Supplementary Information

Global hunger and climate change adaptation through international trade

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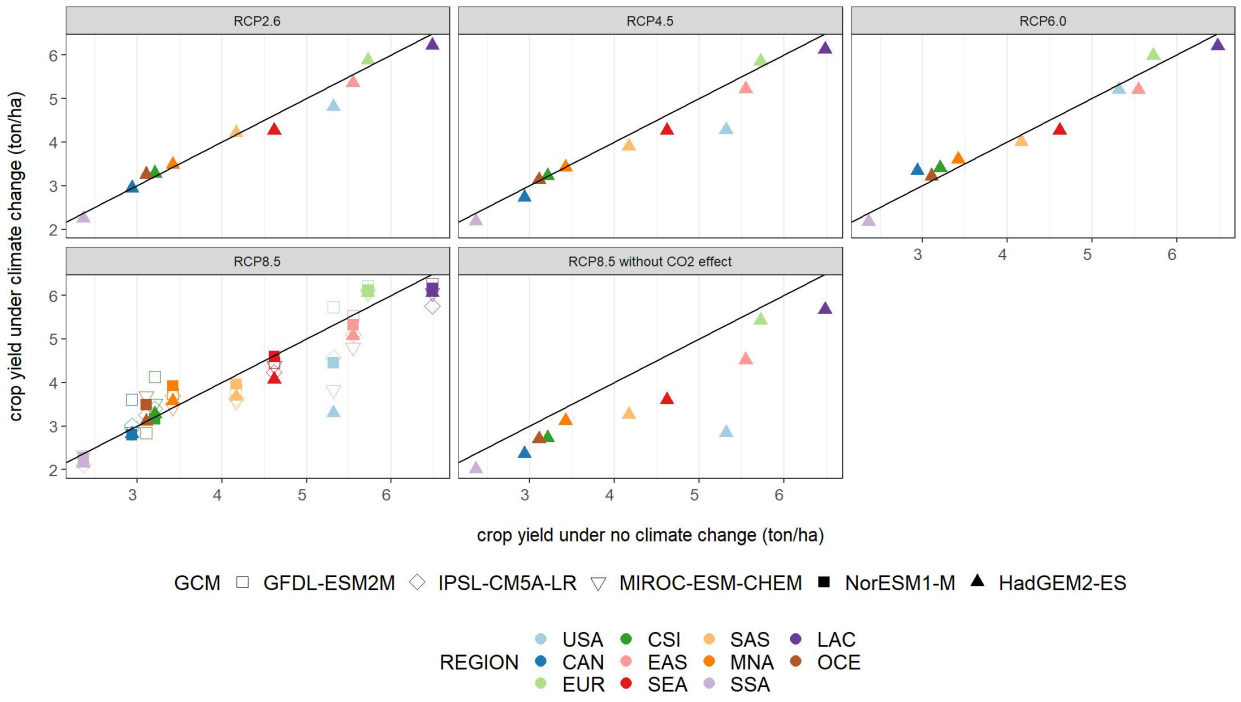
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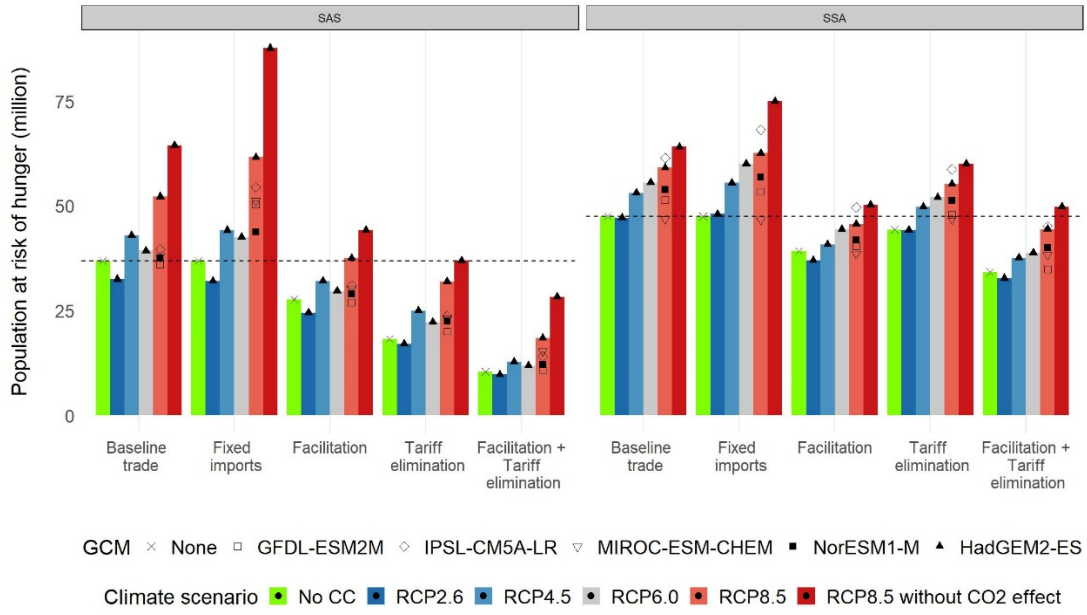
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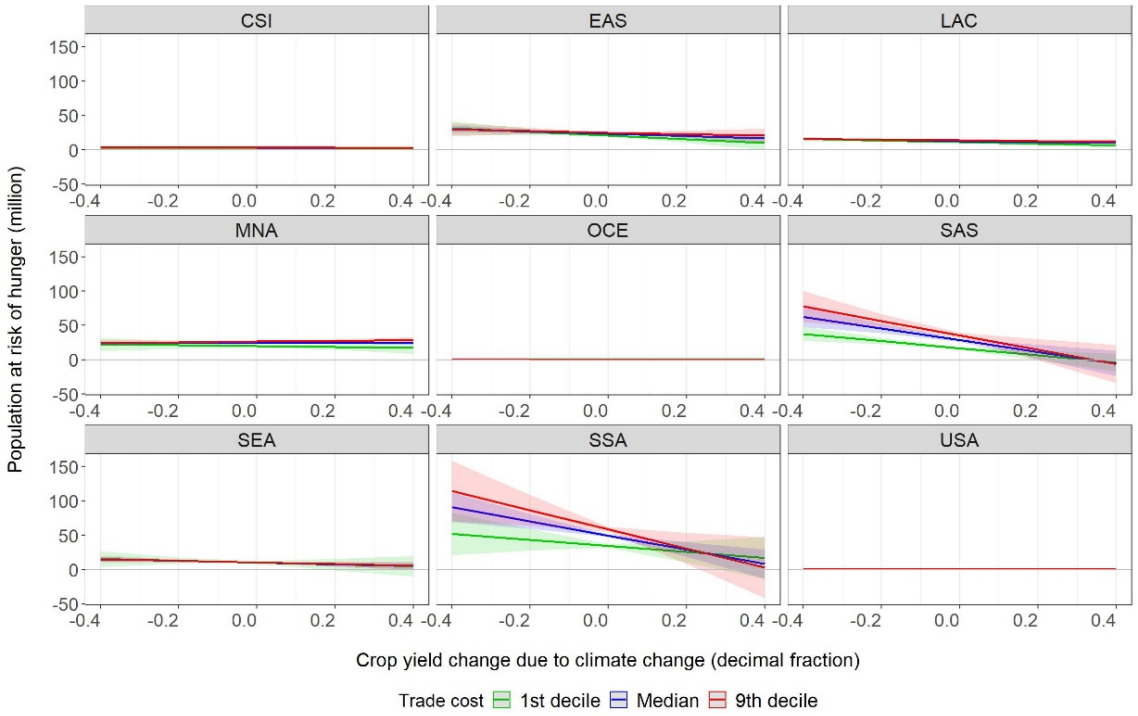
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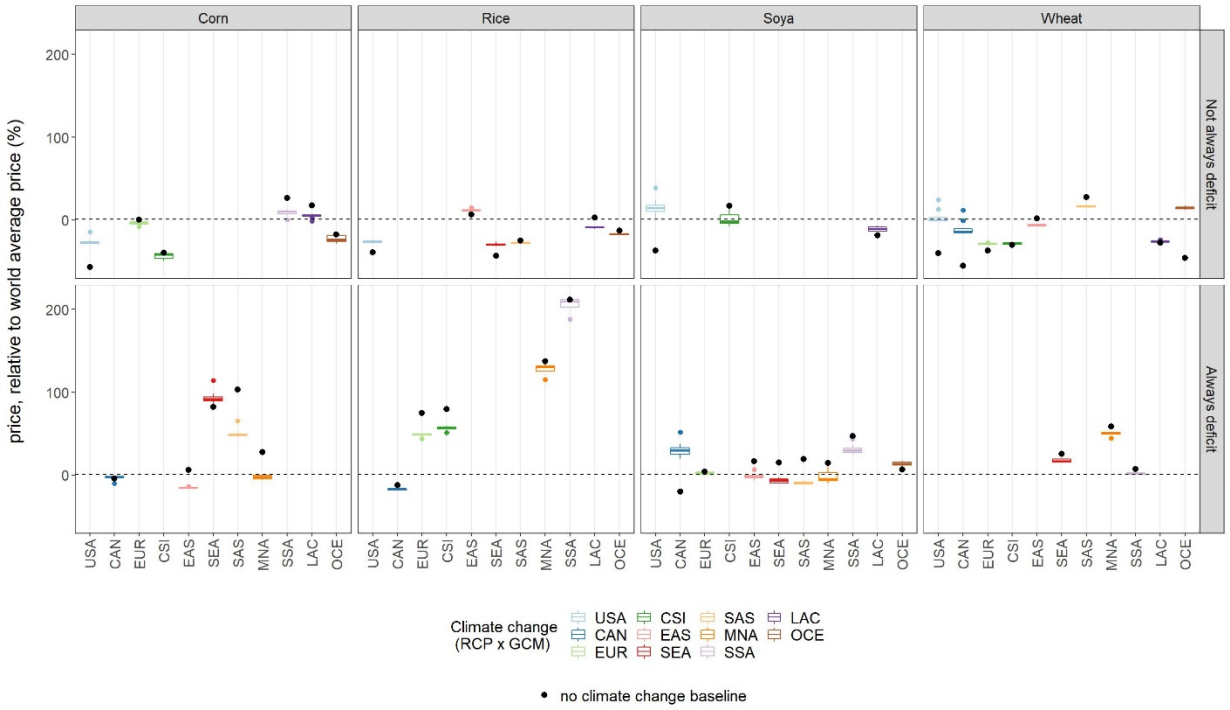
Supplementary Figure 1 | Impact of climate change on average crop yield in each region by 2050. The x-axis indicates the crop yield under no climate change (without GLOBIOM market feedback) and y-axis the crop yield as projected by the EPIC crop model under climate change for different RCP x GCM combinations (without adaptation measures). Points above the black line indicate an increase in crop yield, points below a decrease in crop yield.



