Agro-food greenhouse gas emissions are increasingly driven by foreign demand

Supplementary information

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CONTENTS

1. QUALITY ASSURANCE

1.1. Comparison with other studies

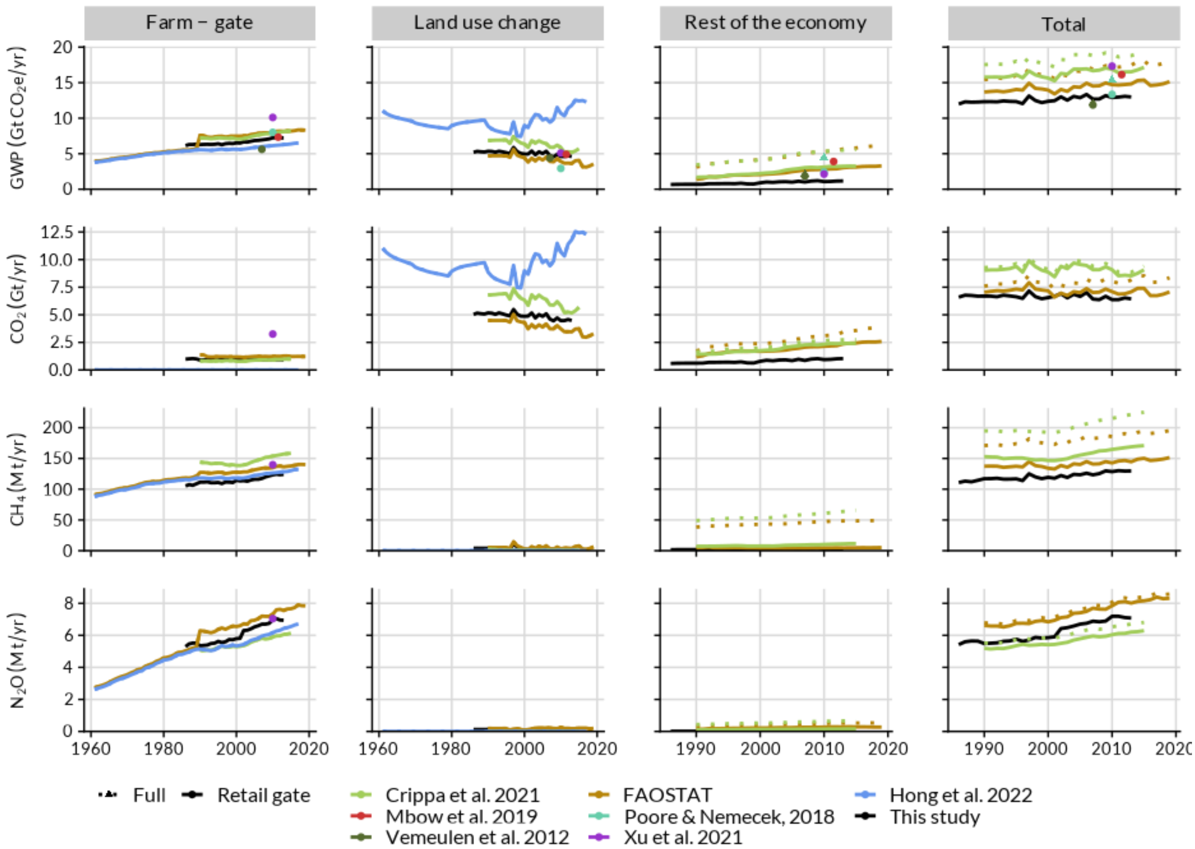

Figure SI-1. Comparison of food system emissions estimated in our study with those estimated by other studies. Emissions are aggregated by food system stage (columns) and by gas (rows). GWP refers to Global Warming Potential. The distinction between 'Full' and 'Retail gate' refers to the inclusion or not (respectively) of post-retail emissions (food preparation in households, restaurants and caterings, and food waste management). This distinction is not made for farm-gate and LUC emissions.

Table SI-1. Summary of methodological differences across studies.

