Science
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Supplementary Materials for

Reducing food's environmental impacts through producers and consumers

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This PDF file includes:

Other Supplementary Materials for this manuscript include the following:

Data S1 to S2 as xls files [Additional reference lists; Data in spreadsheet format].

Materials and Methods

Contents

1) *Study Scope*

a. *Temporal Scope*

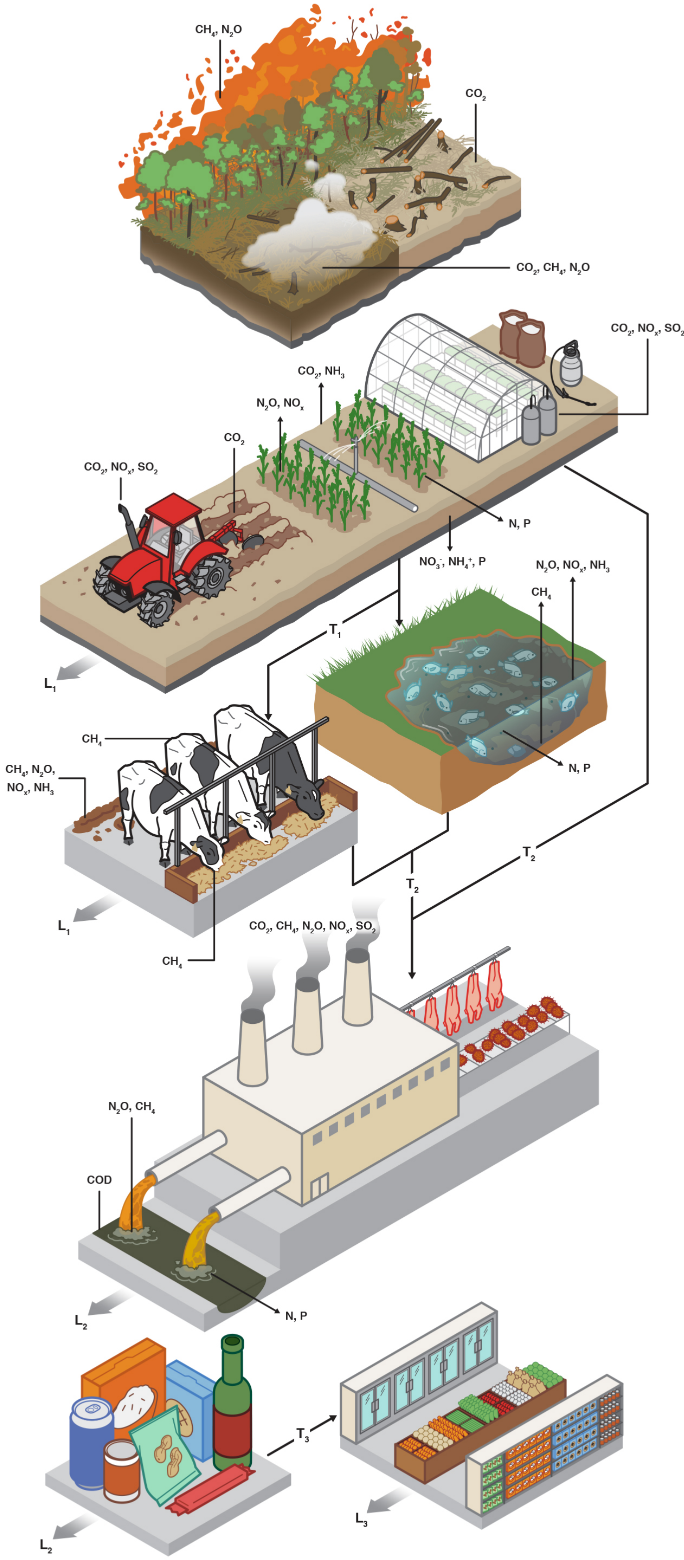
Studies published online between 2000 and June 2016 were included, providing a window to reduce climatic variation while avoiding significant error by including outdated practices. The beginning of this period aligns with the release of standards for methodological harmonization (*41*) of Life Cycle Assessment (LCA) [ISO 14040:1997, ISO 14041:1999, ISO 14042:2000, and ISO 14043:2000]. Observations are approximately centered on the year 2010, and external data used relates to 2009-11.

b. *Production Practices*

Only commercially viable and currently existing production systems were included, avoiding assessment of the gap between identification and implementation of new practices (*30*). Foraged foods and subsistence farming were excluded.

c. *System Boundary*

The supply chain begins with the extraction of resources needed to produce inputs for agricultural production, the initial impact of choice by farmers, and ends at the retail store, the point of choice for consumers (fig. S1). Post-retail stages (cooking and consumer losses) were not considered owing to high variability and low data availability. Materials and Methods Section 6 justifies other exclusions.



Included	Excluded
Land Use Change	
• Above ground C stock change (CO_2) • Below ground C stock change (CO_2) • Forest burning (CH_4, N_2O) • Organic soil burning (CO_2, CH_4, N_2O)	• Leaching, runoff and induced non-CO_2 emissions
Crop Production	
• Seed & nursery • Inputs production • Machinery • Greenhouse & trellis infrastructure • Electricity & fuel • Fertilizer & retained crop residue (N_2O, NH_3, NO_x, NO_3^-, NH_4^+, P, N) • Urea & lime (CO_2) • Flooded rice (CH_4) • Residue burning (CH_4, N_2O, NH_3, NO_x) • Cultivation of drained organic soils (CO_2, N_2O) • Drying / grading • Irrigation water consumption — Land use: seed; fallow; arable and permanent crops	• Soil emissions (CH_4) • Organic fertilizer application (CH_4) • N fixation emissions • C sequestration in crop residue • Runoff (N) • Residue burning indirect emissions (N_2O) • Human labour
Livestock/Aquaculture	
• Pasture management (same as for food/feed) • Feed processing • Housing energy use • Enteric fermentation (CH_4) • Manure management (N_2O, NO_x, NH_3, CH_4) • Aquaculture ponds (N, P, N_2O, NO_x, NH_3, CH_4) • Drinking & service water — Land use: permanent pasture; temporary pasture; aquaculture ponds	• Infrastructure • Pasture residue (emissions or burning) • Pasture N fixation emissions • Pasture runoff (N) • Manure management (P) • Human labour
Processing	
• Energy (CO_2, NO_x, SO_2) • Wood burning (CH_4, N_2O, NO_x, SO_2) • Wastewater (CH_4, N_2O, P, N, COD) • Incineration (CH_4, N_2O, NO_x, SO_2) • Processing water consumption	• Miscellaneous inputs • Human labour • Infrastructure • Land use
Packaging	
• Materials • Material transport • End of life disposal	• Human labour • Infrastructure • Land & water use
Retail	
• Energy use	• Human labour • Infrastructure • Land & water use

Losses	Transport (CO_2, NO_x, SO_2)
L_1 - Storage and transport	T_1 - Feed
L_2 - Processing and packaging	T_2 - Food
L_3 - Wholesale and retail	T_3 - Processed food

Fig. S1. Emissions and resource uses included or excluded by supply chain stage.

d. *Functional Units Used and Products Included*

Co-products with similar nutritional roles, despite differences in value or desirability, were not differentiated. Nutrient densities were derived from food balance sheets (*4*).

Table S1. Functional units (FUs) used.

	Mass / Volume FU	**Nutrition FU**	**Nutrient Density**
Starch-Rich			
Wheat & Rye	1 kg of bread (variable protein wheat)	1000 kcal energy	2695 kcal kg^{-1}
Maize	1 kg of meal (for polenta)		4165 kcal kg^{-1}
Oats	1 kg of rolled oats		2605 kcal kg^{-1}
Rice	1 kg of full grain white or brown rice		3685 kcal kg^{-1}
Potatoes	1 kg of soil free tuber		730 kcal kg^{-1}
Cassava	1 kg of soil free tuber		975 kcal kg^{-1}
Protein-Rich			
Peas	1 kg of dry pea without pod	100 g protein	215 g kg^{-1}
Other Pulses	1 kg of dry pulse without pod		220 g kg^{-1}
Nuts	1 kg of shell free, dry nut		160 g kg^{-1}
Groundnuts	1 kg of shell free, roasted nut		260 g kg^{-1}
Soybeans	1 kg of tofu (~16% protein)		160 g kg^{-1}
Cheese	1 kg of cheese		225 g kg^{-1}
Eggs	1 kg of eggs		110 g kg^{-1}
Poultry Meat	1 kg of fat and bone-free meat and edible offal		175 g kg^{-1}
Pig Meat			160 g kg^{-1}
Lamb & Mutton			200 g kg^{-1}
Beef			200 g kg^{-1}
Fish	1 kg of edible fish		230 g kg^{-1}
Crustaceans	1 kg of head-free meat (shell-free for large shrimp)		150 g kg^{-1}
Alcoholic Beverages			
Barley	1 liter of beer	1 unit (10ml alcohol)	5 units
Wine grapes	1 liter of wine		12.5 units
Other			
Milk	1 liter of pasteurized milk (4% fat, 3.3% protein)	-	-
Soybeans	1 liter of soymilk (~3.3% protein)	-	-
Root Vegetables	1 kg of soil free tuber	-	-
Fruit & Veg.	1 kg of fresh fruit or vegetable	-	-
Cocoa	1 kg of dark chocolate	-	-
Coffee	1 kg of ground, roasted beans	-	-
Oil crops	1 liter of refined/filtered oil	-	-
Sugar crops	1 kg of raw/refined sugar	-	-

e. Allocation

Economic allocation between co-products reflects the rationale for which producers create environmental burdens (*42*) and is used here. The method is also practical and widely used.

f. Characterization

Table S2. Indicators and characterizations used.

Indicator	Characterization	Emissions / Uses Characterized
Land Use * Occupation Time	None	Seed, on- and off-farm arable and permanent crops, fallow land, temporary pasture, permanent pasture
Greenhouse Gas Emissions	IPCC (*43*) AR5 100-year factors with climate-carbon feedbacks	CO_2, CH_4, N_2O to air
Acidification	CML2 Baseline (*44*)	SO_2, NH_3, NO_x to air
Eutrophication	CML2 Baseline (*44*)	NH_3, NO_x to air, NO_3^-, NH_4^+, P, N to water
Freshwater Withdrawals	None	Irrigation, drinking, pond, and processing water
Scarcity-Weighted Freshwater Withdrawals	AWARE (*45*)	Irrigation, drinking, pond, and processing water

For greenhouse gas (GHG) emissions, IPCC (*46*) AR4 characterization factors (CFs) included climate-carbon feedbacks in CO_2 only, but inconsistently not in other GHGs (*43*). The AR5 factors with feedbacks are both more complete (by including the direct and indirect impacts of GHGs) and consistent, and were used here despite higher uncertainty in feedback magnitude. Results under AR4 CFs are presented for comparability (Data S2). 100-year CFs were used, the most common indicator of the impact of mixed gases on the mid- to long-term climate.

2) *Meta-Analysis Approach*

a. Study Inclusion Criteria

Based on the above, the following criteria were used to identify studies that:

1. Are included in peer-reviewed journals, or are PhD theses, ISO compliant reports, LCA databases, or conference proceedings with clear data and methods
2. Are published in print or online between 2000 and June 2016
3. Report results not presented in another included study
4. Assess commercially farmed products
5. For crops, report real, not simulated yield and inventory data, from specific farms, regions, or countries
6. Use LCA or similar methodology
7. Calculate according to our system boundary or provide sufficient inventory data to recalculate
8. Calculate according to our functional units, or make recalculation possible
9. Use attributional modeling and economic allocation, or make recalculation possible
10. Calculate GHG emissions, characterized under IPCC AR5 100-year factors with climate-carbon feedbacks, or make recharacterization possible
11. Calculate on- and off-farm land use, or make calculation possible.

b. Aggregating Results

Results were included as a separate observation (line of the database), when they:

1. Represented different systems or practices, e.g., input level, rotation, cultivar
2. Represented significantly different geographies, e.g., regions or countries.

Otherwise, results were averaged into a single observation with standard deviations calculated across farms. Results were averaged across years to ensure independence of observations.

c. Literature Search

A comprehensive approach was used by: searching for publications using the terms "life cycle assessment" OR "life cycle analysis" OR "GHG emissions" AND the relevant product name, in Google Scholar; following references within publications and citations to publications; identifying LCA conference proceedings; and identifying online LCA datasets. This resulted in 1530 studies for potential inclusion. Where data were unavailable in the publication, 346 authors were contacted directly. Of these studies, 570, supplemented with additional data provided by 139 authors, met our criteria. This resulted in 2278 unique observations, covering ~38,700 regional or farm level inventories in 119 countries (fig. S2). Observations are concentrated in Europe, North America, Oceania, Brazil, and China, but limited in Africa and Central Asia, demonstrating the need for study weights that allow one geography to represent another (Materials and Methods, Section 8).

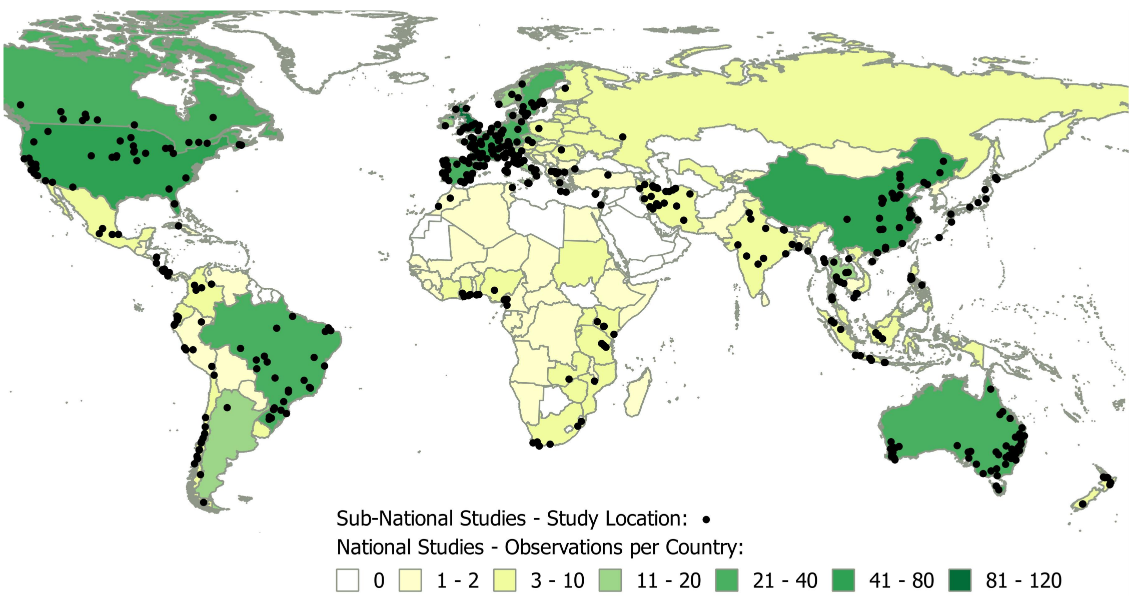


Fig. S2. Map of study locations for all products. Black circles represent locations of subnational studies (n observations = 1160); country shading represents the number of national-level studies per country (n observations = 1118).

