's adaptation effect and climate-induced specialization patterns. The adaptation effect is strongest for hunger-affected import-dependent regions. In hunger-affected export-oriented regions, however, partial trade integration can lead to increased exports at the expense of domestic food availability. While trade integration is a key component of adaptation, it needs sensitive implementation to benefit all regions.

Approximately 11% of the 2017 world population or 821 million people suffered from hunger[1]. Undernourishment is increasing since 2014 due to conflict, climate variability and extremes, and is most prevalent in Sub-Saharan Africa (23.2% of population), the Caribbean (16.5%) and Southern Asia (14.8%)[1]. Climate change is projected to raise agricultural prices[2] and to expose an additional 77 million people to hunger risks by 2050[3], thereby jeopardizing the UN Sustainable Development Goal to end global hunger[4]. Adaptation policies to safeguard food security range from new crop varieties and climate-smart farming, to reallocation of agricultural production[2,5].

International trade can be an important adaptation mechanism[6,7]. Trade links food-deficit and -surplus countries and raises consumption possibilities through specialization according to comparative advantage. Climate change affects regions and crops differently[8], possibly shifting regional comparative advantages and altering trade patterns. Studies report that restricting trade exacerbates the impact of climate change on agricultural production, while liberalizing trade alleviates it[9–14]. The current literature is, however, incomplete in its scenario design and does not comprehensively assess whether, and if so why, the role of trade becomes larger under climate change (see Method and Supplementary Text). The 'Adaptation Illusion Hypothesis' argues that many farm practices are wrongly identified as adaptation because they have equal beneficial impacts with or without climate change[15,16]. We investigate the case of adaptation through trade, and reveal whether climate change alters the pattern of comparative advantage and increases the impact of trade integration on hunger. With the emerging integration between climate and trade policy agendas[17], a better understanding is needed to guide international policies to reduce hunger.

Prevailing trade barriers may affect trade's adaptation potential. Border protection is widespread and importantly influences agri-food trade[18,19]. Despite substantial liberalization efforts under the ongoing Doha Round, tariffs remain high for agricultural products[20]. We investigate the impact of pre-Doha tariff levels as well as further liberalization of agricultural tariffs. Also other trade costs associated with infrastructure, logistics and custom procedures are high, particularly in agricultural trade and in developing countries[21]. Reducing such barriers could create larger trade gains than reductions in border protection[18]. We compare the adaptation potential of trade liberalization – through reduction of tariff barriers - and facilitation – through reduction of other trade costs.

We focus on global hunger projections towards 2050 and analyze how climate change and trade interact in their impact on hunger. Our economic (Global Biosphere Management Model, GLOBIOM) and crop (Environment Policy Integrated Model, EPIC) modeling approach (see Method) is well-established to investigate agricultural climate change impacts[22–25]. We advance on current literature by analyzing 60 integrated scenarios that capture variability in trade barriers and in climate projections originating from general circulation models (GCMs), emissions scenarios (RCPs – Representative Concentration Pathways), and assumptions about CO_2 fertilization. Through statistical analyses on the scenario sample we assess if, where and how climate change influences the effect of trade on the risk of hunger.

The adaptive effect of international trade on global hunger

Building on Baker et al.[24], we use ten climate change and six trade scenarios, and analyze hunger effects at global and regional level. Four RCPs (2.6 Wm^{-2}, 4.5 Wm^{-2}, 6.0 Wm^{-2}, and 8.5 Wm^{-2}) are projected by HadGEM2-ES. RCP8.5 is also implemented with 4 alternative climate models (GFDL-ESM2M, NorESM1-M, IPSL-CM5A-LR, and MIROC-ESM-CHEM). RCP2.6 represents climate stabilization at 2°C, while RCP8.5 represents a likely temperature range of 2.6°C to 4.8°C[26]. We compare strongest climate change impacts (RCP8.5) with intermediate climate scenarios (RCP2.6 to RCP6.0). EPIC projects yields for climatic conditions of each RCP x GCM combination including CO_2 fertilization, which are compared to yields without climate change impacts (No CC). RCP8.5 x HadGEM2-ES is also run without CO_2 fertilization effects, representing the worst possible outcome. Our approach follows the ISI-MIP (www.isimip.org) Fast Track Protocol, which considers scenarios with CO_2 fertilization as the default, and priorities RCP8.5

x HadGEM2-ES for CO_2 sensitivity analyses. We provide a complete CO_2 sensitivity analysis across RCPs in the Supplementary Text. In the *Baseline trade* scenario, trade barriers are kept constant at 2010 level, but trade patterns vary endogenously across different climate impact scenarios. The *Fixed imports* scenario prevents agricultural imports from exceeding levels from the No CC scenario. The *Pre-Doha tariffs* scenario represents the trade environment before global trade liberalization launched by the Doha Round. In the *Facilitation* scenario, additional costs from expanding trade volume beyond the current level (e.g. infrastructure costs) are set close to zero. Under the *Tariff elimination* scenario agricultural tariffs are progressively phased out from -25% in 2020, to -100% in 2050. The *Facilitation + Tariff elimination* scenario combines previous two scenarios. Socioeconomic developments are modelled with the second Shared Socio-Economic Pathway (SSP2)[27]. The scenarios are further discussed in Method.

Through adjustments in trade, supply and demand, the 2050 global population at risk of hunger under climate change and trade scenarios deviates substantially from the SSP2 baseline (*Baseline trade* + No CC) (Fig. 1). Lower trade costs reduce importer prices, increase traded quantities, and/or increase exporter prices, while lower climate-induced crop yields increase prices. On the supply side, this influences the optimal land allocation within each pixel in terms of land cover, crop and management system. On the demand side, regions determine the optimal level of consumption and trade of each product in response to new price levels. Within-country distributional impacts of price changes through agricultural income effects are not considered (see Method). In *Baseline trade*, price changes across RCP8.5 scenarios lead to a reduction in global food availability of -0.2% to -3% compared to the baseline. The corresponding hunger effects are large: an additional 7 to 55 million people are projected to become undernourished (+6% to +45%). Across RCP8.5 scenarios, global cropland area changes by -2% to +3% and the share of irrigated area increases by 1% to 7%. Total agricultural trade volume increases by 1% to 7% across RCP8.5 scenarios through an expansion at intensive and extensive margin (new flows representing 1% to 3% of total trade volume) (Supplementary Table 1). Hunger impacts under intermediate climate change range from a reduction of 1 million to an increase of 14 million undernourished. In RCP2.6 undernourishment is lower than in No CC because crop yields in several regions increase or remain unaffected partly due to the CO_2 fertilization effect (Extended Data Fig. 1 and Supplementary Fig.12). When adaptation through trade is constrained in *Fixed imports*, hunger exacerbates across all RCP8.5 scenarios, up to an additional 73 million undernourished compared to the baseline (+60%). By preventing endogenous market responses to climate change, *Fixed imports* results in lower global crop production efficiency (-1% to -2.5%), lower global food availability (-10 to -37 kcal/cap/day), and higher agricultural prices (+2% to +17%) across RCP8.5 scenarios compared to *Baseline trade* (Supplementary Table 2). *Pre-Doha tariffs* lead to up to 81 million additional undernourished compared to baseline (+67%), highlighting the importance of trade integration already achieved through the Doha Round in alleviating the potential long-term impacts of climate change on hunger.

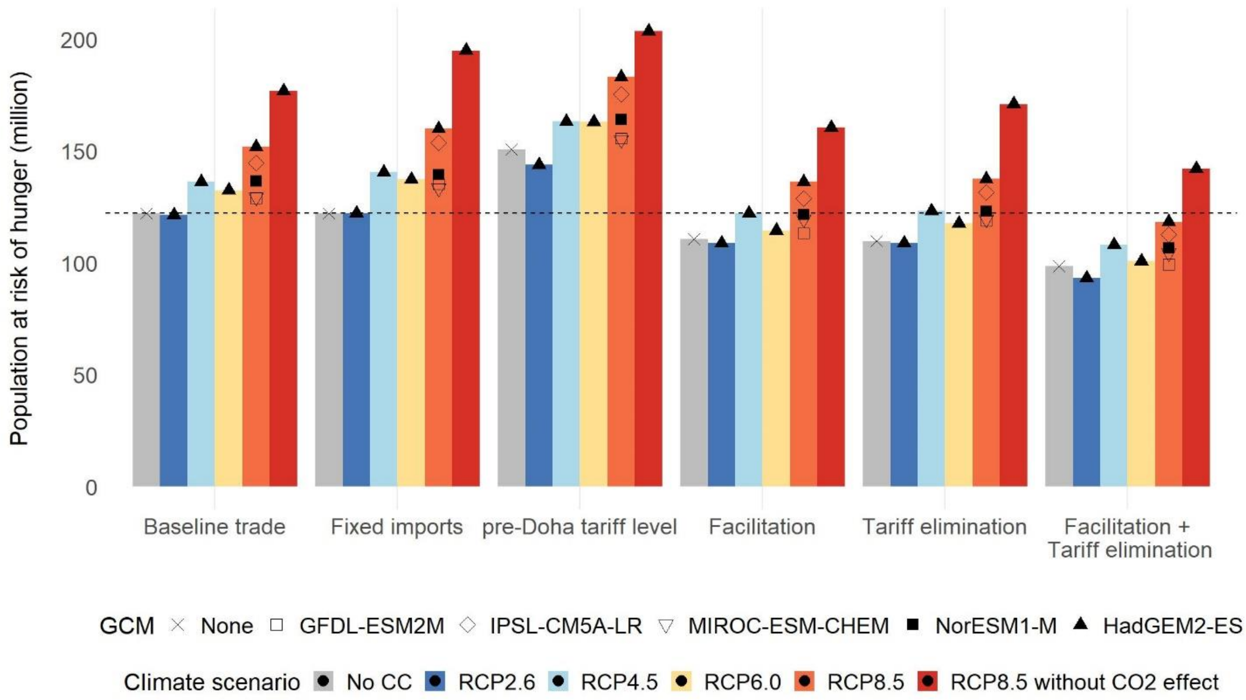

Fig. 1 | Global population at risk of hunger (million) in 2050 across climate change and trade scenarios. Climate change scenarios include the effect of CO_2 fertilization on crop yields. RCP8.5 is implemented with and without the CO_2 effect. The black dotted horizontal line indicates the population at risk of hunger in the SSP2 baseline (122 million).

Facilitation and *Tariff elimination* reduce the global risk of hunger from climate change to a comparable extent, and *Facilitation + Tariff elimination* can even compensate the impact of all but the most extreme climate change scenario. Trade liberalization and facilitation reduce hunger by enhancing climate-induced trade adjustments – total agricultural trade increases by 166% to 262% across RCP8.5 scenarios – by reducing agricultural prices, and by increasing food availability and crop production efficiency (Supplementary Table 1 and 2). The hunger effect under extreme climate change (RCP8.5 without CO_2 effect) is reduced by 31% under *Facilitation*, 11% under *Tariff elimination* and 64% under *Facilitation + Tariff elimination.* These effects are in line with other studies reporting 44% lower hunger effects under market integration[13] and 46% lower price effects under trade liberalization[10] (Supplementary Fig. 5).

Regional perspective on climate change, hunger and trade

The hunger outcomes of climate and trade scenarios differ substantially among the hunger-affected regions (Fig. 2). Climate change has little impact on regions facing positive or small negative crop yield impacts (CSI, MNA) or maintaining a high crop yield (LAC) (Extended Data Fig. 1 for average crop yield, Supplementary Fig. 1 – 4 for four main crops). Regions with negative impacts on medium crop yields face larger hunger impacts (EAS, SEA). SAS and SSA face the most severe hunger impacts from climate change. They experience negative impacts on already low yields, also when including the impact of supply-side adaptation on yields (Extended Data Fig. 2). Across RCP8.5 scenarios, projections for *Baseline trade* range from a 13% to 181% and 2% to 51% increase in population at risk of hunger for SAS and SSA. The effect of trade scenarios on regional undernourishment is largest among baseline net importing regions (SSA, MNA, EAS, SAS) and regions where climate change reduces net exports (SEA) (Extended Data Fig. 3 and 4). *Fixed imports* enlarges hunger impacts in the extreme climate change scenario in SSA, SAS and SEA by raising agricultural prices (Extended Data Fig. 5 and 6), increasing net exports in SEA, and reducing net imports in SSA and SAS. Adverse effects from trade restriction such as the export bans observed during the 2007-2008 world food crisis[28,29] and feared as a result of the global COVID-19 pandemic[30,31], may pose severe hunger risks under climate change. Under *Pre-Doha tariffs* undernourishment in SSA, SAS and EAS is substantially higher compared to *Baseline trade*. Tariff liberalization between 2001 and 2010 reduced average import tariffs in SSA, SAS and EAS by around 30% (Supplementary Table 6). The lower tariffs reduce the overall level of trade costs by 2050 (Supplementary Table 7) and allow for larger agricultural net imports in SSA, SAS and EAS across all climate scenarios (Extended Data Fig. 3). In MNA the average import tariff reduced marginally and in SEA it was already low (Supplementary Table 6). *Facilitation and Tariff elimination* reduces hunger in SSA, MNA, and EAS across all climate scenarios by lowering average trade costs (Supplementary Table 7), thereby reducing agricultural prices and raising agricultural imports (Extended Data Fig. 3 and 5). In some cases trade integration increases rather than reduces a region's undernourishment under climate change. The largest adverse effects occur under *Tariff elimination* in SEA and SAS (Extended Data Fig. 7). While *Facilitation* reduces hunger in the extreme climate change scenario by 16% and 8%, *Tariff elimination* increases hunger impacts by 4% and 16% in SEA and SAS, respectively. Both trade scenarios reduce average trade costs (Supplementary Table 7), but tariff elimination increases rice exports from SAS and SEA, thereby reducing domestic calorie availability. *Facilitation and Tariff elimination* compensates calorie loss from rice exports through increased imports of other agricultural goods and lowers the hunger effect of extreme climate change by 26% and 11% in SEA and SAS. Our sensitivity analysis shows that the effects of trade on climate-induced hunger are robust to CO_2 fertilization assumptions (Supplementary Fig. 13 & 14).

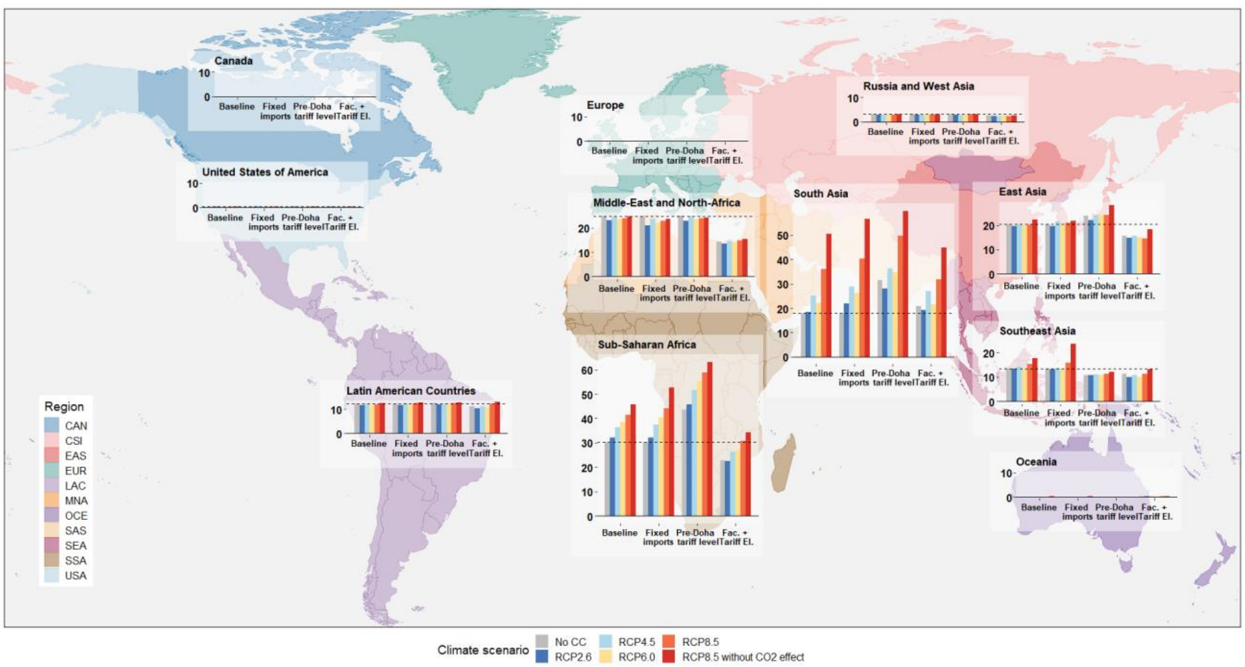

Fig. 2 | Population at risk of hunger in 2050 (million) across climate change and trade scenarios in each region. Only results from the GCM HadGEM2-ES are shown – see Extended Data Fig. 7 for full scenario set. Regions are United States of America (USA), Russia and West Asia (CSI), East Asia (EAS), Southeast Asia (SEA), South Asia (SAS), Middle-East and North-Africa (MNA), Sub-Saharan Africa (SSA), Latin American Countries (LAC), Oceania (OCE), Canada (CAN) and Europe (EUR). The black dotted horizontal lines indicate the population at risk of hunger in the SSP2 baseline.

A larger role for trade under climate change?

To reveal whether the effect of trade enlarges under climate change and thus plays a real adaptation role, we analyze hunger outcomes from GLOBIOM on crop yield shifts projected by EPIC and average trade costs in regional level regression models (Table 1). We interpret these results for a 5.4% reduction in crop yields and a 23% reduction in average trade costs, which correspond to average impacts of climate change and trade integration scenarios, respectively. Regression results reveal that a 5.4% reduction in crop yields within a region leads to an average food availability reduction of 11 kcal/cap/day (95% confidence interval (CI), 15 – 8 kcal/cap/day) and an additional 0.52 million people at risk of hunger (CI, 0.25 – 0.79 million). For a 23% decrease in trade costs, we project an increase in average food availability within a region by 13 kcal/cap/day (CI, 9 – 16 kcal/cap/day) and a reduction of 1.22 million people undernourished (CI, 1.52 – 0.93 million). When excluding regions that experience negative impacts in some trade scenarios (SAS, SEA), we find a significant negative interaction effect between trade costs and crop yields. For example, under extreme climate change (i.e. a 20% crop yield reduction), the positive effect of a 23% reduction in trade costs is 1.97 million fewer people undernourished, consisting of a direct (-1.50 million) and a climate-induced trade effect (-0.47 million). These results confirm the existence of positive trade effects on food availability and hunger alleviation[13,32] and reveal an additional climate-induced effect of lowering trade costs.

Table 1 | Results from OLS estimation of the impact of crop yields, trade costs and their interaction on regional hunger and food availability. Observations are GLOBIOM output for the 11 world regions under five different trade scenarios (Baseline, pre-Doha tariffs, Facilitation, Tariff elimination, and Facilitation + Tariff elimination) and ten climate change scenarios in 2050. The regression models are described in Method.

	Population at risk of hunger (million)				Food availability (kcal/cap/day)			
sample	*(1) all regions*		*(2) without SAS and SEA*		*(1) all regions*		*(2) without SAS and SEA*	
Crop yield	-9.70	***	-1.80		213.00	***	173.00	***
(% change)	(2.60)		(1.40)		(29.00)		(31.00)	
Trade cost (log	4.70	***	5.80	***	-49.00	***	-80.00	***
of US$/$10^6$ kcal)	(0.58)		(0.73)		(7.40)		(9.40)	
Crop yield x	3.30		-8.90	**	14.00		191.00	***
Trade cost	(6.20)		(3.60)		(60.00)		(74.00)	

Significance levels: *p<0.1; **p<0.05; ***p<0.01. Regional fixed effects included. Heteroskedastic robust standard errors in brackets. N = 550 for (1) and 450 for (2). Adjusted R squared is 0.890 (1) and 0.930 (2) for hunger regressions and 0.950 (1) and 0.920 (2) for food availability regressions.

We run the regressions presented in Table 1 with regional interaction effects (Supplementary Table 3). In most regions, climate-induced decreases in crop yields reduce food availability and increase hunger while reduced trade costs have opposite effects. The food availability impacts of crop yield changes are largest for SAS, SSA and SEA, while the effect of trade costs is largest for regions maintaining net imports under climate change (SSA, MNA and EAS). The corresponding impact on hunger is largest in low-income regions (SSA and SAS), followed by middle-income regions (EAS, MNA, and SEA). The interaction effect, which reveals if climate change alters the relation between trade costs and hunger, is most pronounced in SSA, followed by EAS. Fig. 3 plots the predicted hunger-yield relationship in EAS and SSA for different trade cost levels, illustrating that hunger is less sensitive to climate-induced yield changes under reduced trade costs.

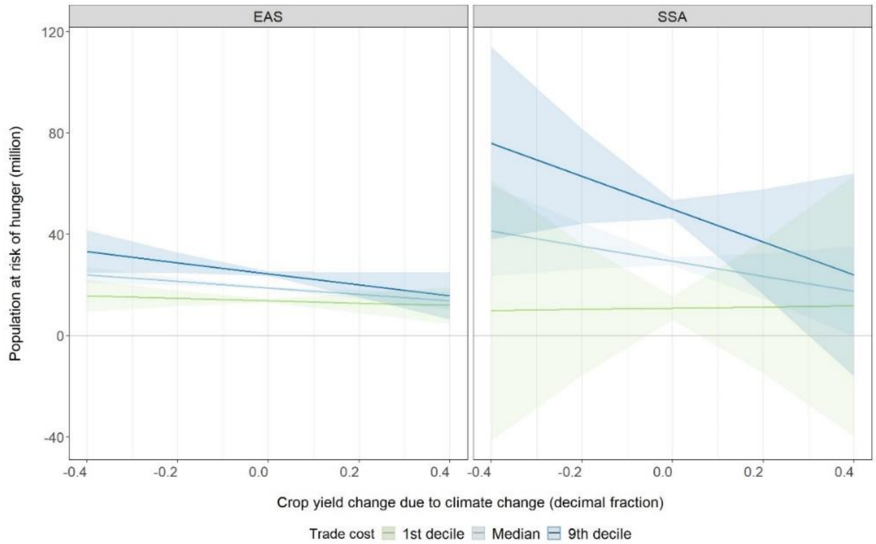

Fig. 3 | Fitted linear response of population at risk of hunger (million) to climate-induced crop yield change in EAS and SSA for different values of trade costs (1st decile, median, 9th decile). Shaded areas indicate prediction intervals. Prediction based on an OLS estimation of the regional level linear regression of the impact of crop yield change, trade costs and their interaction on population at risk of hunger. Regression results are shown in Supplementary Table 3 and the regression model is described in Method. Extended Data Fig. 8 presents the fitted response for all regions.

Inter-regional specialization

In Fig. 4 we assess to what extent climate change shifts the pattern of comparative advantage of four important crops (corn, wheat, soya, and rice). In line with Ricardo's theory, a region is regarded as having a comparative advantage when it specializes in a certain crop, such that its share of world production increases when trade costs decrease (see Method and Supplementary Text). Under no climate change, trade integration increases the global production share of USA in corn, LAC in soya, CSI, EUR and LAC in wheat, and SAS and EAS in rice (Fig. 4a). Trade integration has similar impacts on specialization under climate change (Fig. 4b). Fig. 4c compares regions' specialization in response to trade cost reduction, with negative values indicating reductions and positive values gains in comparative advantage under climate change compared to no climate change. For example, MNA still decreases its share of global wheat production in response to trade integration under climate change, but to a lesser extent than under no climate change. The small and mainly insignificant values indicate that the pattern of comparative advantage of the four crops remains similar under climate change. While climate change affects crop yields and cost competitiveness of regions, it does not radically alter the relative position between regions (Supplementary Fig. 8 - 10). Results on crop shares in a region's total production, export shares in a region's crop production, and revealed comparative advantage corroborate this finding (Supplementary Fig. 6, 7 and 11).