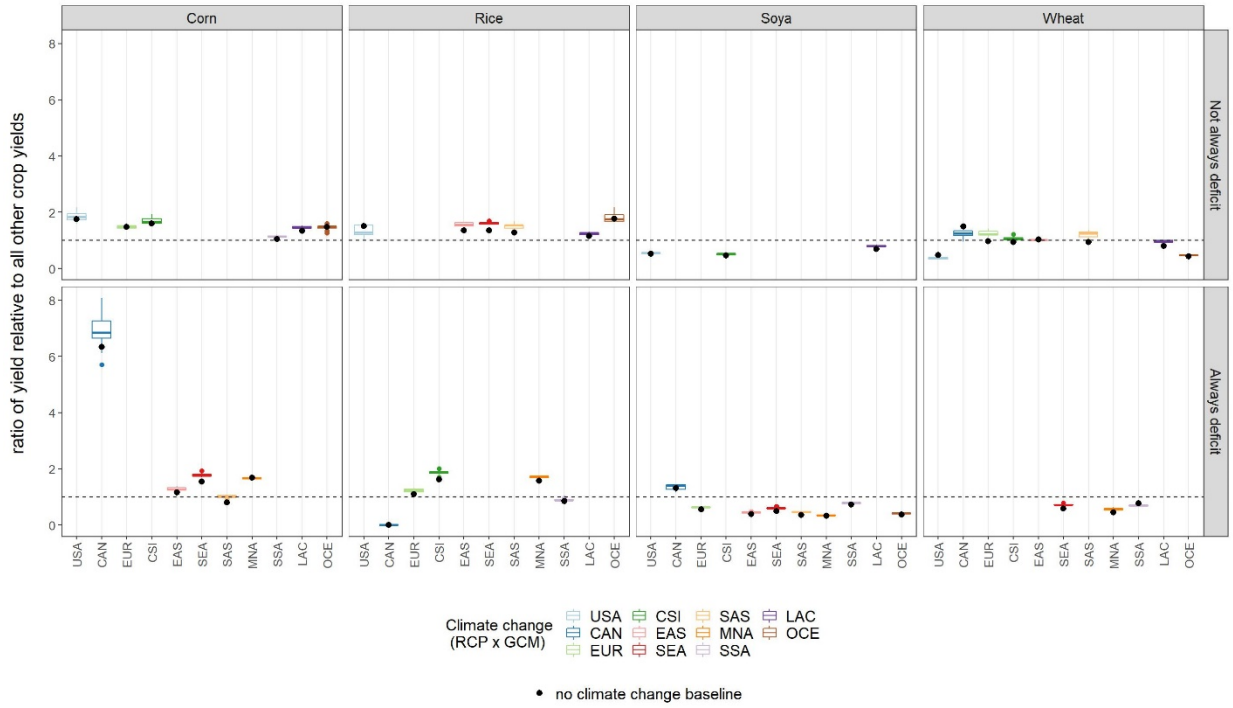
Supplementary Figure 2 | Population at risk of hunger in 2050 in South Asia (SAS) and Sub-Saharan Africa (SSA) under different climate change and trade scenarios (million). The black dotted horizontal lines indicate the population at risk of hunger in the SSP2 baseline.