3) Building and Standardizing the Inputs and Management Inventory

Inventory data were recorded to allow recalculation of missing emission sources. Some inventory items, if missing, could reasonably be estimated from external sources.

a. Data Derived from Study Locations

Studies with co-ordinates were point-sampled. Regional studies were linked to GADM regions (*47*), and the mean was taken within that area. For eco-climate zones (discrete), the mode was taken.

Table S3. Sources of spatial data.

Inventory Item	**Source**
Soil Characteristics	
pH H_2O	HWSD (*48*)
Clay Content (% weight, 0-30cm)	HWSD (*48*)
Sand Content (% weight, 0-30cm)	HWSD (*48*)
Organic Carbon (% weight, 0-30cm)	HWSD (*48*)
Total Nitrogen (kg N t^{-1}, 0-50cm)	ISRIC/WDC-Soils (*49*)
Phosphorus (kg P t^{-1}, 0-50cm)	Scherer and Pfister (*50*)
Drainage (6 classes)	HWSD (*48*)
Erodibility (t h MJ^{-1} mm^{-1})	Scherer and Pfister (*50*)
Geography	
Slope Length (dimensionless)	GMTED (*50*, *51*)
Slope (%)	GMTED (*50*, *51*)
Phosphorus reaching aquatic environment (%)	Scherer and Pfister (*50*)
Climate	
Precipitation (mm $year^{-1}$)	WorldClim (*52*)
Winter-type Precipitation Correction	WorldClim (*52*)
Average Temperature (°C)	WorldClim (*52*)
Potential Evapotranspiration (mm)	Zomer *et al.* (*53*)
Eco-Climate Zones (12 classes)	Hiederer *et al.* (*54*)
Other	
Irrigated Water Applied (m^3 ha^{-1})	Pfister and Bayer (*55*)
CF_{AWARE} (water scarcity for each basin, relative to global water scarcity) (m^3_{world} m^{-3})	Boulay *et al.* (*45*)
Cropping Intensity	MIRCA2000 (*56*)

i. *Irrigation Water Applied*

Evapotranspiration from irrigation was drawn from a basin-level dataset of 160 crops (*55*). For flooded rice, data including flood water evaporation were used (*57*). To convert from evapotranspiration to field applied water, application efficiency factors (*58*), weighted by country shares of irrigation system (*59*), were applied.

ii. *Aquaculture Water Requirements*

Evaporation from aquaculture ponds was estimated from potential evapotranspiration (PET) (*53*) and factors converting PET to open water evaporation (*60*).

iii. *Multiple Cropping and Fallow*

Land use was calculated from inverse yield and occupation time. Occupation time is reduced by multiple cropping but increased by fallow requirements. Many studies did not provide crop timetables, and derivation was required.

From MIRCA2000 (*56*), minimum crop fallow requirements were calculated as cropland extent (CE_{MIRCA}) over maximum monthly growing area (MMGA) (*61*). MMGA is the maximum area required for the crop rotation in that location. CE_{MIRCA} is the area used for arable crops including fallow (*62*). Fallow land was treated as insignificant for greenhouse crops, vineyards, and bananas. Given the large variation in orchard lifecycles, fallow requirements were set based on commercial lifespans using literature data. Longer fallow requirements for some practices (e.g., organic) were not considered.

Multiple cropping was calculated from the ratio of MMGA to area harvested (AH) (*61*). AH is counted each time a crop is harvested in a year (e.g., for double cropping, MMGA/AH = 2). Land use, calculated from yield, can be multiplied by each of these ratios in turn, to reconcile to global cropland extent from FAOSTAT (Materials and Methods, Section 6a).

b. Data Derived from External Datasets

Table S4. External datasets used.

Inventory Item	Source / Methodology
Seed (kg ha^{-1})	Food Balance Sheets (*4*)
Nursery Land Use (m^2·year m^2·year^{-1})	Literature sources
Nutrient Composition of Org. Fert. (kg ha^{-1})	Webb *et al.* (*63*); Sintermann *et al.* (*64*); AGRIBALYSE (*65*)
Nutrient Content of Excreta (kg ha^{-1})	ASAE (*66*); EEA (*67*)
Synthetic Fertilizer Composition (%)	FeedPrint (*68*)
Fuel & Machinery Use (kg ha^{-1})	AGRIBALYSE (*65*)
Energy for Irrigation (kWh ha^{-1})	WFLDB (*58*)
Dry Matter (%) & Crop Composition	Feedipedia (*69*); other sources
Share of Residue Removed and Burnt (%)	GNOC (*70*); other sources
Residue Remaining (kg DM ha^{-1}; kg N ha^{-1})	IPCC (*71*); other sources
Infrastructure (kg ha^{-1} year^{-1})	Kowata *et al.* (*72*)
Water Use by Feed Crops (L kg^{-1})	Pfister *et al.* (*55*)
Animal Drinking & Service Water (L kg LW^{-1})	Mekonnen and Hoekstra (*73*)

i. Nutrient Composition Content of Organic Fertilizer

The nitrogen (N), phosphorus (P), and total ammoniacal nitrogen (TAN) content of manure at the point of application, not excretion, was used here, given differing mineral loss rates in housing and storage. No data were collected on the storage method prior to application, and a range was drawn from literature sources to reflect this variation.

For solid manure the meta-analysis of Webb *et al.* (*63*) was used, which included 266 observations by animal. For liquid manure, data from Sintermann *et al.* (*64*) were used which included 345 observations by animal, supplemented with data from AGRIBALYSE (*65*). For compost, TAN was taken from AGRIBALYSE. Green manure was taken to have no NH_3 emissions, and TAN was set to 0.

ii. Fuel and Machinery Use

Most studies did not account for the impact of machinery production and delivery to farm. From 139 processes in AGRIBALYSE, the ratio of machinery depreciated per unit of fuel consumed (kg machinery kg diesel^{-1}) was established. Recognizing that farms in less developed countries have poorer access to capital and maintain farm machinery for longer, the machinery-to-diesel ratio was doubled in countries with a Human Development Index (*74*) less than 0.8.

c. Allocation and Conversion Factors

For allocation between beef and milk, and lamb and wool, economic allocation factors were recalculated where required, using national price data and the yield of each product. For grain and straw, roots and feed grade roots, and nut kernels and hulls, global allocation factors were taken from literature sources.

4) Standardizing the Impact / Resource Use Indicators

For studies consistent with our system boundary, impact and resource use indicators were recorded directly.

Where the system boundary was consistent, but indicators were provided under a different characterization, direct conversion was possible if major emissions were reported for each gas or liquid separately.

Where different characterizations were used, and gas and liquid emissions were not reported separately, recalculation was still possible in some cases:

- **GHG emissions:** Most studies included use AR4 characterization factors (CFs). Only separately reported CH_4 emissions are required for recalculation under AR5 CFs with climate-carbon feedbacks, given the same CF is used for N_2O.
- **Acidification:** NH_3 is the dominant acidifying emission in agriculture, and the characterization was converted based on the ratio between the CML2 baseline CF and the studies CF for this gas. SO_2 was used as the dominant gas for post-farm processes.
- **Eutrophication:** EDIP2003 (*75*) and ReCiPe (*76*) split emissions into P and N equivalents. P emissions were directly recharacterized under CML2 Baseline. For N emissions, we weighted CFs by global agricultural N emissions (*77*) by type to derive a conversion factor.

5) Standardizing the Functional Unit

i. Arable and Permanent Crops

For grains, oilseeds, pulses, and soybeans, where studies presented results in fresh weight, mass change from drying was included by using dry matter shares at harvest and storage (*69*). For nuts, standard kernel weights (*4*) were used for conversions.

ii. Meat, Fish, and Crustaceans

Weight definitions for meat and fish vary by animal and country. The following definitions were standardized to as much as possible:

- Liveweight (LW): weight of the living animal leaving the farm.

  <u>*Meat:*</u>
- Hot standard carcass weight (HSCW): weight at slaughter, after removal of hides, head, feet, tail, and inedible offal. For poultry, also after removal of feathers. For pigs, also after removal of skin. Includes bones.
- Retail weight (RW): weight after removal of bones and excess fat.
- Edible offal (EO): non-muscle parts considered edible, variable by country.

  <u>*Fish:*</u>
- Filleted weight: weight after removal of head, fins, skin, bones, and organs.
- Edible weight: weight excluding large bones and inedible organs.

Data were collected from literature sources. A carcass weight adjustment of -2% was made for dairy breeds. For fish, data by species were used (*78*).

Table S5. Meat processing conversions used.

	HSCW / LW			RW+EO / HSCW			By Product Value		
Product	**Avg.**	**SD**	**n**	**Avg.**	**SD**	**n**	**Avg.**	**SD**	**n**
Beef	52%	3%	101	72%	2%	4	7%	5%	13
Mutton	47%	3%	27	71%	1%	2	7%	5%	7
Pork	75%	3%	12	68%	2%	3	5%	3%	8
Poultry	72%	2%	2	72%	4%	2	2%	2%	5

iii. Milk, Soymilk, and Tofu

Animal milk purchase prices are largely determined on fat and protein content. During processing, milk is standardized by removing and adding back solids to form grades of milk. The relevant functional unit for milk is therefore one that controls for fat and protein, and here milk was standardized to 4% fat and 3.3% protein (*79*) for all ruminants (*80*).

For soy products, protein is lost during processing as by-products or waste. Data were collected on the protein conversion from beans to soymilk or tofu, and then standardized to 3.3% and 16% protein respectively. This ensures nutritional unit results are robust to changes in processed-product protein content.

6) Filling Gaps in the System Boundary or Recalculating Indicators

Land use was split into five types (table S2). Farm-stage GHG emissions were split into 20 sources, gaps filled, and the total recalculated. For land use, acidification, and eutrophication, the entire indicator was recalculated from the inventory if calculated inconsistently with our system boundary (except aquaculture, where NO_x and NH_3 emissions were added to existing values otherwise consistent with our system boundary).

a. Land Use

i. Temporary and Permanent Crops

$$\boldsymbol{Land\ Use = \frac{10{,}000}{Yield} \cdot \frac{Seed + Yield}{Yield} \cdot \frac{Crop\ Duration}{365} \cdot \frac{Rotation\ Duration}{Cultivated\ Duration}}$$

where $Land\ Use$ is the area occupied to produce 1 kg of product, in m^2·year, $Yield$ and $Seed$ are in kg ha^{-1} and are on the same marketable weight basis (e.g., 15% moisture post field losses), and the $Duration$ terms are in days.

For temporary crops, yields for all studies included here, and in most statistical datasets (*4*), represent output per harvest, not output per year. Where multiple cropping occurs, a time-based allocation was used to apportion land use between crops in the rotation, as $Crop\ Dur/365$ where $Crop\ Dur \leq 365$ represents the time from crop preparation to the beginning of preparation for the next crop (*81*). For permanent crops, excluding orchard crops, yield represents life-cycle yield from establishment to eradication, and $Crop\ Dur$ was set to 365. No allocation was used for intercropping.

$Rotation\ Duration$ is the duration of the whole rotation including marketed crops and fallow, and $Cultivated\ Duration$ is the period cultivated with marketed crops. The difference between these terms is the fallow period. Including fallow allows for a reconciliation to the FAOSTAT (*4*) term “Arable land and permanent crops”.

ii. Orchard Crops

$$\boldsymbol{Land\ Use} = \frac{\mathbf{10,000}}{\boldsymbol{Yield}} \cdot \frac{\boldsymbol{Cultivated\ Duration}}{\boldsymbol{Bearing\ Duration}} \cdot \boldsymbol{Nursery} \cdot \frac{\boldsymbol{Rotation\ Duration}}{\boldsymbol{Cultivated\ Duration}}$$

where $Yield$ represents the period when the orchard is bearing marketed fruit ($Bearing\ Duration$), consistent with FAOSTAT (*82*). $Cultivated\ Duration$ represents the period from orchard establishment to removal. The difference between $Bearing\ Duration$ and $Cultivated\ Duration$ is the non-bearing period after establishment, typically 1-4 years. The fallow period after orchard removal and before replanting is $Rotation\ Duration/Cultivated\ Duration$.

For orchard crops seed is not significant, but the nursery period is. The additional area required for the nursery stage per kilogram of product was calculated as:

$$\boldsymbol{Nursery} = \mathbf{1} + \frac{\boldsymbol{Nursery\ Duration}/\mathbf{365}}{\boldsymbol{Sapling\ Yield}} \cdot \frac{\boldsymbol{Orchard\ Density}}{\boldsymbol{Cultivated\ Duration}}$$

where $Nursery\ Duration$ is the time from planting seedlings to the sale of marketable trees (in days); $Sapling\ Yield$ is the number of marketable saplings produced per hectare per year; and $Orchard\ Density$ is the number of trees required for 1 ha of mature orchard.

iii. Animal Products

For animal products, land used for feed was further disaggregated into the five feed crops that used most land. For each feed, the crop, geographic origin, and land use share were recorded. Fallow land and seed requirements were then recalculated for each crop-geography. Where feed originated from the farm, and temporary pasture was recorded on that farm, on-farm fallow was taken to be used as temporary pasture, and fallow was set to 0.

b. Freshwater Withdrawals and Scarcity-Weighted Freshwater Withdrawals

Freshwater withdrawals were calculated directly from inventory items: irrigation withdrawals; irrigation withdrawals embedded in feed; drinking water for livestock; water for aquaculture ponds; and processing water. For irrigation withdrawals embedded in feed, we recorded the feed crop type and its country of origin.