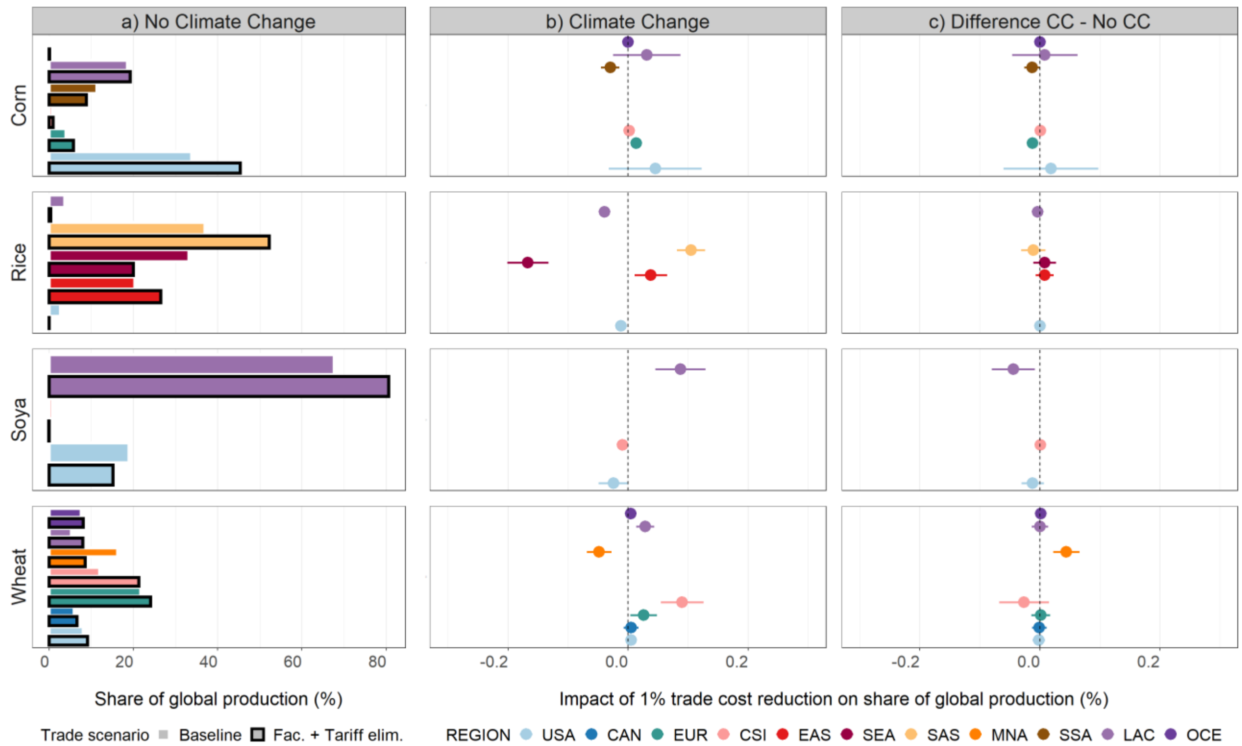

Fig. 4 | Inter-regional specialization in corn, rice, soya, and wheat in response to trade cost reduction in 2050. a) presents the share of global production under no climate change in *Baseline trade* and *Facilitation + Tariff Elimination*. In **b)** each point shows the estimated impact of a 1% trade cost reduction for each region on share of world production in percentage, with lines denoting the corresponding 95% confidence interval (heteroskedastic robust standard errors). Idem for **c)**, except that the outcome variable is the difference in share of world production compared to no climate change. Regression models are described in Method.

Adaptation to climate change occurs through changes in existing and new inter-regional trade flows (Supplementary Tables 8 - 11). Across RCP8.5 scenarios, the largest export growth originates from major baseline producing regions (corn from USA and LAC, soya from LAC and USA, rice from SAS and SEA, and wheat from EUR and CAN, Supplementary Fig. 9). The largest new trade flows are new corn exports from

USA to EAS, CAN, LAC, and SEA, from EUR to MNA and from LAC to EAS; new soya exports from LAC to SAS and from USA to CAN and MNA; and new wheat exports from CSI to EUR, and from MNA to SSA. Climate change does not induce substantial new rice trade flows. There is uncertainty across RCP8.5 scenarios in bilateral trade patterns, but several exports to hunger-affected regions increase consistently (e.g. wheat from EUR to SSA, soya from LAC to SAS, or corn from LAC to MNA). Hunger-affected regions are, however, not only engaging in trade at the importer side, but also increase certain exports (wheat in MNA, corn in SSA, and rice in EAS and SAS) (Extended Data Fig. 10).

Discussion

International trade contributes globally to climate change adaptation. The impact of worst climate change on global risk of hunger increases by 33% to 47% under restricted trade scenarios, and decreases by 11% to 64% under open trade scenarios. The gain from reducing trade costs is largest for regions that remain import-dependent under climate change. Climate change increases the role of trade in reducing the risk of hunger for some regions, although it does not substantially alter the pattern of comparative advantage of main staple crops. It is the ability to link food surplus with deficit regions that underpins trade's adaptation effect. These conclusions are robust across RCPs, and independent from the assumption on CO_2 fertilization effects. Lastly we find that the number of undernourished increases with climate change, irrespective of trade scenarios. Climate change mitigation thus remains crucial for hunger eradication.

Our study is comprehensive in its scenario design and rigorous in its analysis of the processes driving adaptation through trade. Nevertheless, it is important to stress that the focus of this study is global and long term. Trade policies and climate change have important within-country distributional consequences through income and food access effects[33–35], which are theoretically ambiguous and which our modelling approach does not consider. Across households with different food access channels, from urban net-consumers to rural subsistence farmers, impacts can differ even in their direction[34]. Also, current global studies, including ours, focus on crop and grass yield impacts, and other direct and indirect climate change effects are so far not represented, e.g. heat stress on animals, pest and disease incidence, sea level rise or reduced pollination. Finally, we take a long-term equilibrium perspective ignoring the negative effects of extreme weather events. All these aspects require substantial new research.

Albeit the limitations mentioned above, our study brings novel policy implications. We find that liberalization already achieved under the Doha Round substantially reduces climate-induced hunger impacts. A careful approach to trade integration covering different types of trade barriers can further limit hunger risks. The full removal of agricultural tariffs leads to increases in food availability in SSA, MNA and EAS, but may increase exports and lower regional food availability in SEA and SAS. Further trade facilitation can reduce undernourishment in all hunger-affected regions. The effective realization of trade facilitation requires, however, considerable investments in transport infrastructure and technology. Especially in low-income regions, like SSA, infrastructure is weak[36]. An estimated $130 – 170 billion a year is needed to bridge the infrastructure gap in SSA by 2025[37]. Infrastructure finance averaged 75$ billion in recent years, with largest contribution from budget constrained national governments[37]. Alternative financing through institutional and private investments, called for by the African Development Bank Group and the World Bank Group[36,37], could be not only crucial for economic growth, but for climate change adaptation as well. In essence, our results demonstrate that trade instruments can mitigate an important part of the adverse hunger effects of long-term climate change. Our results thereby endorse the importance of holistic approaches to international trade negotiations, and could prove also relevant in the face of trade policy reactions in more acute crisis situations, such the global COVID-19 pandemic.

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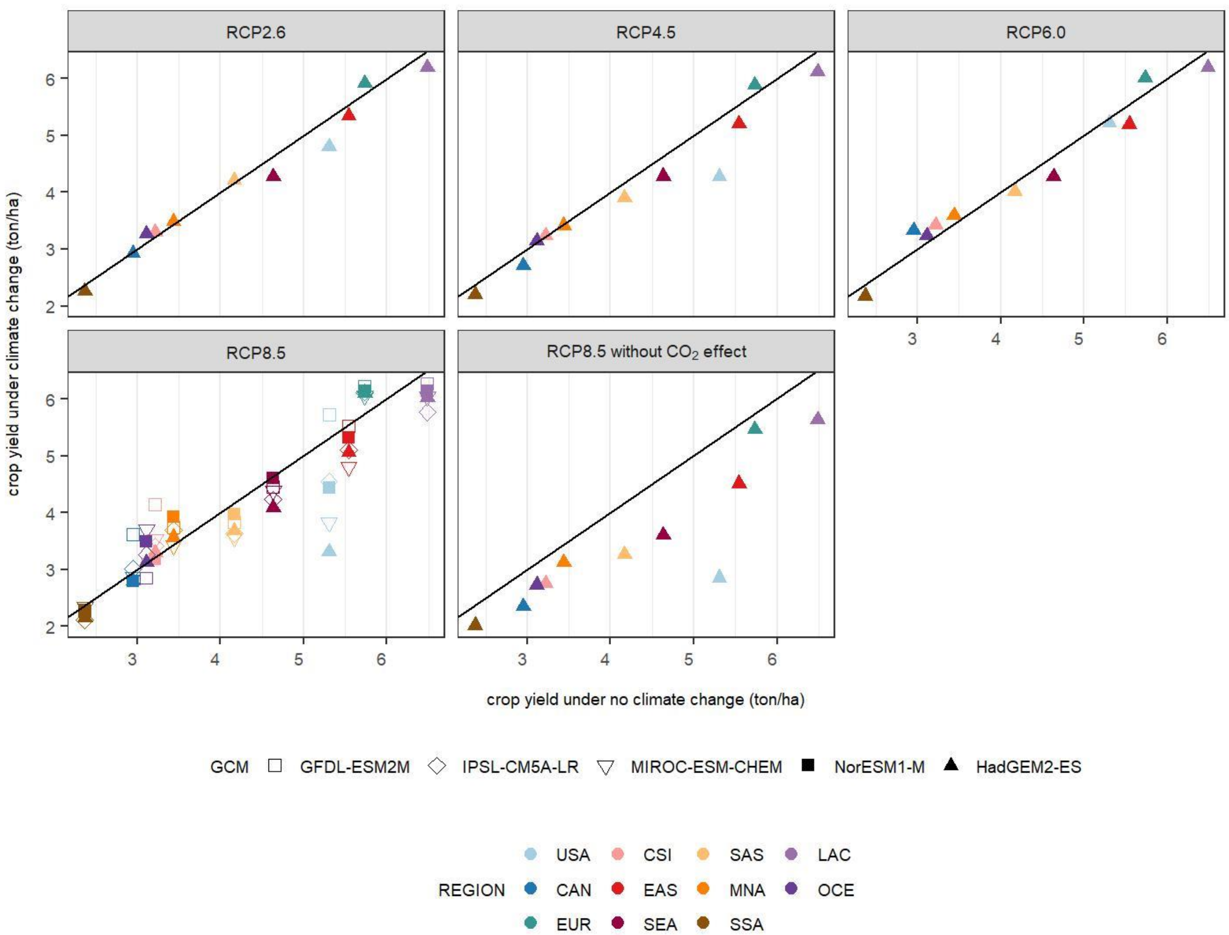
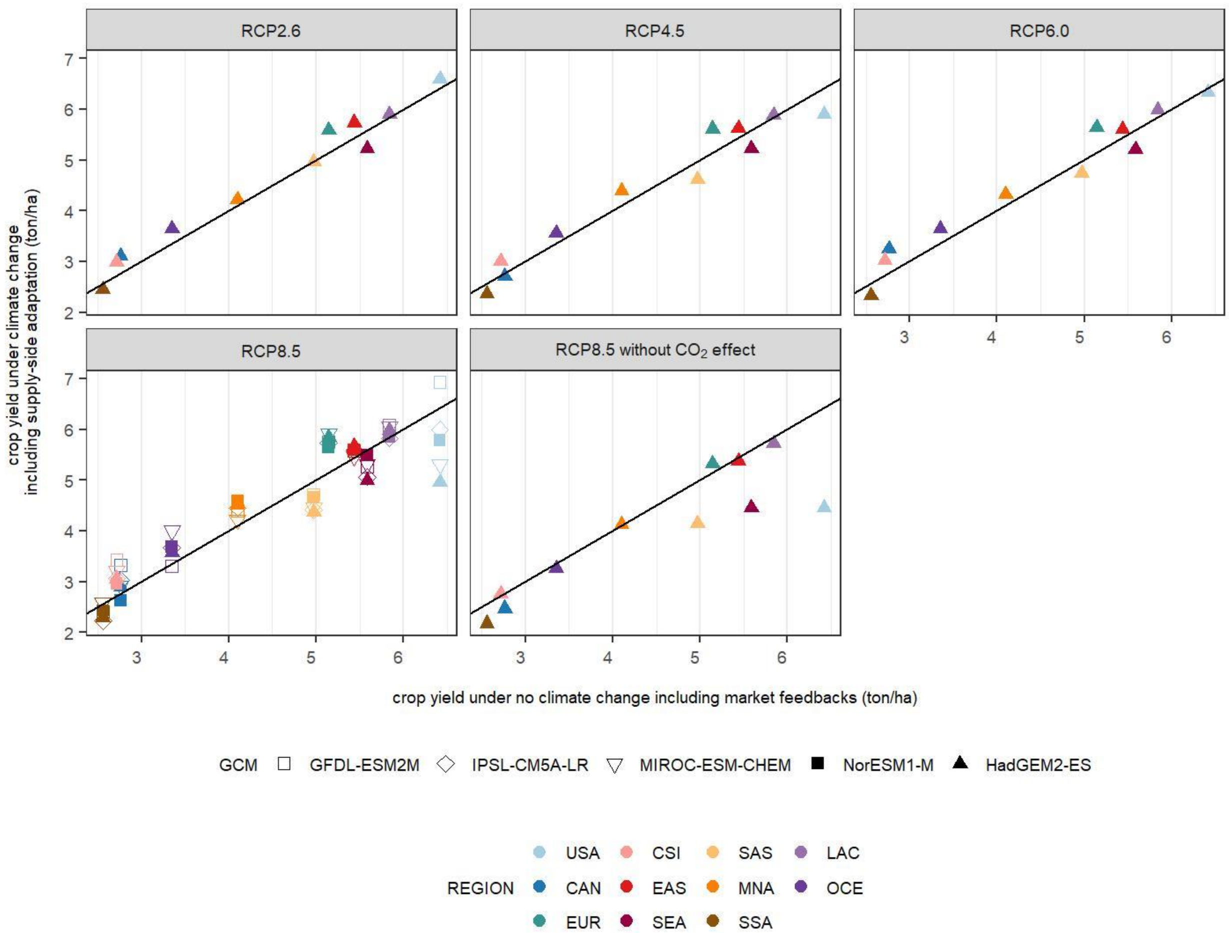
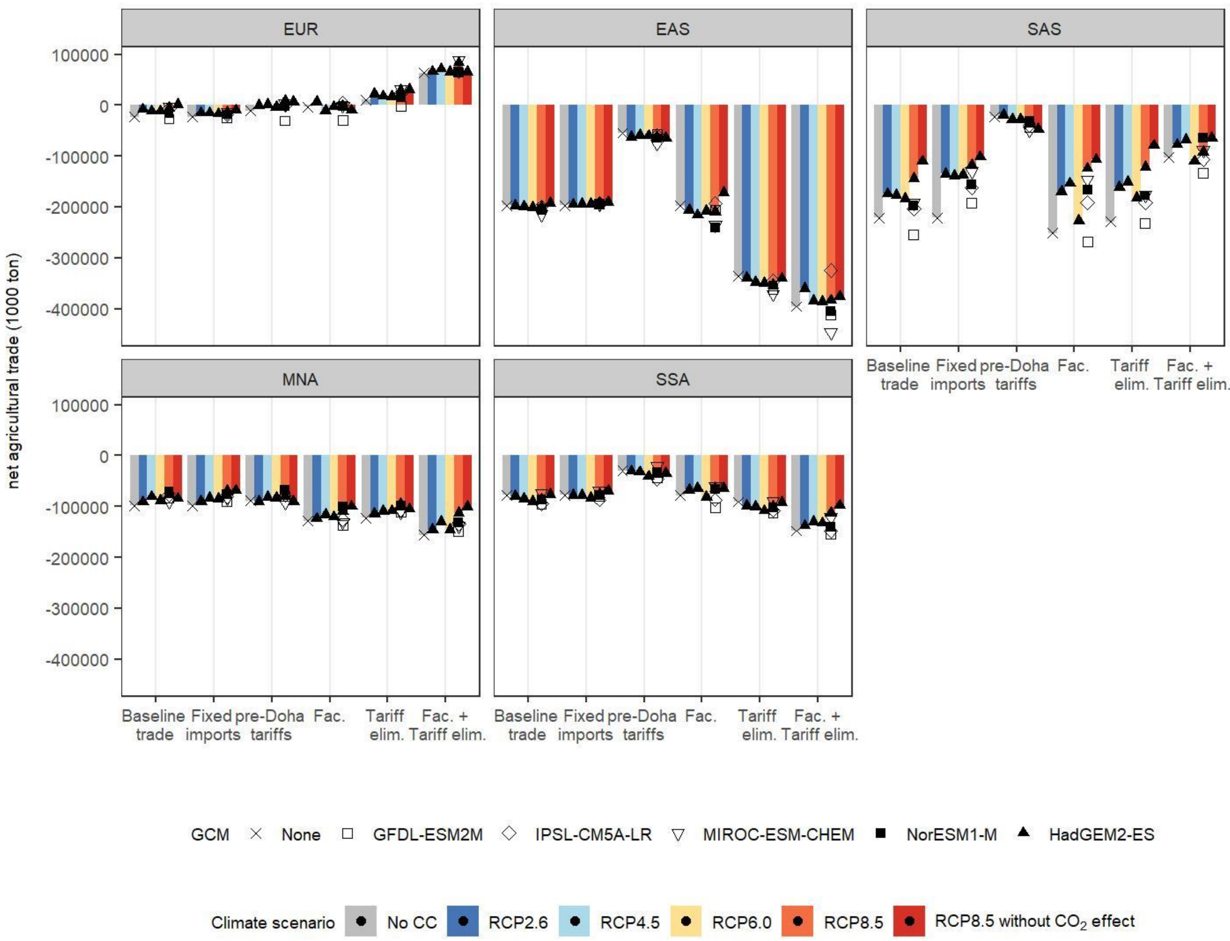
Extended Data



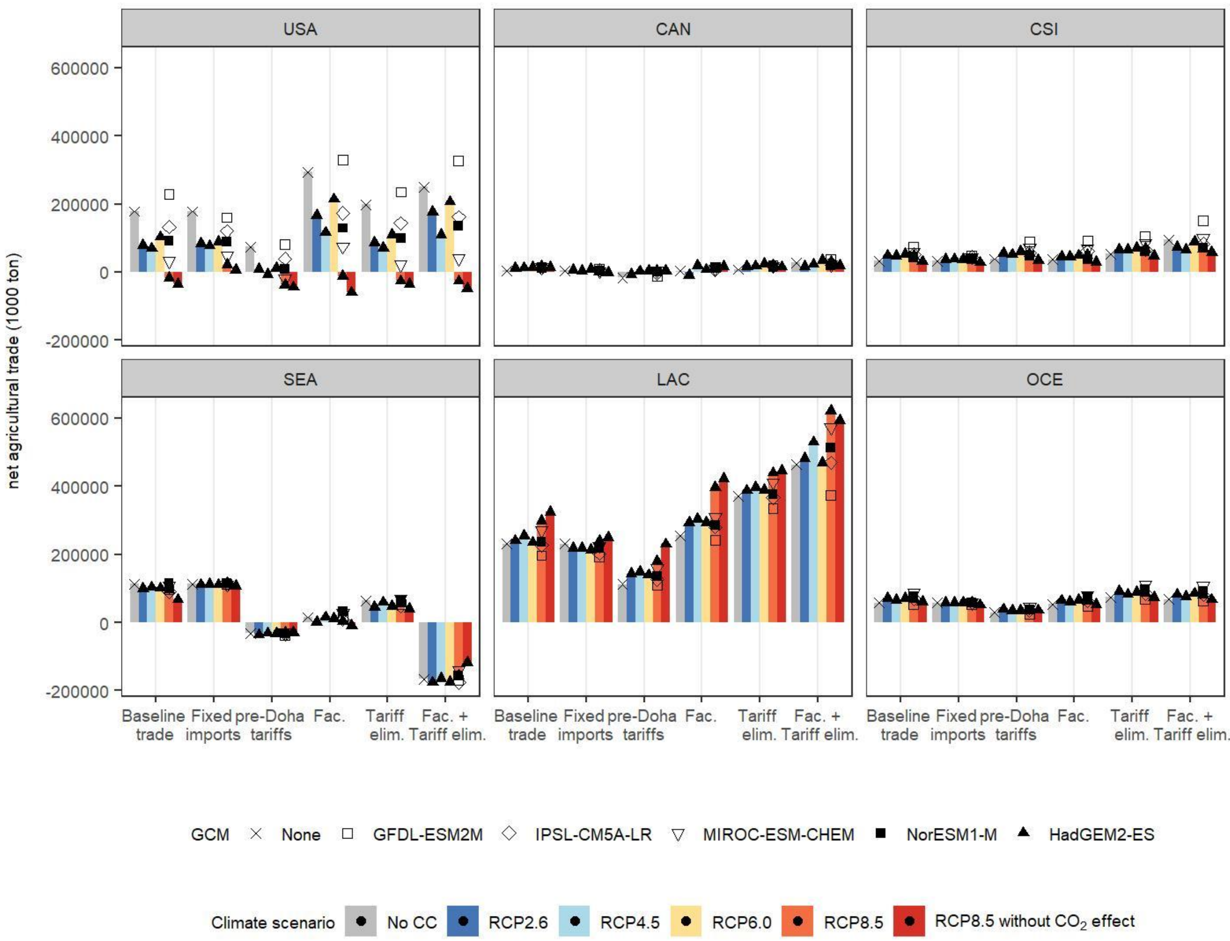
ED Fig. 1 | Biophysical impact of climate change on average crop yield in each region by 2050 as projected by the EPIC crop model. Yields in ton dry matter per ha. The x-axis indicates the crop yield under no climate change and y-axis the crop yield under climate change for different RCP x GCM combinations without market feedback and adaptation measures. Under no climate change yields are determined by base year yield and assumptions on technological development over time, under climate change an additional climate impact shifter is applied. Points above the black line indicate an increase in crop yield, points below a decrease in crop yield.



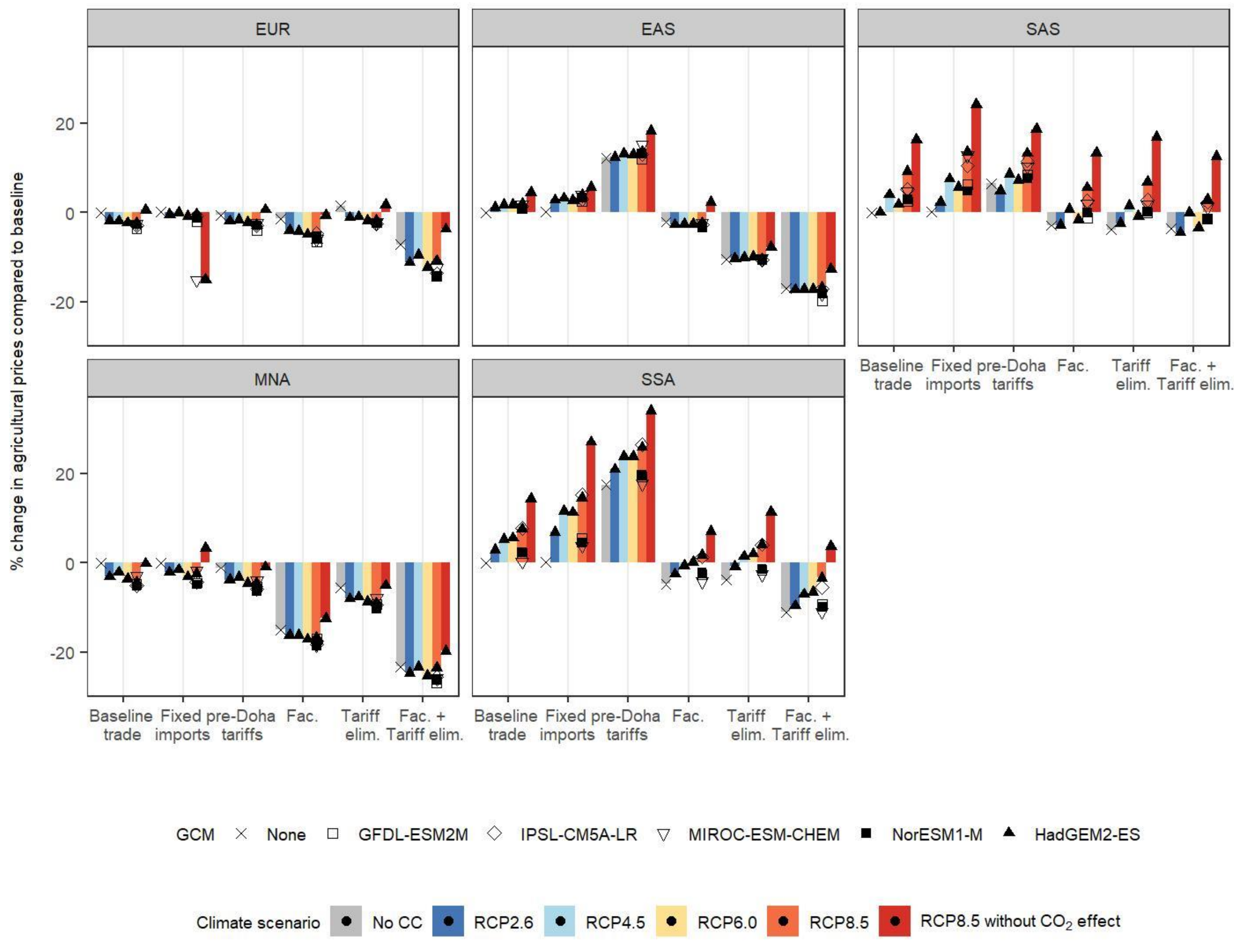
ED Fig. 2 | Impact of climate change on average crop yield after supply-side adaptation in each region by 2050 as projected by GLOBIOM. Yields in ton dry matter per ha. The x-axis indicates the crop yield under no climate change and y-axis the crop yield under climate change for different RCP x GCM combinations with GLOBIOM market feedback and supply-side adaptation (changes in management system and reallocation of production across spatial units in response to price changes). Points above the black line indicate an increase in crop yield, points below a decrease in crop yield.