		This study	Hong et al., 2022[1]	Tubiello et al., 2022[2]	Tubiello et al., 2021[3]	Xu et al., 2021[4]	Hong et al 2021[5]	Crippa et al., 2021[6]	Mbow et al., 2019[7]	Poore and Nemecek, 2018[8]	Bennetzen et al., 2016[9]	Vermeulen et al., 2012[10]
Period		1986-2013	2004,2007, 2011,2014, 2017	1990-2019	1990 and 2018	2007-2013 (mean)	1961-2017	1990-2015	2007-2016 (mean)	2000-2016 studies, 2009-2011 sample	1970-2007-2050	ca. 2005-2008
Scope		Food consumption	AFOLU, Food consumption	Agro-food system, AFOLU	Agro-food system, AFOLU	Food consumption	AFOLU	Agro-food system	Agro-food system, AFOLU	Agro-food system	Agricultural production	Agro-food system
Resolution		Country	Country	Continent (by country in SI)	AI-NAI[a)]	Gridded-region	Country	Country	Global	Global	Region	Global
Allocation		Economic/mass	Not allocated	Not allocated	Not allocated	Energy/main product	Not allocated[b)]	Not allocated	Not allocated	Economic	Dry matter	Not allocated
GWP[c)]		AR5 wCCF[d)]	AR5 wCCF[d)]	SAR[e)]	SAR[e)]	AR5 wCCF[d)]	AR5 wCCF[d)]	AR5 woCCF[f)]	AR5 woCCF[f)]	AR5 wCCF[d)]	SAR[e)]	NA
On-farm	*Source*	FAOSTAT	FAOSTAT. Energy not included	FAOSTAT	FAOSTAT	ISAM model (Soil) - FAOSTAT (Animals)	FAOSTAT. Energy not included	EDGAR, IEA[11]	FAOSTAT and US EPA	Meta-analysis of literature[g)]	Estimated	Smith et al., 2007[12]
	Method	IPCC 2006 Tier 1	IPCC 2006 Tier 1	IPCC 2006 Tier 1	IPCC 2006 Tier 1	IPCC 2006 Tier 1	IPCC 2006 Tier 1	IPCC 2006 Tier 1[h)]	IPCC 2006 Tier 1	Literature[i)]	IPCC 1997 Tier 1	IPCC 1997 Tier 1
Pre-farm	*Source*	EXIOBASE[13]		Tubiello et al., 2021b[14]	FAO, 2011[15]	Kool et al., 2012[16]		EDGAR[17]	Poore and Nemecek, 2018[8], Fischedick et al., 2014[18]	Meta-analysis of literature	Estimated	Bellarby et al., 2008[19], Steinfeld et al., 2006[20]
	Method	MRIO		LCA-based	Attribution to agriculture	LCA-based		Attribution to agriculture	LCA-based, attribution to agriculture	LCA-based	Energy-based	LCA-based
LUC, forests	*Source*	LUH2[21]	Blue[22]-LUH2[21]	FAOSTAT[j)]	FAOSTAT[j)]	ISAM (Soil)[23] - LUH2 (Biomass) [21]	Blue[22]-LUH2[21]	FAOSTAT[k)]	FAOSTAT[k)]	Meta-analysis of literature[l)]	CDIAC[24]	van der Werf et al., 200[25]9, Blaser and Robledo, 2007[26]
	Components	Biomass	Soil and Biomass	Biomass and fire emissions	Biomass and fire emissions	Soil and Biomass	Soil and Biomass	Biomass, burning,	Biomass and fire emissions	Soil, Biomass fire emissions	Biomass	Biomass
	Method	Amortization 100 years	Legacy	Annual emissions	Annual emissions	Annual emissions	Legacy	Annual emissions	Annual emissions	Amortization 20 years	Legacy	NA
LUC, peat	*Source*	FAOSTAT	FAOSTAT	FAOSTAT	FAOSTAT		FAOSTAT[m)]	FAOSTAT	FAOSTAT	FAOSTAT		
	Method	IPCC 2006 tier 1	IPCC 2006 tier 1	IPCC 2006 tier 1	IPCC 2006 tier 1		IPCC 2006 tier 1	IPCC 2006 tier 1	IPCC 2006 tier 1	IPCC 2006 tier 1		
Transport	*Source*	EXIOBASE[13]		Various sources	Various sources	Ecoinvent[27] and Kinnon, 2011[28]		EDGAR[17], Eurostat, FAO	Poore and Nemecek, 2018[8], Fischedick et al., 2014[18]	Ecoinvent and James, 2010[29]		Chen and Zhang, 2010[30]

	Method	MRIO		Energy-based and attribution to food	Attribution to food	LCA-based		Energy-based and attribution to food	LCA-based and attribution to food	LCA-based		NA
Processing	*Source*	IEA[11], EXIOBASE[13]		Tubiello et al., 2021b[14]	FAO, 2011[15]	NA		IEA[11]	Poore and Nemecek, 2018[8], Fischedick et al., 2014[18]	Meta-analysis of literature		Chen and Zhang, 2010[30]
	Method	Combustion-based		Energy-based and attribution to food	Attribution to agriculture	LCA-based		Energy-based and attribution to food	LCA-based, attribution to agriculture	LCA-based		NA
Packaging	*Source*	EXIOBASE[13]		Tubiello et al., 2021b[14]	FAO, 2011[15]			Various sources	Poore and Nemecek, 2018[8], Fischedick et al., 2014[18]	Meta-analysis of literature		Chen and Zhang, 2010[30]
	Method	MRIO		Energy-based and attribution to food	NA			Energy-based and attribution to food	LCA-based, attribution to agriculture	LCA-based		NA
Retail	*Source*	EXIOBASE[13]		Tubiello et al., 2021b[14]	FAO, 2011[15]							
	Method	MRIO		Energy-based and attribution to food	NA							
Trade	*Source*	FABIO[31]	GTAP[32]			FAOSTAT detailed trade matrix						
	Method	MRIO	MRIO			Bilateral trade[n)]						

NA Not Available

[a)] Annex I and Non-Annex I countries.
[b)] They also provide an alternative scenario in which feed emissions are allocated to animals based on energy requirements.
[c)] Global warming potential. All studies use a 100-year time horizon.
[d)] Fifth Assessment Report, with climate change feedbacks.
[e)] Second Assessment Report.
[f)] Fifth Assessment Report, without climate change feedbacks.
[g)] Except savannah burning, from FAOSTAT, and fisheries, from Parker et al. (2018)[33].
[h)] Except cattle enteric fermentation and rice (Tier 2).
[i)] Filling gaps with IPCC (2006)[34] Tiers 1 and 2, Ecoinvent[27], Stehfest and Bouwman, 2006[35], Tubiello et al., 2016[36], EEA, 2016[37].
[j)] New dataset which separates agriculture-related emissions.
[k)] Former dataset in which all emissions are attributed to agriculture.
[l)] Except cattle enteric fermentation and rice (Tier 2).
[m)] With assumptions to estimate the pre-1990 period.
[n)] Emission intensities of the exporter country are assumed for exports.