To calculate scarcity-weighted freshwater withdrawals, we assumed that all irrigation water is evapo-transpired or embedded in the product, and none is returned to the watershed through percolation. This is sometimes true and sometimes an overestimation, depending on the need of the crop and the irrigation technique, but good data is lacking here, and we leave assessment of freshwater returns to further research. We therefore directly multiplied freshwater withdrawals by the spatially explicit AWARE (*45*) characterization factors by basin and/or country. We differentiated the location of each feed crop and the location of post-farm water use.

c. Production and Transport of Farm Inputs

Inputs required on-farm were grouped as: seed and nursery; fertilizers, pesticides, and lime; fuel and machinery; infrastructure; and electricity. For seed and nursery, emissions were calculated based on a closed-loop as for land use. For the remaining inputs, two consistent sources, ecoinvent (*83*) and AGRIBALYSE (*65*), were used to derive global average emissions and standard deviations.

d. On-Farm Emissions

Table S6. On-farm emissions and methodology to fill gaps.

Source	Emission	Methodology
Fuel use	CO_2, SO_2, and NO_x to air	ecoinvent (*83*)
Fertilizer application on mineral soils and excretion on pasture	N_2O to air	Stehfest and Bouwman (*84*); IPCC (*71*) Tier 1
Crop residues left on field	N_2O to air	IPCC (*71*) Tier 1
Flooded rice cultivation	CH_4 to air	*Recalculation not required*
Urea application	CO_2 to air	IPCC (*71*) Tier 1
Lime application	CO_2 to air	IPCC (*71*) Tier 1
Synthetic fertilizer application	NH_3 to air	EEA (*85*) Tier 2
Organic fertilizer application	NH_3 to air	Webb *et al.* (*63*); Sintermann *et al.* (*64*)
Excretion on pasture	NH_3 to air	EEA (*67*) Tier 2
Crop residues left on field	NH_3 to air	de Ruijter *et al.* (*86*)
Fertilizer application, excretion on pasture and crop residues left on field	NO_x to air	Stehfest and Bouwman (*84*)
Fertilizer application and site conditions	NO_3^- and N to water	Meta-analysis; Scherer and Pfister (*50*)
Crop residues left on field	NO_3^- to water	IPCC (*71*) Tier 1
Fertilizer application and site conditions	P to water	Scherer and Pfister (*50*)
Fertilizer and crop residue leaching, runoff, and volatilization	N_2O indirect to air	IPCC (*71*)
Crop residue burning	CH_4, N_2O, NH_3, and NO_x to air	Akagi *et al.* (*87*); IPCC (*71*) Tier 1
Cultivated organic soils	N_2O and CO_2 to air	IPCC (*88*) Tier 1 country-level data
Enteric fermentation	CH_4 to air	IPCC (*71*) Tier 2; WFLDB (*58*)
Aquaculture	N_2O, NH_3 to air	Literature sources
Aquaculture	N and P to water	*Recalculation not required*
Aquaculture	CH_4 to air	Model; Literature review
Manure management	N_2O, NO_x, NH_3, and CH_4 to air	EEA (*67*) Tier 2; IPCC (*71*) Tier 2

i. Direct N_2O and NO_x emissions to air from fertilizer applied on mineral soils, excretion on pasture (and crop residues left on field)

Fertilizer-induced direct N_2O and NO_x emissions on mineral soils were calculated using a global model (*84*), derived from a meta-analysis of 1008 and 189 field observations respectively (*89*) as:

$$N_2O - N = \exp(c + 0.0038 \cdot (F_{SN} + F_{ON} + F_{PRP}) + \sum_{i=1}^{n} E_i) - \exp(c + \sum_{i=1}^{n} E_i)$$

$$0 \leq N_2O - N/(F_{SN} + F_{ON} + F_{PRP}) < 7.2\%$$

$$NO_x - N = \exp(c + 0.0061 \cdot (F_{SN} + F_{ON} + F_{PRP} + F_{CR}) + \sum_{i=1}^{n} E_i) - \exp(c + \sum_{i=1}^{n} E_i)$$

$$0 \leq NO_x - N/(F_{SN} + F_{ON} + F_{PRP}) < 2.5\%$$

where c is the regression constant; F_{SN}, F_{ON}, and F_{PRP} are synthetic fertilizer, organic fertilizer, and excreta respectively in kg N ha^{-1}; and E_i denotes the effect values of the remaining i significant effects from Stehfest and Bouwman (*84*). This specification isolates the fertilizer-induced effect. Here, the function is constrained to the 95th-percentile induced effect from the original study dataset. For NO_x, crop residues (F_{CR}) were included in this function, given the lack of other models.

The N_2O model relies on geographically specific inputs, and for country-level studies, IPCC (*71*) Tier 1 emissions factors were used. For NO_x experimentally-grounded Tier 1 factors are not available. Here, we implemented the NO_x model at a global level, using spatial data specified in table S3. We then averaged within countries to derive country average emission factors. This avoids problems with nonlinearity of the exponential function.

Emissions for synthetic fertilizer, organic fertilizer, and excreta were then allocated by share of N applied. Crops grown in substrates lacking nitrifying and denitrifying bacteria (e.g., rock wool) were taken to have no emissions.

ii. Direct N_2O emissions to air from crop residues left on field

Experimental results are uncertain, suggesting both no significant net N_2O emission (*90*) and significant net N_2O emissions determined by multiple factors (*91*). Given this, IPCC (*71*) Tier 1 values were used.

iii. NH_3 emissions to air from organic fertilizer application

For solid manure, the same dataset as for TAN content was used (*63*). This provided 215 observations, covering different animals, practices, and measurement/ experimental techniques, which were aggregated into a single EF with standard deviation of 0.56±0.34 kg NH_3-N kg TAN^{-1}.

For liquid manure, the same dataset as for TAN slurry content was used (*64*), but based on the discussion in that study about significant changes in practice after the year 2000, we excluded studies before that date. This provided 109 observations, with no significant difference between animal type or land use, and gave an EF of 0.25±0.16 kg NH_3-N kg TAN^{-1}.

iv. NH_3 emissions to air from crop residues left on field

NH_3 emissions from residue vary by crop and management practice (*86*). Research in this area is scarce, and here a linear model of N in above-ground crop residues (N_{AG}) in kg and total above-ground residue dry matter (AG_{DM}) in kg (*86*) was used:

$$NH_3 - N = a \cdot N_{AG}\ ,\ \ a = (0.38 \cdot N_{AG} \cdot 1000/AG_{DM} - 5.44)\ /100\ ,\ 0 \leq a < 17\%$$

where 0% and 17% are the bounds of observations in the study. The model therefore predicts no volatilization when the N content is less than 14.3g N kg DM^{-1} (e.g., cereal straw).

v. N leaching, erosion, and runoff from fertilizer application, excretion, and crop residues left on field

The IPCC (*71*) Tier 1 approach can be decomposed into $FRAC_{LEACH}$ (N lost below the root zone to nearby or distant rivers and streams), $FRAC_{EROSION}$ (loss of surface N contained in eroded soil), and $FRAC_{RUNOFF}$ (loss of residual surface N in runoff water).

After an extensive search, no reliable N leaching models were identified that would work with typical LCA inventory data, and we developed a model to estimate this. For leaching, background losses are non-negligible given leaching of mineralized soil organic N and atmospherically deposited N among other sources. The interest here is only in assessing the observed anthropogenic N_2O source (*92*) in relation to the observed atmospheric N_2O increase, as well as anthropogenically induced eutrophication. Therefore, induced leaching has to be isolated from background leaching. This can be estimated from experimental leaching studies that measure leaching L of mineral N (kg NO_3-N or NH_4-N ha^{-1}) under two or more fertilizer levels $F_1 > F_0$ (kg N ha^{-1}) for the same crop, site, and year, assuming linearity, as:

$$FRAC_{LEACH} = \frac{L_1 - L_0}{F_1 - F_0}$$

To control data quality, above-ground biomass uptake U (kg N ha^{-1}) was also recorded, and results were treated as erroneous where $(L_1 - L_0) + (U_1 - U_0) > (F_1 - F_0)$.

To ascertain these data, a literature review was conducted. The search terms “nitrate leaching” AND “uptake” AND “experiment” were used in Google Scholar, and any studies cited in or citing these studies were also selected, until 1000 studies were identified. Experiments using lysimeters, suction cups with water balances, or tile drains were included. From these studies, 91 included treatments with multiple fertilizer levels and provided leaching in kg N ha^{-1}. This yielded 417 observation pairs, of which 53 were excluded based on the uptake criterion or other factors that made fertilizer treatments incomparable.

Site-specific conditions are major determinants in N leaching (*93*). In very low-permeability soils, in areas with low water input, or under deep-rooted crops, leaching will be low (*94*). Equally, under highly permeable soils, in areas with high water input, or under shallow-rooted crops, leaching will be high. $FRAC_{LEACH}$ was therefore estimated for different rooting depths, soil textures (sand and clay fraction), water input (only precipitation was used here, which is more subject to leaching given higher variability), and water table height (flooded or non-flooded crops). Cut-off levels for each factor were based on visual inspection of the data and sample size. Four groups were then created (Kruskal-Wallis test, $p < 0.001$; Dunn’s post hoc tests, $p < 0.05$).

Table S7. Fraction of fertilizer leached as mineral nitrogen.

	$FRAC_{LEACH}$ (kg NO_3-N kg N^{-1} unless stated)					
	Avg.	**SD**	**Obs. Pairs**	**Avg.**	**SD**	**Obs. Pairs**
***Low Leaching Conditions**, at least one of:*						
Max. Root Depth > 1.3m	6.5%	5.2%	23			
Clay > 50%	7.8%	5.8%	11	6.7%	5.1%	45
Precipitation < 500mm	5.8%	4.5%	11			
***High Leaching Conditions**, at least one of:*						
Max. Root Depth < 0.5m	28.0%	13.0%	8			
Sand > 85%	21.6%	15.7%	26	23%	14%	42
Precipitation > 1300mm	26.8%	13.6%	10			
***Other Conditions** (or both high and low leaching conditions):*						
All Other Conditions				12%	10%	252
Flooded Rice						
Flooded Rice (NO_3-N)	2.8%	3.4%	25	3.5%	3.1%	22
Flooded Rice (NH_4-N)	1.3%	1.3%	22			

Given the small number of LCA studies where recalculation of leaching on pasture was required, a value of 7±2% was used, based on the average value for pasture-dominant New Zealand (*95*).

Surface runoff requires simultaneously occurring factors: water input greater than evapotranspiration and infiltration, causing surface accumulation; slope or ditches so water runs-off rather than puddles; field outlets; and residual N on the surface at the time of runoff. Additional information on the quantity of N that reaches rivers or streams, as opposed to neighboring terrestrial areas, is also required. These data requirements make runoff difficult to model with available LCA inventory data. Further, most global studies do not model this flow (*93*, *96*). The data requirements, and more limited set of conditions that this flow occurs in, make it reasonable not to consider it here.

$FRAC_{EROSION}$ was estimated following Scherer and Pfister (*50*), replacing soil P with soil N derived from the HWSD (*48*). $FRAC_{EROSION}$ is a total N flow and is only included in eutrophication calculations.

vi. *Indirect N_2O emissions to air from fertilizer and crop residues left on field, from leaching, runoff, and volatilization*

Indirect N_2O emissions were then calculated as (*71*):

$$N_2O - N = 0.01 \cdot (NH_3 - N + NO_x - N) + 0.0075 \cdot NO_3 - N$$

For some studies that did not provide sufficient information to calculate NH_3 or NO_x, the default fraction volatilized from IPCC (*71*) was used.

vii. *P loss to water from fertilizer application and site conditions*

The model of Scherer and Pfister (*50*) estimates P loss to water from four mechanisms: soil erosion, runoff, drainage, and leaching. Their original specification was modified by setting maximum field slope to 5% for flooded rice, where terracing or other mechanisms are used to prevent water loss.

viii. *N_2O and NH_3 emissions to air from aquaculture*

The difference between N inputs as feed and fertilizer (N_{IN}) and N outputs in liveweight (N_{OUT}) is subject to gaseous losses during the aqueous phase. N consumed but not assimilated is excreted by aquatic animals with approximately 80% TAN (*97*). To allow for feed not consumed, excreted TAN was estimated as the minimum of $(N_{IN} - N_{OUT}) \cdot 0.8$, or $3.31 \cdot N_{OUT} \cdot 0.8$, where the coefficient in the latter is based on 23% of feed N converted to fish biomass N (*98*). Emissions of N_2O are likely higher from the TAN component of excreta, and an emissions factor of 1.8±0.7% N_2O-N kg TAN^{-1} was used (*98*). N_2O emissions from unconsumed feed and solid excreta are likely lower, and an emissions factor of 0.5±6.2% N_2O-N kg N^{-1} was used (*71*). N_2 and NO_x emissions were calculated from nitrification/ denitrification ratios proposed by Dämmgen (*99*). NH_3-N volatilized was estimated from data on freshwater ponds as 0.3·TAN (*100*), constrained to a maximum of 50 mg m^{-2} day^{-1} in systems where the surface area for diffusion is limited (*101*). Emissions from pond drainage and refilling (*67*) were not considered.

ix. *CH_4 emissions to air from aquaculture*

Organic carbon (OC) in excreta, unconsumed feed, fertilizer, and net primary production (NPP) can mineralize to CH_4 when they accumulate in anoxic sediments with low sulfate and nitrate levels. These conditions allow methanogenesis to become a significant source of mineralization, as sulfate reduction, nitrification and aerobic mineralization become less dominant pathways (*102*). Here, we develop an initial model for these emissions that are included in few LCAs or climate models.