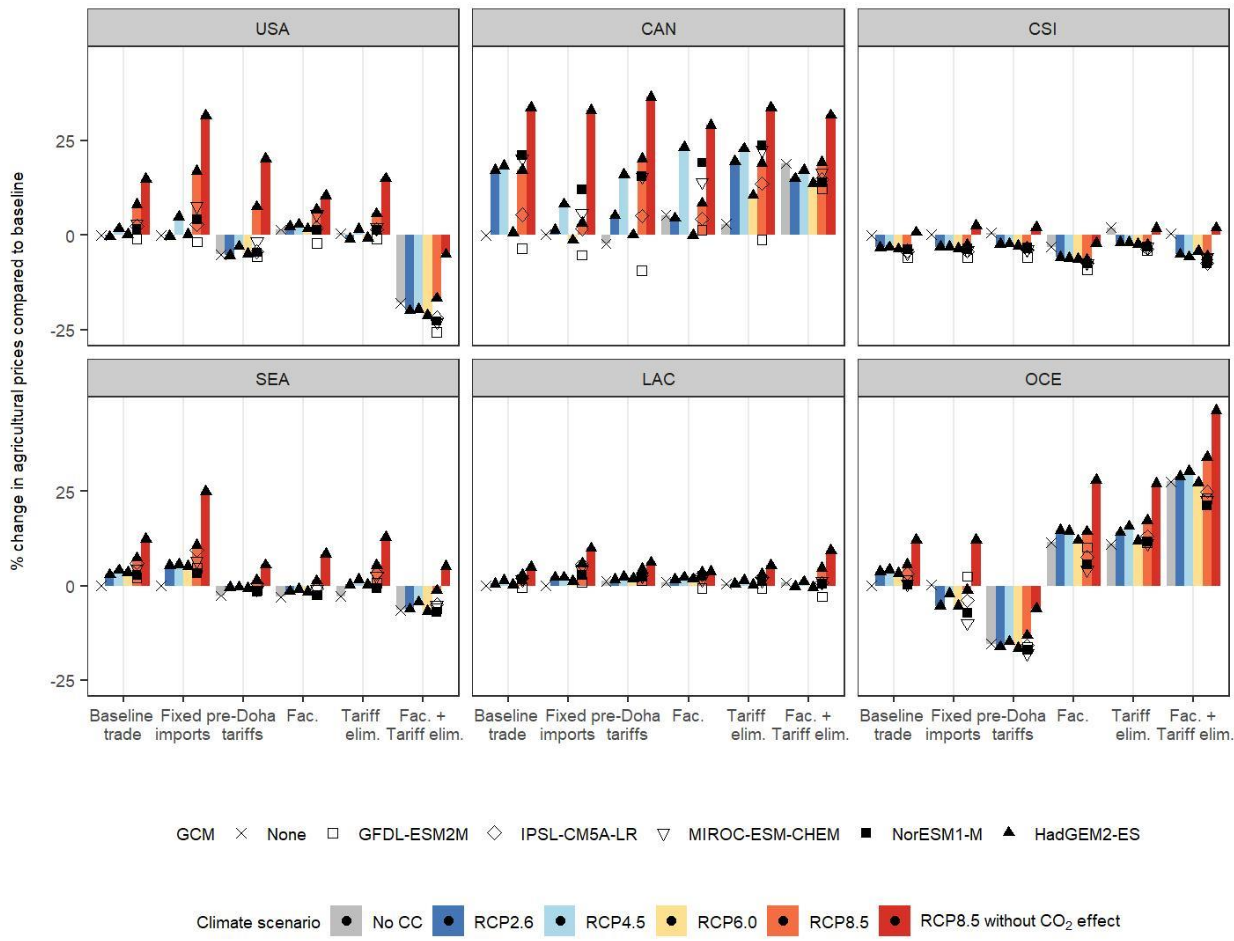
ED Fig. 3 | Net agricultural trade of baseline net importing regions in 2050 under trade and climate change scenarios. Net agricultural trade in ton dry matter. Fac. = Facilitation, Tariff elim. = Tariff elimination.



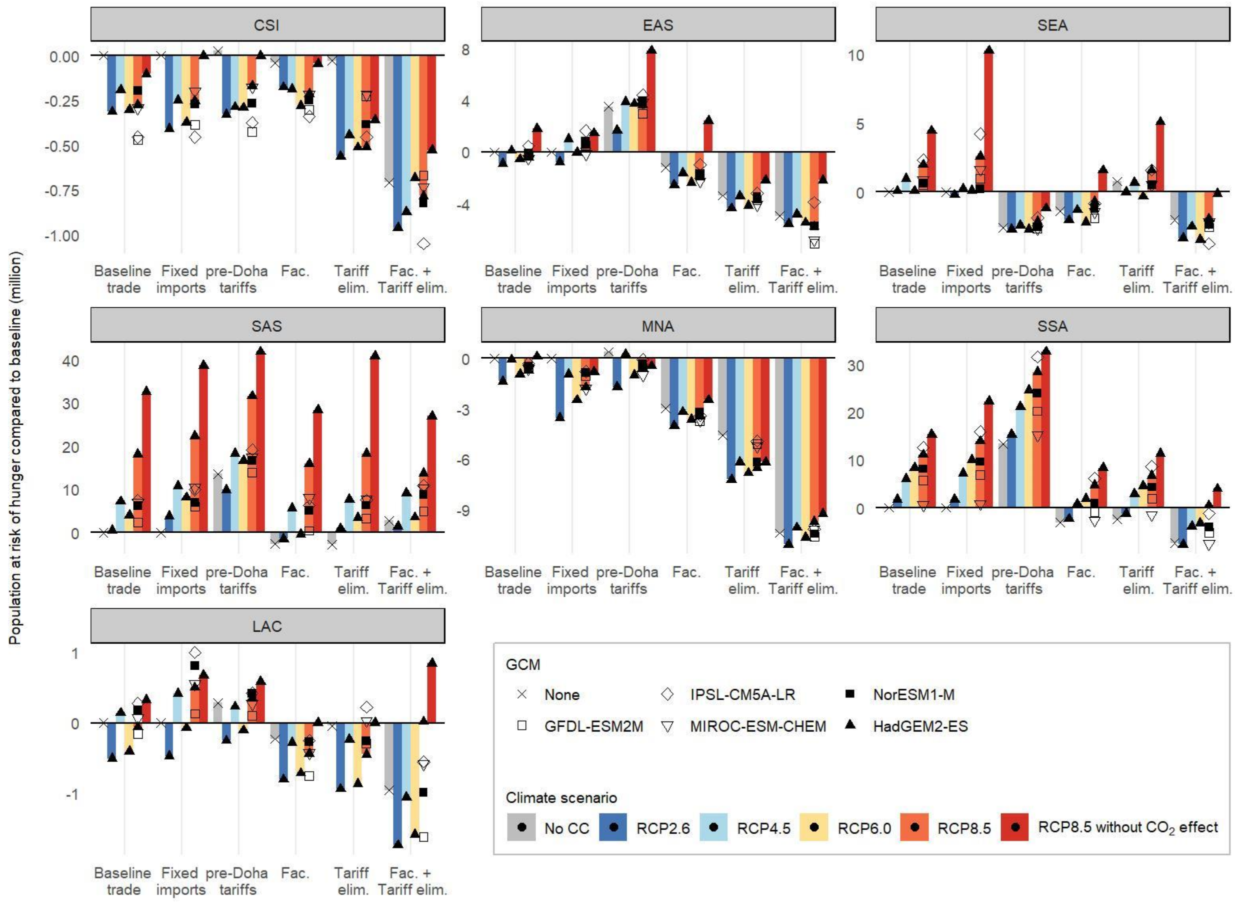
ED Fig. 4 | Net agricultural trade of baseline net exporting regions in 2050 under trade and climate change scenarios. Net agricultural trade in ton dry matter. Fac. = Facilitation, Tariff elim. = Tariff elimination.



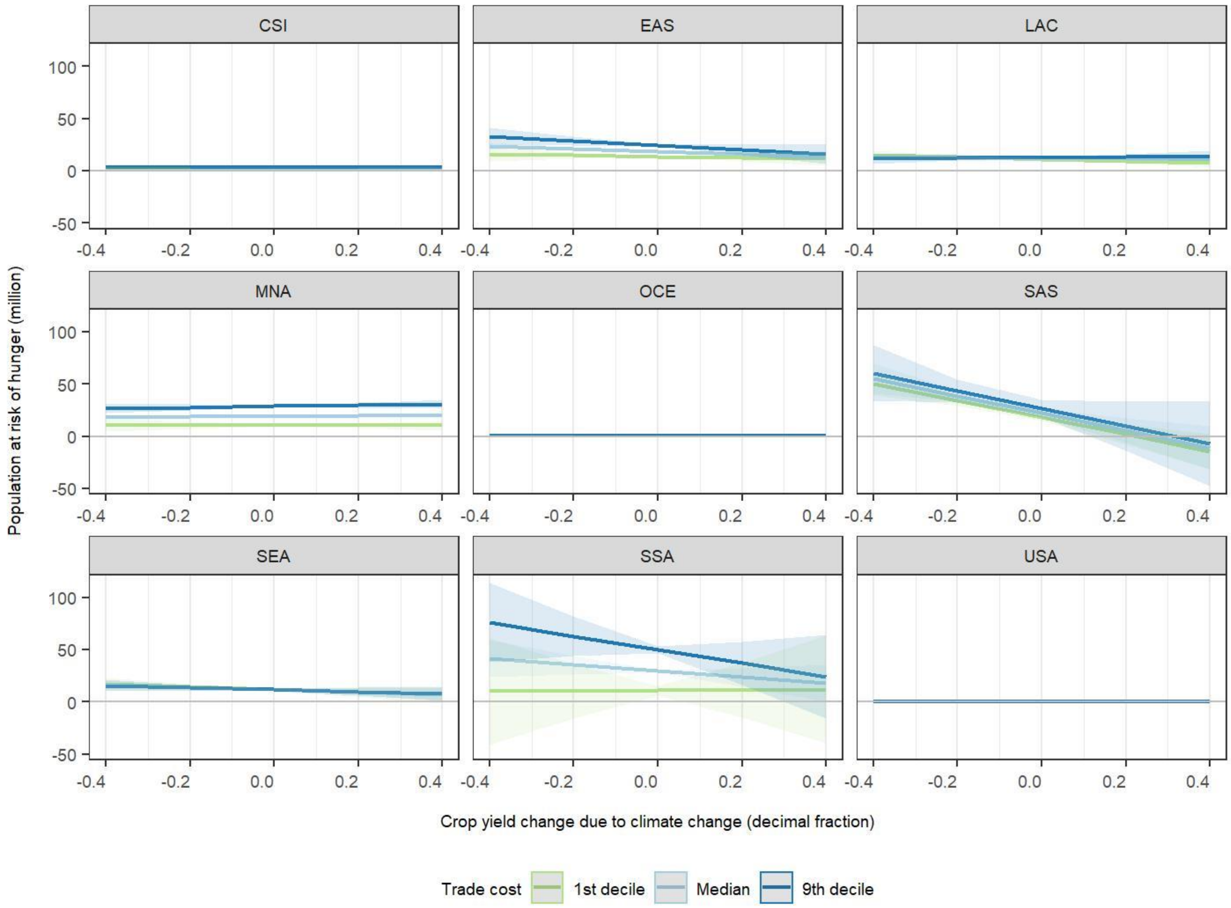
ED Fig. 5 | Change in agricultural prices of baseline net importing regions in 2050 under trade and climate change scenarios compared to SSP2 baseline. Fac. = Facilitation, Tariff elim. = Tariff elimination.



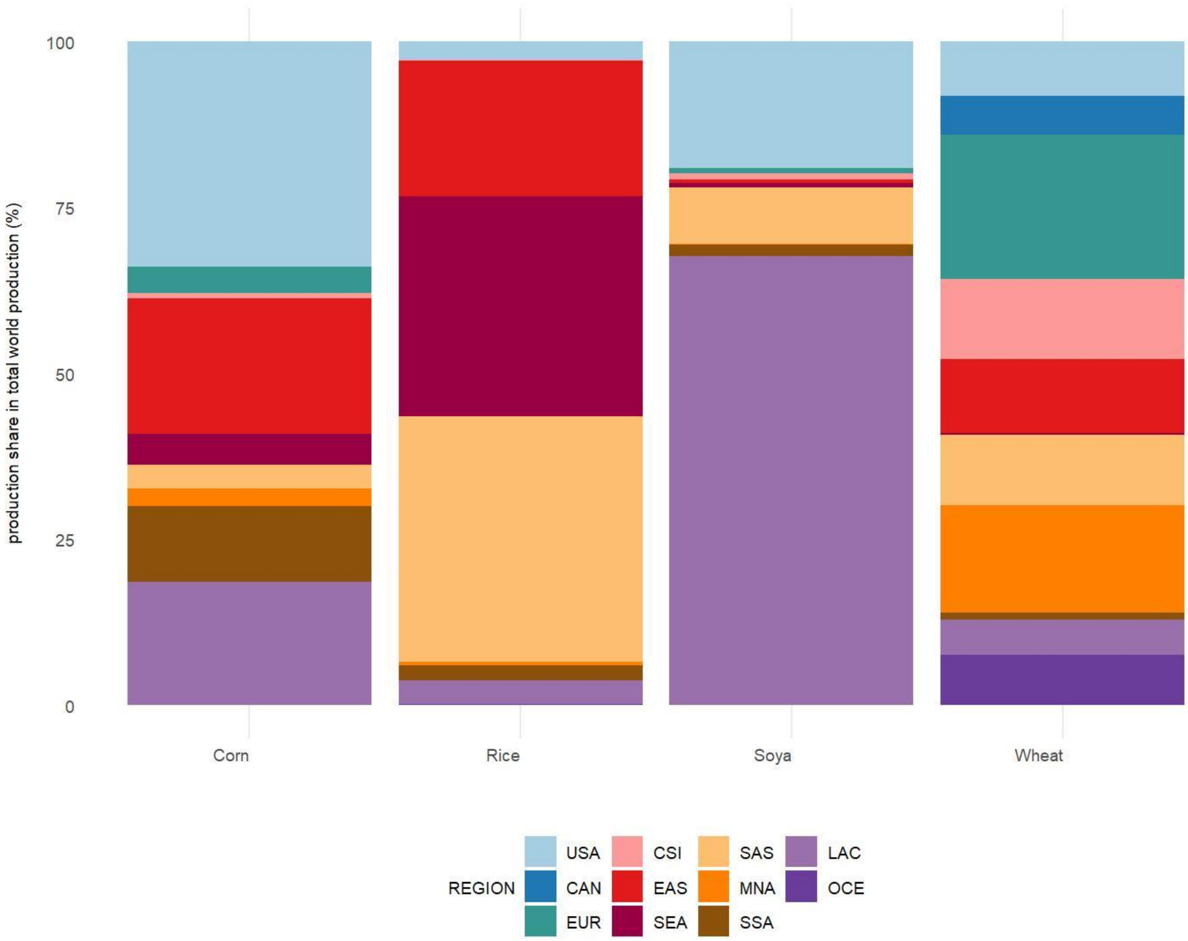
ED Fig. 6 |Change in agricultural prices of baseline net exporting regions in 2050 under trade and climate change scenarios compared to SSP2 baseline. Fac. = Facilitation, Tariff elim. = Tariff elimination.



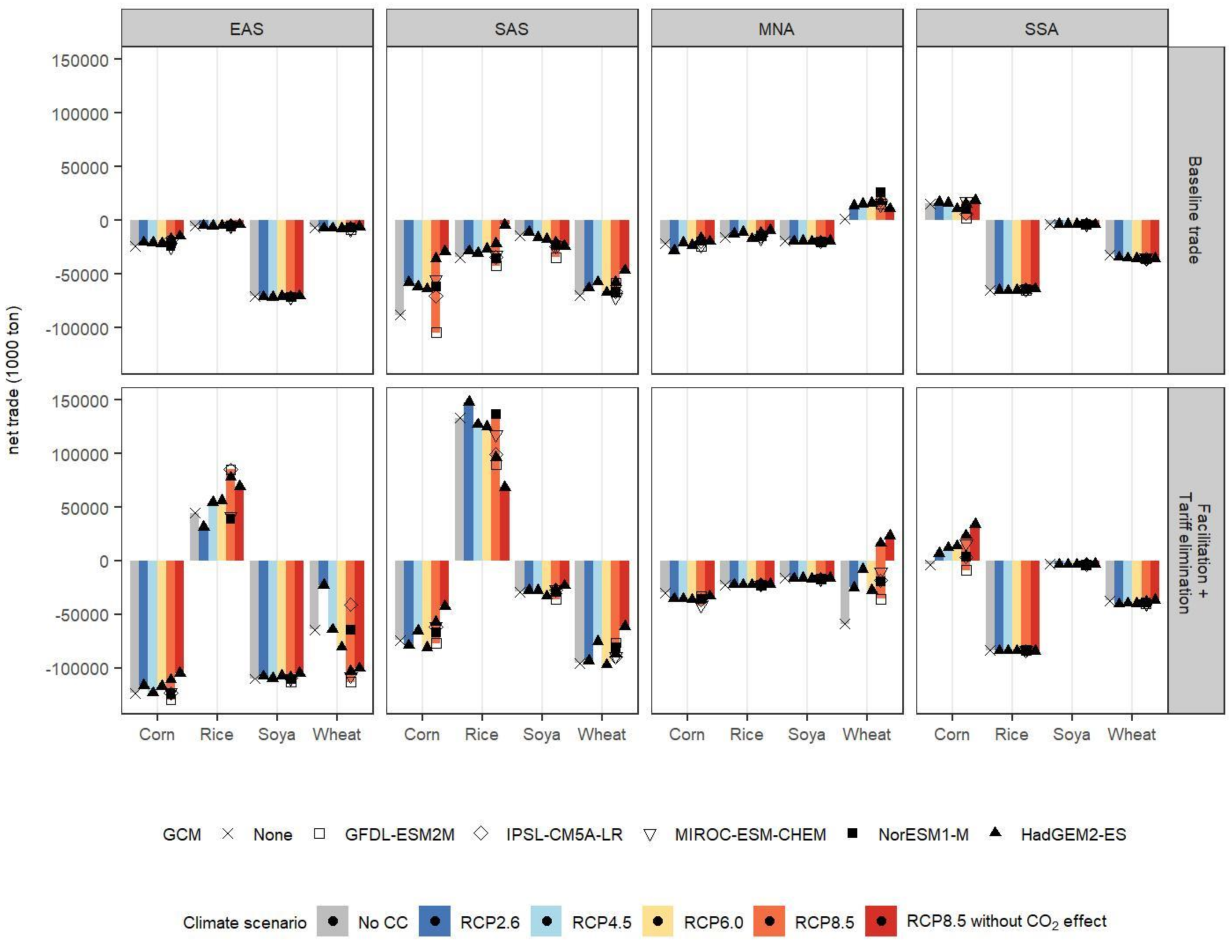
ED Fig. 7 | Change in population at risk of hunger in 2050 in hunger-affected regions under climate change and trade scenarios compared to SSP2 baseline. Fac. = Facilitation, Tariff elim. = Tariff elimination.



ED Fig. 8 | Plot of the fitted linear response of population at risk of hunger (million) to climate-induced crop yield change for different values of trade costs (1st decile, median, 9th decile). Shaded areas indicate prediction intervals. Prediction based on an OLS estimation of a regional level linear regression of the impact of crop yield change, trade costs and their interaction on population at risk of hunger. Regression results are shown in Supplementary Table 3 and the regression model is described in Method.



ED Fig. 9 | Share of production volume that each region represents of total world production for corn, rice, soya and wheat in the SSP2 baseline in 2050. The projected total world production by 2050 in the SSP2 baseline is 1213 Mt for corn, 884 Mt for rice, 309 Mt for soya and 794 Mt for wheat.



ED Fig. 10 | Net trade (1000 ton) in East Asia (EAS), Middle East and North Africa (MNA), South Asia (SAS) and Sub-Saharan Africa (SSA) for corn, rice, soya and wheat under climate change and trade scenarios in 2050. Net agricultural trade in ton dry matter. Values above zero indicate net exports, negative values indicate net imports.

Method

Modelling framework We use the Global Biosphere Management Model (GLOBIOM), a recursive dynamic, spatially explicit, economic partial equilibrium model of the agriculture, forestry and bioenergy sector with bilateral trade flows and costs, which can model new trade patterns[38]. The model computes a market equilibrium in 10-year time steps from 2000 to 2050 by maximizing welfare (the sum of consumer and producer surplus) subject to technological, resource and political constraints. In each time step, market prices adjust endogenously to equalize supply and demand for each product and region. On the demand side, a representative consumer for each of 30 economic regions optimizes consumption and trade in response to product prices and income. Food demand depends endogenously on product prices via an iso-elastic demand function and exogenously on GDP and population projections[39]. We mainly present model results aggregated to 11 regions (Supplementary Table 4): United States of America (USA), Canada (CAN), Europe (EUR), Oceania (OCE), Southeast Asia (SEA), South Asia (SAS), Sub-Saharan Africa (SSA), Middle-East and North-Africa (MNA), East Asia (EAS), Russia and West Asia (CSI) and Latin American Countries (LAC). GLOBIOM is a bottom-up model building on a high spatial grid-level resolution on the supply side. Land is disaggregated into Simulation Units, clusters of 5 arcmin pixels which are aggregated based on altitude, slope and soil class, 30 arcmin pixel, and country boundaries. GLOBIOM's crop production sector includes 18 major crops (barley, beans, cassava, chickpeas, corn, cotton, groundnut, millet, palm oil, potato, rapeseed, rice, soybean, sorghum, sugarcane, sunflower, sweet potato, wheat) under 4 management systems (irrigated – high input, rainfed – high input, rainfed – low input, and subsistence). The allocation of acreage by crop and management system is determined by potential yields, production costs and expansion constraints[23]. Crop production parameters are based on the detailed biophysical crop model EPIC. Additional biophysical models are used to represent the livestock [RUMINANT – Herrero et al.[40]] and forestry [G4M

– Forsell et al.[41]] sectors. Further information on model structure and parameters is documented in Havlík et al.[42,43].

As a partial equilibrium model, GLOBIOM focuses only on specific sectors of the economy and does not represent feedbacks on consumer income and GDP from trade and climate change. Yet, the partial equilibrium model allows for more detail in represented sectors, and a more accurate assessment of biophysical impacts. This because of high spatial and commodity resolution and physical instead of monetary representation of variables, compared to general equilibrium models which explicitly cover income feedbacks. Crop yields adjust endogenously through the management system or location of production, and exogenously according to long-term technological development and climate change impacts[23]. Output from EPIC is used to compute in each time step yield shifters for each climate change scenario and each crop and management system at a disaggregated spatial scale (Simulation Unit). EPIC simulates scenario-specific yields based on inputs from climate models (daily climatic conditions including solar radiation, min and max temperature, precipitation, wind speed, relative humidity, and CO_2 concentration). Climate change impacts on livestock production are modelled through crop and grassland yield impacts on feed availability. EPIC crop and grassland yield impacts, and their implementation in GLOBIOM, are further explained in Leclère et al.[23] and Baker et al.[24].

International trade International trade is represented in GLOBIOM through Enke-Samuelson-Takayama-Judge spatial equilibrium assuming homogenous goods[38,44]. Bilateral trade flows between the 30 economic regions are determined by the initial trade pattern, relative production costs of regions, and the minimization of trading costs[38]. The initial trade pattern is informed by the BACI database from CEPII averaging across 1998 – 2002[45]. Trade costs are composed of tariffs from the MAcMap-HS6 database[46], transport costs[47] and a non-linear trade expansion cost. The MAcMap-HS6 2001 release from CEPII-ITC provides ad valorem and specific tariffs, and shadow tariff rates of tariff rate quotas for the model calibration in the base year 2000[48]. To incorporate trade liberalization developments under the Doha

Round, the tariff data is updated in the 2010 time step with the 2010 release of MAcMap-HS6[49] (Supplementary Table 6). We use the estimation from Hummels (2001) to compile input data on bilateral transport costs based on the distance between trade pairs and the weight-value ratio of agricultural products. Transport costs are set to 30 USD/ton minimum, based on the 5th percentile of the OECD Maritime Transport Cost database (2003 – 2007), and are kept constant at base year level over the simulation period as the drivers of transport costs (e.g. fuel prices, containerization[50]) are not represented in the partial equilibrium model. In the scenario simulations, the non-linear expansion cost raises per unit trade costs when traded quantity increases over time to model persistency in trade flows. A constant elasticity function is used for trade flows observed in the base year, and a quadratic function for new trade flows. The non-linear element reflects the cost of trade expansion in terms of infrastructure and capacity constraints in the transport sector and is reset after each 10 year time step. Compared to other global economic models, GLOBIOM's trade representation is positioned between the rigid Armington approach of general equilibrium models and the flexible world pool market approach of many partial equilibrium models.