1.2. Analysis of GHG intensities of food products

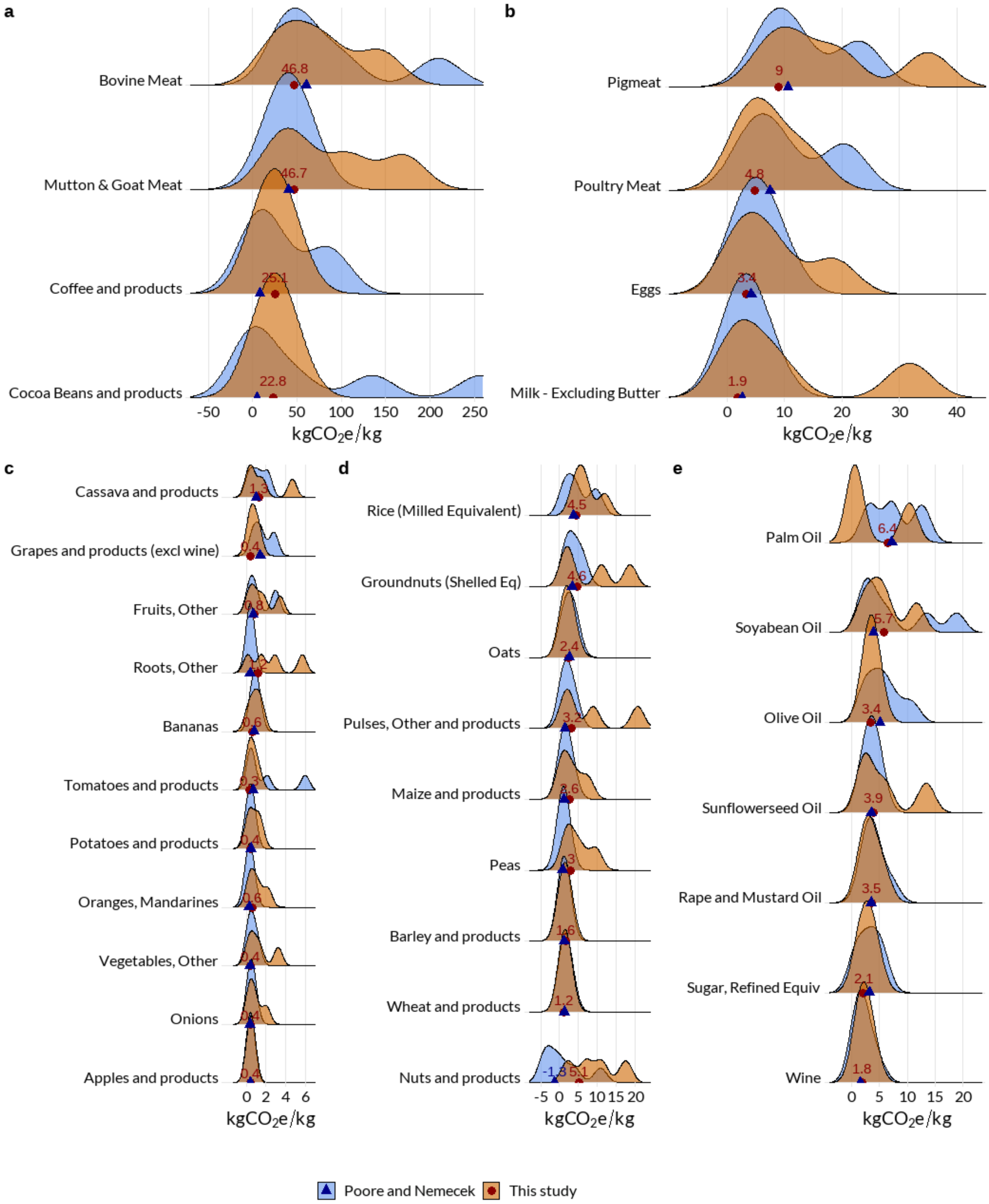

Figure SI-2. Comparison of global variation in the carbon footprint of a selection of products in our study with the variation in a compilation of published life-cycle assessment studies reported by Poore and Nemecek[8], 2018. The dots represent the weighted mean in our study and the median in Poore and Nemecek, 2018[8]. When the dots are very close, only the value of our study is shown to facilitate visualization. a. High-emissions animal and vegetal products; b. Vegetables, fruits, tubers and roots; c. Other animal products; d. Cereals, pulses and nuts; e. Processed vegetal products.

1.3. Sensitivity analysis of amortization periods of land use change emissions

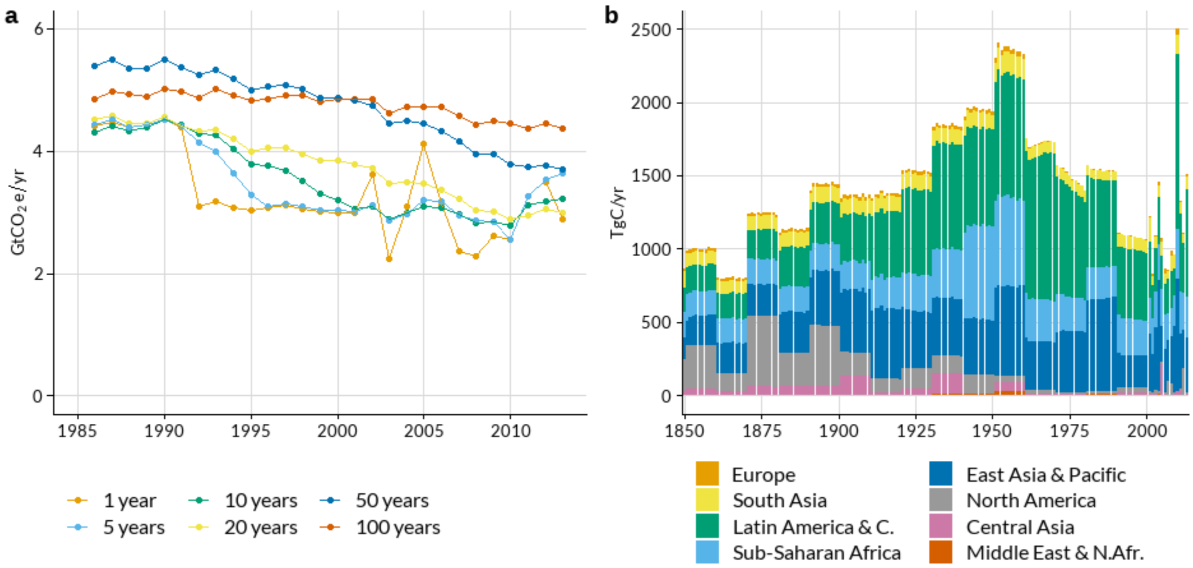

Figure SI-3. a. Land use change emissions by amortization period in the study years (1986-2013). b. Land use change-related carbon release by world region from 1850 to 2015 (LUH2 database).