To estimate OC sedimentation, a carbon balance was used. OC input from feed and fertilizer (C_{IN}) was estimated from feed energy contents, more widely reported than carbon contents as 21 g C MJ^{-1} based on typical feeds. OC input from NPP was estimated based on temperature (*103*, *104*). The dominant OC outputs are respiration by fish (C_{RESP}), carbon removed in fish biomass at harvest (C_{FISH}), and mineralization in the dissolved OC pool. We assumed the ratio of fish biomass to respiration to excretion was 40:40:20 (*105*), which we calculated from liveweight (LW) and expressed in kg C kg LW^{-1}. Taking aqueous OC outflow to be 0, OC available for sedimentation C_S was calculated as:

$$C_S = \max(C_{IN} + C_{NPP} \cdot Cycle\ Time/Stocking\ Density - C_{FISH} - C_{RESP}, C_{EXCR}) \cdot S$$

where C_{IN} and C_S are in kg C kg liveweight^{-1} (LW) produced, C_{NPP} is in kg C m^{-2} day^{-1}, $Cycle\ Time$ is in days and $Stocking\ Density$ is in kg LW m^{-2} cycle^{-1}. S is a constant reflecting the share of the carbon pool deposited as sediment, influenced by a large range of factors. We set S within the range of literature sources as 35±5% for freshwater (*101*, *106*, *107*) and 55±10% for marine (*108*, *109*).

CH_4-C emissions were then calculated as:

$$CH_4 - C = \min(C_S \cdot M \cdot M_{CH_4} \cdot R,$$
$$CH_4 - C_{max} \cdot Cycle\ Time/Stocking\ Density)$$

where M is total mineralization of sedimented OC, M_{CH_4} is the share mineralized as CH_4-C, and R is the share of CH_4 not oxidized at the sediment/water interface or in the water column, and instead released by diffusion or ebullition into the atmosphere. $CH_4 - C_{max}$ is the maximum observed methane flux (0.5 g CH_4-C m^{-2} day^{-1}) from a meta-analysis of 474 methane emission estimates from freshwater bodies (*110*). R varies by depth, and here we set it to 61±22% for shallow systems (<2m) (*111*, *112*) and 22±20% (≥2m) (*112*).

Experimental data (*112*) shows that temperature limits M_{CH_4}. Here, we estimate M_{CH_4} by using our previous formula for $CH_4 - C$, substituting in known values of the variables from global data. C_S was calculated by latitude using NPP data for lakes. M was set to 100% as a long-term value without sediment removal. R was set to the average of shallow and deep water (41.5%). Resultant $CH_4 - C$ values were taken from the methane flux meta-analysis (*110*). M_{CH_4} was then calculated. In marine environments, higher sulfate concentrations favor sulfate reduction and M_{CH_4} was determined from literature sources (*108*, *109*).

Table S8. Share of mineralized carbon mineralized as methane.

	% Mineralized C as CH_4-C (M_{CH_4})
Freshwater: fast flowing	0%
Freshwater: slow flowing (<23.5°C surface temperature)	20±20%
Freshwater: slow flowing (≥23.5°C surface temperature)	45±20%
Marine: flow-through	0%
Marine: sea cages/ponds	4±4%

Because in aquaculture, sediment is often removed and mineralization rates differ with temperature, we calibrated mineralization (M) based on observed sediment C:N ratios. To do this we used observations in our meta-analysis where sufficient data were available to calculate C_S, and where we had observations for sediment N. We found M values of 60% and 30% for warm (average annual temperature ≥23.5°C) and cool climates respectively yielded C:N sediment ratios in line with literature values. These M values were used here.

x. N_2O, NO_x, NH_3, and CH_4 emissions to air from manure management

For livestock, the EEA (*67*) mass balance approach was used, with adjustments to emissions factors based on EPA (*113*) Annex 3, IPCC (*71*) and other literature sources.

For aquaculture sediment, N was calculated as unconsumed feed and solid excreta less gaseous losses (Materials and Methods, Section 6c. viii). Liquid N excreta was assumed to be lost from the system (e.g., in drainage water). Sediment OC was calculated as deposited OC after mineralization ($C_S \cdot M$). OC was multiplied by 2.05 to estimate volatile solids, a value that was derived from a linear regression on aquaculture residue composition (*114*). A maximum methane potential (B_0) of 0.31 was used (*115*). The fate of sediments was taken from details in each study. Fates typically included field application, pumping/release into other water bodies, or storage in anaerobic sediment ponds or stockpiles. The first two have no emissions, and for the latter, emissions were based on slurry in uncovered anaerobic lagoons (*71*).

7) *Filling Gaps in The Rest of the Supply Chain*

a. Land Use Change

To estimate CO_2 emissions and sequestration from carbon stock change, we used a model consistent with PAS2050-1 (*116*). The model uses above- and below-ground carbon pools (*71*) by country and accounts for multiple climates and soil types (*117*). It then uses agricultural land expansion by country (*4*) to estimate emissions. Emissions are amortized over 20 years (*118*). We also estimated CH_4 and N_2O emissions from forest burning, and CO_2, CH_4 and N_2O emissions from peat burning, using country forest and peat burning extent (*119*). Country data, as opposed to farm or sub-regional data, better reflect the drivers of land use change which cover multiple actors (*42*).

We adapted the model by defining when a specific crop's expansion translates into losses from another land class. First, arable crops were taken to expand into existing arable area first, and permanent crops into existing permanent crop area first. Second, where the sum of expansion and contraction of all crops (net expansion) was positive, arable cropland was assumed to expand into permanent cropland if a negative balance existed in the other, and vice versa. Third, both arable crops, permanent crops, and permanent pasture were taken to expand proportionately into deforested area. Fourth, any remaining cropland not accounted for was taken to expand into pasture or vice versa if a negative balance existed in the other. Finally, any remaining agricultural area expansion was allocated to the 'other land' category (which includes degraded land).

Under this approach, 61% of 1990-2010 forest loss was attributable to commercial agriculture (excluding shifting cultivation). This value reconciles to survey data (*120*). We used FAO data (*4*) as a consistent annual inventory of multiple land classes, but recognize that total deforestation in the Forest Resources Assessment (*4*) is below remote sensing estimates (*121*). Our approach likely underestimates agriculturally induced land use change, but benefits by reconciling to FAO data.

b. Transport

Distances, modes, and emissions were adapted from ecoinvent (*122*). The ecoinvent methodology took annual global transport volumes by mode (*123–125*) and allocated these between different products and transport modes using data from US freight surveys of 42 goods, and EU-27 freight surveys of 20 goods. Here, we estimated the chilled transport share from UK data (*126*). We drew emissions from a dataset considering average load factors and the full transport life-cycle (*127*).

c. Processing

Data from 117 LCA studies provided 232 observations on GHG emissions, acidification and eutrophication, and processing conversions across ~495 processes. The data were consolidated into averages and standard deviations, weighted by the number of processing plants assessed per observation.

d. Packaging

Data from previously used studies and an additional 34 LCA studies provided 171 observations. Studies were included that assessed end-of-life disposal and calculated at least GHG emissions. The observations were consolidated into 11 product groups with similar pack types.

e. Retail

Data from a further two LCA studies, combined with studies previously used, provided 58 observations across three groups: fresh, chilled, and ambient.

f. Losses

Following the FAO (*128*), food losses occur at five stages, during: harvest and pre-harvest operations (L_0); storage and transport between farm and distribution (L_1); processing and packaging (L_2); wholesale and retail distribution (L_3); and consumption (L_4). Consumption losses are not included in this study.

Production and yield in FAOSTAT and the food balance sheets (FBS) are net of harvest and pre-harvest losses (L_0) (*129*). Here, all yield data collected from LCA studies were entered in the database net of harvest and pre-harvest losses to ensure reconciliation. Storage and transport losses (L_1) were occasionally reported by LCAs, and if missing this gap was filled. Estimates of losses at this stage were taken from the FBSs, following Gustavsson *et al.* (*130*). Processing and packaging (L_2), and wholesale and retail (L_3) losses were taken from Gustavsson *et al.* (*130*). Losses at these stages represent an average for the crop/geography, not necessarily the consumption mode in this study.

Losses were calculated as the additional food required to deliver one functional unit to the consumer as:

$$T = \frac{\left[\frac{\left[\frac{(LUC + Feed + Farm)}{(1 - L_1)} + Proc\right]}{(1 - L_2)} + Trans + Pack + Rtl\right]}{(1 + L_3)}$$

$$L = T - (LUC + Feed + Farm + Proc + Trans + Pack + Rtl)$$

where T represents the total mass flow including losses, and L represents losses. If by-products are marketed (e.g., feed-grade vegetables), allocation means that the mass flow does not equal the environmental flow.

8) Weights

a. Within-Country Weights

Study representativeness within a country was determined first, either based on values reported by the author, or by derivation from global datasets on tillage (*131*), irrigation (*132*), organic farming (*133*), and/or sub-national production censuses.

b. Between-Country Weights

i. Temporary and Permanent Crops

Where ≥75% of global production was represented by observations, countries were weighted by production (eight crops).

Where <75% of global production was represented, agro-ecological suitability (*134*) and macro-nutrient input levels (*7*), were used to group countries by similarity. HDI was used as a proxy for macro-nutrient input if not available (*74*). This created a 2×2 high-low suitability-input matrix of countries for 21 crops. The production weights of all countries in each quadrant were scaled up to the share of global production represented by each quadrant.

For the remaining four crops, weights were based on the share of each country's production.

ii. Animal Products

For milk, countries were split into three groups (low, medium, and high yield per cow) (*4*) where boundaries between each group split global production in thirds. For fish, shares of production by species were taken from FishStatJ (*135*). For other animal products, weights were based on country production (*4*, *136*).

9) Randomization and Resampling

Some studies group farms into a single observation and provide an average mid-point impact and associated standard deviation. When we fill gaps in the supply chain, variance is also associated with: emissions factors (but here not characterization factors); processing, packaging, retail, and transport impacts; processing conversions; and other conversions (e.g., dry matter weights).

To include all these sources of variance, as well as the variance among observations, we re-specified all values associated with variance as normally distributed variables. A random number was then generated, creating a new value for each observation. For each product one observation was randomly recorded, with likelihood based on the observation weights. A new random number was generated, and the process repeated creating 10,000 observations for each product.

This approach has limitations if studies did not report standard deviations, or remodeling from inventory data were used to fill different emissions gaps for each study. Nevertheless, it was the best way identified to effectively incorporate these multiple sources of variance.

Supplementary Text

Reconciliation of values from this meta-analysis to independent estimates

Table S9. Weighted average global yields for this study vs. FAO global average yields.

Crop (*n* = observations)	**FAO Yield** (t ha^{-1}, '09-11 avg.)		**This Study Yield** (t ha^{-1}, ~2010)		**Bias** (Study - FAO Yield) / FAO Yield	
	Mean	**90th-pctl**	**Mean**	**90th-pctl**	**Mean**	**90th-pctl**
Wheat & Rye (*n* = 261)	3.1	6.4	3.2	7.1	6%	11%
Maize (152)	5.2	9.7	5.3	10.0	3%	4%
Barley (93)	2.7	6.1	2.7	6.4	-2%	6%
Oats (17)	2.3	4.6	2.4	3.2	8%	-30%
Rice (flooded) (65)	4.4	6.6	4.5	7.2	2%	9%
Potatoes (91)	16.6	41.1	19.8	41.0	19%	0%
Cassava (52)	11.4	20.1	11.2	23.7	-1%	18%
Sugar Cane (53)	71.0	78.5	73.0	85.0	3%	8%
Sugar Beet (36)	51.4	90.0	49.9	75.6	-3%	-16%
Other Pulses (44)	0.8	1.7	1.0	1.3	25%	-22%
Peas (33)	1.6	3.0	2.0	4.4	23%	47%
Nuts (23)	1.4	4.3	1.4	3.8	2%	-12%
Groundnuts (24)	1.6	3.4	2.1	3.6	27%	4%
Soybeans (49)	2.5	2.9	2.3	3.0	-5%	3%
Palm (30)	14.2	20.9	19.4	23.0	37%	10%
Sunflower (31)	1.4	2.3	1.4	2.4	-2%	5%
Rapeseed (77)	1.9	3.6	2.1	3.6	8%	1%
Olives (24)	2.0	2.9	2.0	9.9	0%	238%
Tomatoes (82)	33.6	81.5	30.3	198.5	-10%	144%
Onions & Leeks (29)	18.4	45.4	24.5	47.2	33%	4%
Root Vegetables (30)	29.8	54.1	40.3	80.2	35%	48%
Brassicas (32)	24.9	34.5	24.1	57.1	-3%	65%
Citrus Fruit (30)	14.4	31.1	16.8	36.9	17%	19%
Bananas (23)	20.7	41.6	28.2	45.9	36%	11%
Apples (66)	15.0	38.8	24.4	42.9	62%	11%
Berries (40)	13.6	29.7	13.5	72.8	-1%	145%
Coffee (28)	0.8	2.0	1.0	2.2	26%	12%
Cocoa (19)	0.5	0.6	0.5	0.7	9%	21%

Comparing mean yields to FAOSTAT (*4*), 17 of 28 crops reconcile to within ±10% (table S9). For pulses, peas, potatoes, and groundnuts, we have low representation in low-yielding

African and Asian countries, and our yield estimates are on average 24% higher than FAOSTAT. The remaining crops that did not reconcile are primarily trees and vegetables. For the former, FAOSTAT data include trees in residential areas or small orchards (*82*), not captured in this dataset. Further, the distinction between bearing and non-bearing periods is inexact and has likely reduced comparability. For palm, data for Nigeria, a country with high production volume and low yields, are missing from the LCA literature and therefore this meta-analysis, with a significant effect on the yield reconciliation. In summary, this dataset overestimates yield for some tree crops. For vegetable crops, many countries group multiple crops into 'Vegetables, fresh nes' for FAOSTAT reporting. Equally, values in this meta-analysis for China (the largest producer) do not reconcile to FAOSTAT, although they do reconcile to Chinese economic census data (*137*). It is unclear whether vegetable crop yields in this meta-analysis represents an under- or over-estimate.

We also calculated weighted 90th-percentile yields between countries from FAOSTAT. For 24 of 28 crops, 90th-percentile yield is higher in this dataset than FAOSTAT, which would be expected as this dataset captures both within- and between-country variation.

Table S10. Global land for this study vs. FAO.

Land Use (Mha)	**FAO** (2009-11 avg.)	**This Study** (~2010)	**Bias** (Study - FAO) / FAO
Arable Land & Permanent Crops	1535	1415	-7.8%
Area Harvested	1284	1096	-14.6%
Feed	-	422	-
Food	-	547	-
Non-Food*	-	127	-
Fallow	251	319	27.1%
Feed	-	116	-
Food	-	157	-
Non-Food*	-	46	-
Fiber Crops, Rubber & Tobacco	16	-	-
Permanent Meadows & Pasture	3322	1761	-47.0%
Feed	-	1534	-
Non-Food*	-	227	-

* Includes biofuels, leather, wool, processing by-products, and other non-food products derived from products assessed in this study.