Risk of hunger We measure the population at risk of hunger, or the number of people whose food availability falls below the mean minimum dietary energy requirement, based on Hasegawa et al.[51–53]. Four parameters are used: the mean minimum dietary energy requirement (MDER), the coefficient of variation (CV) of the distribution of food within a country, the mean food availability in the country (kcal per capita per day), and total population. Minimum dietary energy requirements are exogenously calculated based on demographic composition (age, sex) of future population projections. Future changes in the inequality of food distribution within a country are exogenous and follow projected national income growth. This is based on an estimated relationship between income and the CV of food distribution with observed historical national-level data. Poor infrastructure, remoteness and a high prevalence of subsistence farming limit local markets in distributing food equally across households[7].

Income is lowest in SAS and SSA, regions where the share of land under subsistence farming is the largest (27% in SAS and 43% in SSA)[54]. Food availability in kcal per capita per day is endogenously determined by GLOBIOM at the regional level. One limitation of the approach is that it does not include within-country distributional consequences of trade integration and/or climate change through income effects. Trade policies and climate change alter food prices, which affects individual incomes, purchasing power and food access depending on households being net-consumers or net-producers of food[33]. At the aggregate regional level, the bias from not considering these distributional effects may be upward or downward, depending on the share of net-consuming vs. net-producing households, degree of subsistence farming vs. agricultural wage work, and share of rural vs. urban population in each country.

Climate change adaptation Climate change adaptation is defined by the IPCC as "*The process of adjustment to actual or expected climate and its effects*"[26]. Adaptation of the agricultural sector to climate-induced changes in crop yields may include adjustments in consumption, production and international trade[2]. Demand-side adaptation is captured in GLOBIOM by changes in regional consumption levels in response to market prices. Supply-side adaptation includes the reallocation of land for each crop by grid-cell and management system, and the expansion of cropland to other land covers[23]. Whereas Leclère et al.[23] assess supply-side adaptation, this study focuses on international market responses, where our analysis approach is inspired by the 'Adaptation illusion Hypothesis' postulated by Lobell[15] and confirmed by Moore et al.[55]. They argue that farm-level practices identified as adaptation measures by many crop modelling studies, cannot be referred to as *climate adaptation* as they have the same yield impact in current climate as under climate change. In a similar fashion, we intend to investigate whether, where, and if so, why, trade integration has a larger positive impact on the risk of hunger under climate change. We define the adaptation effect of trade as the sum of the effect of reducing trade costs on hunger under current climate (direct trade effect), and any additional positive or negative impact of trade integration under climate change (climate-induced trade effect).

The **adaptation effect of trade** can be understood through Ricardo's theory of comparative advantage (see also Supplementary Text)[11,12]. Reducing trade costs promotes trade according to comparative advantage[56] and facilitates the role of trade as a transmission belt in linking food deficit and food surplus regions[57]. Climate change impacts differ across crops and regions[8]. Depending on the spatial distribution of these impacts, the current pattern of comparative advantage may be intensified, maintained or radically altered. This may lead to increased food deficits in certain regions. Trade is argued to have a larger role under climate change as it facilitates adjustment to changes in comparative advantage[11,12] and allows to link food surplus with food deficit regions[6,7,57].

Scenario design Our choice of climate change scenarios is determined by the ISI-MIP Fast Track Protocol used by crop modelers to calculate crop and grass yield impacts[8,58]. We use all four representative concentration pathways (RCPs) that reflect increasing levels of radiative forcing by 2100 (2.6 Wm^{-2} scenario, 4.5 Wm^{-2} scenario, 6 Wm^{-2} scenario and 8.5 Wm^{-2} scenario)[59] as projected by the HadGEM2-ES general circulation model (GCM)[60,61]. RCP8.5 is implemented with 4 additional GCMs to reflect uncertainty in climate models: GFDL-ESM2M[62], IPSL-CM5A-LR[63], MIROC-ESM-CHEM[64], and NorESM1-M[65]. RCP2.6 represents climate stabilization at 2°C and RCP8.5 a temperature range of 2.6°C to 4.8°C[26]. Yield impacts are based on simulations from the crop model EPIC[23,24]. Each RCP x GCM combination is modelled including CO_2 fertilization effects. RCP8.5 x HadGEM2-ES is additionally simulated without the CO_2 effect, which reflects the most severe climate change scenario. These scenarios represent the Tier 1 set of ISI-MIP scenarios and climate change impacts are simulated individually for all 18 GLOBIOM crops, except for oil palm, and for grasslands. Scenarios without CO_2 fertilization for other RCPs than RCP8.5 were considered of secondary importance in the ISI-MIP Fast Track – and in the latest simulation protocol for ISI-MIP 3b – and thus were available only for four main crops (corn, rice, soya, wheat). We carry out a comprehensive sensitivity analysis with respect to the CO_2 fertilization effect for all RCPs, however, as this requires extrapolating climate change impacts from the four crops to the other crops, and thus would introduce inconsistency with the Tier 1 scenarios, the analysis is presented separately in Supplementary Text. In the scenario with no climate change (No CC) exogenous yield change originates only from long-term technological development assumptions.

We implement six trade scenarios to analyze the role of trade in climate change adaptation. The first scenario, *Fixed imports*, limits imports to the level observed in the No CC scenario or less. This represents restricting trade flow adjustments in response to climate change, or limiting trade as an adaptation mechanism. The second scenario, *Pre-Doha tariffs,* excludes the tariff update in 2010, representing the trade environment before global trade liberalization launched by the Doha Round (see Supplementary Table 6 for comparison of average tariff rates). We additionally implement three trade integration scenarios to assess promotion of the trade adaptation mechanism. In the first scenario, *Facilitation,* the non-linear part of trade costs is set close to zero from 2020 onwards, following Baker et al.[24]. This reflects the impact of reducing transaction costs, infrastructure costs and other institutional barriers limiting the expansion of trade[1]. The per unit transport costs are kept constant at the base year level. In the second scenario, *Tariff elimination*, all agricultural tariffs are progressively phased out between 2020 and 2050, i.e. -25% in 2020, -50% in 2030, -75% in 2040 and -100% in 2050. This scenario leads to a 70% growth in total agricultural trade (Supplementary Table 1), comparable in magnitude to the agricultural import (+36%) and export (+60%) growth under tariff liberalization reported by Anderson and Martin[66]. The last one, *Facilitation + Tariff elimination,* is a combination of the previous two and presents the most extensive open trade scenario. In the *Baseline trade* scenario trade barriers

[1] Trade facilitation is defined by the WTO as the "*simplification of trade procedures*"[71]. In economic literature it refers to the reduction of trade transaction costs that are determined by the efficiency of customs procedures, infrastructure services, domestic regulations etc. [18,71]. Other trade costs that are relevant in agricultural trade are non-tariff measures (NTMs). UNCTAD defines NTMs as *"all policy-related trade costs incurred from production to final consumer, with the exclusion of tariffs"* [72]. Typical examples of NTMs are technical measures such as sanitary and phytosanitary measures (SPS), and price and quantity control measures such as quotas and subsidies. Some studies include also the above mentioned transaction costs in the category of non-tariff measures (NTMs)[73,74], while others make the explicit distinction[18,75].

are kept constant at 2010 levels, but trade patterns vary endogenously across the different climate impact scenarios. Supplementary Table 7 provides a comparison of average trade costs across the different scenarios.

Socioeconomic developments are modelled according to the second Shared Socio-Economic Pathway (SSP2), which reflects a 'Middle of the Road' scenario where population reaches 9.2 billion by 2050 and income grows according to historical trends in each region[27]. The technological development assumed by SSP2 leads to an increase in global average crop yields of 66% between 2000 and 2050 (Supplementary Table 12). The SSP scenarios are widely discussed and often used as a basis for harmonizing key macroeconomic assumptions for integrated assessment modeling of different climate futures, e.g. Riahi et al.[67]. SSP2 projects a decrease in the global population at risk of hunger from 867 million in 2000 to 122 million by 2050. This because of an increase in food consumption – global food availability increases from 2700 to 3007 kcal/cap/day – and an improved food distribution within regions, which are both related to the assumed income growth under SSP2[68]. Income projections lead to changes in food preferences. Under SSP2, the share of livestock products in diets increases globally from 16% in 2000 to 17.3% in 2050, with largest increases in Asian regions[69]. Such changes affect the baseline trade pattern: e.g. increased production and consumption of livestock products in SAS, EAS and SEA imply an increase in imports of feed crops such as corn and soya by 2050.

Statistical analysis – hunger regression We analyze the results from the scenario runs with a regional level linear regression model to infer the underlying relationship between trade costs, crop yield changes, and hunger as predicted by GLOBIOM. The following models are estimated by Ordinary Least Squares (OLS) (Table 1):

$$Population\ at\ risk\ of\ hunger_{itr} =$$

$$\beta_1^{(1)} Crop\ yield_{ir} + \beta_2^{(1)}\ Trade\ costs_{itr} + \beta_3^{(1)} Crop\ yield_{ir} *\ Trade\ costs_{itr} + \sum_i \beta_{4i}^{(1)} Region_i + \varepsilon_{itr}^{(1)}$$

$$Food\ availability_{itr} =$$

$$\beta_1^{(2)} Crop\ yield_{ir} + \beta_2^{(2)}\, Trade\ costs_{itr} + \beta_3^{(2)} Crop\ yield_{ir} *\ Trade\ costs_{itr} + \sum_i \beta_{4i}^{(2)} Region_i +\ \varepsilon_{itr}^{(2)}$$

We estimate the models also with regional interaction terms (Fig. 3 and Supplementary Table 3):

$$Population\ at\ risk\ of\ hunger_{itr} =$$

$$\sum_i \big(\beta_{1i}^{(3)} Crop\ yield_{ir} * Region_i + \beta_{2i}^{(3)}\, Trade\ costs_{itr} * Region_i + \beta_{3i}^{(3)} Crop\ yield_{ir} *\ Trade\ costs_{itr} * Region_i +\ \beta_{4i}^{(3)} Region_i\big) +\ \varepsilon_{itr}^{(3)}$$

$$Food\ availability_{itr} =$$

$$\sum_i \big(\beta_{1i}^{(4)} Crop\ yield_{ir} * Region_i + \beta_{2i}^{(4)}\, Trade\ costs_{itr} * Region_i + \beta_{3i}^{(4)} Crop\ yield_{ir} *\ Trade\ costs_{itr} * Region_i +\ \beta_{4i}^{(4)} Region_i\big) +\ \varepsilon_{itr}^{(4)}$$

Population at risk of hunger$_{itr}$ gives the number of people at risk of hunger (million) and *Food availability*$_{itr}$ the food availability (kcal/cap/day) in 2050 in each region i, trade scenario t and climate change scenario r. *Crop yield*$_{ir}$ gives the change in average crop yield (kcal/ha) compared to average crop yield in no climate change in 2050. *Trade cost*$_{itr}$ gives the log of the weighted average trade costs (US$/$10^6$ kcal) on all trade flows in 2050. To obtain a measure that reflects the implication of trade scenarios on overall trading costs, we calculate the trade-weighted average of trade costs over all agricultural imports, exports and intra-regional trade flows for each region i, trade scenario t and climate change scenario r: $average\ trade\ cost_{itr} = \sum_k \frac{x_{iktr}}{total\_x_{itr}} * trade\ cost_{iktr}$. x_{iktr} are the trade flows of crop k in, out and within region i in each scenario (t, r) and $total\_x_{itr}$ is the sum of all trade flows in, out and within region i in each scenario (t, r). The variables *Crop yield*$_{ir}$ and *Trade cost*$_{itr}$ are centered (demeaned) to solve structural multicollinearity. For the regional fixed effects ($Region_i$) dummy variables are used.

$\beta_{ki}^{(m)}$ are the slope coefficients to be estimated for variable k in regression model m (with $k = 1, \dots, 4$ and $m = 1, \dots, 4$). $\varepsilon_{itr}^{(m)}$ is an independently and identically normally distributed error term with zero mean and $\sigma_{(m)}^{2}$ variance. Standard errors are estimated robust to heteroscedasticity using the HC3 method as recommended by Long and Ervin[70][2]. The calculation of standard errors of the regional interaction effects is done with the Delta Method. The F statistic of overall significance rejects the null hypothesis at 1% significance level for all models. The sample is composed of GLOBIOM regional output under five different trade scenarios (Baseline, pre-Doha tariffs, Facilitation, Tariff elimination, and Facilitation + Tariff elimination) and ten climate change scenarios in 2050. The sample size is 550 for models with regional fixed effects [11 regions x 5 trade x 10 climate change scenarios] and 450 for models with regional interaction terms [9 regions (EUR and CAN excluded) x 5 trade x 10 climate change scenarios]. Summary statistics of all variables are shown in Supplementary Table 5.

Statistical analysis - comparative advantage To assess comparative advantage we estimate a linear regression model of the effect of trade cost reduction on the share of production of a crop that region i represents in total world production of the crop in each trade scenario t and climate change scenario r (*Share of world production$_{itr}$*); the share of each crop in a region's total crop production (*Share of regional crop production$_{itr}$*); and the share of a region's production that is exported (*Share of production exported$_{itr}$*). The following models are estimated separately for wheat, corn, rice and soya by OLS (Fig. 4 and Supplementary Fig. 16 and 17):

$$Share\ of\ world\ production_{itr} = \sum_{i} \beta_{1i}^{(5)}\, Trade\ costs_{itr} * \ Region_i \ + \ \beta_{2i}^{(5)} Region_i + \ \varepsilon_{itr}^{(5)}$$

[2] HC3 is a refined version of White's method for estimation of heteroskedastic standard errors (HC0). Long and Ervin [70] demonstrate with Monte Carlo simulations that the HC3 method outperforms HC0 for small sample sizes (N < 250).

$$Share\ of\ regional\ crop\ production_{itr} = \sum_i \beta_{1i}^{(6)}\ Trade\ costs_{itr} *\ Region_i + \beta_{2i}^{(6)} Region_i + \varepsilon_{itr}^{(6)}$$

$$Share\ of\ production\ exported_{itr} = \sum_i \beta_{1i}^{(7)}\ Trade\ costs_{itr} *\ Region_i + \beta_{2i}^{(7)} Region_i + \varepsilon_{itr}^{(7)}$$

For sub-panels b, the dependent variable is the outcome under climate change, while for sub-panels c, the dependent variable is the difference in outcome between climate change and no climate change. *Trade costs*$_{itr}$ is the log of trade-weighted average of trade costs (USD/ton) per region i, trade scenario t and climate change scenario r (Supplementary Table 7). The variable *Trade cost*$_{itr}$ is centered (demeaned) to solve structural multicollinearity. Dummy variables are used for regional fixed effects ($Region_i$). Observations are taken from the nine RCP x GCM scenarios and four trade integration scenarios (Baseline trade, Facilitation, Tariff, Facilitation + Tariff) with exclusion of regions that have a deficit production at least 90% of the trade and climate change scenarios. N is 189 for corn, 180 for rice, 98 for soya and 246 for wheat. Standard errors are estimated robust to heteroscedasticity using the HC3 method and standard errors of regional interaction effects are calculated with the Delta Method.

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Acknowledgements

We acknowledge research funding from Research Foundation Flanders (FWO) (FWO contract / 180956 / SW) and support from the US Environmental Protection Agency (EPA) (Contract BPA-12-H-0023, Call Order # EP-B15H-0143). The views and opinions expressed in this paper are those of the authors alone and do not necessarily state or reflect those of the EPA, and no official endorsement should be inferred. This paper has also received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776479 for the project CO-designing the Assessment of Climate CHange costs (https://www.coacch.eu/). We thank Houssein Guimbard and CEPII for their contribution in terms of trade policy data and are grateful to Aline Mosnier for her indispensable support in the trade modelling work prior to this study.

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Author contributions

All authors have contributed substantially to the manuscript. P.H., J.B., T.K. and C.J. developed the concept and designed scenarios. P.H., E.S., T.H., C.J. and D.L. provided code and model simulations. C.J., T.K. and P.H. have analyzed the data. C.J., P.H., T.K., J.B., and M.M. interpreted the data and wrote the manuscript, to which S.F., H.V., N.V.L., E.S., T.H., S.O., and S.R. commented.

Competing Interests Statement

The authors declare no competing interests.

Data Availability Statement

The authors declare that the main data supporting the findings of this study are available within the article and the supplementary information. Additional data are available upon request from the authors.

Code Availability Statement

Code used for the statistical analysis of the scenario data is available upon request from the authors.

Supplementary Information

Global hunger and climate change adaptation through international trade

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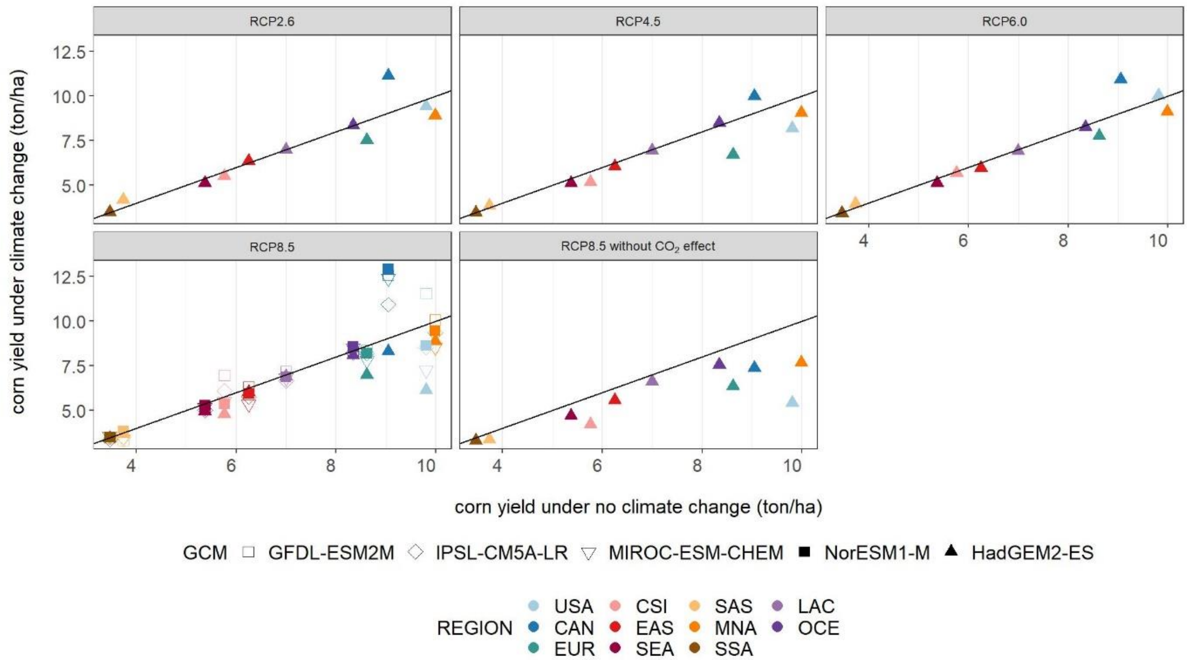
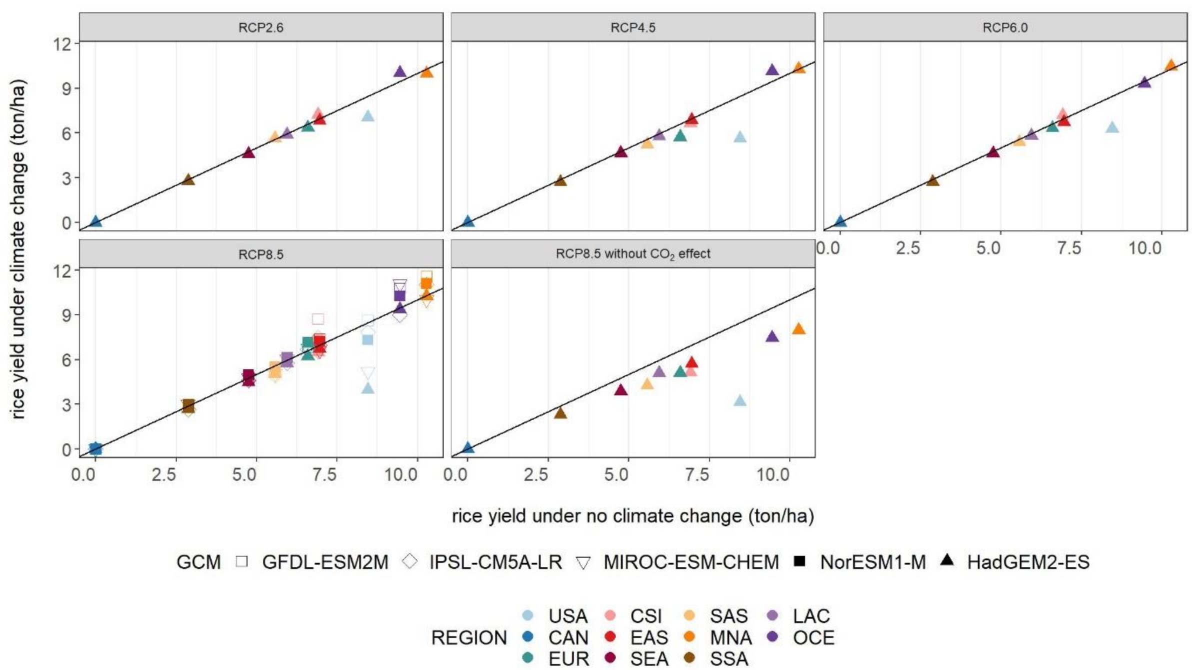
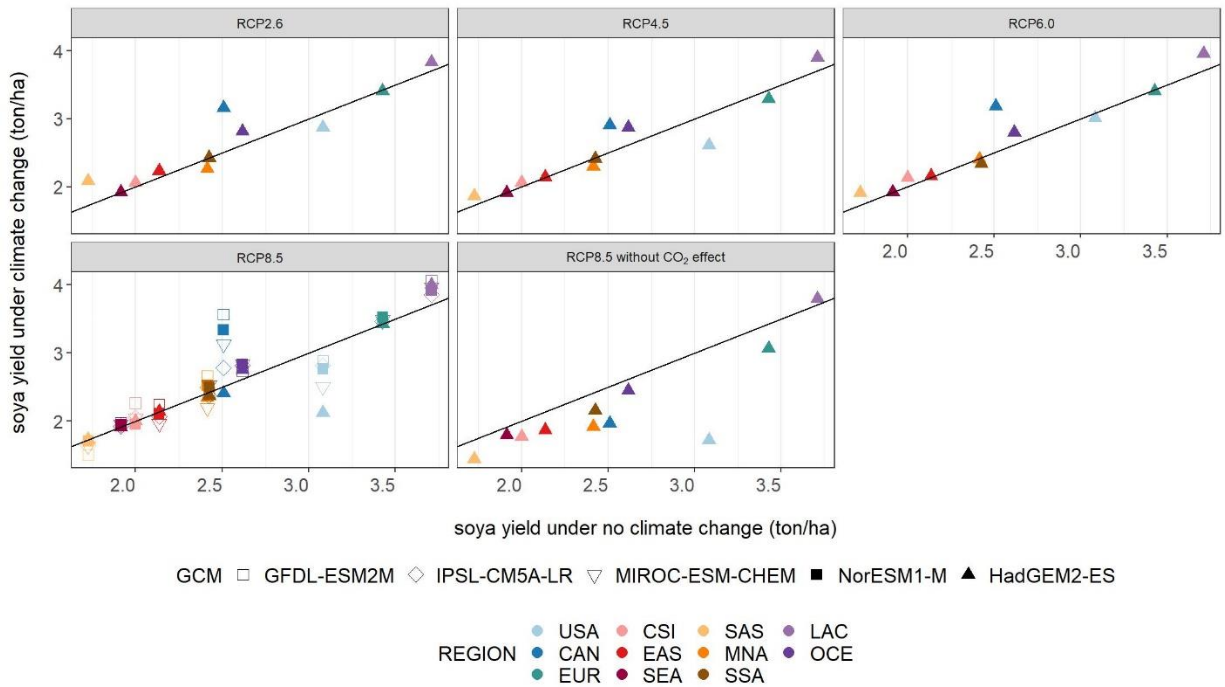
Supplementary Figures



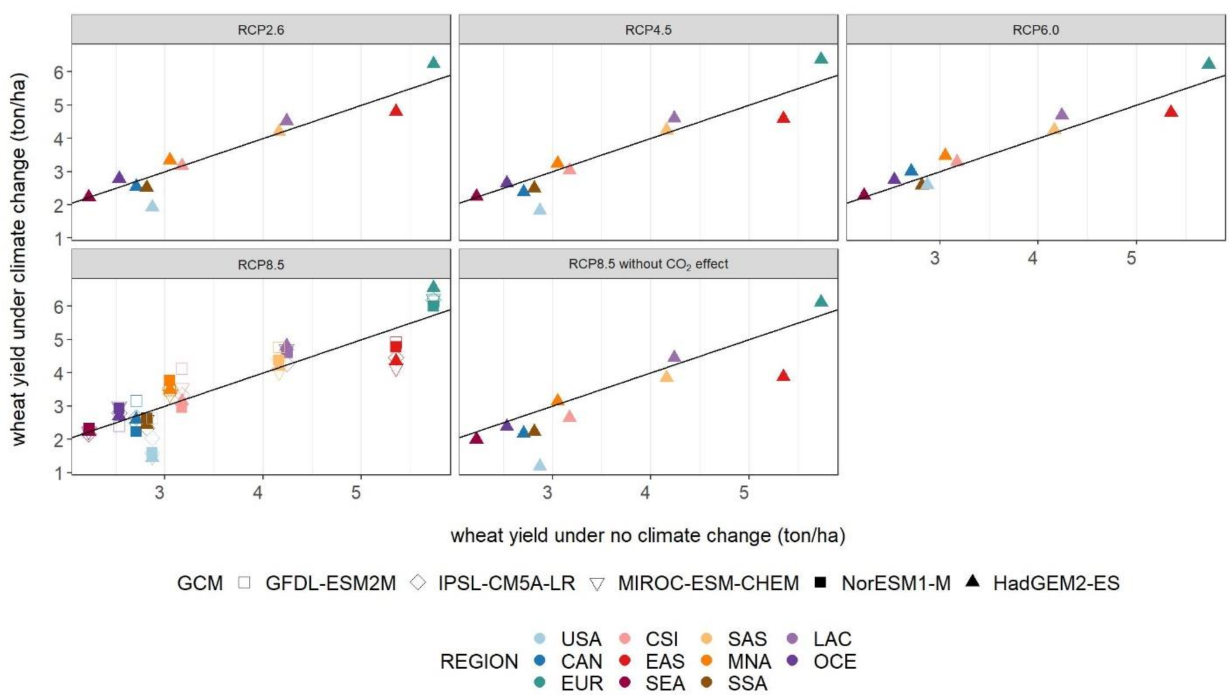
Supplementary Fig. 1 | Corn yield under climate change and under no climate change in each region by 2050 projected by the EPIC crop model. Yields in ton dry matter per ha. Under no climate change yields are determined by base year yields and assumptions on technological development over time, under climate change an additional climate impact shifter is applied.