2. SUPPLEMENTARY RESULTS

2.1. Carbon footprint of food consumption vs. domestic GHG emissions of food production

A. South Asia

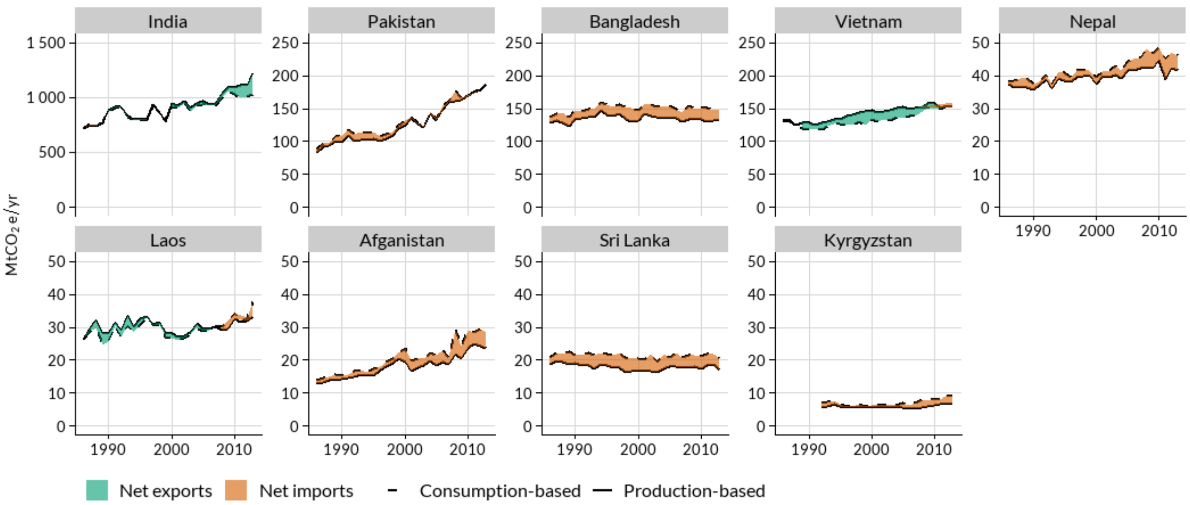

Figure SI-4. Carbon footprint of food consumption vs. domestic GHG emissions of food production in $GtCO_2e$ for South Asian countries.

B. Europe

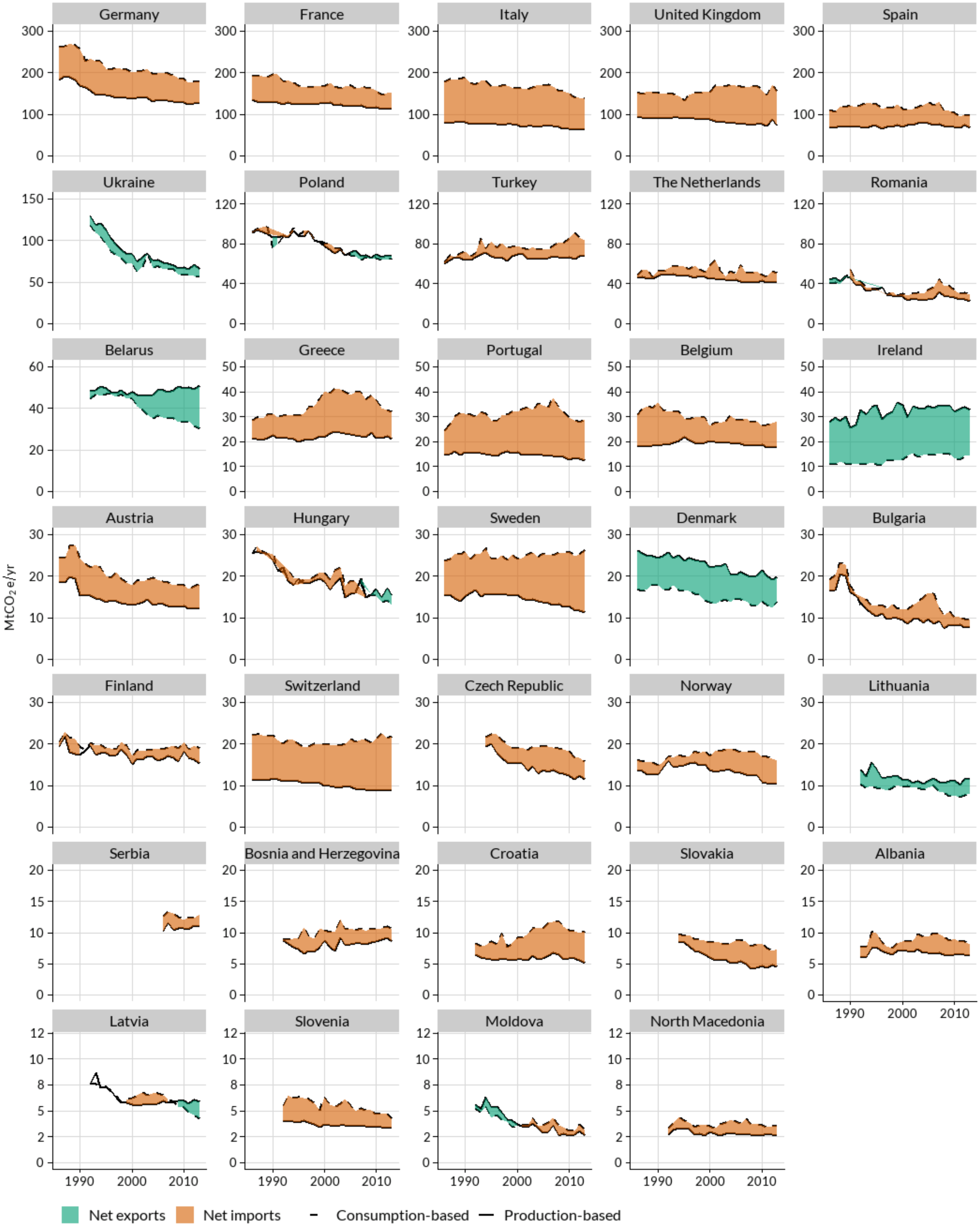

Figure SI-5. Carbon footprint of food consumption vs. domestic GHG emissions of food production in $GtCO_2e$ for European countries.