We converted land use for each observation from Retail Weight (table S1) to the functional units used by the FBSs (e.g., from ‘fat and bone-free meat and edible offal’ to ‘carcass weight’), and extrapolated globally with weights using FBS consumption, losses, and non-food uses (table S10). Arable land and permanent crops reconcile to -7.8% of FAOSTAT. Of this, we estimate that 538 Mha (38%) was used for feed, 6% lower than Mottet *et al.*’s (*34*) estimate of 570 Mha, but 53% larger than Foley *et al.*’s (*2*) estimate of 350 Mha. This difference is primarily because our study and Mottet *et al.* economically allocated between crops and crop by-products (such as straw or palm kernel expeller) used as feed or bedding in animal production. These by-products represent ~150 Mha of arable land.

Our non-food arable land estimate is 12%, close to the 10% non-food mass flow in the FBSs. In this study, non-food uses are excluded by using economic allocation and by considering food mass flows only.

For permanent meadows and pasture, we have limited observations on ruminants in Africa, representing 27% of global pasture area, and no observations in Saudi Arabia, Kazakhstan, or Mongolia, representing 14% (*4*). From FAOSTAT data, pasture area is 1010 m^2 kg $carcass^{-1}$ and 5330 m^2 kg $carcass^{-1}$ respectively in these areas, well above the global average (*4*). While FAOSTAT data may be overestimated (*62*), missing LCAs in these regions puts a strong downward bias on our estimate of ruminant land use. This also puts a downward bias on our estimate of emissions from cultivated organic soils. It has a smaller effect on our land use change estimates, which are driven by countries where pasture area reconciles. For our global land use totals and diet change estimates, we correct by the difference in our estimate and FAOSTAT to bring the total global pasture value to 3322 Mha. While we are unable to reconcile to FAOSTAT, our estimate is just 10% lower than that of Mottet *et al.* (*34*) who used a similar modeling approach.

Areas under permanent ice and deserts are generally unsuitable for agriculture. In 2000, 0.8% of desert was cropland and 16.5% was extensive rangelands (extensive rangelands are not recorded as pasture in many countries) (*138*). Using an ice-, and desert-free area of 11,250 Mha (*138*), agriculture occupies ~43% of the world’s land.

Table S11. Global CH_4 emissions for this study (~2010) vs. estimates drawn from the literature (~2005-2011).

Emissions Source (Mt CH_4)	**Literature** Min - Max	n	**This Study** Average
Flooded Rice	20.0 - 37.5	4	32.6
Enteric Fermentation	76.2 - 105.6	7	78.3
Manure Management	9.1 - 12.7	7	10.7

Our estimates of agricultural methane reconcile to literature sources for flooded rice and manure management (table S11). For enteric fermentation, our estimate is closest to the lowest value we identify, a Tier 2/3 estimate by Herrero *et al.* (*139*). For N_2O, not all LCAs included break out these emissions, meaning we cannot perform a reconciliation.

For land use change, we estimate that 61% of 1990-2010 forest loss was attributable to commercial agriculture (Materials and Methods, Section 7a), and that agriculturally induced land use change emissions from carbon stock changes and fires are 2.9 Gt CO_2eq year^{-1} (this includes food and non-food). Approximating total land use change emissions by dividing 2.9 by 61% yields 4.7 Gt CO_2eq year^{-1}, close to Houghton *et al.*'s (*140*) roughly comparable inventory based estimate for the same period of 4.2±0.7 Gt CO_2eq year^{-1}, and within the range of a separate estimate of 3.3±1.8 Gt CO_2eq year^{-1} for 2004-13 (*141*).

AQUASTAT (*59*) reports irrigation withdrawals of 2770 km^3 year^{-1}, close to our food and non-food estimate of 2430 km^3 year^{-1}, which unlike AQUASTAT, excludes fibers, rubber, and tobacco. Industrial and municipal withdrawals are 1230 km^3 year^{-1} (*59*). Agriculture's share is therefore ~66%. Using withdrawals and marginal AWARE CFs, scarcity-weighted withdrawals are 74,300 km^{3}eq year^{-1} for food and 81,200 km^{3}eq year^{-1} for agriculture.

Boulay *et al*. (*45*) report consumptive water use, which accounts for water returned to rivers and groundwater, putting agricultures share at 90%. Using consumptive water use and marginal AWARE CFs, agriculture contributes 95% of scarcity-weighted water use. For global analysis, many researchers suggest using average CFs (*45*), which are unpublished. At the margin, irrigation typically drives basin stress, meaning differences between average CFs for irrigation and other uses should be smaller. We therefore report the range 90-95%.

Variance decomposition

Variance-based sensitivity analysis allocates a portion of the variance in the output of a model to each input. When inputs are statistically dependent, commonly used Sobol' or R^2 decompositions are difficult to interpret and often do not sum to total variance. Recently introduced Shapley effects, under the methodology proposed by Song *et al.* (*26*), allow for nonlinear models with dependent inputs, and sum to the total variance of the output. From our sample, we calculated covariance matrices and means of model inputs, and used the Shapley effects implementation in R (*142*). See fig. S10 for further results.

Table S12. Variance-based sensitivity analysis of CH_4 emissions model for freshwater aquaculture ponds. Shading indicates temperature-determined inputs. *n*=39 observations.

Model Input	Model Input Formula	Contribution to Output Variance
Carbon input as NPP per m^2 of pond	C_{NPP}	23%
Conversion of C_{NPP} per m^2 to kg liveweight	$Cycle\ Time/Stocking\ Density$	32%
Other carbon additions to pond	$C_{IN} + C_{FISH} - C_{RESP}$	8%
Mineralization of sedimented carbon	M	10%
Share of M mineralized as methane	M_{CH_4}	15%
- Temperature	M_{CH_4}	*4%*
- Flow	M_{CH_4}	*11%*
Methane released to atmosphere	R	12%
Contribution of Temperature to Variance		**37%**

Table S13. Variance-based sensitivity analysis of reactive N loss models, assessing the fraction of N lost. Shading indicates geographically determined inputs. For these sensitivity analyses, performed across multiple products, we calculated weighted covariance matrices and weighted means of model inputs. 'Total' is an average of effects by row, weighted by the share of each emission in total volatile N emissions from crops. Fert = synthetic (syn) and organic (org) fertilizer. Res = crop residue.

Model Input	N_2O Fert	N_2O Resid.	NO_x	NH_3 Syn	NH_3 Org	NH_3 Res	NO_3^-	Total
***n* = observations**	**674**	**1397**	**620**	**1134**	**632**	**993**	**783**	**-**
N per hectare	13%	-	41%	-	-	-	-	2%
Crop/Fertilizer type	35%	100%	-	85%	100%	100%	32%	56%
Soil organic carbon	5%	-	-	-	-	-	-	-
Soil nitrogen	-	-	36%	-	-	-	-	-
Soil pH	3%	-	-	11%	-	-	-	-
Soil texture	3%	-	-	-	-	-	27%	-
Temp/Precipitation	41%	-	23%	4%	-	-	41%	-
Contrib. of Geog.	**52%**	**0%**	**59%**	**15%**	**0%**	**0%**	**68%**	**42%**

Diet change estimates

Current diets are taken from FBSs (*3*). The mix of protein sources in the 'No animal products' diet is taken from survey data (*n* = 120) reported in Haddad and Tanzman (*143*). Fruit and vegetable consumption increases by 20% under the 'No animal products' diet based on survey data (*n* = 2041) reported in Springmann *et al.* (*144*).

Table S14. Per capita composition of global diets. FBS weight is 'Food supply quantity' in the FAO food balance sheets. It is in the units used in the FBSs (e.g., carcass weight) and includes storage and transport losses only (Materials and Methods Section 7f). Retail Weight includes losses between distribution and retail, but not consumer losses, and is expressed in Retail Weight functional units (e.g., fat and bone-free meat, table S1). Calories and protein are in Retail Weight. On a Retail Weight basis, farmed animal products provide 18% of calories and 37% of protein.

	Current Diet (2009-11 avg.)				**No Animal Products**		
	FBS Weight (g/d)	Retail Wt. (g/d)	Calories (kcal/d)	Protein (g/d)	Retail Wt. (g/d)	Calories (kcal/d)	Protein (g/d)
Beef (beef herd)	16	10	22	2.1	0	0	0
Lamb & Mutton	5.7	3.7	11	0.7	0	0	0
Beef (dairy herd)	13	8.6	18	1.7	0	0	0
Buffalo	2.7	1.8	2.8	0.4	0	0	0
Crustaceans (farmed)	4.3	2.1	1.1	0.2	0	0	0
Cheese	8.3	8.0	27	1.7	0	0	0
Pig Meat	45	28	112	4.5	0	0	0
Fish (farmed)	18	7.4	12	1.7	0	0	0
Poultry Meat	39	26	51	4.5	0	0	0
Eggs	24	24	34	2.6	0	0	0
Fish (capture)	21	8.4	13	1.9	0	0	0
Crustaceans (capture)	8.5	4.2	2.1	0.4	0	0	0
Tofu	3.5	3.2	2.5	0.5	53	40	8.4
Groundnuts	4.3	3.5	21	0.9	5.9	36	1.6
Other Pulses	16	15	51	3.1	55	188	12
Nuts	6.0	2.7	16	0.5	4.7	28	0.8
Peas	2.3	2.1	7.2	0.5	7.9	27	1.8
Milk	185	171	105	6.1	0	0	0
Butter, Cream & Ghee	4.8	4.6	29	0.1	0	0	0
Soymilk	10	9.1	5.1	0.3	185	104	6.1
Cassava	55	45	44	0.4	45	44	0.4
Rice	148	134	494	9.3	146	538	10
Oatmeal	1.6	1.0	2.6	0.1	1.1	2.9	0.1
Potatoes	115	90	66	1.3	90	66	1.3

Wheat & Rye (Bread)	182	166	471	14	181	513	15
Maize (Meal)	47	28	127	3.1	31	138	3.3
Cereals & Oilcr. Misc.	39	34	93	3.2	37	101	3.5
Palm Oil	6.6	6.7	52	0	7.5	59	0
Soybean Oil	10	10	77	0	11	87	0
Olive Oil	1.2	1.3	10	0	1.5	11	0
Rapeseed Oil	4.0	4.1	33	0	4.7	37	0
Sunflower Oil	3.8	3.8	31	0	4.3	35	0
Oils Misc.	5.1	4.7	41	0	5.2	47	0
Animal Fats	4.2	3.8	27	0	0	0	0
Tomatoes	55	37	6.7	0.4	44	8.0	0.4
Brassicas	28	25	6.2	0.3	30	7.5	0.4
Onions & Leeks	29	23	8.7	0.3	28	10	0.4
Root Vegetables	13	11	2.8	0.2	14	3.4	0.2
Other Vegetables	241	213	53	2.9	256	64	3.4
Aquatic Plants	5.0	4.4	1.8	0.1	5.3	2.1	0.1
Berries	11	7.5	4.3	0	9.0	5.1	0.1
Bananas	42	29	19	0.2	35	23	0.3
Apples	25	22	9.2	0.1	27	11	0.1
Citrus	48	40	11	0.2	47	13	0.2
Other Fruit	77	58	26	0.3	69	32	0.4
Cane Sugar	50	41	145	0	41	145	0
Beet Sugar	10	7.9	28	0	7.9	28	0
Sweeteners & Honey	8.3	6.7	20	0	6.7	20	0
Beer	72	63	28	0.3	63	28	0.3
Wine	9.1	8.0	5.3	0	8.0	5.3	0
Dark Chocolate	1.7	0.6	3.0	0.1	0.6	3.0	0.1
Coffee	3.1	1.7	0.7	0.1	1.7	0.7	0.1
Stimul. & Spices Misc.	5.3	3.5	6.8	0.4	3.5	6.8	0.4
Total	**1792**	**1480**	**2494**	**72**	**1573**	**2516**	**72**

For the USA, the share of imported and domestic food was estimated from the FBSs. Global impacts were used for imported food. For domestic consumption, environmental impacts were recalculated using observations from the USA and Canada.

Table S15. Per capita mass and nutritional composition for diets in the USA. FBS weight is 'Food supply quantity' in the FAO food balance sheets. It is in the units used in the FBSs (e.g., carcass weight) and includes storage and transport losses only (Materials and Methods Section 7f). Retail Weight includes losses between distribution and retail, but not consumer losses, and is expressed in Retail Weight functional units (e.g., fat and bone-free meat, table S1). Calories and protein are in Retail Weight.