Supplementary Fig. 2 | Rice yield under climate change and no climate change in each region by 2050 projected by the EPIC crop model. Yields in ton dry matter per ha. Under no climate change yields are determined by base year yield and assumptions on technological development over time, under climate change an additional climate impact shifter is applied.



Supplementary Fig. 3 | Soya yield under climate change and no climate change in each region by 2050 projected by the EPIC crop model. Yields in ton dry matter per ha. Under no climate change yields are determined by base year yield and assumptions on technological development over time, under climate change an additional climate impact shifter is applied.



Supplementary Fig. 4 | Wheat yield under climate change and no climate change in each region by 2050 projected by the EPIC crop model. Yields in ton dry matter per ha. Under no climate change yields are determined by base year yield and assumptions on technological development over time, under climate change an additional climate impact shifter is applied.

Supplementary Tables

Supplementary Table 1 | Global agricultural trade adjustments under trade and climate change scenarios by 2050. Total trade growth and specific extensive margin trade growth, the latter indicated as new trade flows compared to the 2000 trade pattern, the baseline SSP2 trade pattern, or the No CC trade pattern. RCP: Representative Concentration Pathway, GCM: General Circulation Model. Climate change scenarios include the effect of CO_2 fertilization on crop yields. RCP8.5 is also implemented without the CO_2 effect (RCP8.5 wo).

			Trade adjustments			
RCP	GCM	Trade scenario	Total agricultural trade volume (1000 ton)	Total volume of new trade flows w.r.t. 2000 (1000 ton)	Total volume of new trade flows w.r.t. SSP2 baseline (1000 ton)	Total volume of new trade flows w.r.t. No CC (1000 ton)
SPP2 Baseline						
No CC	None	Baseline	2 231 882	34 485	0	0
Trade and Climate Change scenarios						
RCP2.6	HadGEM2-ES	Baseline	2 279 118	36 859	27 603	27 603
RCP4.5	HadGEM2-ES	Baseline	2 296 414	38 420	27 019	27 019
RCP6.0	HadGEM2-ES	Baseline	2 331 759	37 971	36 719	36 719
RCP8.5	GFDL-ESM2M	Baseline	2 392 550	35 078	72 927	72 927
RCP8.5	HadGEM2-ES	Baseline	2 312 236	40 476	39 203	39 203
RCP8.5	IPSL-CM5A-LR	Baseline	2 310 881	38 543	35 854	35 854
RCP8.5	MIROC	Baseline	2 348 640	36 387	38 593	38 593
RCP8.5	NorESM1-M	Baseline	2 258 274	36 500	24 813	24 813
RCP8.5 wo	HadGEM2-ES	Baseline	2 296 093	44 733	53 881	53 881
No CC	None	Fixed imports	2 231 726	34 475	0	0
RCP2.6	HadGEM2-ES	Fixed imports	1 997 757	32 063	0	0
RCP4.5	HadGEM2-ES	Fixed imports	1 993 885	32 095	0	0
RCP6.0	HadGEM2-ES	Fixed imports	2 002 783	31 817	0	0
RCP8.5	GFDL-ESM2M	Fixed imports	2 081 805	31 172	0	0
RCP8.5	HadGEM2-ES	Fixed imports	1 896 043	31 165	0	0
RCP8.5	IPSL-CM5A-LR	Fixed imports	1 983 152	30 977	0	0
RCP8.5	MIROC	Fixed imports	1 950 371	30 541	0	0
RCP8.5	NorESM1-M	Fixed imports	2 021 484	31 656	0	0
RCP8.5 wo	HadGEM2-ES	Fixed imports	1 814 691	31 475	0	0
No CC	None	Pre-Doha tariffs	1 046 349	27 493	194 246	0
RCP2.6	HadGEM2-ES	Pre-Doha tariffs	1 137 845	30 149	206 727	70 453
RCP4.5	HadGEM2-ES	Pre-Doha tariffs	1 153 749	31 735	200 281	75 508
RCP6.0	HadGEM2-ES	Pre-Doha tariffs	1 158 766	31 224	212 409	72 076
RCP8.5	GFDL-ESM2M	Pre-Doha tariffs	1 190 440	28 164	243 935	57 923
RCP8.5	HadGEM2-ES	Pre-Doha tariffs	1 205 015	34 072	208 108	99 349
RCP8.5	IPSL-CM5A-LR	Pre-Doha tariffs	1 172 956	31 732	209 515	67 207
RCP8.5	MIROC	Pre-Doha tariffs	1 229 682	28 918	221 895	97 333
RCP8.5	NorESM1-M	Pre-Doha tariffs	1 108 162	29 159	197 632	65 287
RCP8.5 wo	HadGEM2-ES	Pre-Doha tariffs	1 272 373	38 217	232 223	133 426

Supplementary Table 1 *continued.*

RCP	GCM	Trade scenario	Trade adjustments			
			Total trade agricultural volume (1000 ton)	Total volume of new trade flows w.r.t. 2000 (1000 ton)	Total volume of new trade flows w.r.t. SSP2 baseline (1000 ton)	Total volume of new trade flows w.r.t. No CC (1000 ton)
No CC	None	Facilitation	4 808 943	45 157	126 711	0
RCP2.6	HadGEM2-ES	Facilitation	4 700 270	47 367	143 739	162 972
RCP4.5	HadGEM2-ES	Facilitation	4 637 072	50 034	157 980	180 892
RCP6.0	HadGEM2-ES	Facilitation	4 731 794	49 026	147 581	210 790
RCP8.5	GFDL-ESM2M	Facilitation	4 932 717	47 846	161 146	133 028
RCP8.5	HadGEM2-ES	Facilitation	4 375 589	52 343	171 053	361 853
RCP8.5	IPSL-CM5A-LR	Facilitation	4 618 677	50 190	163 629	132 825
RCP8.5	MIROC	Facilitation	4 710 517	49 657	195 841	223 134
RCP8.5	NorESM1-M	Facilitation	4 750 893	50 412	172 771	105 570
RCP8.5 wo	HadGEM2-ES	Facilitation	4 035 029	54 202	187 829	384 270
No CC	None	Tariff elimination	3 790 254	67 245	657 770	0
RCP2.6	HadGEM2-ES	Tariff elimination	3 879 544	67 863	715 503	33 870
RCP4.5	HadGEM2-ES	Tariff elimination	3 873 057	69 490	674 132	25 098
RCP6.0	HadGEM2-ES	Tariff elimination	3 975 979	68 151	721 417	34 852
RCP8.5	GFDL-ESM2M	Tariff elimination	3 987 976	64 978	770 460	52 951
RCP8.5	HadGEM2-ES	Tariff elimination	3 793 240	70 838	672 491	41 509
RCP8.5	IPSL-CM5A-LR	Tariff elimination	3 840 614	67 378	681 601	45 064
RCP8.5	MIROC	Tariff elimination	3 915 428	65 089	737 766	45 928
RCP8.5	NorESM1-M	Tariff elimination	3 849 080	65 463	699 887	21 403
RCP8.5 wo	HadGEM2-ES	Tariff elimination	3 592 066	77 612	643 519	47 724
No CC	None	Facilitation + Tariff	7 376 216	120 597	2 271 954	0
RCP2.6	HadGEM2-ES	Facilitation + Tariff	7 274 863	118 722	2 258 514	138 416
RCP4.5	HadGEM2-ES	Facilitation + Tariff	7 041 356	119 501	2 039 335	176 055
RCP6.0	HadGEM2-ES	Facilitation + Tariff	7 559 279	118 072	2 361 007	73 203
RCP8.5	GFDL-ESM2M	Facilitation + Tariff	8 077 702	116 314	2 718 236	95 738
RCP8.5	HadGEM2-ES	Facilitation + Tariff	6 576 789	118 638	2 066 236	195 542
RCP8.5	IPSL-CM5A-LR	Facilitation + Tariff	7 089 250	120 332	2 079 449	124 048
RCP8.5	MIROC	Facilitation + Tariff	7 115 186	114 886	2 275 812	143 824
RCP8.5	NorESM1-M	Facilitation + Tariff	7 424 135	120 259	2 290 354	74 486
RCP8.5 wo	HadGEM2-ES	Facilitation + Tariff	5 937 251	119 122	1 745 582	303 873

GCM MIROC: MIROC-ESM-CHEM

Supplementary Table 2 | Global market responses to trade scenarios compared to the *Baseline trade* scenario by 2050 under the different climate change scenarios. RCP: Representative Concentration Pathway, GCM: General Circulation Model. Climate change scenarios include the effect of CO_2 fertilization on crop yields. RCP8.5 is also implemented without the CO_2 effect (RCP8.5 wo). Global crop production efficiency is defined as the total global crop production over the total global cropland area.

			Market responses			
RCP	GCM	Trade scenario	Global crop production efficiency, difference to *Baseline trade* (%)	Global crop calorie production, difference to *Baseline trade* (%)	Global food availability , difference to *Baseline Trade* (kcal/cap/day)	Agricultural prices, difference compared to *Baseline trade* (%)
No CC	None	Fixed imports	0.00%	0.00%	0.00	0.09%
RCP2.6	HadGEM2-ES	Fixed imports	-1.87%	-1.92%	-14.24	1.90%
RCP4.5	HadGEM2-ES	Fixed imports	-1.87%	-2.06%	-11.70	2.36%
RCP6.0	HadGEM2-ES	Fixed imports	-1.56%	-2.18%	-14.39	2.16%
RCP8.5	GFDL-ESM2M	Fixed imports	-1.97%	-2.40%	-16.41	2.18%
RCP8.5	IPSL-CM5A-LR	Fixed imports	-1.56%	-2.24%	-18.13	3.08%
RCP8.5	MIROC	Fixed imports	-2.22%	-2.77%	-16.70	16.68%
RCP8.5	NorESM1-M	Fixed imports	-1.05%	-1.48%	-9.53	1.72%
RCP8.5	HadGEM2-ES	Fixed imports	-2.24%	-2.35%	-19.52	3.42%
RCP8.5 wo	HadGEM2-ES	Fixed imports	-2.45%	-2.67%	-36.85	8.58%
No CC	None	Pre-Doha tariffs	-2.63%	-4.19%	-50.43	5.13%
RCP2.6	HadGEM2-ES	Pre-Doha tariffs	-2.37%	-3.51%	-41.43	4.39%
RCP4.5	HadGEM2-ES	Pre-Doha tariffs	-1.89%	-3.23%	-41.76	4.17%
RCP6.0	HadGEM2-ES	Pre-Doha tariffs	-2.07%	-3.62%	-45.85	4.47%
RCP8.5	GFDL-ESM2M	Pre-Doha tariffs	-2.74%	-4.20%	-44.35	4.74%
RCP8.5	IPSL-CM5A-LR	Pre-Doha tariffs	-1.65%	-3.08%	-41.95	4.16%
RCP8.5	MIROC	Pre-Doha tariffs	-2.07%	-3.39%	-46.69	4.43%
RCP8.5	NorESM1-M	Pre-Doha tariffs	-1.86%	-3.30%	-42.92	4.24%
RCP8.5	HadGEM2-ES	Pre-Doha tariffs	-1.61%	-2.62%	-42.45	4.24%
RCP8.5 wo	HadGEM2-ES	Pre-Doha tariffs	-1.51%	-2.19%	-39.44	4.41%
No CC	None	Facilitation	2.66%	1.49%	31.65	-3.23%
RCP2.6	HadGEM2-ES	Facilitation	2.29%	1.53%	35.35	-3.40%
RCP4.5	HadGEM2-ES	Facilitation	1.55%	1.12%	35.96	-3.51%
RCP6.0	HadGEM2-ES	Facilitation	3.11%	2.48%	35.34	-3.81%
RCP8.5	GFDL-ESM2M	Facilitation	3.11%	2.10%	33.37	-3.85%
RCP8.5	IPSL-CM5A-LR	Facilitation	1.93%	1.46%	28.09	-3.64%
RCP8.5	MIROC	Facilitation	1.06%	0.55%	33.89	-3.41%
RCP8.5	NorESM1-M	Facilitation	1.82%	1.19%	35.42	-3.46%
RCP8.5	HadGEM2-ES	Facilitation	1.63%	1.34%	32.48	-3.84%
RCP8.5 wo	HadGEM2-ES	Facilitation	1.62%	1.19%	25.35	-3.45%

Supplementary Table 2 ***continued.***

RCP	GCM	Trade scenario	Market responses: Global production efficiency, difference to *Baseline trade* (%)	Global crop calorie production, difference to *Baseline trade* (%)	Global food availability , difference to *Baseline trade* (kcal/cap/day)	Agricultural prices, difference compared to *Baseline trade* (%)
No CC	None	Tariff elimination	2.34%	1.86%	29.29	-3.59%
RCP2.6	HadGEM2-ES	Tariff elimination	1.78%	1.52%	27.94	-3.55%
RCP4.5	HadGEM2-ES	Tariff elimination	1.85%	1.58%	28.78	-3.60%
RCP6.0	HadGEM2-ES	Tariff elimination	2.29%	2.01%	30.56	-3.74%
RCP8.5	GFDL-ESM2M	Tariff elimination	1.70%	1.23%	23.31	-3.22%
RCP8.5	IPSL-CM5A-LR	Tariff elimination	1.90%	1.72%	29.23	-3.53%
RCP8.5	MIROC	Tariff elimination	1.92%	1.72%	27.63	-3.65%
RCP8.5	NorESM1-M	Tariff elimination	2.06%	1.85%	25.23	-3.82%
RCP8.5	HadGEM2-ES	Tariff elimination	1.79%	1.67%	31.95	-3.64%
RCP8.5 wo	HadGEM2-ES	Tariff elimination	1.53%	1.17%	18.11	-2.54%
NoCC	None	Facilitation + Tariff	2.03%	0.06%	65.49	-9.75%
RCP2.6	HadGEM2-ES	Facilitation + Tariff	2.87%	1.57%	73.87	-11.23%
RCP4.5	HadGEM2-ES	Facilitation + Tariff	2.14%	1.36%	67.91	-10.93%
RCP6.0	HadGEM2-ES	Facilitation + Tariff	2.98%	1.98%	72.34	-11.53%
RCP8.5	GFDL-ESM2M	Facilitation + Tariff	2.52%	1.37%	75.56	-11.77%
RCP8.5	IPSL-CM5A-LR	Facilitation + Tariff	2.52%	1.96%	69.11	-11.43%
RCP8.5	MIROC	Facilitation + Tariff	1.55%	1.17%	71.06	-11.85%
RCP8.5	NorESM1-M	Facilitation + Tariff	2.15%	1.56%	75.34	-11.95%
RCP8.5	HadGEM2-ES	Facilitation + Tariff	2.70%	2.36%	68.54	-10.96%
RCP8.5 wo	HadGEM2-ES	Facilitation + Tariff	2.35%	1.60%	53.64	-8.72%

GCM MIROC: MIROC-ESM-CHEM

Supplementary Table 3 | Impact of crop yields and trade costs on risk of hunger and food availability by region. Results from OLS regression of the impact of crop yield change (1), trade costs (2), and both (3) on food availability and risk of hunger including regional interaction effects. Regression models and sample are described in Method.

		Population at risk of hunger (million)			Food availability (kcal/cap/day)		
		(1)	(2)	(3)	(1)	(2)	(3)
Crop yield (% change)	CSI	-0.56 *		-0.37	223.36 ***		233.73 ***
		(0.31)		(0.34)	(32.47)		(40.29)
	EAS	-10.74		-12.78 ***	230.18		267.68 ***
		(9.43)		(4.18)	(175.86)		(69.10)
	LAC	-6.52 ***		-3.24 ***	355.64 ***		283.90 ***
		(1.90)		(1.24)	(76.29)		(63.92)
	MNA	-0.20		1.76	175.42		137.27 ***
		(7.29)		(2.87)	(139.37)		(51.39)
	OCE	-0.19		-0.27	214.93		192.17
		(0.15)		(0.31)	(161.74)		(291.50)
	SAS	-81.21 ***		-82.83 ***	485.73 ***		475.97 ***
		(16.18)		(21.66)	(73.48)		(93.33)
	SEA	-10.94 **		-11.21 *	372.98 ***		383.02 ***
		(5.42)		(5.85)	(116.26)		(121.74)
	SSA	-105.86 ***		-29.70	928.48 **		317.41
		(38.34)		(22.43)	(365.54)		(254.20)
	USA	-0.07 ***		-0.06	156.78 ***		136.54 *
		(0.02)		(0.04)	(47.00)		(74.61)
Trade cost (log of US$/106 kcal)	CSI		0.49 ***	0.48 ***		-31.78 ***	-28.47 *
			(0.09)	(0.12)		(11.85)	(14.25)
	EAS		6.99 ***	6.61 ***		-137.53 ***	-132.81 ***
			(0.46)	(0.45)		(8.38)	(7.41)
	LAC		1.16 ***	1.07 ***		-21.60 ***	-17.53 *
			(0.20)	(0.18)		(7.52)	(7.94)
	MNA		11.36 ***	11.36 ***		-233.76 ***	-231.44 ***
			(0.47)	(0.55)		(11.98)	(10.97)
	OCE		-0.16 ***	-0.17 ***		172.75 ***	174.33 ***
			(0.03)	(0.05)		(31.88)	(51.23)
	SAS		5.42 ***	5.39 *		-27.80 ***	-32.17 *
			(2.03)	(3.02)		(10.20)	(15.00)
	SEA		-0.11	0.00		15.28	11.11
			(0.53)	(0.63)		(12.96)	(14.33)
	SSA		26.18 ***	24.29 ***		-257.76 ***	-248.05 ***
			(2.56)	(2.41)		(15.77)	(16.51)
	USA		0.03 ***	0.03 ***		-67.11 ***	-58.26 ***
			(0.01)	(0.01)		(15.39)	(16.30)
Crop yield x Trade cost	CSI			-0.19			112.59 ***
				(0.33)			(34.44)
	EAS			-10.56			140.65
				(7.95)			(91.48)
	LAC			8.32			-201.69
				(5.93)			(216.83)
	MNA			3.24			-81.95
				(3.19)			(72.73)
	OCE			-0.04			180.52
				(0.28)			(237.69)
	SAS			-2.18			-33.26
				(26.74)			(104.01)
	SEA			1.47			-55.54
				(6.32)			(120.10)
	SSA			-41.85			-15.56
				(29.88)			(186.45)
	USA			-0.01			14.40
				(0.05)			(79.25)

Significance levels: *p<0.1; **p<0.05; ***p<0.01. Heteroskedastic robust standard errors in brackets. EUR and CAN are not included as zero hunger. N = 450. Adjusted R squared is 0.999 for food availability (1) - (3) and 0.947 (1), 0.961 (2) and 0.976 (3) for hunger regressions.

Supplementary Table 4 | Aggregate regions, GLOBIOM regions and countries.

Aggregate Region	*GLOBIOM Region*	*Country*
CAN	Canada	Canada
CSI	Former USSR	Belarus, Moldova, Ukraine, Russia, Azerbaidjan, Kazakhstan, Turkmenistan, Uzbekistan, Armenia, Georgia, Kyrgyzstan, Tajikistan
EAS	China	People's Republic of China, Hong Kong
	Japan	Japan
	South Korea	Korea
EUR	EU Baltic	Estonia, Latvia, Lithuania
	EU Central East	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia
	EU Mid-West	Austria, Belgium, France, Germany, Luxembourg, Netherlands
	EU North	Denmark, Finland, Ireland, Sweden, United Kingdom
	EU South	Cyprus, Greece, Italy, Malta, Portugal, Spain
	Rest of Central Eastern Europe (RCEU)	Albania, Bosnia Herzegovina, Croatia, Macedonia, Serbia
	Rest of Western Europe (ROWE)	Iceland, Norway, Switzerland, Greenland
LAC	Brazil	Brazil
	Mexico	Mexico
	Central America (RCAM)	Bahamas, Belize, Costa Rica, Cuba, Dominican Republic, El Salvador, Guadeloupe, Guatemala, Jamaica, Nicaragua, Panama, Trinidad and Tobago
	South America (RSAM)	Argentina, Bolivia, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
MNA	Middle East and North Africa	Egypt, Algeria, Libya, Morocco, Tunisia, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen
	Turkey	Turkey
OCE	ANZ	Australia, New Zealand
	Pacific Islands	Fiji, French Polynesia, New Caledonia, Papua New Guinea, Samoa, Solomon Islands, Vanuatu
SAS	India	India
	Rest of South Asia (RSAS)	Afghanistan, Bangladesh, Bhutan, Nepal, Pakistan, Sri Lanka
SEA	South East Asia – other Pacific Asia (RSEA_OPA)	Brunei Daressalam, Indonesia, Malaysia, Myanmar, Philippines, Singapore, Thailand, East Timor
	South East Asia – (ex-)planned economies (RSEA_PAC)	Cambodia, DPR of Korea, Laos, Mongolia, Viet Nam
SSA	Congo Basin	Cameroon, Central African Republic, Congo Republic, Democratic Republic of Congo, Equatorial Guinea, Gabon
	Eastern Africa	Burundi, Ethiopia, Kenya, Tanzania, Uganda, Rwanda
	South Africa	South Africa
	Southern Africa	Angola, Botswana, Comoros, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Reunion, Swaziland, Zambia, Zimbabwe
	Western Africa and Rest of Sub-Saharan Africa	Benin, Burkina Faso, Cape Verde, Chad, Côte d'Ivoire, Djibouti, Eritrea, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Somalia, Sudan, Togo
USA	USA Region	United States, Puerto Rico

Supplementary Table 5 | Descriptive statistics of the dependent and explanatory variables (at regional level). The sample is composed of observations for the 11 regions for five trade scenarios (Baseline, pre-Doha tariffs, Facilitation, Tariff elimination, and Facilitation + Tariff elimination) and 10 climate change scenarios (N = 550).

	Min	Average	Max
Population at risk of hunger (million)	0.00	12.04	63.06
Food availability (kcal/cap/day)	2518	3074	3510
Crop yield (difference with NoCC)	-38%	-5%	+35%
Trade costs (US$/$10^6$ kcal)	17.91	73.93	225.66

Supplementary Table 6 | Average ad valorem tariffs on GLOBIOM agricultural goods in 2001 and 2010. Tariff rates from MAcMap-HS6 database 2001 and 2010 with weighted average by macro-region and product based on MAcMap reference group weights[1,2]. Specific tariffs are converted to ad valorem equivalent with MAcMap unit values.