C. Americas

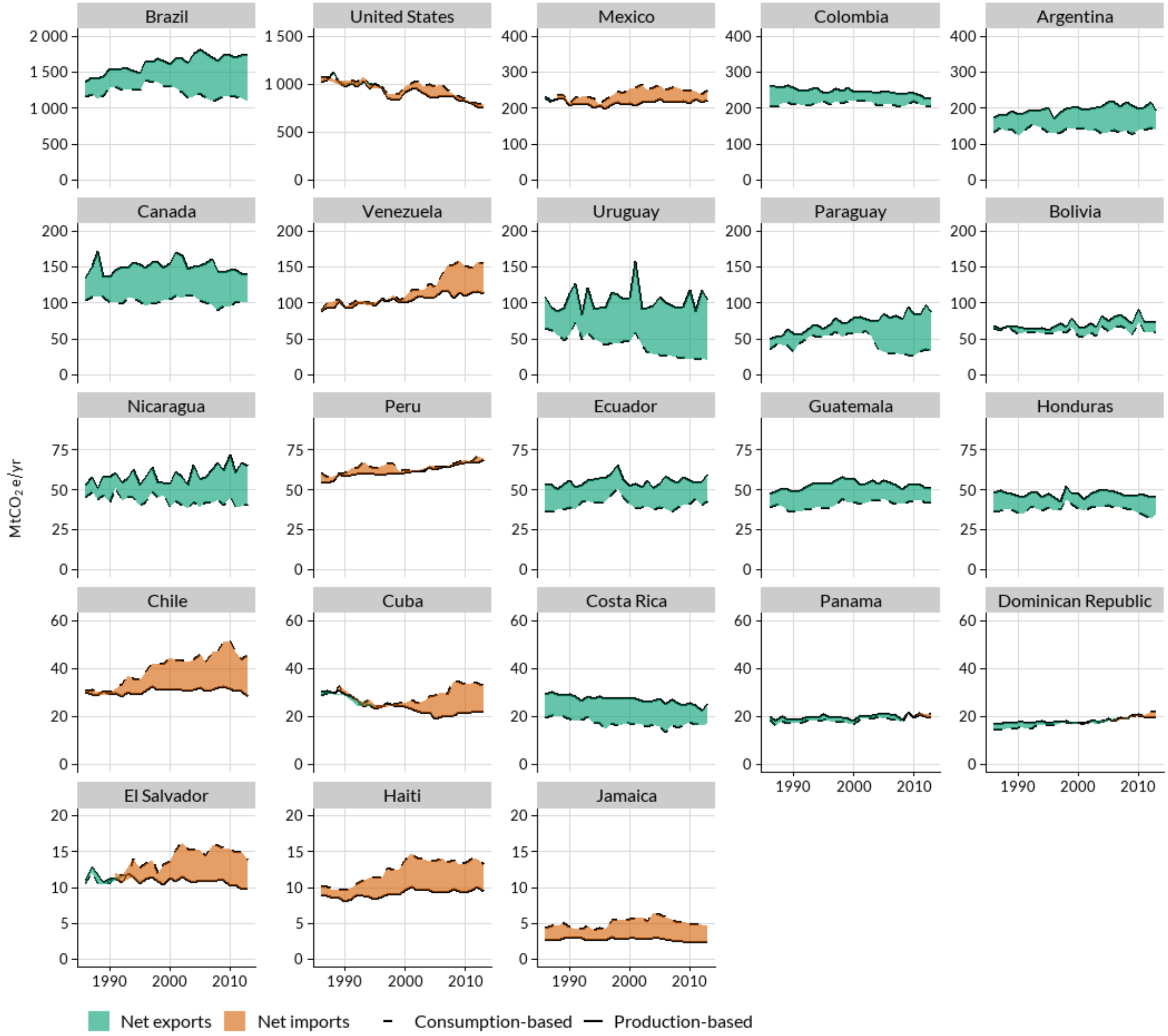

Figure SI-6. Carbon footprint of food consumption vs. domestic GHG emissions of food production in $GtCO_2e$ for North American and Latin American countries.