		Current Diet (2009-11 avg.)				**No Animal Products**		
	Share Imported	FBS Weight (g/d)	Retail Wt. (g/d)	Calories (kcal/d)	Protein (g/d)	Retail Wt. (g/d)	Calories (kcal/d)	Protein (g/d)
Beef (beef herd)	10%	79	51	72	8.9	0	0	0
Lamb & Mutton	55%	1.2	0.8	2.7	0.1	0	0	0
Beef (dairy herd)	10%	26	18	25	3.1	0	0	0
Buffalo	3%	2.2	1.5	1.8	0.4	0	0	0
Crustaceans (farmed)	85%	3.2	1.6	0.9	0.2	0	0	0
Cheese	4%	45	43	172	11	0	0	0
Pig Meat	5%	77	47	112	6.8	0	0	0
Fish (farmed)	61%	1.3	0.5	0.9	0.1	0	0	0
Poultry Meat	1%	138	92	182	17	0	0	0
Eggs	0%	38	37	52	4.0	0	0	0
Fish (capture)	61%	31	12	20	2.6	0	0	0
Crustaceans (capture)	85%	24	12	6.4	1.2	0	0	0
Tofu	1%	2.2	2.0	1.6	0.3	104	79	17
Groundnuts	4%	8.4	6.8	47	2.1	23	159	7.2
Other Pulses	20%	9.2	8.4	29	1.9	108	366	24
Nuts	46%	11	5.1	30	0.9	17	102	2.9
Peas	32%	1.3	1.2	4.1	0.3	16	52	3.8
Milk	4%	373	346	183	10	0	0	0
Butter, Cream & Ghee	3%	5.6	5.4	38	0	0	0	0
Soymilk	1%	6.2	5.7	3.1	0.2	357	191	12
Cassava	100%	2.7	2.2	0.8	0	2.2	0.8	0
Rice	23%	19	17	66	1.2	20	75	1.4
Oatmeal	66%	11	7.2	17	0.7	8.2	20	0.8
Potatoes	15%	152	119	72	1.9	119	72	1.9
Wheat & Rye (Bread)	13%	221	202	531	17	232	610	20
Maize (Meal)	0%	35	20	84	1.5	23	97	1.7
Cereals Misc.	13%	11	10	27	0.7	11	31	0.8
Palm Oil	100%	0.2	0.2	1.5	0	0.2	1.7	0
Soybean Oil	2%	63	63	478	0.2	70	528	0.2
Olive Oil	100%	2.5	2.7	20	0	3.0	23	0
Rapeseed Oil	84%	5.1	5.2	41	0	5.8	46	0
Sunflower Oil	23%	0.6	0.7	5.0	0	0.7	5.5	0
Oils Misc.	45%	4.0	3.7	30	0	4.1	34	0
Animal Fats	2%	8.8	8.0	55	0	0	0	0

Tomatoes	11%	111	74	13	0.6	88	15	0.7
Brassicas	26%	5.9	5.2	1.2	0.1	6.3	1.5	0.1
Onions & Leeks	11%	28	22	7.1	0.2	27	8.6	0.3
Root Vegetables	26%	7.3	6.4	1.5	0.1	7.7	1.8	0.1
Other Vegetables	26%	175	155	37	1.7	186	44	2.1
Berries	14%	20	15	8.1	0.1	17	10	0.1
Bananas	93%	31	21	13	0.2	26	16	0.2
Apples	54%	59	52	18	0	63	22	0
Citrus	39%	103	86	23	0.4	103	28	0.5
Other Fruit	60%	70	53	26	0.3	63	31	0.4
Cane Sugar	31%	69	56	208	0	56	208	0
Beet Sugar	31%	13	10	37	0	10	37	0
Sweeteners & Honey	7%	86	70	222	0.1	70	222	0.1
Beer	12%	224	197	83	0.6	197	83	0.6
Wine	30%	20	17	12	0	17	12	0
Dark Chocolate	100%	7.5	2.7	10	0.4	2.7	10	0.4
Coffee	100%	11	6.1	3.4	0.5	6.1	3.4	0.5
Stimul. & Spices Misc.	86%	3.9	2.6	5.1	0.3	2.6	5.1	0.3
Total	**-**	**2463**	**2011**	**3138**	**100**	**2074**	**3249**	**100**

Here, we report four sensitivities to the diet change scenarios. These are not reflected in the reported confidence intervals.

1. Oil production creates meals that are primarily fed to animals. For sunflower, palm, and rapeseed, 10-30% of the environmental impact is apportioned to animal products using economic allocation, increasing to ~60% for soy. Here, we assume 100% is apportioned to oil. This is a worst-case scenario: meal is a food (e.g., soy flour), and it can fertilize crops, suppress weeds, and build soil fertility (*145*).
2. We estimate the change in emissions from replacing manure and slurry with synthetic fertilizer. We include emissions from fertilizer production and all N losses. We use studies with full inventory data on N flows only. We do not account for lower nutrient availability of organic fertilizer to plants.
3. Abandoned pasture can sequester carbon, particularly if it returns to woody vegetation. Stehfest *et al.* (*146*) used 13 potential vegetation types and a spatially explicit model to estimate that 2.7 billion hectares of pasture, abandoned following diet change, sequesters 30 Gt CO_2-C. We amortize this over 20 years.

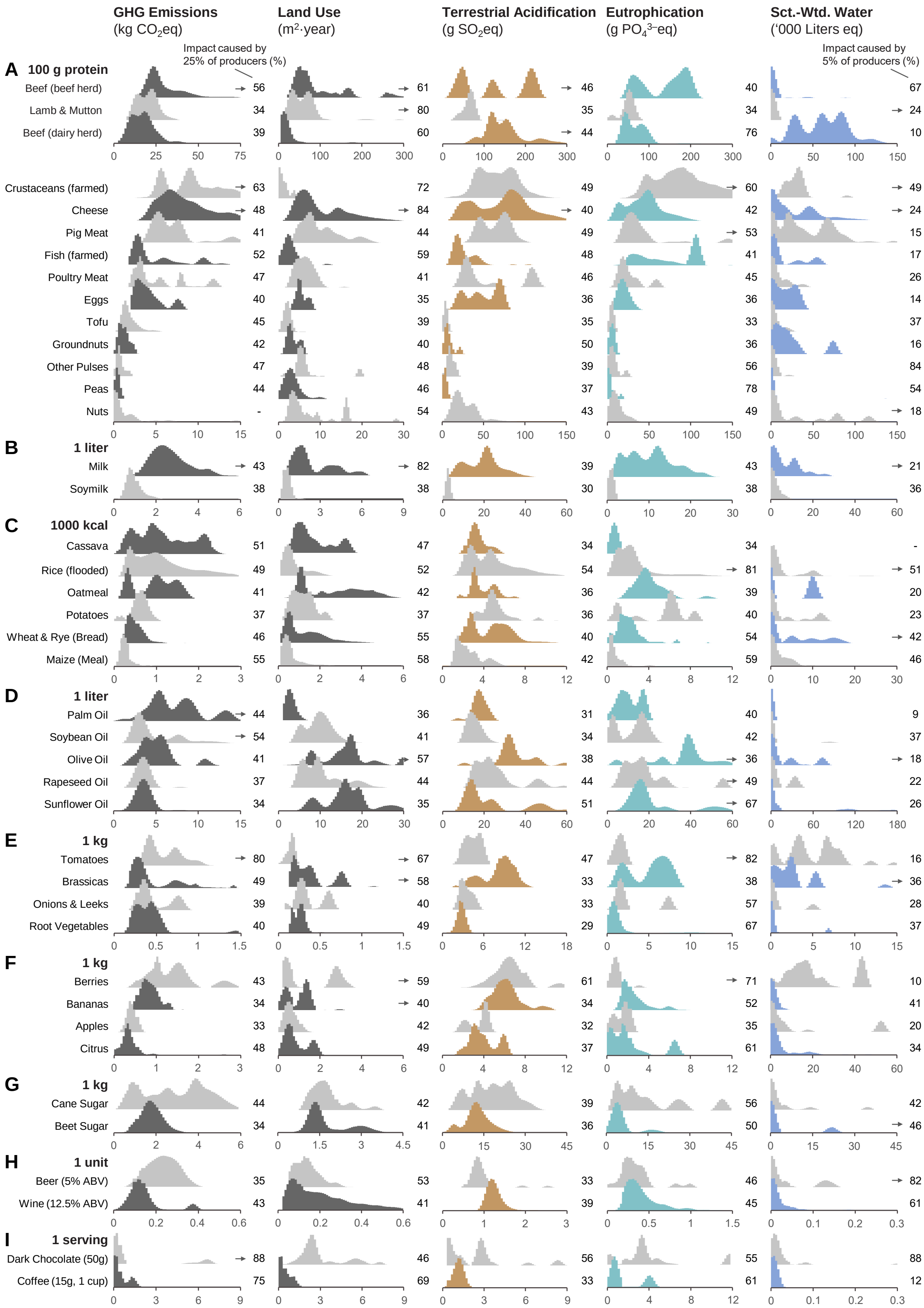
4. Consumer waste, not assessed elsewhere in this study, is 2.5-9% higher in animal than vegetable proteins, but is also high in fresh fruit and vegetables which increase in the 'No animal products' diet. We quantify this using estimated consumer wastage values from Gustavsson *et al.* (*130*).

Table S16. Sensitivity of the 'No animal products' scenario. Showing absolute change in impact, and in parentheses, the percentage change in impact (e.g., for Scenario 3, -40% means foods GHG emissions are reduced by an additional 40%, an 89% total reduction).

Scenario	**Land Use** (Mha)	**GHG** (Gt CO_2eq)	**Acid.** (Mt SO_2eq)	**Eutr.** (Mt PO_4^{3-}eq)	**Sct. Wtr.** (km^3eq)
1. Oilseed meals not utilized	+63 (+1.5%)	+0.38 (+2.8%)	+1110 (+1.3%)	+870 (+1.3%)	+970 (+1.3%)
2. Manure replaced with synthetic fertilizer	-	+0.06 (+0.4%)	+1150 (+1.3%)	+490 (+0.8%)	-
3. Carbon sequestration on abandoned pasture	-	-5.50 (-40%)	-	-	-
4. Lower consumer waste of veg. proteins	-12 (-0.3%)	-0.04 (-0.3%)	-220 (-0.2%)	-160 (-0.2%)	-310 (-0.4%)

Table S17. Global GHG emissions, acidification, and eutrophication by stage of the supply chain for the year ~2010. GHG emissions from savannah burning are taken from FAOSTAT (*4*). Acidification and eutrophication from land use change and savannah burning are taken from EDGAR (*147*). GHG emissions from capture fisheries are from Parker *et al.* (*148*), and acidifying and eutrophying emissions are calculated based on fuel use. Global total GHG emissions are taken from EDGAR, replacing emissions from organic soils, savannah burning, land use change, enteric fermentation, methane emissions from rice, and methane from manure management with values from this study. Total acidifying and eutrophying emissions to air are taken from EDGAR. Non-agricultural phosphorus emissions are taken from Cordell *et al.* (*149*).

	GHG Emissions		**Terrestrial Acidification**	**Freshwater & Marine Eutr.**
Emissions Source	Gt CO_2eq	% Share	(Mt SO_2eq)	(Mt PO_4^{3-}eq)
Land Use Change	2.38	17%	2.5	0.5
Food	0.78	6%	0.8	0.2
Feed	1.60	12%	1.7	0.3
Savannah Burning	0.29	2%	0.8	0.2
Cultivated Org. Soils	0.55	4%	-	-
Food	0.27	2%	-	-
Feed	0.28	2%	-	-
Crop Production	3.68	27%	45.9	45.4
Food	2.87	21%	24.6	25.1
Feed	0.81	6%	21.3	20.3
Livestock/Aquaculture	4.14	30%	23.5	15.9
Capture Fisheries	0.18	1%	2.9	0.3
Processing	0.60	4%	2.2	1.1
Transport	0.80	6%	7.3	0.8
Packaging	0.63	5%	3.5	0.6
Retail	0.39	3%	3.7	0.5
Total	**13.7**	**-**	**92.4**	**65.3**
Food Waste	2.05	-	14.1	11.6
All Sector Total	**52.3**	**-**	**290.5**	**84.2**
Food Share	**26%**		**32%**	**78%**



GHG Emissions
(kg CO_2eq)
Land Use
(m^2·year)
Terrestrial Acidification
(g SO_2eq)
Eutrophication
(g PO_4^{3-}eq)
Sct.-Wtd. Water
('000 Liters eq)
Impact caused by 25% of producers (%)
Impact caused by 5% of producers (%)
A 100 g protein
Beef (beef herd)
Lamb & Mutton
Beef (dairy herd)
Crustaceans (farmed)
Cheese
Pig Meat
Fish (farmed)
Poultry Meat
Eggs
Tofu
Groundnuts
Other Pulses
Peas
Nuts
B 1 liter
Milk
Soymilk
C 1000 kcal
Cassava
Rice (flooded)
Oatmeal
Potatoes
Wheat & Rye (Bread)
Maize (Meal)
D 1 liter
Palm Oil
Soybean Oil
Olive Oil
Rapeseed Oil
Sunflower Oil
E 1 kg
Tomatoes
Brassicas
Onions & Leeks
Root Vegetables
F 1 kg
Berries
Bananas
Apples
Citrus
G 1 kg
Cane Sugar
Beet Sugar
H 1 unit
Beer (5% ABV)
Wine (12.5% ABV)
I 1 serving
Dark Chocolate (50g)
Coffee (15g, 1 cup)

Fig. S3. Distributions of environmental impacts by product. Histograms are normalized and smoothed using a Gaussian kernel, and then rescaled for display to set the largest bin count equal to one. Black arrows indicate that >5% of the data lie outside the plot. Shown to the right of each histogram is the percentage of global environmental impact caused by 25% of production (or by 5% of production for scarcity-weighted freshwater withdrawals). (**A**) Protein-rich products. (**B**) Milks. (**C**) Starch-rich products. (**D**) Oils. (**E**) Vegetables. (**F**) Fruits. (**G**) Sugars. (**H**) Alcoholic beverages (1 unit = 10 ml of alcohol; ABV, alcohol by volume). (**I**) Stimulants. Fisher-Pearson coefficients of skew are provided in Data S2.