	All agricultural goods			
	2001		2010	
REGION	import	export	import	export
CAN	16.63%	7.73%	26.86%	11.41%
CSI	14.02%	12.41%	12.16%	15.21%
EAS	39.15%	22.91%	27.51%	14.12%
EUR	14.10%	14.23%	9.49%	12.65%
LAC	19.96%	19.09%	14.28%	14.87%
MNA	19.68%	21.00%	18.54%	19.31%
OCE	1.89%	30.55%	1.97%	25.04%
SAS	47.21%	27.98%	31.45%	21.70%
SEA	9.63%	21.49%	4.32%	16.51%
SSA	21.98%	10.40%	14.70%	7.86%
USA	4.45%	20.39%	4.79%	15.56%
	Wheat			
	2001		2010	
REGION	import	export	import	export
CAN	1.59%	14.06%	0.00%	20.42%
CSI	10.43%	19.41%	5.41%	28.01%
EAS	28.70%	22.85%	63.16%	10.31%
EUR	12.37%	17.00%	7.95%	17.53%
LAC	9.78%	12.36%	5.29%	26.38%
MNA	16.60%	14.96%	17.84%	21.10%
OCE	0.03%	16.32%	0.03%	20.70%
SAS	67.42%	15.08%	25.60%	17.92%
SEA	7.77%	25.88%	2.52%	19.15%
SSA	11.66%	16.09%	5.73%	18.08%
USA	2.37%	15.15%	1.46%	20.43%

Supplementary Table 6 *continued.*

	Corn			
	2001		2010	
REGION	import	export	import	export
CAN	0.00%	17.24%	0.00%	24.83%
CSI	8.87%	21.54%	2.14%	33.52%
EAS	67.84%	30.98%	82.49%	18.45%
EUR	19.39%	20.36%	1.82%	19.35%
LAC	35.90%	25.38%	5.43%	28.14%
MNA	25.96%	13.30%	29.86%	12.47%
OCE	0.05%	26.33%	0.13%	18.42%
SAS	41.65%	11.48%	9.46%	18.49%
SEA	17.86%	27.34%	4.48%	17.97%
SSA	27.80%	28.40%	7.37%	11.43%
USA	1.06%	30.09%	0.32%	23.52%

	Rice			
	2001		2010	
REGION	import	export	import	export
CAN	0.00%	100.96%	0.00%	30.71%
CSI	8.95%	31.17%	14.60%	34.24%
EAS	362.15%	52.40%	116.56%	29.45%
EUR	71.19%	81.67%	16.70%	27.32%
LAC	21.48%	37.22%	13.67%	33.46%
MNA	18.51%	34.70%	13.60%	35.93%
OCE	0.00%	74.20%	0.32%	23.82%
SAS	56.15%	60.86%	25.84%	30.20%
SEA	14.76%	89.21%	21.75%	26.92%
SSA	28.34%	36.85%	10.80%	20.21%
USA	4.15%	70.13%	2.17%	29.06%

	Soya			
	2001		2010	
REGION	import	export	import	export
CAN	0.00%	20.57%	0.00%	17.00%
CSI	2.87%	28.40%	0.13%	10.18%
EAS	130.66%	18.22%	17.99%	20.27%
EUR	1.90%	20.67%	0.87%	16.13%
LAC	3.83%	25.52%	3.66%	7.61%
MNA	3.79%	21.88%	3.40%	3.18%
OCE	0.03%	22.12%	0.40%	17.66%
SAS	27.42%	18.87%	26.82%	15.71%
SEA	6.01%	33.85%	1.51%	3.71%
SSA	3.43%	11.53%	6.78%	9.08%
USA	0.00%	25.27%	0.00%	6.52%

Supplementary Table 7 | Average total trade cost (USD/ton) on agricultural trade for each region in 2000 and 2010, and in 2050 across trade scenarios. The aggregation is described in Method.

Trade scenario	Region	Tariff cost	Transport cost	Trade expansion cost[1]	Total trade cost
2000 – Baseline trade	CAN	37	248	/	285
	CSI	35	389	/	424
	EAS	185	721	/	906
	EUR	44	353	/	398
	LAC	37	261	/	298
	MNA	33	272	/	305
	OCE	126	812	/	937
	SAS	173	211	/	384
	SEA	89	581	/	670
	SSA	35	494	/	530
	USA	57	283	/	339
2010 – Baseline trade	CAN	25	215	28	268
	CSI	19	314	33	365
	EAS	219	499	129	846
	EUR	20	328	34	382
	LAC	29	250	29	308
	MNA	24	243	27	294
	OCE	120	508	147	775
	SAS	117	184	53	354
	SEA	177	560	74	811
	SSA	22	412	46	480
	USA	32	236	25	293
2050 – Baseline trade	CAN	20	139	6	165
	CSI	12	188	9	209
	EAS	61	107	11	179
	EUR	17	163	20	200
	LAC	14	147	11	171
	MNA	18	143	38	199
	OCE	256	117	58	431
	SAS	62	75	18	155
	SEA	38	126	11	175
	SSA	18	86	16	121
	USA	24	92	18	135
2050 – Pre-Doha tariff levels	CAN	8	142	8	158
	CSI	18	262	8	288
	EAS	98	267	6	371
	EUR	20	228	24	272
	LAC	23	186	9	218
	MNA	24	181	53	258
	OCE	54	294	48	397
	SAS	189	130	25	343
	SEA	103	339	16	458
	SSA	23	206	19	249
	USA	36	187	10	233

Supplementary Table 7 ***continued.***

Trade scenario	Region	Tariff cost	Transport cost	Trade expansion cost[1]	Total trade cost
2050 – Trade facilitation	CAN	27	125	7	160
	CSI	12	111	2	125
	EAS	62	76	1	139
	EUR	23	90	1	115
	LAC	18	106	3	127
	MNA	26	94	5	125
	OCE	231	71	9	311
	SAS	48	71	2	121
	SEA	36	99	2	137
	SSA	42	108	4	154
	USA	36	79	3	118
2050 – Tariff elimination	CAN	0	131	15	146
	CSI	0	144	21	164
	EAS	0	68	15	83
	EUR	0	100	34	135
	LAC	0	101	16	117
	MNA	0	104	36	140
	OCE	0	96	48	143
	SAS	0	64	19	83
	SEA	0	103	16	119
	SSA	0	79	26	105
	USA	0	76	21	97
2050 – Trade facilitation + Tariff elimination	CAN	0	97	5	102
	CSI	0	64	24	88
	EAS	0	64	5	69
	EUR	0	71	20	91
	LAC	0	67	3	70
	MNA	0	71	6	78
	OCE	0	88	24	112
	SAS	0	52	3	55
	SEA	0	84	3	86
	SSA	0	99	4	103
	USA	0	49	3	52

[1] The trade expansion cost reflects the cost of infrastructure and capacity constraints in the transport sector and is reset to zero after a decade if the traded quantity does not increase anymore. It is not present in the base year 2000.

Supplementary Table 8 | Corn trade pattern in response to climate change (RCP8.5 scenarios under *Baseline trade*) at macro-region level. Bilateral trade flows among 30 sub-regions are aggregated to reflect inter-regional trade among macro-regions and the magnitude of intra-regional trade. No climate change gives the trade volume (1000 ton) in the SSP2 baseline. Min and max CC impact give the minimum and maximum trade change (%) that occurs across RCP8.5 scenarios. Min and max CC new trade give the minimum and maximum trade volume (1000 ton) across RCP8.5 scenarios that is new compared to the SSP2 baseline.

Exporter		Importer										
		CAN	CSI	EAS	EUR	LAC	MNA	OCE	SAS	SEA	SSA	USA
CAN	No climate change	0	0	0	0	0	0	0	0	0	0	0
	Min CC impact (%)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Max CC impact (%)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Min CC new trade	0	0	0	0	45	0	0	0	0	0	0
	Max CC new trade	0	0	0	0	45	0	0	0	0	0	0
CSI	No climate change	0	0	0	37	0	1393	0	0	0	0	0
	Min trade growth	0%	0%	0%	-1%	0%	14%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	0%	221%	0%	106%	0%	0%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
EAS	No climate change	0	0	5357	0	0	0	0	0	8580	0	0
	Min trade growth	0%	0%	-5%	0%	0%	0%	0%	0%	-8%	0%	0%
	Max trade growth	0%	0%	22%	0%	0%	0%	0%	0%	113%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
EUR	No climate change	0	0	2407	25938	0	2662	0	0	1773	0	0
	Min trade growth	0%	0%	-25%	-15%	0%	18%	0%	0%	-4%	0%	0%
	Max trade growth	0%	0%	85%	13%	0%	127%	0%	0%	114%	0%	0%
	Min new trade	0	573	0	0	0	0	0	0	0	0	0
	Max new trade	0	573	660	0	0	1522	0	0	0	0	0
LAC	No climate change	13643	0	0	10112	52812	7945	0	14776	4147	17419	0
	Min trade growth	-71%	0%	0%	1%	-2%	5%	0%	-40%	-64%	-37%	0%
	Max trade growth	-41%	0%	0%	44%	8%	114%	0%	222%	72%	4%	0%
	Min new trade	0	0	2069	0	0	0	0	0	0	0	0
	Max new trade	0	0	2151	0	0	0	0	0	0	0	0
MNA	No climate change	0	0	0	14659	0	0	0	0	0	0	0
	Min trade growth	0%	0%	0%	-59%	0%	0%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	0%	-10%	0%	0%	0%	0%	0%	0%	0%
	Min new trade	0	0	0	0	0	336	0	0	0	0	0
	Max new trade	0	0	0	0	0	798	0	0	0	0	0
OCE	No climate change	0	0	677	0	0	0	0	0	0	0	0
	Min trade growth	0%	0%	-30%	0%	0%	0%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	9%	0%	0%	0%	0%	0%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	2	0	130	0	0
	Max new trade	0	0	0	0	0	0	8	0	221	0	0
SAS	No climate change	0	0	0	0	0	0	0	0	8393	0	0
	Min trade growth	0%	0%	0%	0%	0%	0%	0%	0%	12%	0%	0%
	Max trade growth	0%	0%	0%	0%	0%	0%	0%	0%	126%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
SEA	No climate change	0	0	12015	0	0	0	0	0	0	0	0
	Min trade growth	0%	0%	-16%	0%	0%	0%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	11%	0%	0%	0%	0%	0%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	542	0	0
	Max new trade	0	0	0	0	0	0	0	0	3704	0	0

Supplementary Table 8 ***continued.***

Exporter		Importer										
		CAN	CSI	EAS	EUR	LAC	MNA	OCE	SAS	SEA	SSA	USA
SSA	No climate change	0	0	21455	0	2548	13936	0	0	2033	0	0
	Min trade growth	0%	0%	-49%	0%	-84%	-93%	0%	0%	4%	0%	0%
	Max trade growth	0%	0%	8%	0%	49%	-1%	0%	0%	169%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	517	0	0	0	0	0	0	0	0
USA	No climate change	0	0	0	6131	1437	14442	491	97388	0	4382	0
	Min trade growth	0%	0%	0%	-99%	4%	-15%	0%	-88%	0%	-75%	0%
	Max trade growth	0%	0%	0%	90%	738%	35%	132%	36%	0%	107%	0%
	Min new trade	5669	0	10516	0	0	0	0	0	91	0	0
	Max new trade	5669	0	10516	0	4865	0	0	537	3343	165	0

Supplementary Table 9 | Rice trade pattern in response to climate change (RCP8.5 scenarios under *Baseline trade*) at macro-region level. Bilateral trade flows among 30 sub-regions are aggregated to reflect inter-regional trade among macro-regions and the magnitude of intra-regional trade. No climate change gives the trade volume (1000 ton) in the SSP2 baseline. Min and max CC impact give the minimum and maximum trade change (%) that occurs across RCP8.5 scenarios. Min and max CC new trade give the minimum and maximum trade volume (1000 ton) across RCP8.5 scenarios that is new compared to the SSP2 baseline.

Exporter		Importer										
		CAN	CSI	EAS	EUR	LAC	MNA	OCE	SAS	SEA	SSA	USA
EAS	No climate change	0	0	0	0	170	33	0	0	630	71663	0
	Min trade growth	0%	0%	0%	0%	-6%	-6%	0%	0%	0%	-3%	0%
	Max trade growth	0%	0%	0%	0%	7%	11%	0%	0%	170%	1%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
EUR	No climate change	619	0	0	316	5554	17432	0	0	0	2304	0
	Min trade growth	0%	0%	0%	-75%	-70%	-39%	0%	0%	0%	-16%	0%
	Max trade growth	0%	0%	0%	-6%	5%	2%	0%	0%	0%	57%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	1	0	0	0	0	0
LAC	No climate change	0	0	0	2805	6730	743	0	0	0	834	0
	Min trade growth	0%	0%	0%	2%	-8%	-15%	0%	0%	0%	-3%	0%
	Max trade growth	0%	0%	0%	104%	24%	73%	0%	0%	0%	125%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	296	0	0	0	0	0	640	0
MNA	No climate change	0	0	0	1255	0	0	0	0	0	0	0
	Min trade growth	0%	0%	0%	-33%	0%	0%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
OCE	No climate change	0	0	0	290	0	0	0	0	0	0	0
	Min trade growth	0%	0%	0%	-7%	0%	0%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	0%	17%	0%	0%	0%	0%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
SAS	No climate change	0	88	0	1525	0	1957	175	0	9038	1098	0
	Min trade growth	0%	0%	0%	-7%	0%	-97%	-59%	0%	-18%	-79%	0%
	Max trade growth	0%	0%	0%	8%	0%	5%	111%	0%	287%	4%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
SEA	No climate change	0	0	78592	939	0	0	294	54530	0	414	3097
	Min trade growth	0%	0%	-3%	-41%	0%	0%	-49%	-23%	0%	-21%	-60%
	Max trade growth	0%	0%	1%	6%	0%	0%	18%	12%	0%	6%	486%
	Min new trade	0	0	0	0	0	1	0	0	0	0	0
	Max new trade	0	0	0	104	0	84	0	0	0	0	0
SSA	No climate change	0	0	0	119	58	0	0	0	0	58	0
	Min trade growth	0%	0%	0%	-15%	-17%	0%	0%	0%	0%	-17%	0%
	Max trade growth	0%	0%	0%	3%	5%	0%	0%	0%	0%	1%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0

Supplementary Table 9 *continued.*

Exporter		Importer										
		CAN	**CSI**	**EAS**	**EUR**	**LAC**	**MNA**	**OCE**	**SAS**	**SEA**	**SSA**	**USA**
USA	No climate change	0	0	0	24310	0	0	0	0	0	0	0
	Min trade growth	0%	0%	0%	-49%	0%	0%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	0%	-5%	0%	0%	0%	0%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	108	0	0	0	0
	Max new trade	0	0	0	369	0	0	108	0	0	0	0

Supplementary Table 10 | Wheat trade pattern in response to climate change (RCP8.5 scenarios under *Baseline trade*) at macro-region level. Bilateral trade flows among 30 sub-regions are aggregated to reflect inter-regional trade among macro-regions and the magnitude of intra-regional trade. No climate change gives the trade volume (1000 ton) in the SSP2 baseline. Min and max CC impact give the minimum and maximum trade change (%) that occurs across RCP8.5 scenarios. Min and max CC new trade give the minimum and maximum trade volume (1000 ton) across RCP8.5 scenarios that is new compared to the SSP2 baseline.

Exporter		Importer										
		CAN	CSI	EAS	EUR	LAC	MNA	OCE	SAS	SEA	SSA	USA
CAN	No climate change	0	0	5961	0	1056	0	0	0	0	2503	8185
	Min trade growth	0%	0%	-1%	0%	67%	0%	0%	0%	0%	-48%	126%
	Max trade growth	0%	0%	0%	0%	67%	0%	0%	0%	0%	-48%	262%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
CSI	No climate change	0	0	1733	4391	0	11553	0	0	0	0	0
	Min trade growth	0%	0%	-35%	-73%	0%	-27%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	125%	153%	0%	60%	0%	0%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	5872	0	0	0	0	0	0	0
EAS	No climate change	0	0	4600	0	0	0	0	0	0	0	0
	Min trade growth	0%	0%	-47%	0%	0%	0%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	13%	0%	0%	0%	0%	0%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
EUR	No climate change	0	360	42	13319	13222	2456	0	0	14637	18336	0
	Min trade growth	0%	-68%	438%	-45%	66%	-4%	0%	0%	-2%	12%	0%
	Max trade growth	0%	54%	593%	37%	74%	410%	0%	0%	1%	34%	0%
	Min new trade	0	0	0	0	0	0	0	112	0	0	0
	Max new trade	0	0	7	0	0	0	0	602	0	0	0
LAC	No climate change	0	0	0	0	0	6930	0	515	0	2156	0
	Min trade growth	0%	0%	0%	0%	0%	-17%	0%	1%	0%	3%	0%
	Max trade growth	0%	0%	0%	0%	0%	49%	0%	157%	0%	26%	0%
	Min new trade	0	75	0	0	0	0	0	0	0	0	0
	Max new trade	0	75	0	0	0	0	0	2	0	0	0
MNA	No climate change	0	0	0	18500	0	0	0	0	0	12649	0
	Min trade growth	0%	0%	0%	58%	0%	0%	0%	0%	0%	19%	0%
	Max trade growth	0%	0%	0%	80%	0%	0%	0%	0%	0%	42%	0%
	Min new trade	0	0	0	0	0	1085	0	0	0	0	0
	Max new trade	0	0	0	0	0	1085	0	0	0	1466	0
OCE	No climate change	0	0	0	0	0	0	228	59506	0	0	0
	Min trade growth	0%	0%	0%	0%	0%	0%	-5%	-11%	0%	0%	0%
	Max trade growth	0%	0%	0%	0%	0%	0%	0%	39%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
SAS	No climate change	0	0	0	0	0	0	0	5711	0	0	0
	Min trade growth	0%	0%	0%	0%	0%	0%	0%	-57%	0%	0%	0%
	Max trade growth	0%	0%	0%	0%	0%	0%	0%	40%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
SEA	No climate change	0	0	3	0	0	0	0	0	63	4	0
	Min trade growth	0%	0%	9%	0%	0%	0%	0%	0%	25%	-52%	0%
	Max trade growth	0%	0%	66%	0%	0%	0%	0%	0%	125%	12%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0

Supplementary Table 10 ***continued.***

Exporter		Importer										
		CAN	CSI	EAS	EUR	LAC	MNA	OCE	SAS	SEA	SSA	USA
SSA	No climate change	0	2	3	4	1	1	8	1	0	4	0
	Min trade growth	0%	-58%	-2%	-80%	-26%	43%	-8%	51%	0%	-28%	0%
	Max trade growth	0%	13%	51%	96%	68%	51%	59%	480%	0%	1394%	0%
	Min new trade	0	0	0	0	0	0	0	2	0	0	0
	Max new trade	0	0	0	2	0	0	0	3	0	58	0
USA	No climate change	0	0	0	0	0	0	0	21859	0	0	0
	Min trade growth	0%	0%	0%	0%	0%	0%	0%	-99%	0%	0%	0%
	Max trade growth	0%	0%	0%	0%	0%	0%	0%	-36%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0

Supplementary Table 11 | Soya trade pattern in response to climate change (RCP8.5 scenarios under *Baseline trade*) at macro-region level. Bilateral trade flows among 30 sub-regions are aggregated to reflect inter-regional trade among macro-regions and the magnitude of intra-regional trade. No climate change gives the trade volume (1000 ton) in the SSP2 baseline. Min and max CC impact give the minimum and maximum trade change (%) that occurs across RCP8.5 scenarios. Min and max CC new trade give the minimum and maximum trade volume (1000 ton) across RCP8.5 scenarios that is new compared to the SSP2 baseline.

Exporter		Importer										
		CAN	CSI	EAS	EUR	LAC	MNA	OCE	SAS	SEA	SSA	USA
CAN	No climate change	0	0	3994	160	0	0	0	0	437	0	0
	Min trade growth	0%	0%	-10%	-14%	0%	0%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	11%	2%	0%	0%	0%	0%	15%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	1
	Max new trade	0	0	0	0	0	0	0	0	0	0	1
CSI	No climate change	0	0	16418	0	0	0	0	0	0	0	0
	Min trade growth	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	12%	0%	0%	0%	0%	0%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
EAS	No climate change	0	0	1294	0	0	0	0	0	0	0	0
	Min trade growth	0%	0%	-33%	0%	0%	0%	0%	0%	0%	0%	0%
	Max trade growth	0%	0%	-1%	0%	0%	0%	0%	0%	0%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	3	0
	Max new trade	0	0	6	0	0	0	0	0	0	3	0
EUR	No climate change	0	10313	6171	8137	1199	908	910	0	7088	2999	0
	Min trade growth	0%	3%	-73%	26%	-7%	0%	-40%	0%	16%	-1%	0%
	Max trade growth	0%	10%	-63%	64%	208%	19%	21%	0%	60%	23%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	465	3	0	0	0	0	145	0
LAC	No climate change	5375	1029	50840	59989	22140	23805	217	18666	14279	835	0
	Min trade growth	-29%	-55%	8%	-7%	-22%	-5%	-8%	46%	3%	-30%	0%
	Max trade growth	67%	12%	13%	13%	4%	9%	13%	89%	26%	-1%	0%
	Min new trade	0	0	0	0	0	0	0	249	0	0	0
	Max new trade	0	0	382	0	1	0	1	1327	0	2	0
MNA	No climate change	0	4033	0	0	0	0	0	0	0	0.08	0
	Min trade growth	0%	9%	0%	0%	0%	0%	0%	0%	0%	478%	0%
	Max trade growth	0%	22%	0%	0%	0%	0%	0%	0%	0%	1256%	0%
	Min new trade	0	0	0	0	0	0	0	276	0	0	0
	Max new trade	0	0	0	0	1	0	0	593	0	0	0
OCE	No climate change	0	0	42	0	0	0	0	0	675	0	0
	Min trade growth	0%	0%	0%	0%	0%	0%	0%	0%	7%	0%	0%
	Max trade growth	0%	0%	33%	0%	0%	0%	0%	0%	28%	0%	0%
	Min new trade	0	0	0	0	0	0	0	23	0	0	0
	Max new trade	0	0	0	0	1	0	0	45	0	0	0
SAS	No climate change	0	0	173	0	1	0	0	9068	4110	0	0
	Min trade growth	0%	0%	-10%	0%	-38%	0%	0%	-35%	-23%	0%	0%
	Max trade growth	0%	0%	206%	0%	117%	0%	0%	-19%	8%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
SEA	No climate change	0	0	7	0	0	0	0	0	1546	0	0
	Min trade growth	0%	0%	-6%	0%	0%	0%	0%	0%	-11%	0%	0%
	Max trade growth	0%	0%	297%	0%	0%	0%	0%	0%	26%	0%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	11	0	0	0	0	0	0	0	0

Supplementary Table 11 ***continued.***

Exporter		Importer										
		CAN	CSI	EAS	EUR	LAC	MNA	OCE	SAS	SEA	SSA	USA
SSA	No climate change	0	0	0	0	0	0	0	0	0	546	0
	Min trade growth	0%	0%	0%	0%	0%	0%	0%	0%	0%	-9%	0%
	Max trade growth	0%	0%	0%	0%	0%	0%	0%	0%	0%	54%	0%
	Min new trade	0	0	0	0	0	0	0	0	0	0	0
	Max new trade	0	0	0	0	0	0	0	0	0	0	0
USA	No climate change	0	0	607	1235	5111	284	0	1333	7385	279	0
	Min trade growth	0%	0%	-61%	-58%	-40%	1162%	0%	-67%	-61%	102%	0%
	Max trade growth	0%	0%	3%	28%	8%	1162%	0%	89%	26%	102%	0%
	Min new trade	1983	0	0	0	0	3374	472	0	0	188	0
	Max new trade	1983	0	0	340	0	3374	472	0	264	188	0

Supplementary Table 22 | Technology-induced exogenous crop yield growth rates between 2000 and 2050 under SSP2.