D. Africa

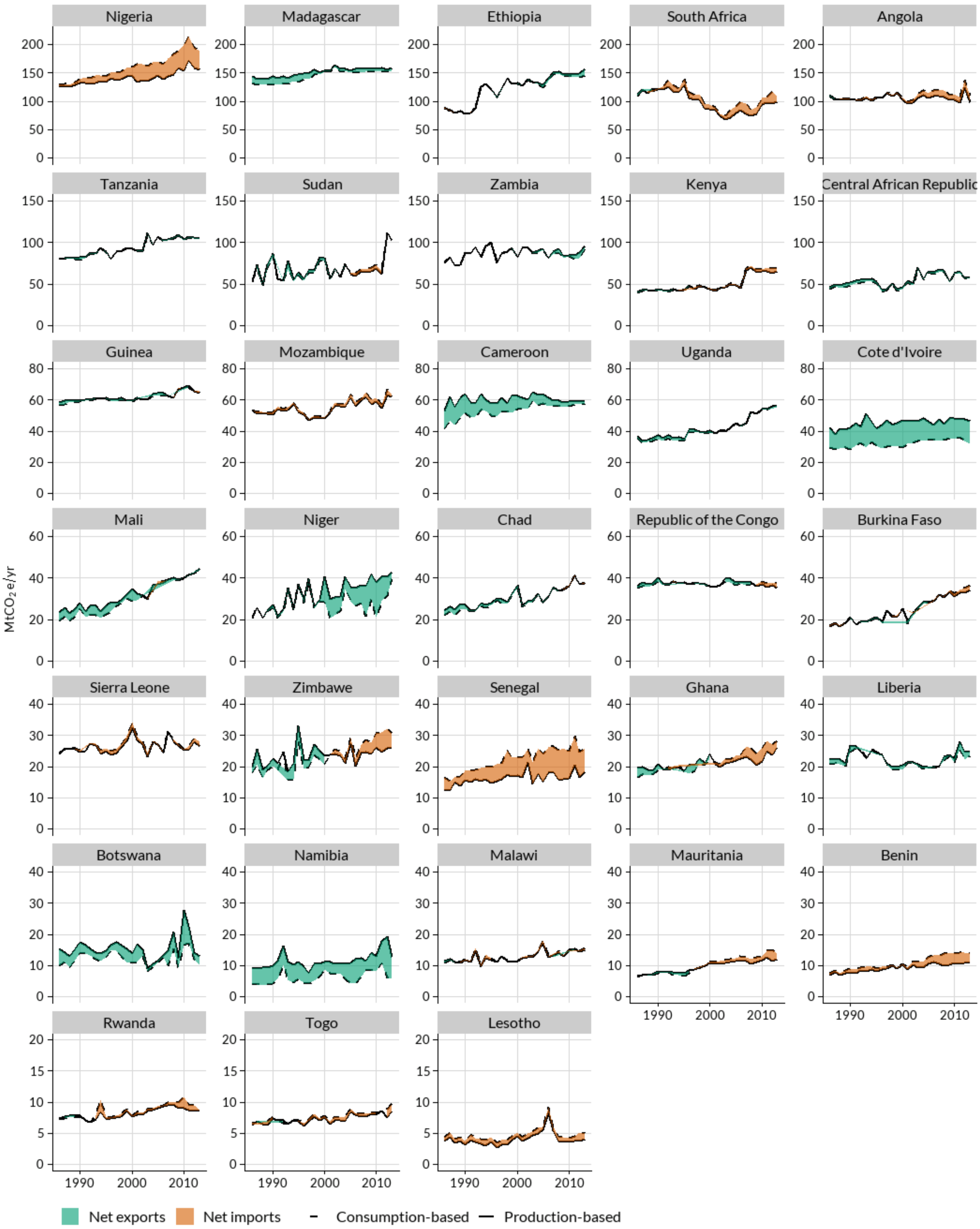

Figure SI-7. Carbon footprint of food consumption vs. domestic GHG emissions of food production in $GtCO_2e$ for Sub-Saharan African countries.

E. Central Asia

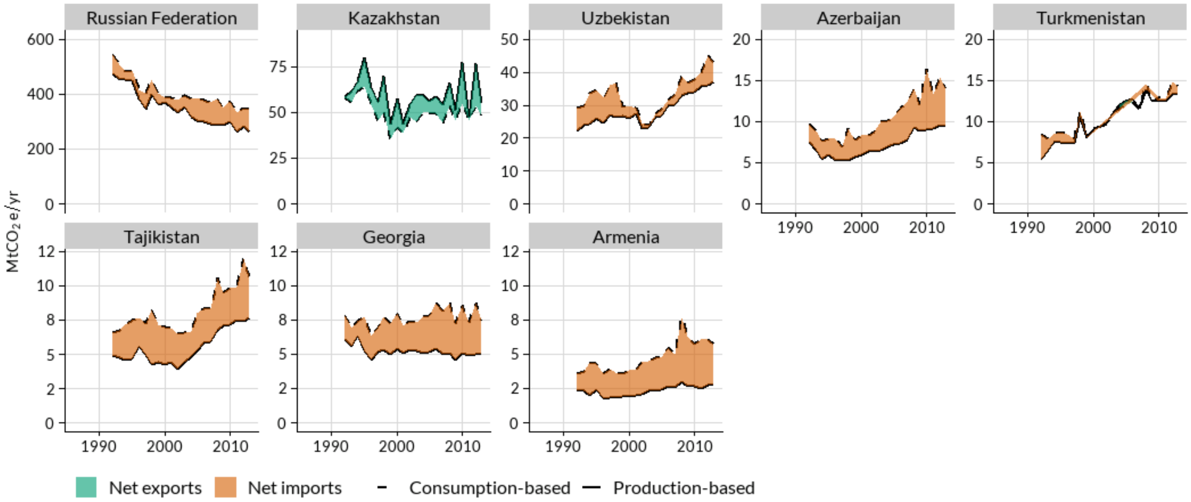

Figure SI-8. Carbon footprint of food consumption vs. domestic GHG emissions of food production in $GtCO_2e$ for Central Asian countries.

F. Middle East and North Africa

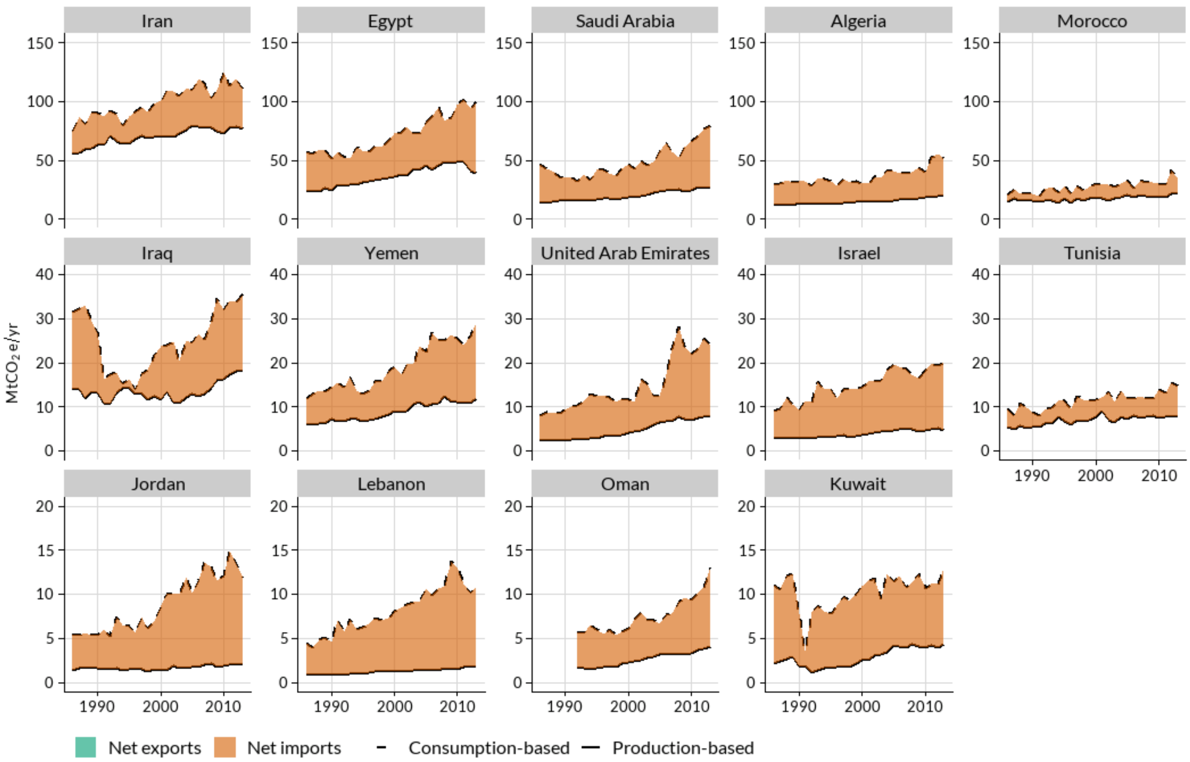

Figure SI-9. Carbon footprint of food consumption vs. domestic GHG emissions of food production in $GtCO_2e$ for Middle East and North African countries.