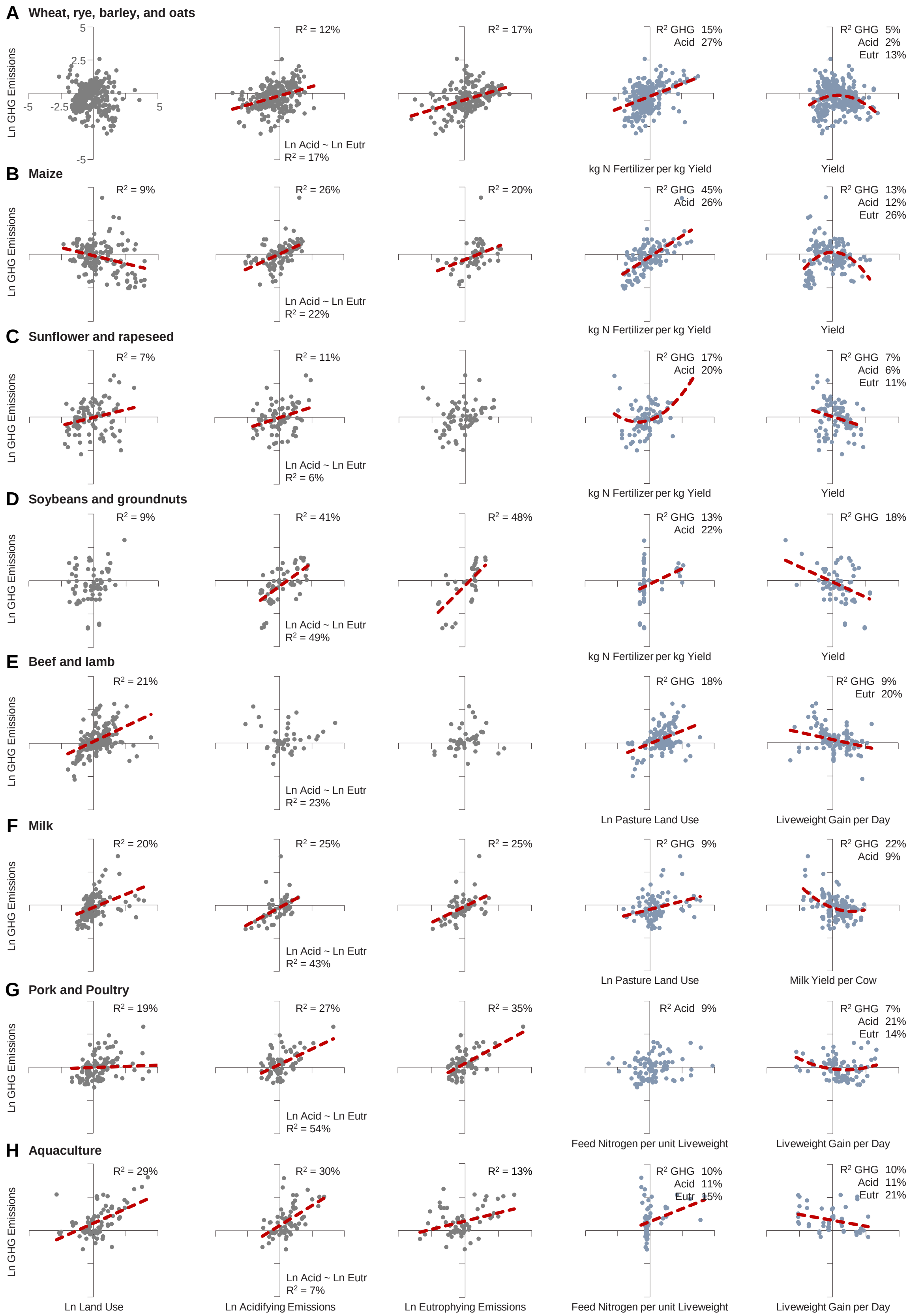
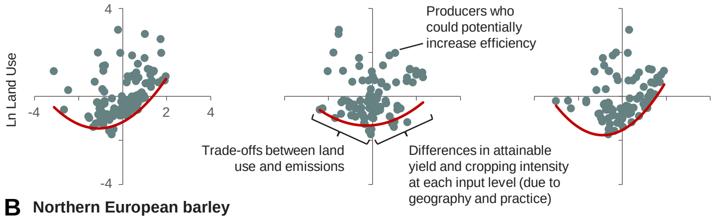

A Wheat, rye, barley, and oats
R² = 12%
R² = 17%
R² GHG 15%
Acid 27%
R² GHG 5%
Acid 2%
Eutr 13%
Ln Acid ~ Ln Eutr
R² = 17%
kg N Fertilizer per kg Yield
Yield
B Maize
R² = 9%
R² = 26%
R² = 20%
R² GHG 45%
Acid 26%
R² GHG 13%
Acid 12%
Eutr 26%
Ln Acid ~ Ln Eutr
R² = 22%
kg N Fertilizer per kg Yield
Yield
C Sunflower and rapeseed
R² = 7%
R² = 11%
R² GHG 17%
Acid 20%
R² GHG 7%
Acid 6%
Eutr 11%
Ln Acid ~ Ln Eutr
R² = 6%
kg N Fertilizer per kg Yield
Yield
D Soybeans and groundnuts
R² = 9%
R² = 41%
R² = 48%
R² GHG 13%
Acid 22%
R² GHG 18%
Ln Acid ~ Ln Eutr
R² = 49%
kg N Fertilizer per kg Yield
Yield
E Beef and lamb
R² = 21%
R² GHG 18%
R² GHG 9%
Eutr 20%
Ln Acid ~ Ln Eutr
R² = 23%
Ln Pasture Land Use
Liveweight Gain per Day
F Milk
R² = 20%
R² = 25%
R² = 25%
R² GHG 9%
R² GHG 22%
Acid 9%
Ln Acid ~ Ln Eutr
R² = 43%
Ln Pasture Land Use
Milk Yield per Cow
G Pork and Poultry
R² = 19%
R² = 27%
R² = 35%
R² Acid 9%
R² GHG 7%
Acid 21%
Eutr 14%
Ln Acid ~ Ln Eutr
R² = 54%
Feed Nitrogen per unit Liveweight
Liveweight Gain per Day
H Aquaculture
R² = 29%
R² = 30%
R² = 13%
R² GHG 10%
Acid 11%
Eutr 15%
R² GHG 10%
Acid 11%
Eutr 21%
Ln Acid ~ Ln Eutr
R² = 7%
Ln GHG Emissions
5
2.5
-5
-2.5
5
-5
Ln Land Use
Ln Acidifying Emissions
Ln Eutrophying Emissions
Feed Nitrogen per unit Liveweight
Liveweight Gain per Day

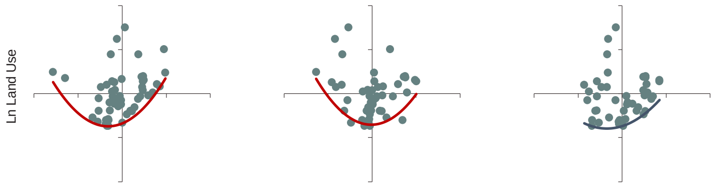
Fig. S4. Correlations between different environmental impacts, and between environmental impacts and proxies, for all producers globally. R^2 is shown when $p \leq 0.05$ on the regression coefficient. Emissions for crops exclude land use change and cultivated organic soils that are calculated at the country level and cannot be changed directly by individual farmers. We do not assess indirect land use change in this study but including it would increase correlations with yield. Emissions for animal products include land use change and cultivated organic soils caused by feed. LCA modeling means variance in environmental impact accumulates multiplicatively, and impacts are log-transformed to control for this. Proxies are not log-transformed, and relationships are fitted by including a quadratic term if significant at $p \leq 0.05$. Observations are normalized by subtracting the weighted mean and dividing by the weighted standard deviation of each crop or animal product, allowing similarly produced products to be compared together. Observations with values on any indicator or proxy greater than ±5 SD are excluded (n = 9). (**A**) Wheat, rye, barley, and oats. (**B**) Maize. (**C**) Sunflower and rapeseed. (**D**) Soybeans and groundnuts. (**E**) Beef and lamb. (**F**) Milk. (**G**). Pork and poultry. (**H**) Aquaculture (fish and crustaceans). Sample sizes, R^2 and p-values are provided for all regressions in Data S2.

A **Northern European wheat**



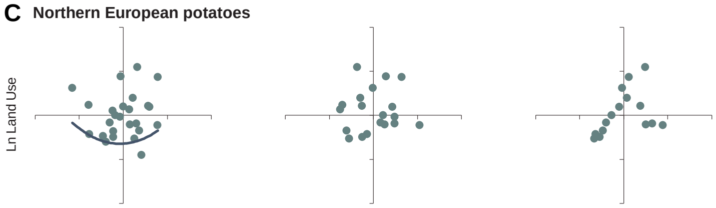
Correlation between indicators (R^2)	Land Use	GHG Emissions	Acidification
GHG Emissions	18%	-	-
Acidification	0.9%	19%	-
Eutrophication	6.3%	24%	35%

B **Northern European barley**



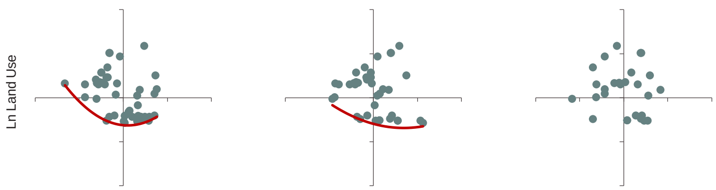
Correlation between indicators (R^2)	Land Use	GHG Emissions	Acidification
GHG Emissions	6.4%	-	-
Acidification	0.8%	40%	-
Eutrophication	0.7%	43%	49%

C **Northern European potatoes**



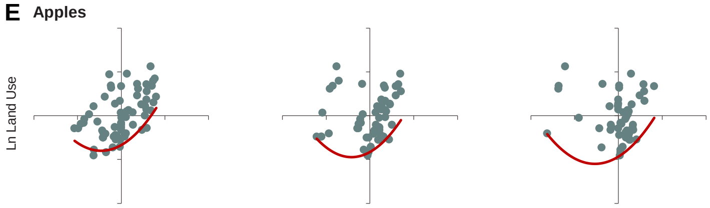
Correlation between indicators (R^2)	Land Use	GHG Emissions	Acidification
GHG Emissions	0.8%	-	-
Acidification	0.5%	11%	-
Eutrophication	16%	23%	33%

D **Greenhouse tomatoes**



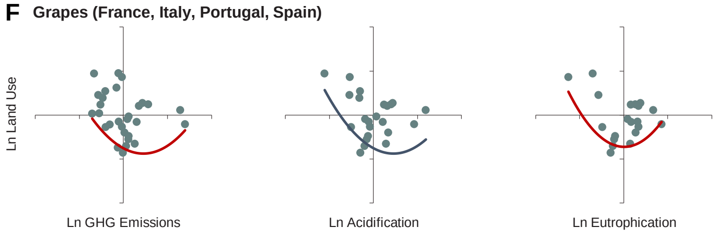
Correlation between indicators (R^2)	Land Use	GHG Emissions	Acidification
GHG Emissions	19%	-	-
Acidification	3.0%	42%	-
Eutrophication	1.1%	15%	43%

E **Apples**



Correlation between indicators (R^2)	Land Use	GHG Emissions	Acidification
GHG Emissions	25%	-	-
Acidification	1.8%	0.8%	-
Eutrophication	1.5%	2.8%	65%

F **Grapes (France, Italy, Portugal, Spain)**



Correlation between indicators (R^2)	Land Use	GHG Emissions	Acidification
GHG Emissions	5.2%	-	-
Acidification	6.9%	74%	-
Eutrophication	9.5%	47%	74%

Fig. S5. Trade-offs and correlations between environmental impacts for products in similar geographies or systems. Only emissions that producers can control (fertilizer, pesticide, crop residue, lime, machinery, fuel) are included. Emissions that are largely fixed per hectare and cannot be controlled directly by an individual producer (land use change and emissions from organic soils) are excluded; greater fixed emissions will make yield increases more beneficial. Observations are normalized by subtracting the weighted mean and dividing by the weighted standard deviation. We assume we have sufficient observations of input optimizing producers, and fit the frontier of lowest land use and emissions using maximum likelihood estimation of the stochastic frontier (*150*). The red line represents significance at $p \leq 0.05$ on the quadratic term, and the grey line represents a positive but insignificant quadratic term. We also show R^2 values for the linear regression of log-transformed land use on log-transformed emissions (same as fig. S4, but for crops in similar geographies and systems). (**A**) Northern European (Denmark, Finland, France, Germany, Ireland, Netherlands, Poland, Sweden, Switzerland, and United Kingdom) wheat. (**B**) Northern European barley. (**C**) Northern European potatoes. (**D**) Greenhouse tomatoes. (**E**) Apples. (**F**) Grapes cultivated in France, Italy, Portugal, and Spain. Sample sizes and *p*-values are provided in Data S2.

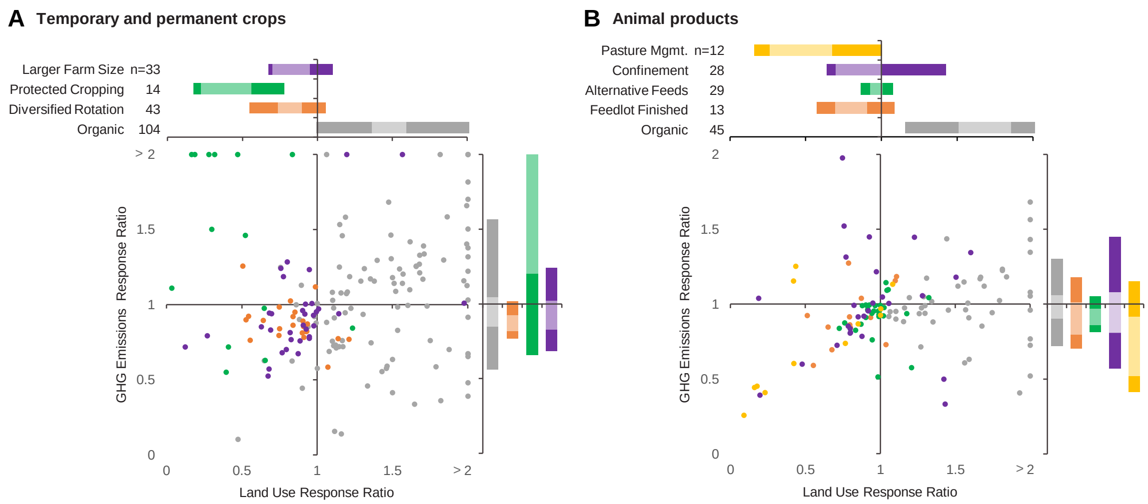


Fig. S6. Effect of practice changes on environmental impact. (**A**) Effect of four commercially viable practice changes for crops (larger vs. smaller farms; protected vs. open-field cropping; diversified rotation vs. monoculture; organic vs. conventional). Studies are included only if they assess specific farms in the same location and year. Dark shaded bars represent the 10th- and 90th-percentiles. Light shaded bars represent the 95% confidence interval of the logged and back-transformed response ratio. *n* = observation pairs. (**B**) Same as (A) but for animal products (improved vs. unmanaged or degraded pasture; confinement vs. grazing or free-range; alternative feed vs. current feed (e.g., European legumes vs. imported soy); feedlot finished vs. grass finished beef; organic vs. conventional). For animal products, GHG emissions include land use change and cultivated organic soils associated with feed.