Region	All crops	Corn	Rice	Soya	Wheat
USA	34%	39%	42%	35%	18%
CAN	36%	45%	0%	13%	43%
EUR	44%	66%	17%	37%	39%
CSI	110%	123%	128%	87%	111%
EAS	45%	49%	32%	36%	68%
SEA	67%	140%	60%	64%	166%
SAS	93%	137%	117%	98%	86%
MNA	77%	124%	66%	56%	75%
SSA	114%	185%	108%	154%	56%
LAC	86%	172%	96%	63%	106%
OCE	47%	56%	30%	34%	67%

Supplementary Text

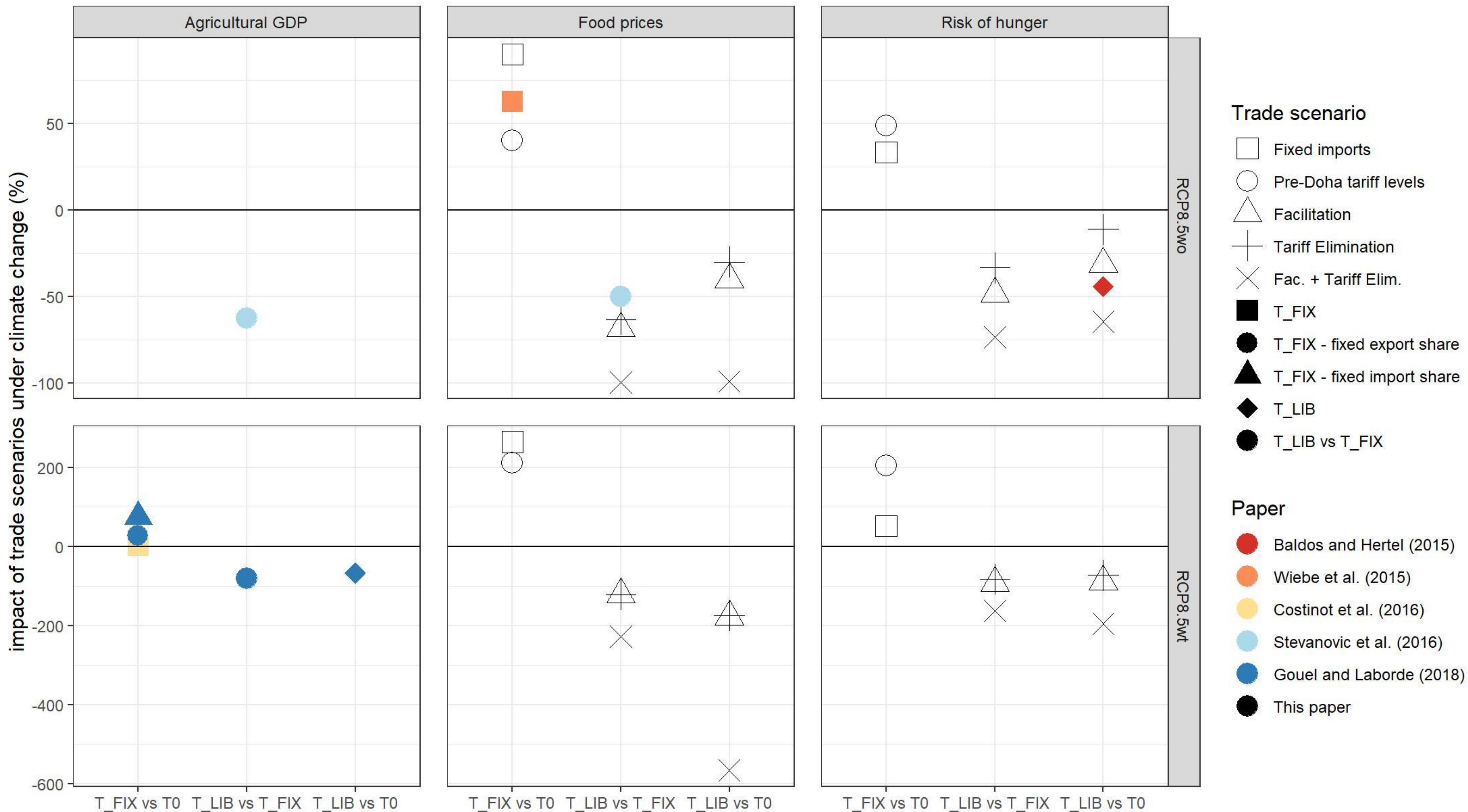
Contribution to existing literature

To determine whether international trade can act as an adaptation mechanism to climate change, global simulation studies assess whether for a particular indicator, the outcome under climate change is worse under a restricted trade setting or better under a liberalized trade setting. Supplementary Table 13 presents an overview of the trade and climate change scenarios assessed in recent literature. Most studies focus on either trade liberalization or trade restriction, or do not compare the impact of trade under climate change to the impact of trade under current climate. By analyzing a comprehensive set of both trade and climate change scenarios, this paper intends to contribute to this research gap and investigates whether the impact of trade becomes larger under climate change.

Supplementary Fig. 5 compares the results in this paper to previous simulation studies. It reveals that there is an agreement on the direction of the impact of trade: trade restriction worsens the adverse impact of climate change on agricultural GDP, prices or risk of hunger, while trade integration alleviates it. It further shows that our scenarios identify a wider range of impacts compared to previous literature. For example, we find that trade restriction increases the adverse impact of climate change on food prices by 40% to 90%, compared to 63% in Wiebe et al[3], or that trade integration reduces the adverse impact of climate change on hunger by 11% to 64%, compared to 44% in Baldos and Hertel[4] (Supplementary Fig. 5).

Supplementary Table 13 | Comparison of global simulation studies[3–9] on climate change adaptation in the agricultural sector through international trade. Overview of scenarios assessed: restricted (T_FIX) or liberalized (T_LIB) trade, under current climate (No CC) or climate change (CC).

Paper	**Indicator**	**Economic model**	**Climate change scenarios**	**No CC**	**No CC + T_FIX**	**No CC + T_LIB**	**CC**	**CC + T_FIX**	**CC + T_LIB**	**Trade scenarios**
Randhir and Hertel (2000)	Equivalent Variation	GTAP	Crop yield distribution from Tsigas et al. (1997)				x	x	x	T_FIX: market insulation T_LIB: removal of all agricultural trade distortions and producer subsidies
Costinot et al. (2016)	Agr. GDP	Static CGE	SRES A1F1 (~RCP8.5) with CO_2	x			x	x		T_FIX: fixed export share T_LIB: /
Stevanovic et al. (2016)	Agr. GDP, prices	MagPIE	RCP8.5 without CO_2		x	x		x	x	T_FIX: relative share of regional trade is fixed to the level of 1995 T_LIB: reduce trade barriers by 10% per decade
Gouel and Laborde (2018)	Agr. GDP	Static CGE	SRES A1F1 (~RCP8.5) with CO_2	x			x	x	x	T_FIX: fixed import share or fixed export share T_LIB: integrated world markets
Baldos and Hertel (2015)	Hunger	SIMPLE	RCP8.5 without CO_2				x		x	T_FIX: / T_LIB: integrated world market
Wiebe et al. (2015)	Prices	ENVISAGE, FARM, IMPACT, MAGNET, MAgPIE	RCP4.5, RCP6, RCP8.5 without CO_2	x			x	x	x	T_FIX: tariffs between macro-regions doubled T_LIB: removal of tariffs and export subsidies on agri-food trade (phased out over 2020–2035).
Cui et al. (2018)	GDP, prices, …	MAGNET	RCP6 without CO_2	x		x	x		x	T_FIX: / T_LIB: removal of import tariffs, export taxes and export subsidies.
This paper	Hunger, prices	GLOBIOM	RCP2.6, RCP4.5, RCP6, RCP8.5 with CO_2 + RCP8.5 without CO_2	x	x	x	x	x	x	T_FIX: fixed max. import volume or pre-Doha tariff levels T_LIB: removal of tariffs on agricultural trade, trade facilitation or both

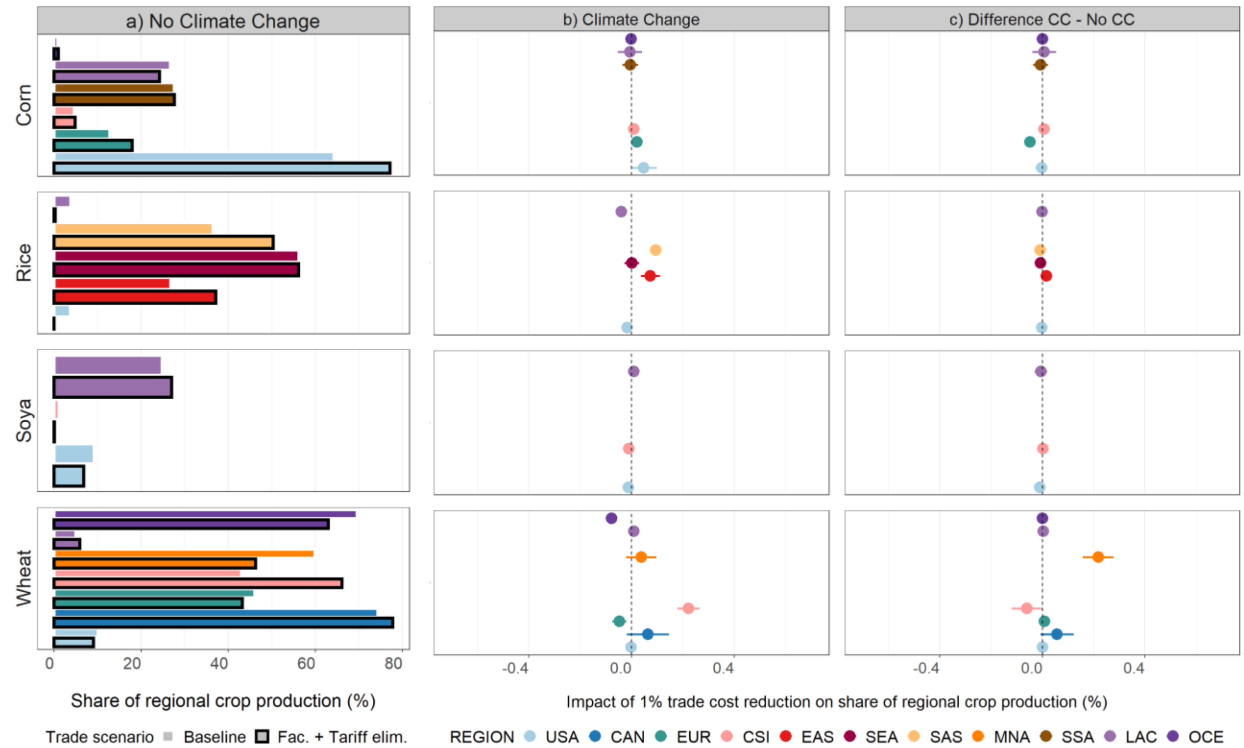


Supplementary Fig. 5 | Comparison of literature on climate change adaptation in agricultural sector through international trade: impact of restricted (T_FIX) or liberalized (T_LIB) trade compared to baseline trade scenario (T0) under RCP8.5 with (wt) or without (wo) CO_2 fertilization. T_FIX vs T0 indicates how restricting trade alters the impact climate change ($\frac{Impact\ CC\ under\ T\_FIX}{Impact\ CC\ under\ T0} - 1$). T_LIB vs T0 gives the impact of liberalizing or facilitating trade on climate change effects ($1 - \frac{Impact\ CC\ under\ T\_LIB}{Impact\ CC\ under\ T0}$). T_FIX vs T_LIB compares the impact of restricting trade compared to open trade under climate change $\left(1 - \frac{Impact\ CC\ under\ T\_LIB}{Impact\ CC\ under\ T\_FIX}\right)$. For details on the restricted (T_FIX) and liberalized (T_LIB) trade scenarios of each paper, see Supplementary Table 13.

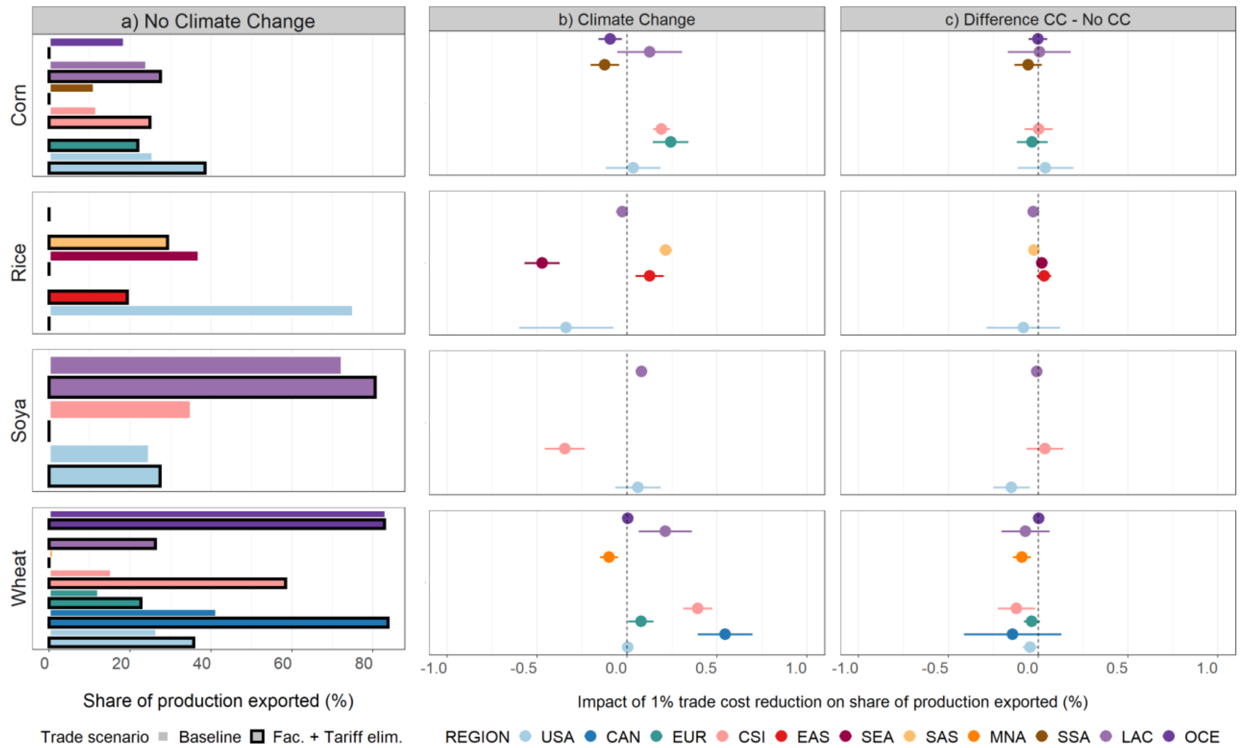
Comparative advantage analysis

Ricardo's theory of comparative advantage postulates that a country has a comparative advantage if the opportunity cost of producing a certain good in terms of other goods is smaller than it is in other countries[10]. Trade benefits countries when they export goods for which they have a comparative advantage through gains in efficiency and consumption possibilities. Less resources are needed for the same level of consumption, or equivalently, a higher consumption level can be reached for the same amount of resources. Our indicators of comparative advantage are inspired by the application of Ricardo's trade theory to a multi-country multi-good setting by Constinot et al.[11]. They propose that when trade barriers are removed, a country should not produce and export only the goods for which it has a comparative advantage, but it should produce and export relatively more of these goods. Using linear regression models, we estimate whether trade cost reduction increases the share of production of a crop that region represents in total world production of the crop (Fig. 4 in main text), the share of each crop in a region's total crop production (Supplementary Fig. 6), and the share of a region's production that is exported (Supplementary Fig. 7). Production and export effects mostly correspond, but there are some cases where reduced trade costs increase export shares without corresponding increases in production shares, e.g. corn in CSI and EUR, or wheat in CAN. These specialization indicators take into account differences in land productivity, land endowment and competitiveness between crops and regions.

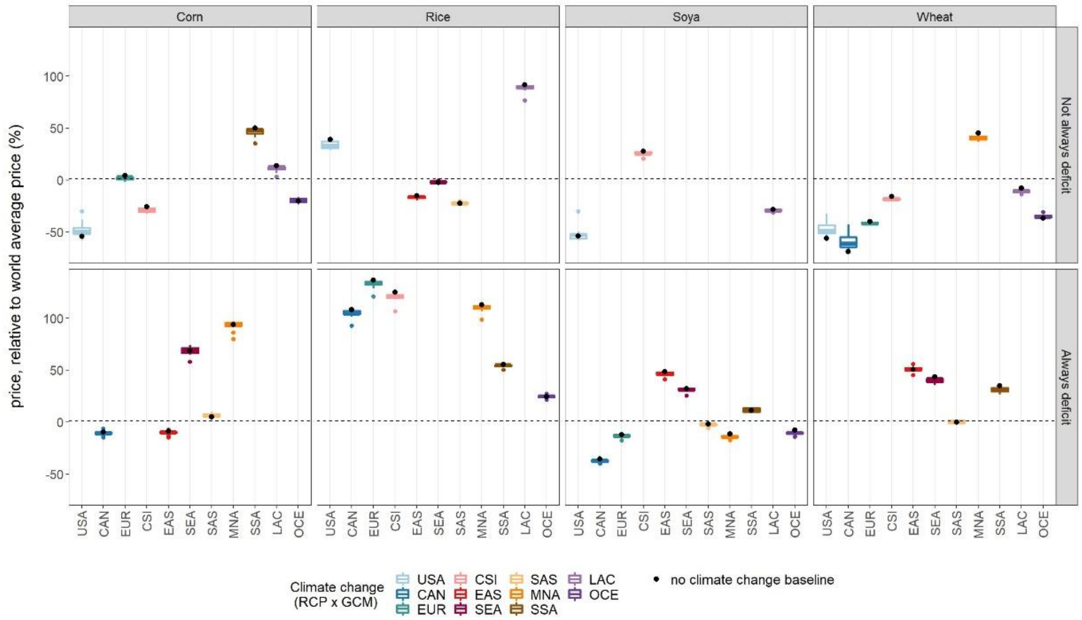
As a robustness check, we report additional indicators of comparative advantage that are common in the literature. The original definition of comparative advantage in the Ricardo trade model states that "*A country has a comparative advantage in producing a good if the opportunity cost of producing that good in terms of other goods is lower in that country than it is in other countries*." (Krugman and Obstfeld[10] p. 14). The assessment of comparative advantages requires tackling the fundamental identification problem of unobserved relative productivity differences across countries under complete specialization[12]. Costinot and Donaldson[13] demonstrate that the identification problem can be solved in the context of agricultural production by using agronomic predictions of crop yields in each country. They define comparative advantage in terms of the relative crop yield (productivity A_{cf}^{g}) between two crops (goods g) and two fields (factors f): *"If two factors located in country c are such that* $\left(\frac{A_{cf_2}^{g_2}}{A_{cf_2}^{g_1}} > \frac{A_{cf_1}^{g_2}}{A_{cf_1}^{g_1}}\right)$ *for two goods* g_1 *and* g_2*, then field* f_2 *has a comparative advantage in good* g_2*".* We use a similar measure, but perform a cross-region comparison with for each crop the ratio of yield to the average yield of all other crops (Supplementary Fig. 8). A second related indicator is the relative competitiveness across crops and regions. GLOBIOM is a perfect competition model implying that producer prices reflect marginal costs. By comparing for each region and crop its producer price to the world average price and regional average crop price, we assess to what extent a region can produce a certain crop at a lower cost compared to other regions and compared to other crops (Supplementary Fig. 9 and 10). Lastly, we report the Balassa Index[14] of Revealed Comparative Advantage (RCA) (Supplementary Fig. 11). RCA compares the export performance of a region in a certain crop with the global export performance for that crop. To exclude the impact of trade barriers on export performance, we calculate the index based on the trade pattern in the *Facilitation + Tariff elimination* scenario.



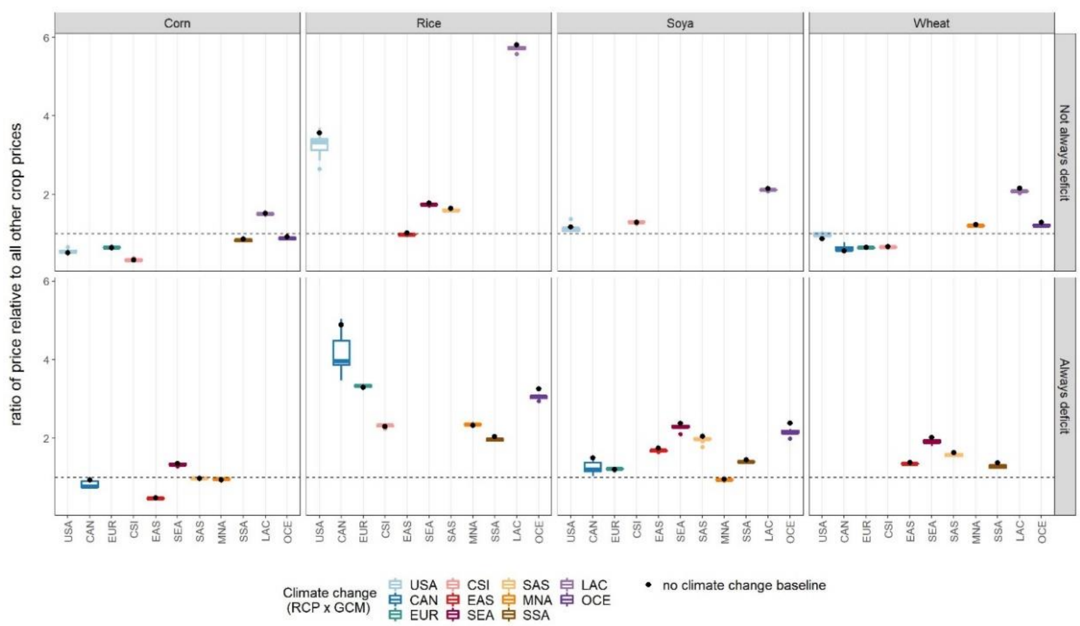
Supplementary Fig. 6 | Intra-regional specialization in corn, rice, soya and wheat in response to trade cost reduction in 2050. **a)** presents the share in total regional crop production under no climate change in *Baseline trade* and *Facilitation + Tariff Elimination*. In **b)** each point shows the estimated impact of a 1% reduction in trade costs for each region on share of regional crop production in percentage, with lines denoting the corresponding 95% confidence interval (heteroskedastic robust standard errors). Idem for **c)**, except that the outcome variable is the difference in share of regional crop production with the no climate change scenario. Regression models are described in Method.



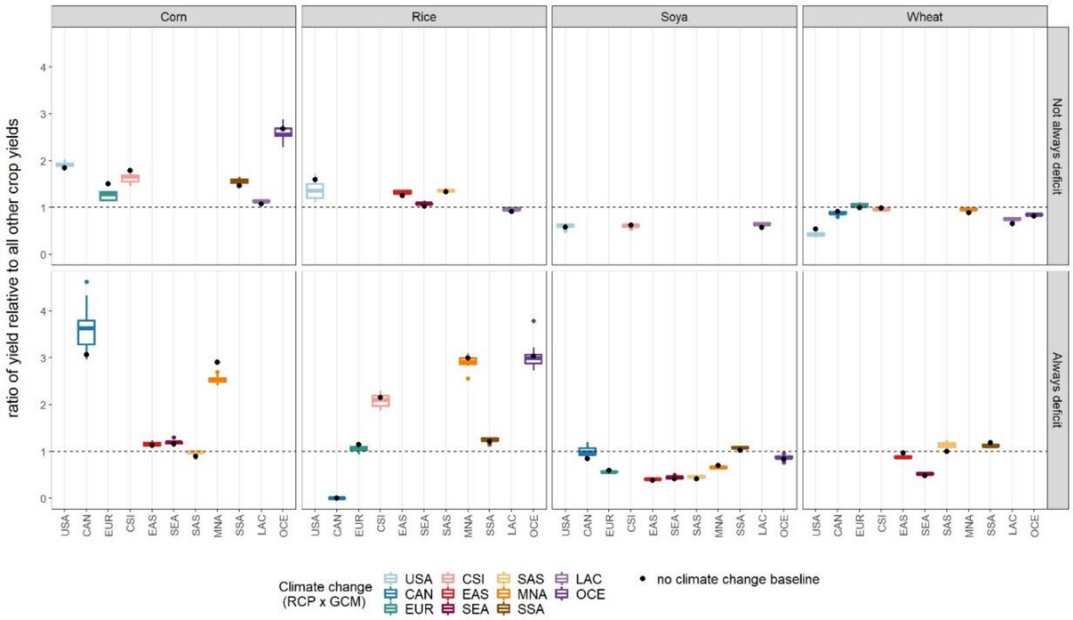
Supplementary Fig. 7 | Export orientation of production in corn, rice, soya and wheat in response to trade cost reduction in 2050. a) presents the share of production exported under no climate change in *Baseline trade* and *Facilitation + Tariff Elimination*. In **b)** each point shows the estimated impact of a 1% trade cost reduction for each region on share of production exported in percentage, with lines denoting the corresponding 95% confidence interval (heteroskedastic robust standard errors). Idem for **c)**, except that the outcome variable is the difference in share of production exported compared to no climate change. Regression models are described in Method.



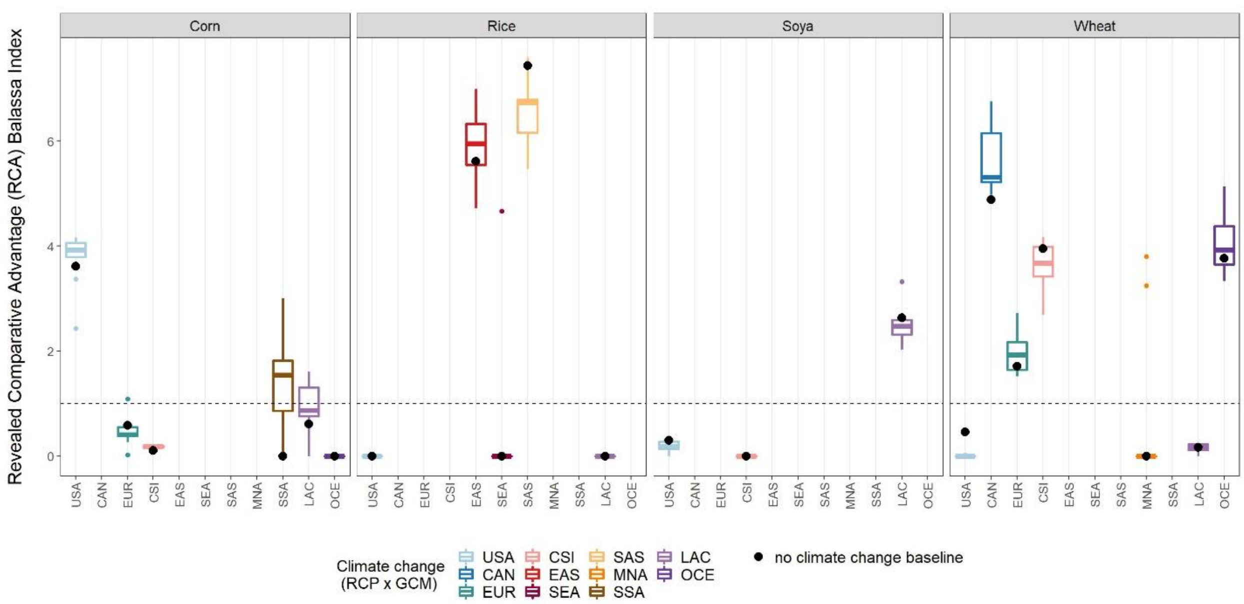
Supplementary Fig. 8 | Relative competitiveness (across regions) in response to climate change in 2050 under *Baseline trade*. The y axis indicates the producer price relative to the world average producer price for each crop, with values below zero indicating an above average competitiveness. Boxplots show the distribution of the relative producer price over the nine climate change scenarios (lower and upper hinges corresponding to 25th and 75th percentiles, whiskers reflecting values no further than 1.5*IQR from the hinges, and points showing outliers). Distinction is made between regions that have a deficit production in at least 90% of trade and climate change scenario (*Always deficit*), and regions that do not (*Not always deficit*).