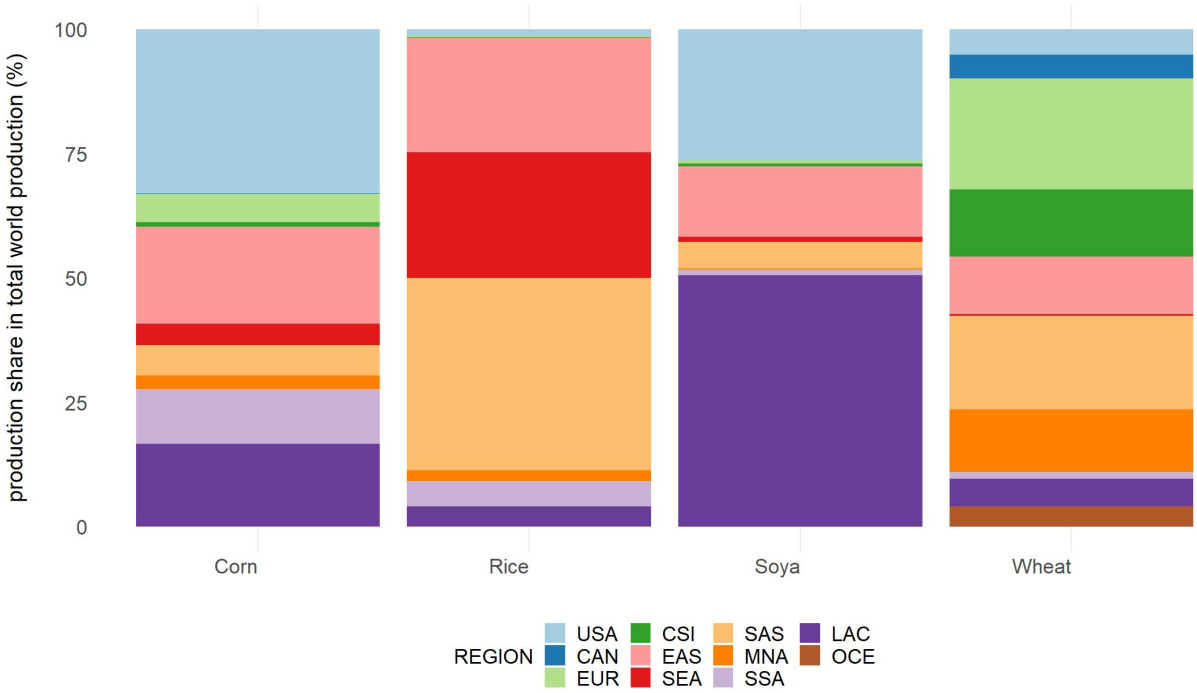
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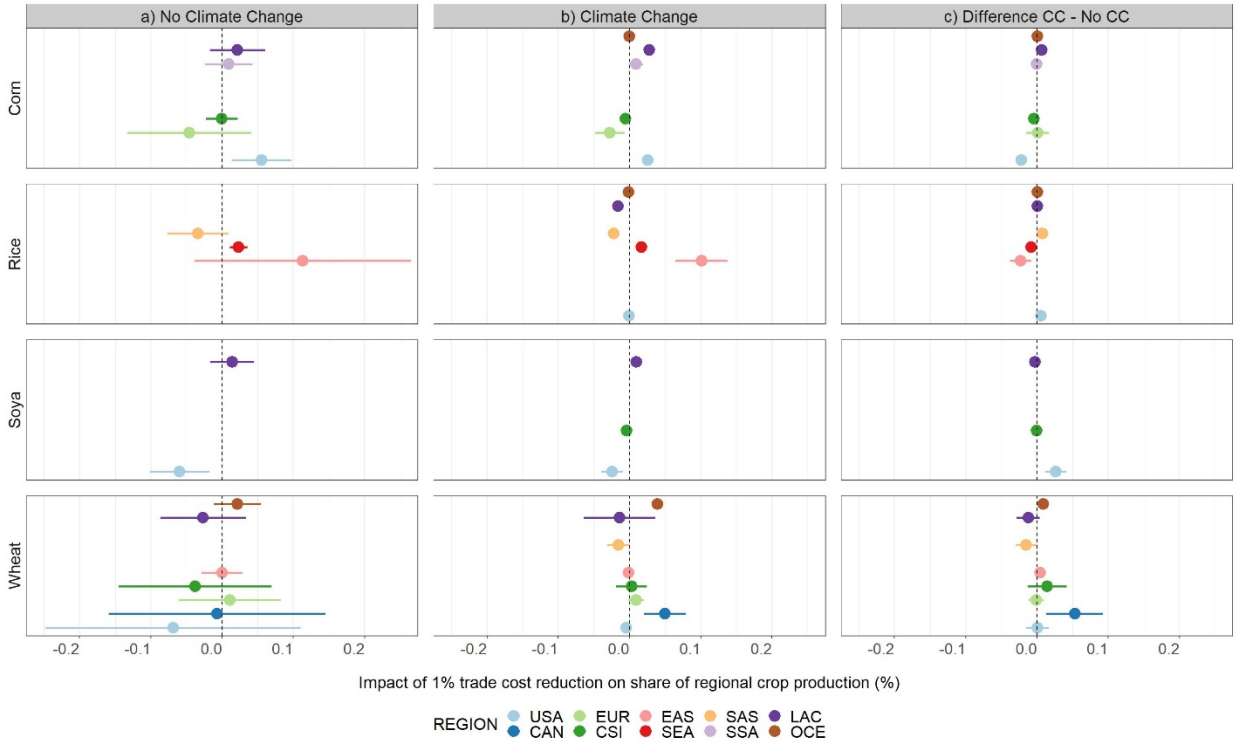
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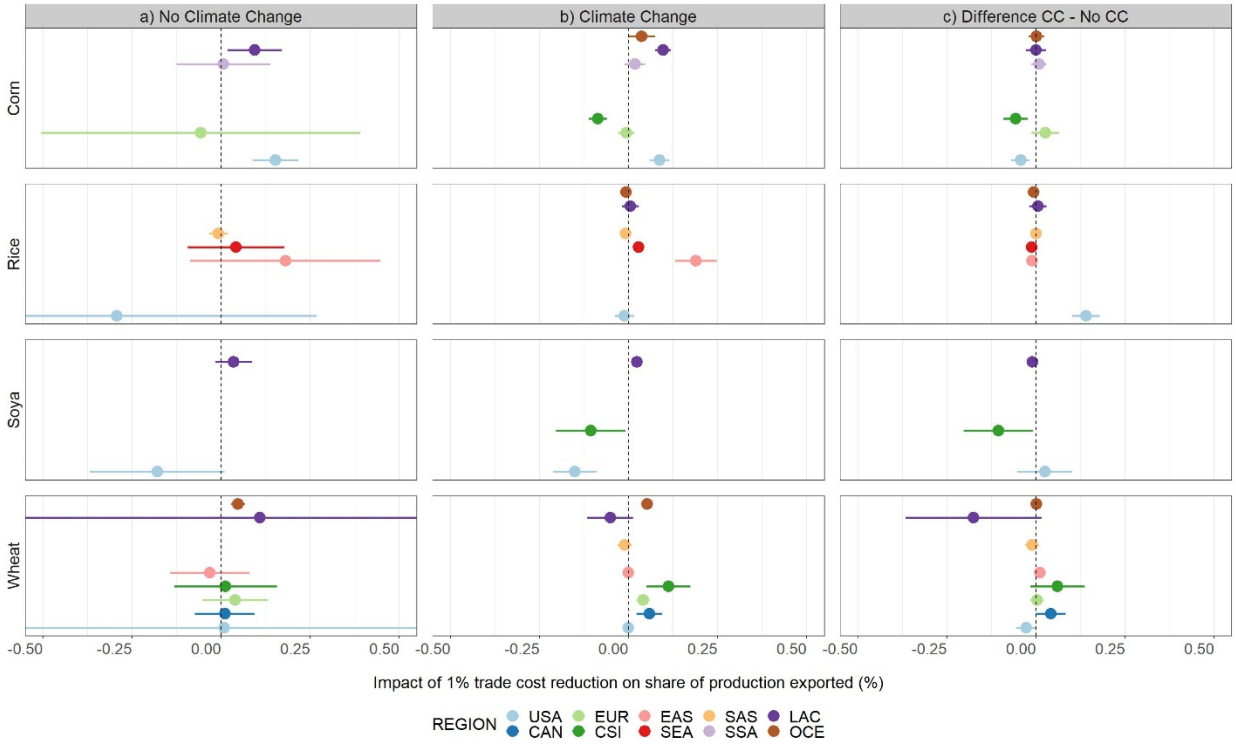
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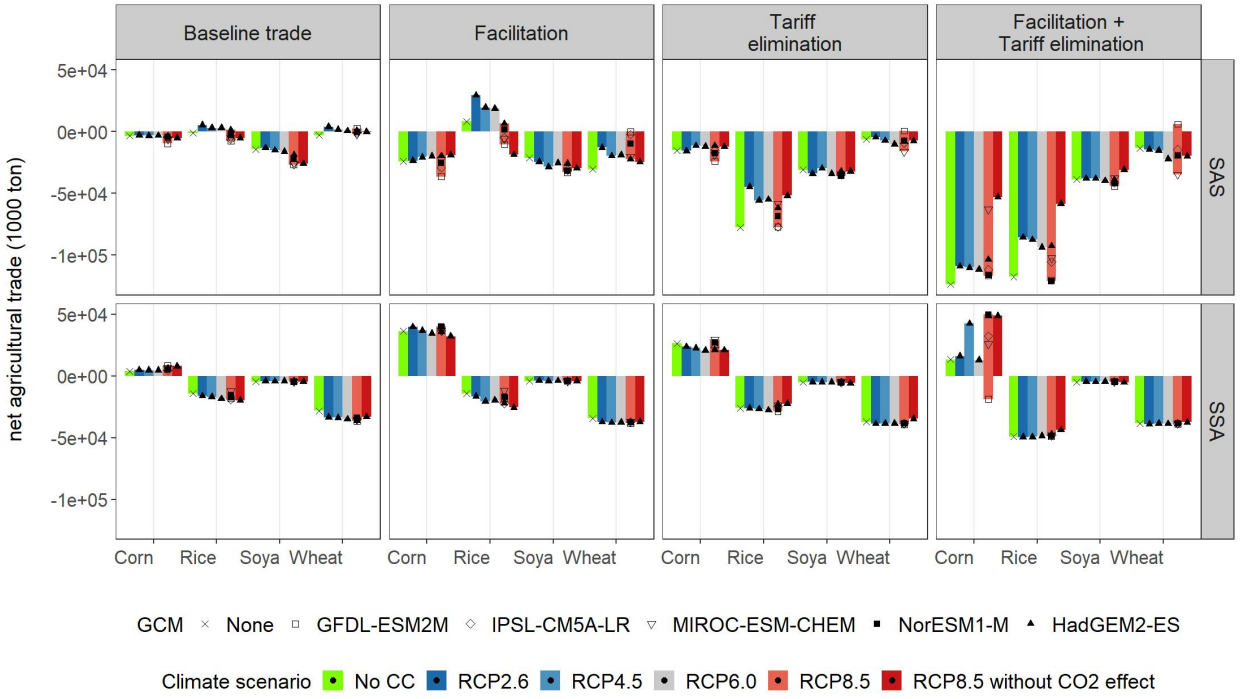