G. East Asia & Pacific

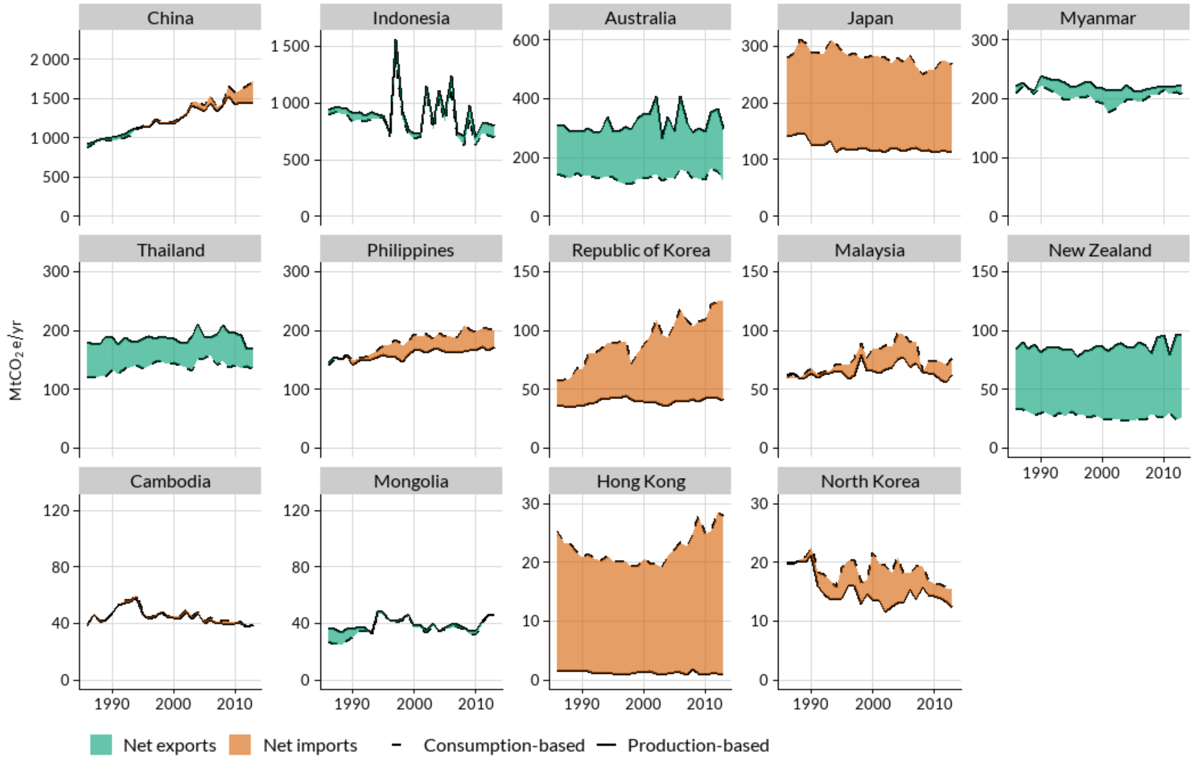

Figure SI-10. Carbon footprint of food consumption vs. domestic GHG emissions of food production in $GtCO_2e$ for East Asia & Pacific countries.

2.2. Income and fraction of food emissions embodied in the import trade

In our yearly dataset, higher incomes are associated at the country level with a higher fraction of emissions embodied in the agro-food import trade (Figure SI-11). This is in addition to the positive correlation between income and absolute food emissions embodied in imports.