Supplementary Fig. 9 | Relative competitiveness (across regions and crops) in response to climate change in 2050 under *Baseline trade*. The y-axis indicates for each crop and region the ratio of the crop price to the average price of all other crops. A ratio below 1 (below the dotted line) indicates a high competitiveness compared to other crops. Boxplots show the distribution of the ratio under the nine climate change scenarios (lower and upper hinges corresponding to 25th and 75th percentiles, whiskers reflecting values no further than 1.5*IQR from the hinge, and points outliers). Distinction is made between regions that have a deficit production in at least 90% of climate change and trade scenario (*Always deficit*), and regions who do not (*Not always deficit*).



Supplementary Fig. 10 | Relative yield of corn, rice, soya and wheat in response to climate change in 2050 under *Baseline trade*. The y-axis indicates for each crop the ratio of yield to the average yield of all other crops. A ratio larger than 1 (above the dotted line) indicates a low opportunity cost in terms of land. Boxplots show the distribution under the nine climate change scenarios (lower and upper hinges corresponding to 25th and 75th percentiles, whiskers reflecting values no further than 1.5*IQR from the hinge, and points outliers). Distinction is made between regions that have a deficit production in at least 90% of climate change and trade scenario (*Always deficit*), and regions who do not (*Not always deficit*).



Supplementary Fig. 11 | Impact of climate change on Revealed Comparative Advantage (RCA) Balassa Index in 2050 under *Facilitation + Tariff elimination*. The y-axis indicates for each crop the share of a region's exports in a region's total crop export relative to the share of the global exports in global total crop exports[14]. A value above one indicates a revealed comparative advantage. Boxplots show the distribution under the nine climate change scenarios (lower and upper hinges corresponding to 25th and 75th percentiles, whiskers reflecting values no further than 1.5*IQR from the hinge, and points outliers). Regions with deficit production in more than 10% of climate change and trade scenarios are excluded.

CO_2 fertilization sensitivity analysis

Model intercomparison studies show that the representation of the CO_2 fertilization effect is one of the key factors causing uncertainty in crop yield projections under climate change[15,16]. The fertilization effect depends on nutrient and water availability, and is heterogeneous across crops and regions[16–18]. Compared to other crop models, EPIC is on the conservative side in terms of the positive impact of CO_2 fertilization[15]. To check the sensitivity of our results to the impact of CO_2 fertilization on crop yields, we ran the full spectrum of RCP scenarios (RCP2.6, RCP4.5, RCP6, RCP8.5) with and without CO_2 fertilization. For the full spectrum, we have, however, only crop projections available from EPIC for four crops (corn, soya, wheat and rice) based on HadGEM2-ES climate change projections. The limited availability of non-CO_2 sensitivity runs is related to priorities set in the ISIMIP Fast Track protocol (see Method). To model climate change shifts for all crops in GLOBIOM, we map the crop yield impacts from the four crops to the other crops in a similar way as the mapping used by Müller and Robertson[19] for DSSAT (Supplementary Table 14).

Supplementary Table 14| Mapping of corn, wheat, rice and soya yield simulations from EPIC to all crops in GLOBIOM for the CO_2 sensitivity analysis (RCP2.6 – RCP8.5: with or without CO_2 fertilization)[1].

GLOBIOM crop	Mapping
C_3 crops (cassava, groundnuts, rapeseed, sunflower, palm, chickpeas, cotton, potatoes, sweet potatoes, beans)	C_3 crops are represented by the average climate impact on the three C_3 crops that are directly simulated (wheat, rice and soybean)[2]
Corn	Corn yield is directly simulated
Millet, sorghum	Millet and sorghum are represented by modified corn yield simulations: only half of the negative effects are applied due to better drought tolerance
Rice	Rice yield is directly simulated
Soybean	Soybean yield is directly simulated
Sugarcane	Sugarcane yield is represented by corn yield simulations
Wheat	Wheat yield is directly simulated
Other grains (barley)	Barley is represented by modified wheat yield simulations: only half of the negative effects are applied due to better drought tolerance

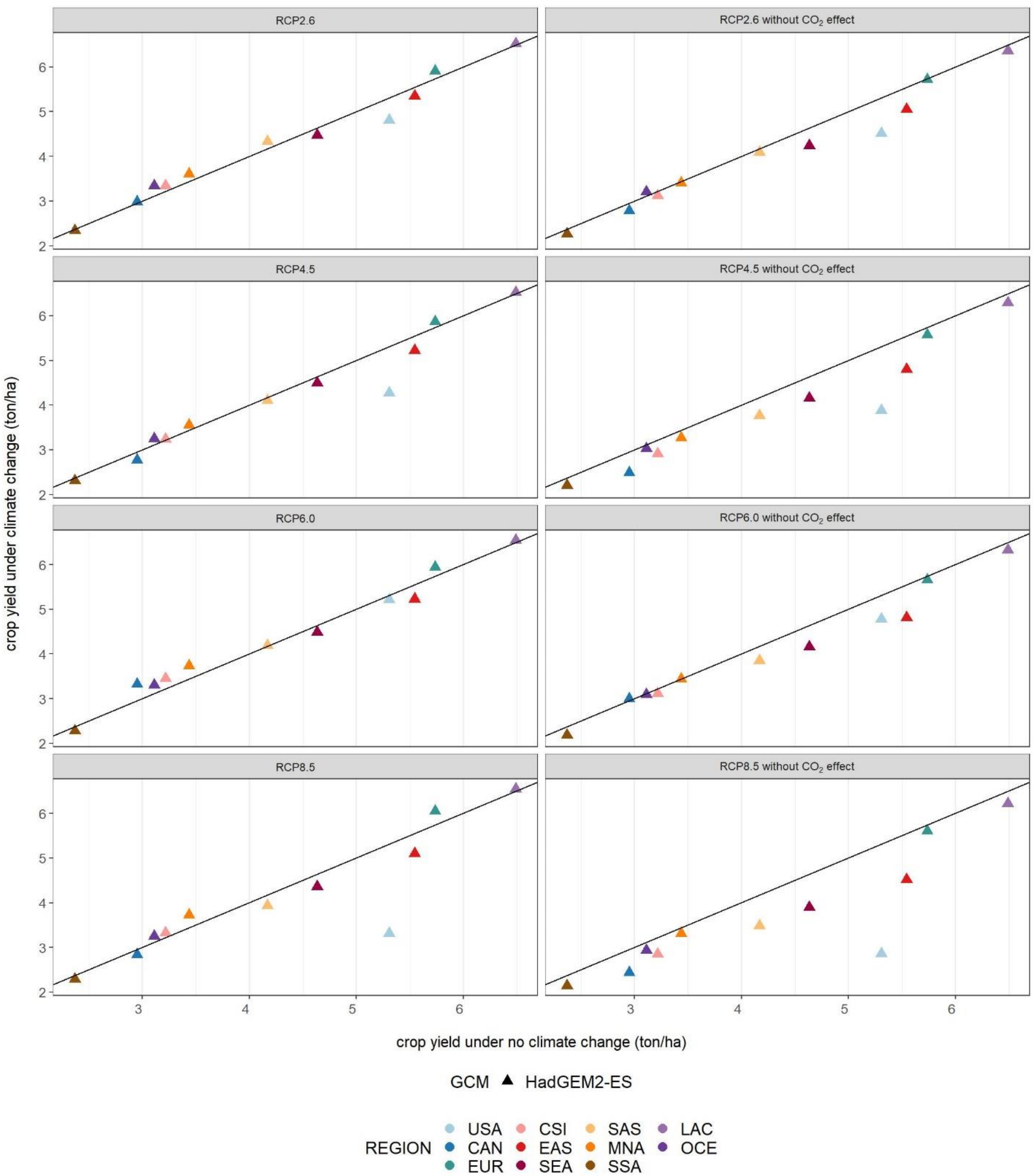
[1]The sensitivity analysis to CO_2 fertilization is limited to crop impacts. For grassland, we use the EPIC yield shifters for each RCP including CO_2 fertilization. [2]We compute the average of wheat, rice and soybean impacts weighted by base year area x yield.

Supplementary Fig. 12 shows the average crop yield impacts under the different RCPs, with and without the effect of CO_2 fertilization. The simulated crop yield under each RCP is lower when CO_2 fertilization is not taken into account. Average crop yields in this scenario set are in most regions larger than the simulations in the paper (Supplementary Table 15). This is a consequence of the bias that is introduced by mapping the impacts of corn, wheat, soya and rice to the other crops compared to the scenario set in the paper where we use direct simulations from EPIC for all crops.

Supplementary Fig. 13 plots the global risk of hunger under the alternative set of climate change scenarios. In the *Baseline trade* scenario, the risk of hunger is always higher without than with CO_2 fertilization. The hunger projections under the scenarios that we miss in the main scenario set (RCP2.6 – RCP6 without CO_2) lie between the lowest (RCP2.6 with CO_2) and highest climate change impact (RCP8.5 without CO_2). This shows that we capture the full range of climate change impacts in our main scenario set. Note that the increase in risk of hunger under these climate change scenarios is lower than in the original runs (Fig. 1 in main text). This is related to the bias introduced by the mapping, as also reflected in the lower average crop yield impacts in the simulations based on the 4 priority crops (Supplementary Table 15). As in the original run, the risk of hunger in RCP4.5 is slightly higher than in RCP6. In 2050 the atmospheric concentration of CO_2 and likely range of global mean temperature increase are slightly higher under RCP4.5 than under RCP6, while by the end of the century the situation is reversed[20,21]. The effect of the trade scenarios is the same as in the original run: *Fixed imports* and *pre-Doha tariffs* increase hunger, while *Tariff elimination*, *Facilitation* and the combined scenario decrease hunger. Also the regional results from the main scenario set (Extended Data Fig. 7) are robust under the alternative set of climate change scenarios (Supplementary Fig. 14). SAS and SSA face the most severe hunger risks. SSA, EAS and MNA benefit the most from trade liberalization and facilitation in terms of hunger reduction, while in SEA and SAS tariff elimination has adverse impacts in some climate change scenarios.

We also analyze the relation between hunger, trade costs and crop yields based on the alternative set of climate change scenarios (Supplementary Table 16). The findings are similar to the results in main text (Table 1): reducing trade costs lowers the risk of hunger and lower crop yields increases the risk of hunger. When excluding regions that experience negative impacts in some trade scenarios (SAS, SEA), we find, however, no significant negative interaction effect. This could be related to the overall lower hunger impacts of the alternative climate change scenario set.

Lastly, to assess the sensitivity of our comparative advantage results to CO_2 fertilization, we cannot use the alternative set of climate change scenarios because comparative advantage is determined by relative crop yield impacts. The mapping used to extrapolate impacts from the 4 crops to other crops implies that crop impacts are by construction correlated and that an analysis of comparative advantage based on these simulations would thus be biased. We therefore use our original scenario set and compare our indicator of comparative advantage between RCP8.5 with and without CO_2 fertilization. Supplementary Fig. 15 illustrates that the changes in share of global production for each crop are similar in the RCP8.5 scenario with and without CO_2 fertilization. This suggests that the conclusion on the impact of climate change on the pattern of comparative advantage is not affected by the CO_2 fertilization effect.

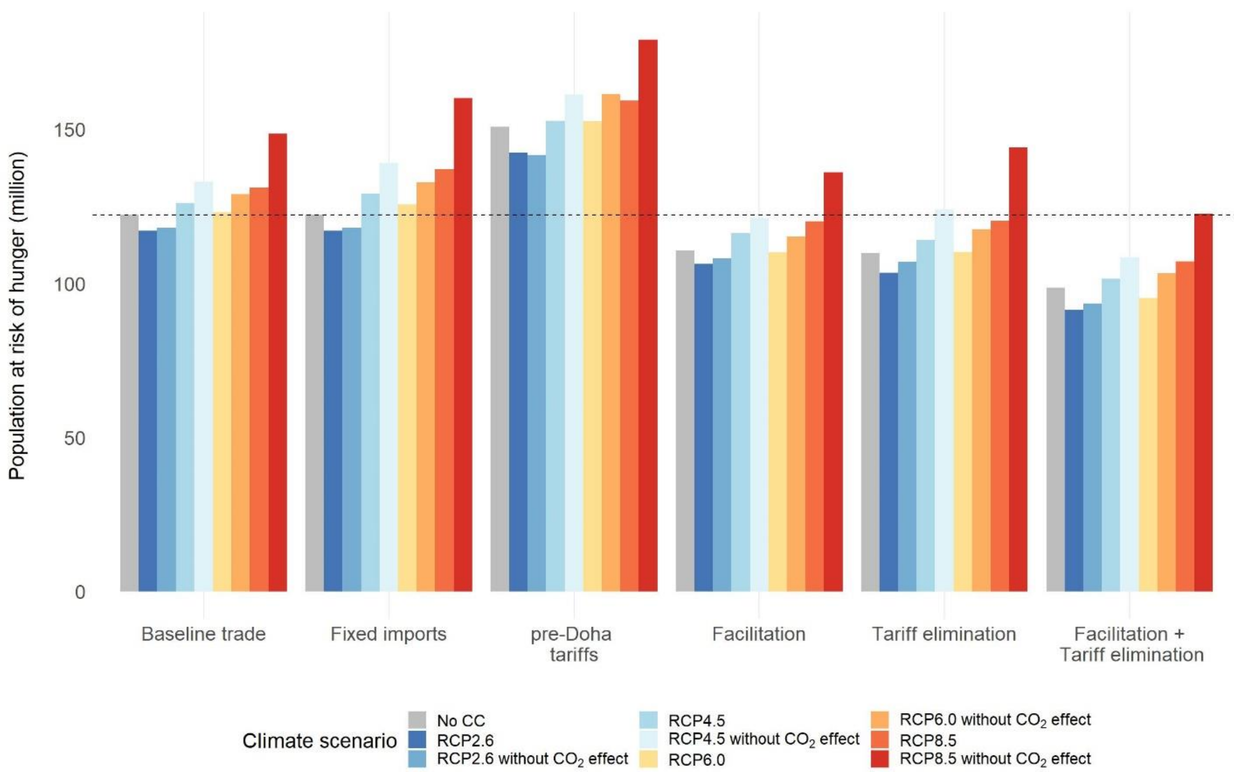


Supplementary Fig. 12 | Biophysical impact of climate change on average crop yield in each region by 2050 as projected by the EPIC crop model. Yields in ton dry matter per ha. The x-axis indicates the average crop yield under no climate change and y-axis the average crop yield under climate change for different RCPs with and without considering the CO_2 fertilization effect. Points above the black line indicate an increase in crop yield, points below a decrease in crop yield. Direct simulations for corn, wheat, rice and soya. Climate change impacts for the other crops are based on the mappings in Supplementary Table 14.

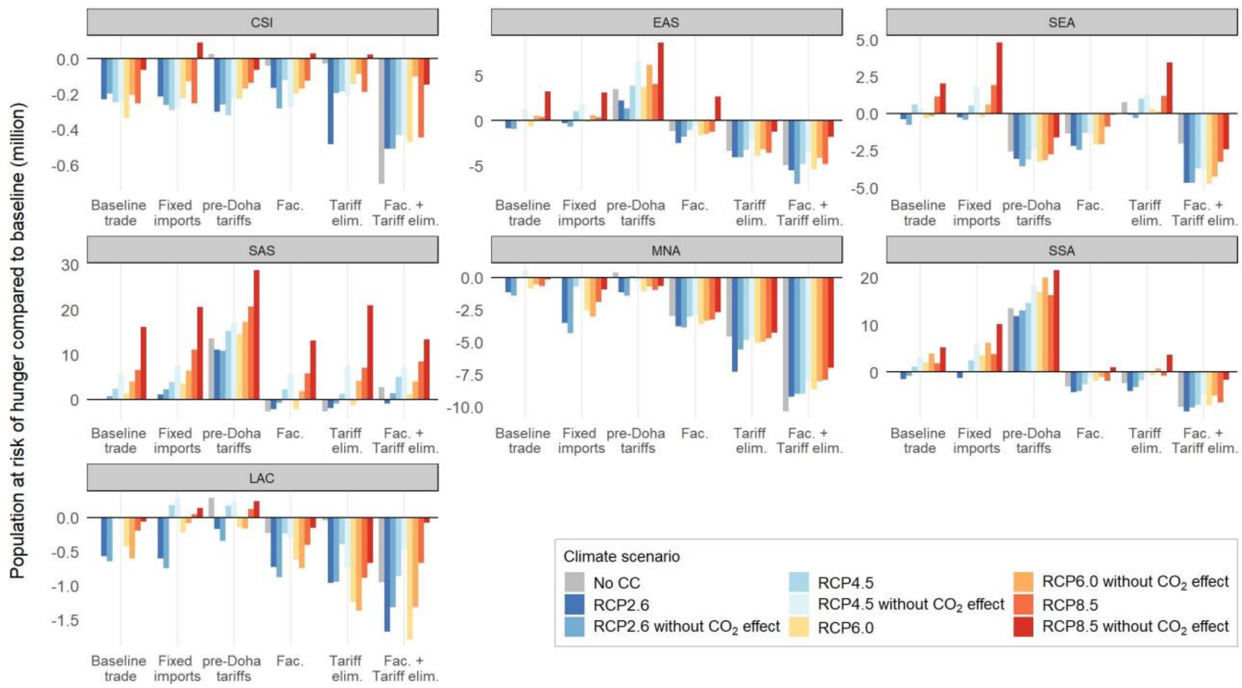
Supplementary Table 15 | Comparison of average crop yield (dm ton/ha) in each region based on direct EPIC simulations on all crops (1) and EPIC simulations based on 4 major crops (2), with (wt) and without (wo) the effect of CO_2 fertilization**.** Climate projections from HadGEM2-ES.

	CAN		CSI		EAS		EUR		LAC		MNA	
Climate scenario	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(2)	(1)	(1)	(2)
RCP2.6 wt CO_2	2.93	2.98	3.29	3.34	5.34	5.35	5.92	5.91	6.20	6.52	3.48	3.61
RCP4.5 wt CO_2	2.71	2.77	3.24	3.24	5.20	5.23	5.88	5.86	6.12	6.52	3.42	3.56
RCP6.0 wt CO_2	3.32	3.33	3.42	3.46	5.20	5.23	6.01	5.94	6.20	6.55	3.60	3.74
RCP8.5 wt CO_2	2.80	2.84	3.29	3.33	5.06	5.10	6.09	6.05	6.02	6.55	3.56	3.73
RCP8.5 wo CO_2	2.35	2.44	2.75	2.85	4.51	4.52	5.46	5.61	5.64	6.22	3.12	3.32

	OCE		SAS		SEA		SSA		USA	
Climate scenario	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
RCP2.6 wt CO_2	3.26	3.35	4.22	4.33	4.28	4.47	2.26	2.34	4.81	4.81
RCP4.5 wt CO_2	3.15	3.25	3.90	4.11	4.28	4.50	2.19	2.31	4.28	4.27
RCP6.0 wt CO_2	3.23	3.30	4.01	4.19	4.28	4.49	2.18	2.28	5.22	5.21
RCP8.5 wt CO_2	3.13	3.26	3.68	3.94	4.08	4.36	2.15	2.29	3.31	3.31
RCP8.5 wo CO_2	2.73	2.93	3.27	3.48	3.61	3.89	2.02	2.15	2.85	2.86



Supplementary Fig. 13 | Global population at risk of hunger (million) in 2050 across RCPs from HadGEM2-ES and trade scenarios – impact of CO_2 fertilization.

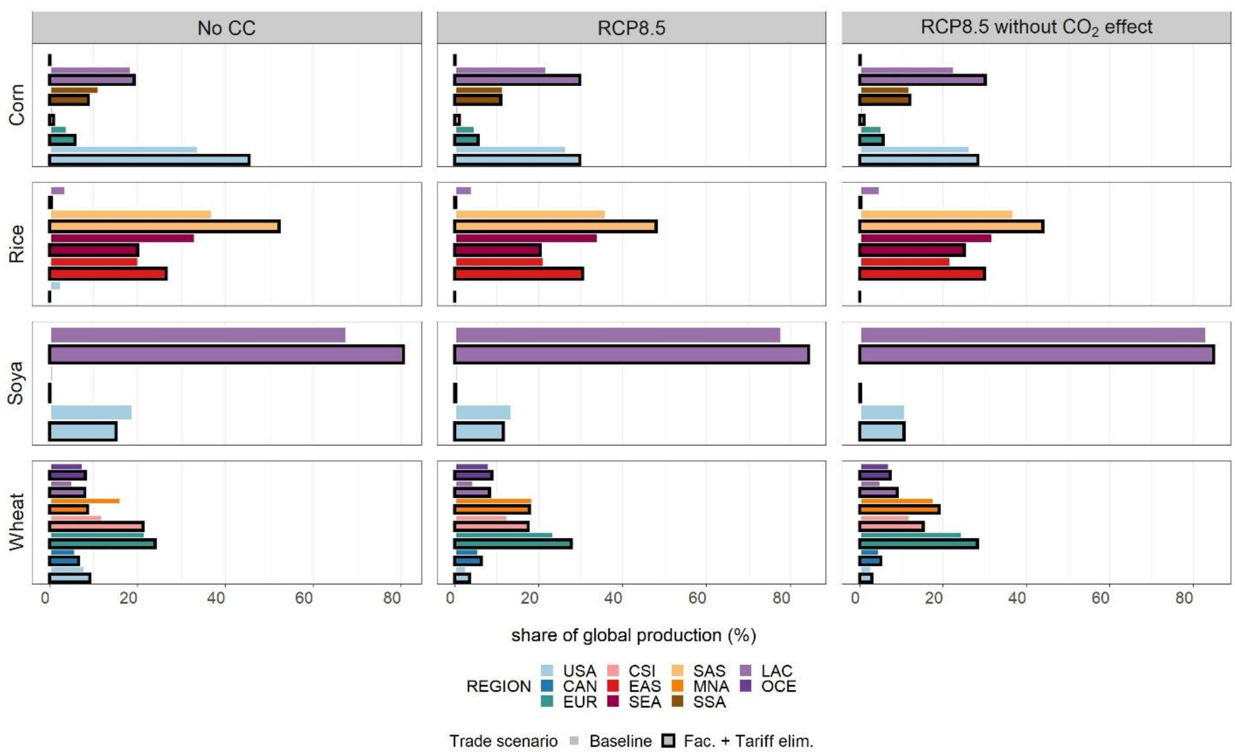


Supplementary Fig. 14 | Population at risk of hunger (million) in 2050 across RCPs from HadGEM2-ES and trade scenarios in hunger-affected regions – impact of CO_2 fertilization.

Supplementary Table 16 | Results from OLS estimation of the impact of crop yields, trade costs and their interaction on population at risk of hunger and food availability. Observations are GLOBIOM output for the 11 world regions under five different trade scenarios (Baseline, pre-Doha tariffs, Facilitation, Tariff elimination, and Facilitation + Tariff elimination) and the set of 9 alternative climate change scenarios in 2050 (No CC, RCP2.6 – RCP8.5: with and without CO_2 fertilization effect projected by EPIC & HadGEM2-ES).

	Population at risk of hunger (million)				Food availability (kcal/cap/day)			
	(1) All regions		(2) without SAS and SEA		(1) All regions		(2) without SAS and SEA	
Crop yield (% change)	-8.35	***	-2.85		241.00	***	210.00	***
	(2.99)		(2.22)		(39.30)		(43.40)	
Trade cost (log of US$/$10^6$ kcal)	4.22	***	4.62	***	-42.90	***	-63.90	***
	(0.53)		(0.60)		(6.56)		(9.68)	
Crop yield x Trade cost	0.01		-5.65		215.00	***	271.00	***
	(5.32)		(4.17)		(74.00)		(85.60)	

Significance levels: *p<0.1; **p<0.05; ***p<0.01. Regional fixed effects included. Heteroskedastic robust standard errors in brackets. N = 495 for (1) and 405 for (2). Adjusted R squared is 0.926 (1) and 0.948 (2) for hunger regressions and 0.955 (1) and 0.920 (2) for food availability regressions.



Supplementary Fig. 15 | Impact of trade liberalization and trade facilitation on regions' share of global production of corn, rice, soya and wheat under no climate change (No CC), RCP8.5 with CO_2 fertilization and RCP8.5 without CO_2 fertilization. Direct EPIC simulations on all crops based on climate change projections from HadGEM2-ES.

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