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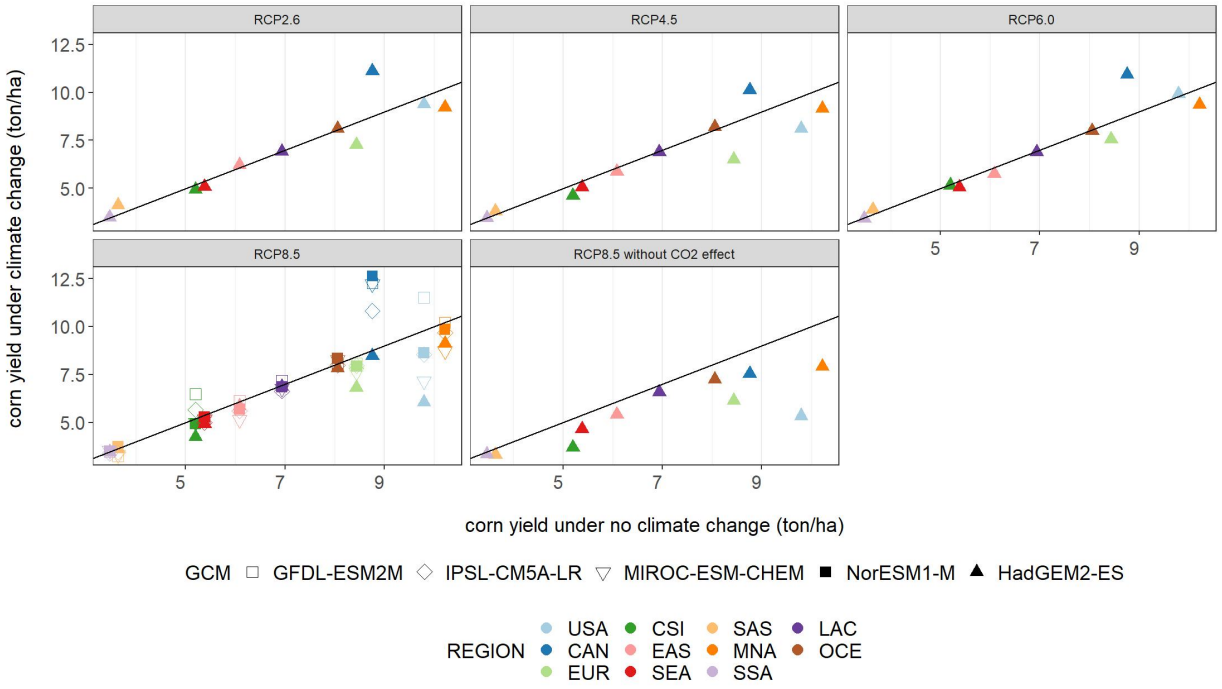
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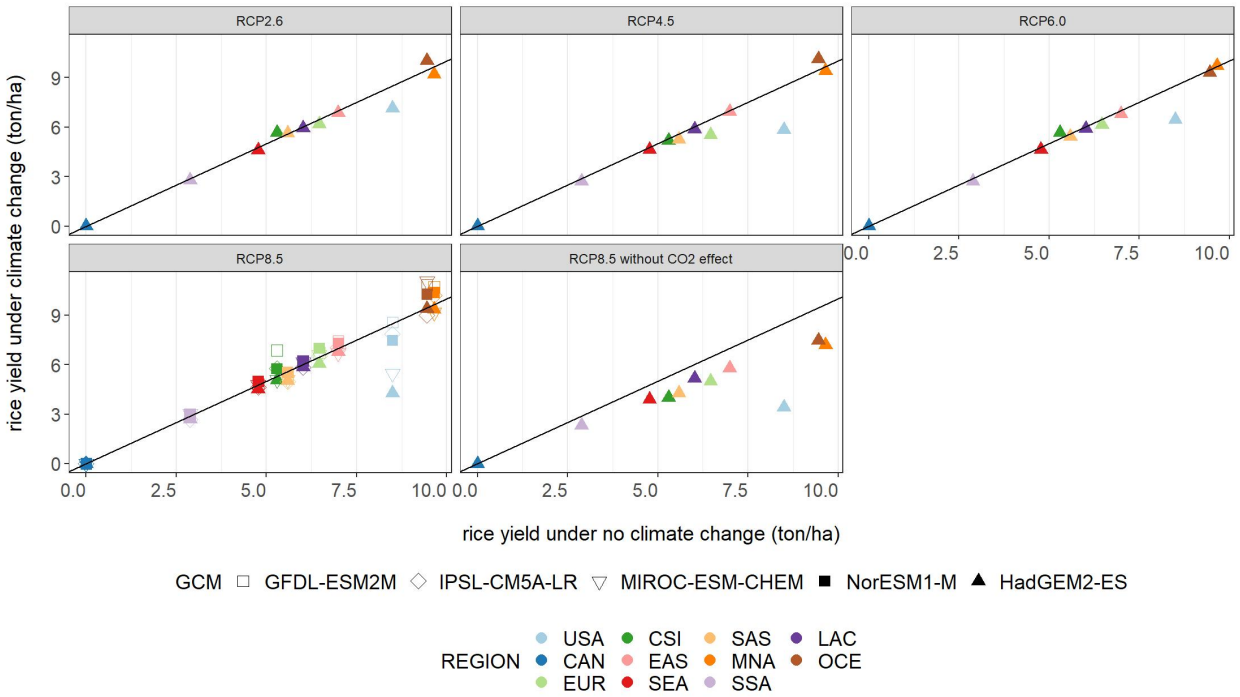
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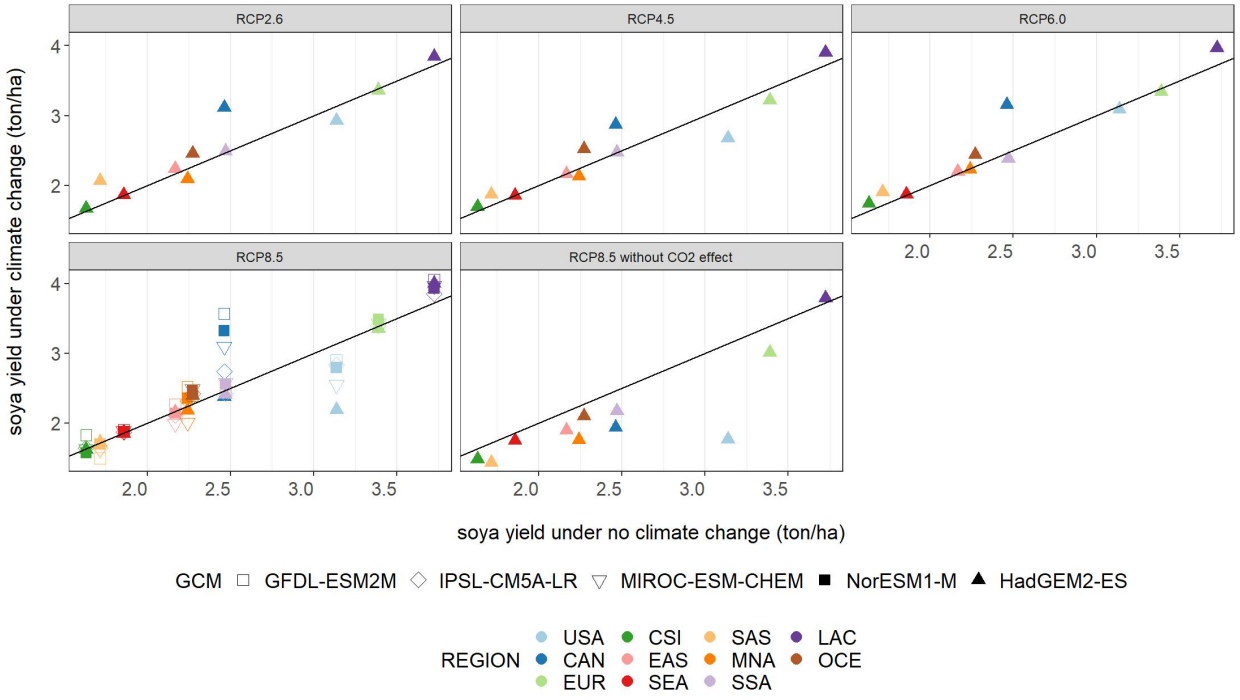
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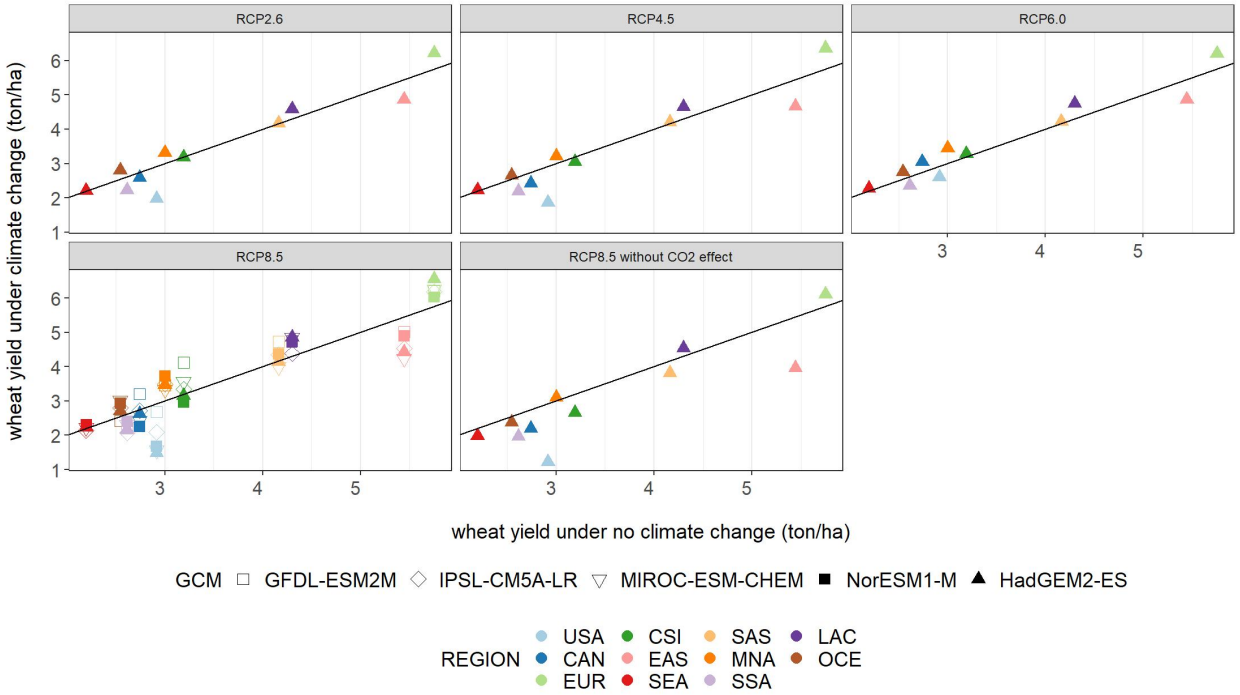
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Supplementary Figure 12 | Soya yield under climate change and no climate change in each region as projected by the EPIC crop model in 2050. Under no climate change crop yields are determined by base year yields and assumptions on technological development over time.