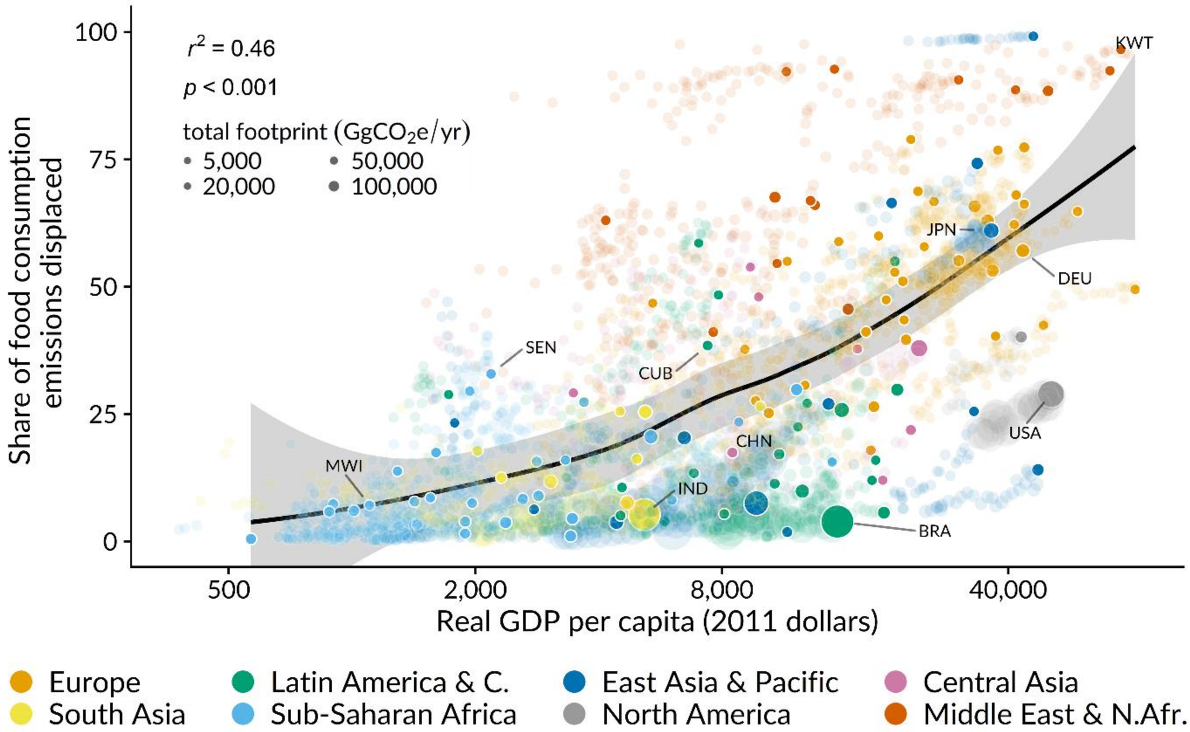

Figure SI-11. Share of food consumption emissions displaced via imports (%) against average incomes (real GDP per capita in 2011 dollars, log scale). Highlighted dots, trendline and correlation coefficients refer only to 2013 data, transparent dots to observations 1986-2012. All countries with population > 2M included.

2.3. Drivers of agro-food emissions embodied in trade

We conduct panel data regression to examine the impact of changes in income and population on agro-food emission displaced via trade. We estimate a combined entity and time fixed-effects model to control for unobserved confounders idiosyncratic to each country which affect agro-food consumption patterns (local environments, cultural traditions, population geography, etc.), as well as for unobserved variables which varied worldwide over time (such as global economic cycles and trade regulations). Our full model is an equation of the following form:

$$DE_{it} = \beta_1 Inc_{it} + \beta_2 Pop_{it} + \beta_3 (Pop_{it} \times Inc_{it}) + \alpha_i + \lambda_t + u_{it}$$

where DE_{it} is the dependent variable (displaced agro-food emissions per capita in country *i* in year *t*); Inc_{it} and Pop_{it} are the independent variables of interest (per capita income and population in country *i* in year *t*); ($Pop_{it} \times Inc_{it}$) is an interaction term between them, so that b_3 is the effect of a one-unit increase in income *and* population above and beyond the sum of the individual effects of an increase in population and income alone; a_i (*i*=1…n) is the intercept for each entity (i.e. the country fixed effect); l_t is the intercept for each time period (i.e. the year fixed effect); and u_{it} is the error term.

The different specifications reported in table SI-3 allow us to focus on longitudinal variation (changes in each country relative to itself in the past, column 1), as well as to include both country and year fixed effects to concentrate on variation across time in each country outside of a general world time trend (columns 2-4). The last specification in column 4 includes the interacted regressor which allows the population effect on displaced emissions to depend on average incomes (and vice versa). Column 3 shows that the effect of income is still large even when accounting for population increase. The coefficients in column 4 show that population increases result in higher agro-food emission displacement only when average incomes increase at the same time. Standard errors are clustered at the country level in all cases to account for serial correlation.

Table SI-3. Impact of income per capita on displaced agro-food emissions per capita, 1986-2013.

	(1)	*(2)*	*(3)*	*(4)*
Income (GDP per capita, log)	0.527***	0.341***	0.328***	0.280
	(0.055)	(0.089)	(0.088)	(0.395)
Population (thousands, log)			-0.304*	-0.345
			(0.157)	(0.347)
Population * Income				0.005
				(0.042)
Country Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	No	Yes	Yes	Yes
Observations	3,493	3,493	3,493	3,493
RMSE	0.30	0.29	0.29	0.29

Notes: displaced agro-food emissions per capita (tCO_2/yr/cap) as the dependent variable. Real GDP per capita (PPP, in 2011 dollars) and population (in thousands of people) as independent variables. Columns 1 shows panel data regression with country fixed effects; columns 2-4 show panel data regression with both country and year fixed effects; column 3 controls for population growth; column 4 shows panel data regression interacting GDP per capita and population. Clustered standard errors at the country level reported in brackets. Observations are year-country pairs. ***, **, and * denote significance at the 1%, 5%, and 10% levels.

Sources: displaced agro-food emissions from the dataset presented in this study; GDP per capita and population data from the Maddison Database[38].

2.4. Leakage of emissions and aggregate per capita agro-food emissions

We conduct a further panel data regression analysis to consider whether leakage of agro-food emissions leads to larger or smaller emissions per capita *in the aggregate*, beyond the relationship of income levels on leakage. The regression equation is:

$$E_{it} = \beta_1 Mshare_{it} + \beta_2 Inc_{it} + \alpha_i + \lambda_t + u_{it}$$

where E_{it} is the dependent variable (total agro-food consumption emissions per capita in country *i* in year *t*); $Mshare_{it}$ and Inc_{it} are the independent variables of interest (import share of total agro-food consumption emissions and per capita income in country *i* in year *t*); a_i (*i*=1…n) is the country fixed effect; l_t is the year fixed effect; and u_{it} is the error term.

The results suggest that increasing the import share of a country's consumption footprint is associated with slightly lower total per capita emissions. When including both country and year fixed effects (column 3), as well as controlling for income, an increase of 1% in the import share of emissions is associated with a decrease of 0.06% in the total per capita agro-food consumption emissions. Clustered standard errors (at the country level) are always calculated to account for serial correlation.

Table SI-4. Impact of emission displacement on total per capita agro-food consumption emissions, 1986-2013.

	(1)	*(2)*	*(3)*
Import share of emissions (log)	-0.146***	-0.049*	-0.063***
	(0.025)	(0.027)	(0.028)
GDP per capita (log)			0.147***
			(0.047)
Country Fixed Effects	Yes	Yes	Yes
Year Fixed Effects	No	Yes	Yes
Observations	3,493	3,493	3,493
RMSE	0.14	0.13	0.13

Notes: results obtained using total per capita agro-food consumption emissions (tCO_2/yr/cap, in logs) as the dependent variable. Share of total agro-food consumption emissions displaced via imports (%) and real GDP per capita (PPP, in 2011 dollars) as independent variables. Column 1 shows the basic pooled OLS regression; columns 2-4 show panel data regressions with fixed effects. Clustered standard errors at the country level reported in brackets. Observations are year-country pairs. ***, **, and * denote significance at the 1%, 5%, and 10% levels.

Sources: agro-food emissions and import share from our own dataset; GDP per capita data from the Maddison Database[38].

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