Supplementary Figure 13 | Wheat yield under climate change and no climate change in each region as projected by the EPIC crop model in 2050. Under no climate change crop yields are determined by base year yields and assumptions on technological development over time.

Supplementary Tables

Supplementary Table 1 | Global trade adjustments under trade and climate change scenarios compared to the SSP2 baseline computed by GLOBIOM by 2050. Total trade growth and specific extensive margin trade growth, the latter indicated as new trade flows compared to the 2000 trade pattern and new trade flows compared to the baseline SSP2 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 trade volume (1000 ton)	Difference in total trade w.r.t. baseline (%)	Total volume of new trade flows w.r.t. 2000 (1000 ton)	Total volume of new trade flows w.r.t. baseline (1000 ton)
No CC	None	Baseline	1317834	0	18727	0
RCP2.6	HadGEM2-ES	Baseline	1359078	0.03	20991	13240
RCP4.5	HadGEM2-ES	Baseline	1375502	0.04	22346	14634
RCP6.0	HadGEM2-ES	Baseline	1383007	0.05	22529	19376
RCP8.5	GFDL-ESM2M	Baseline	1471206	0.12	19937	7485
RCP8.5	HadGEM2-ES	Baseline	1401549	0.06	25142	31346
RCP8.5	IPSL-CM5A-LR	Baseline	1429006	0.08	22770	12219
RCP8.5	MIROC	Baseline	1480669	0.12	19782	32376
RCP8.5	NorESM1-M	Baseline	1348113	0.02	19942	17856
RCP8.5 wo	HadGEM2-ES	Baseline	1497331	0.14	29199	37426
No CC	None	Fixed imports	1317191	0.00	18726	0
RCP2.6	HadGEM2-ES	Fixed imports	1189833	-0.10	17319	0
RCP4.5	HadGEM2-ES	Fixed imports	1178552	-0.11	17344	0
RCP6.0	HadGEM2-ES	Fixed imports	1187908	-0.10	17502	0
RCP8.5	GFDL-ESM2M	Fixed imports	1223395	-0.07	16637	0
RCP8.5	HadGEM2-ES	Fixed imports	1132023	-0.14	16921	0
RCP8.5	IPSL-CM5A-LR	Fixed imports	1214310	-0.08	16295	0
RCP8.5	MIROC	Fixed imports	1144187	-0.13	16166	0
RCP8.5	NorESM1-M	Fixed imports	1174511	-0.11	16569	0
RCP8.5 wo	HadGEM2-ES	Fixed imports	1127856	-0.14	17178	0
No CC	None	Facilitation + Tariff	5845726	3.44	65044	338724
RCP2.6	HadGEM2-ES	Facilitation + Tariff	6266867	3.76	66401	380811
RCP4.5	HadGEM2-ES	Facilitation + Tariff	5960152	3.52	67875	372203
RCP6.0	HadGEM2-ES	Facilitation + Tariff	6167365	3.68	66789	393398
RCP8.5	GFDL-ESM2M	Facilitation + Tariff	6473411	3.91	67580	340295
RCP8.5	HadGEM2-ES	Facilitation + Tariff	5629993	3.27	69609	399729
RCP8.5	IPSL-CM5A-LR	Facilitation + Tariff	5977386	3.54	70197	352002
RCP8.5	MIROC	Facilitation + Tariff	5994512	3.55	65398	383632
RCP8.5	NorESM1-M	Facilitation + Tariff	5745481	3.36	67255	392088
RCP8.5 wo	HadGEM2-ES	Facilitation + Tariff	5182680	2.93	18727	409417

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).

			Market responses			
RCP	GCM	Trade scenario	Global production efficiency, difference to T0 (%)	Crop calorie production, difference to T0 (%)	Food availability , difference to T0 (kcal/cap/day)	Agricultural prices, difference compared to T0 (%)
No CC	None	Fixed imports	0.00	0.00	-0.02	0.00
RCP2.6	HadGEM2-ES	Fixed imports	0.00	-0.01	-3.15	0.01
RCP4.5	HadGEM2-ES	Fixed imports	-0.01	-0.01	-7.59	0.02
RCP6.0	HadGEM2-ES	Fixed imports	-0.01	-0.01	-9.19	0.02
RCP8.5	GFDL-ESM2M	Fixed imports	-0.01	-0.01	-18.01	0.02
RCP8.5	HadGEM2-ES	Fixed imports	-0.01	-0.02	-21.34	0.03
RCP8.5	IPSL-CM5A-LR	Fixed imports	-0.02	-0.02	-21.73	0.04
RCP8.5	MIROC	Fixed imports	-0.01	-0.01	-12.30	0.02
RCP8.5	NorESM1-M	Fixed imports	-0.02	-0.02	-16.71	0.05
RCP8.5 wo	HadGEM2-ES	Fixed imports	-0.03	-0.03	-40.54	0.10
No CC	None	Facilitation + Tariff	0.08	0.08	78.96	-0.17
RCP2.6	HadGEM2-ES	Facilitation + Tariff	0.07	0.08	82.80	-0.17
RCP4.5	HadGEM2-ES	Facilitation + Tariff	0.07	0.08	73.93	-0.17
RCP6.0	HadGEM2-ES	Facilitation + Tariff	0.07	0.08	75.67	-0.17
RCP8.5	GFDL-ESM2M	Facilitation + Tariff	0.09	0.10	84.08	-0.18
RCP8.5	HadGEM2-ES	Facilitation + Tariff	0.07	0.08	63.12	-0.16
RCP8.5	IPSL-CM5A-LR	Facilitation + Tariff	0.05	0.08	65.44	-0.17
RCP8.5	MIROC	Facilitation + Tariff	0.07	0.08	70.55	-0.17
RCP8.5	NorESM1-M	Facilitation + Tariff	0.06	0.08	62.34	-0.16
RCP8.5 wo	HadGEM2-ES	Facilitation + Tariff	0.04	0.05	48.31	-0.15

GCM MIROC: MIROC-ESM-CHEM

Supplementary Table 3 | Results from OLS estimation of the impact of crop yields, trade costs and their interaction on population at risk of hunger and food availability including regional interaction effects. Observations are GLOBIOM output for nine regions (EUR and CAN excluded) under the five different trade scenarios and ten different climate change scenarios in 2050. The regression models are fully described in the Supplementary Methods.

		Food availability (kcal/cap/day)			Population at risk of hunger (million)		
		coefficient	*se*		*coefficient*	*se*	
Crop yield (% change)							
	CSI	144.38	*75.23*	*	-0.98	*0.49*	**
	EAS	315.53	*64.28*	***	-18.93	*6.14*	***
	LAC	286.44	*52.38*	***	-8.52	*1.23*	***
	MNA	94.27	*80.54*		-0.95	*3.76*	
	OCE	66.86	*101.28*		-0.04	*0.12*	
	SAS	429.02	*53.89*	***	-78.95	*18.33*	***
	SEA	312.61	*126.01*	**	-12.51	*6.88*	*
	SSA	614.15	*106.97*	***	-92.60	*20.72*	***
	USA	268.76	*34.80*	***	-0.14	*0.02*	***
Trade cost (log of US$/106 kcal)							
	CSI	-47.51	*10.78*	***	0.30	*0.05*	***
	EAS	-37.11	*3.95*	***	2.61	*0.42*	***
	LAC	-31.18	*6.19*	***	1.71	*0.21*	***
	MNA	-75.09	*14.25*	***	4.31	*0.69*	***
	OCE	35.05	*13.67*	**	-0.02	*0.02*	
	SAS	-68.10	*6.51*	***	11.87	*1.25*	***
	SEA	6.86	*14.40*		0.15	*0.84*	
	SSA	-88.90	*8.93*	***	15.17	*1.67*	***
	USA	32.50	*3.62*	***	-0.02	*0.00*	***
Crop yield x Trade cost							
	CSI	-41.83	*98.17*		0.14	*0.46*	
	EAS	-89.27	*120.41*		10.14	*10.04*	
	LAC	-111.99	*170.29*		3.84	*3.62*	
	MNA	-135.55	*103.49*		7.51	*3.79*	**
	OCE	115.82	*92.49*		-0.10	*0.10*	*
	SAS	4.90	*71.44*		-33.03	*18.35*	*
	SEA	41.41	*201.15*		0.76	*8.64*	
	SSA	163.72	*149.63*		-60.40	*17.33*	***
	USA	115.70	*35.32*	***	-0.07	*0.02*	***

Significance levels: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$. Heteroskedastic robust standard errors. EUR and CAN are not included as they have always zero hunger. One outlier is removed: [CSI, *Fixed imports*, RCP8.5 without CO_2 effect]. N = 449. Adjusted R squared is 0.999 for food availability regression and 0.982 for hunger regression.

Supplementary Table 4 | Regions, sub-regions and countries in GLOBIOM.

Region	Sub-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 – 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 for the regression model with regional fixed effects composed of observations for the 11 regions for the five trade scenarios and 10 climate change scenarios. Two outliers in terms of trade costs are removed: [EUR, *Fixed imports*, RCP8.5 without CO_2 effect] and [CSI, *Fixed imports*, RCP8.5 without CO_2 effect]. This leads to 548 observations (= 11 regions x 5 trade scenarios x 10 climate change scenarios – 2 outliers).

	Min	Average	Max
Population at risk of hunger (million)	0	14.19	87.63
Food availability (kcal/cap/day)	1758	2230	2655
Crop yield (difference with NoCC)	-38%	-5%	+36%
Trade costs (US$/$10^6$ kcal)	15.09	67.60	221.67

Supplementary Method

Trade costs in GLOBIOM

Bilateral trade flows are determined by the initial trade pattern, relative production costs of regions and the minimization of trading costs[1]. Trade costs are composed of tariffs from the MAcMap-HS6 database[2], transport costs[3] and a non-linear element in which trade costs increase with traded quantity to model persistency in trade flows. The latter 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. The implication of the trade scenarios for production, trade patterns and trade costs varies across crops and regions because the level of initial trade barriers is for example different. The impact differs also across climate change scenarios through the dependency of trade on the competitiveness of each region. The spatial price equilibrium approach implies that trade will occur when the cost of trade between two regions is smaller than the regional price difference, and this price difference will become equal to the marginal trade cost in equilibrium[4]. We aggregate these computed trade costs on each trade flow to obtain a measure that reflects the implication of trade scenarios on overall trading costs for each crop and region. GLOBIOM models bilateral trade flows and trade costs at the level of 30 sub-regions. To be in line with the level of analysis of the paper, we aggregate this information to the level of 11 regions (USA, CAN, EUR, MNA, SEA, EAS, SSA, SAS, CSI, OCE, LAC). The correspondence between country, sub-region and region level is shown in Supplementary Table 4.

For the analysis on hunger we calculate the weighted average of trade costs (in US$/$10^6$ kcal) over all agricultural imports, exports and intra-regional trade flows for each region i, trade scenario t and climate change scenario r:

$$average\ trade\ cost_{itr} = \sum_{k} \frac{x_{iktr}}{total_x_{itr}} * trade\ cost_{iktr}$$

where 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).

For the analysis on comparative advantage, we calculate a weighted average of trade cost (in USD/ton) on exports of crop k, region i, trade scenario t and climate change scenario r:

$$average\ trade\ cost_{iktr} = \sum_{l \in i, j \notin i} \frac{x_{ljktr}}{x_{iktr}} * trade\ cost_{ljktr}$$

where x_{ljktr} are export flows of crop k from sub-region l ($\in region\ i$) to sub-region j ($\notin region\ i$) in each scenario (t, r) and x_{iktr} is the total export of crop k from sub-regions l to sub-regions j in each scenario (t, r).

Supplementary References

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3. Hummels, D. *Toward a Geography of Trade Costs David*. (2001).
4. McCarl, B. A. & Spreen, T. H. *Applied Mathematical Programming Using Algebraic Systems*. (Texas A&M University 2011, 2002).