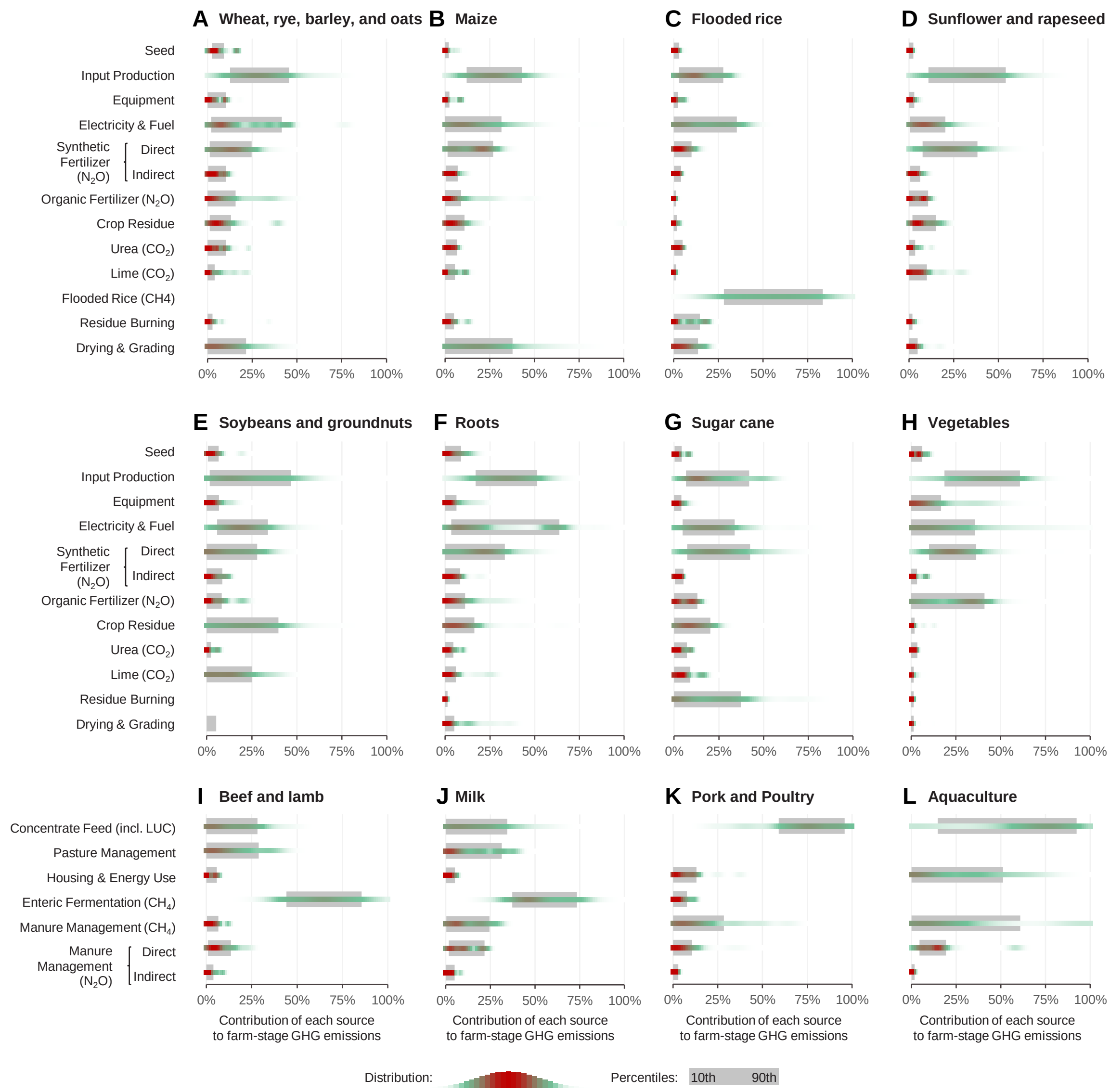


Fig. S7. Contributions of emission sources to total farm-stage GHG emissions. Grey bars show 10th- and 90th-percentile contributions. Shaded bars represent the distribution. Density is estimated using a Gaussian kernel with bandwidth selection performed by biased cross-validation. (**A**) Wheat, rye, barley, and oats. (**B**) Maize. (**C**) Flooded rice. (**D**) Sunflower and rapeseed. (**E**) Soybeans and groundnuts. (**F**) Roots (potatoes, sugar beet, and root vegetables). (**G**) Sugar cane. (**H**) Vegetables (tomatoes, lettuce, cucumber, green beans, and green peas). (**I**) Beef and lamb. (**J**) Milk. (**K**) Pork and poultry. (**L**) Aquaculture (fish and crustaceans), where manure management includes emissions from ponds.

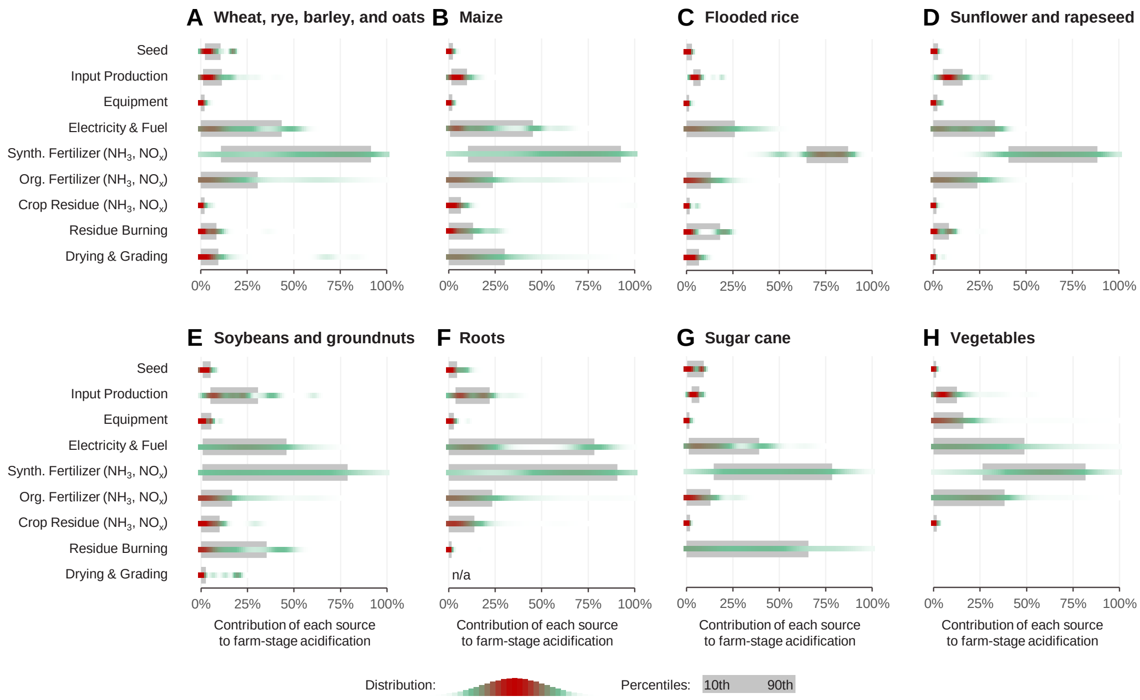


Fig. S8. Contributions of emission sources to total farm-stage acidification. Grey bars show 10th- and 90th-percentile contributions. Shaded bars represent the distribution. Density is estimated using a Gaussian kernel with bandwidth selection performed by biased cross-validation. (**A**) Wheat, rye, barley, and oats. (**B**) Maize. (**C**) Flooded rice. (**D**) Sunflower and rapeseed. (**E**) Soybeans and groundnuts. (**F**) Roots (potatoes, sugar beet, and root vegetables). (**G**) Sugar cane. (**H**) Vegetables (tomatoes, lettuce, cucumber, green beans, and green peas).

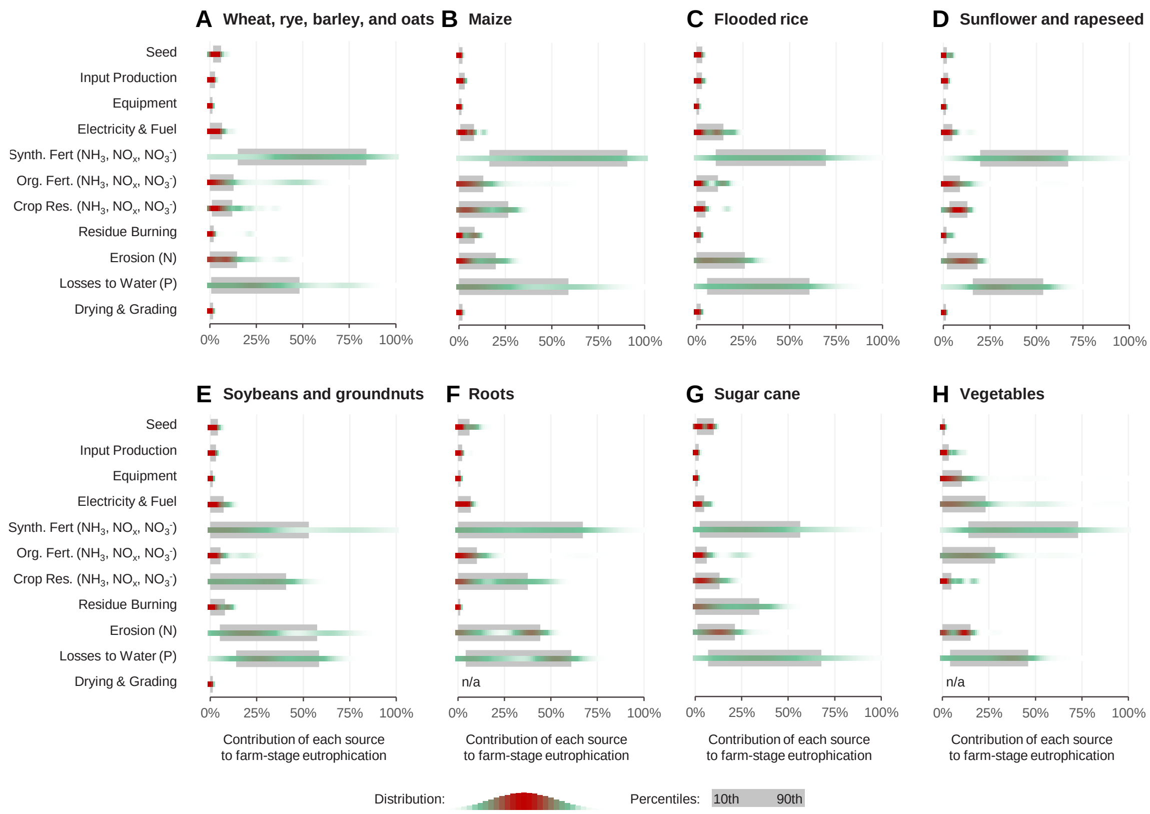
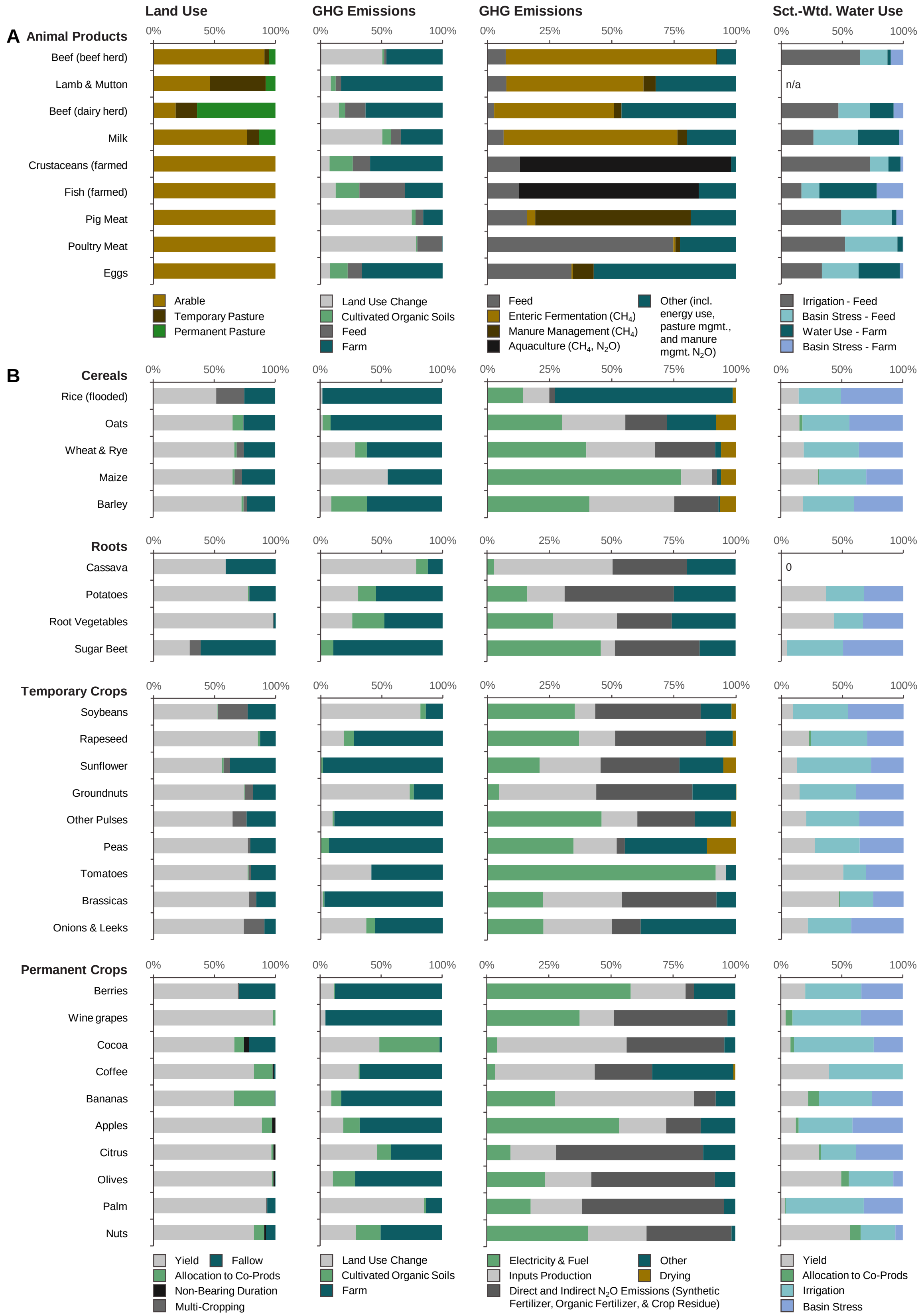
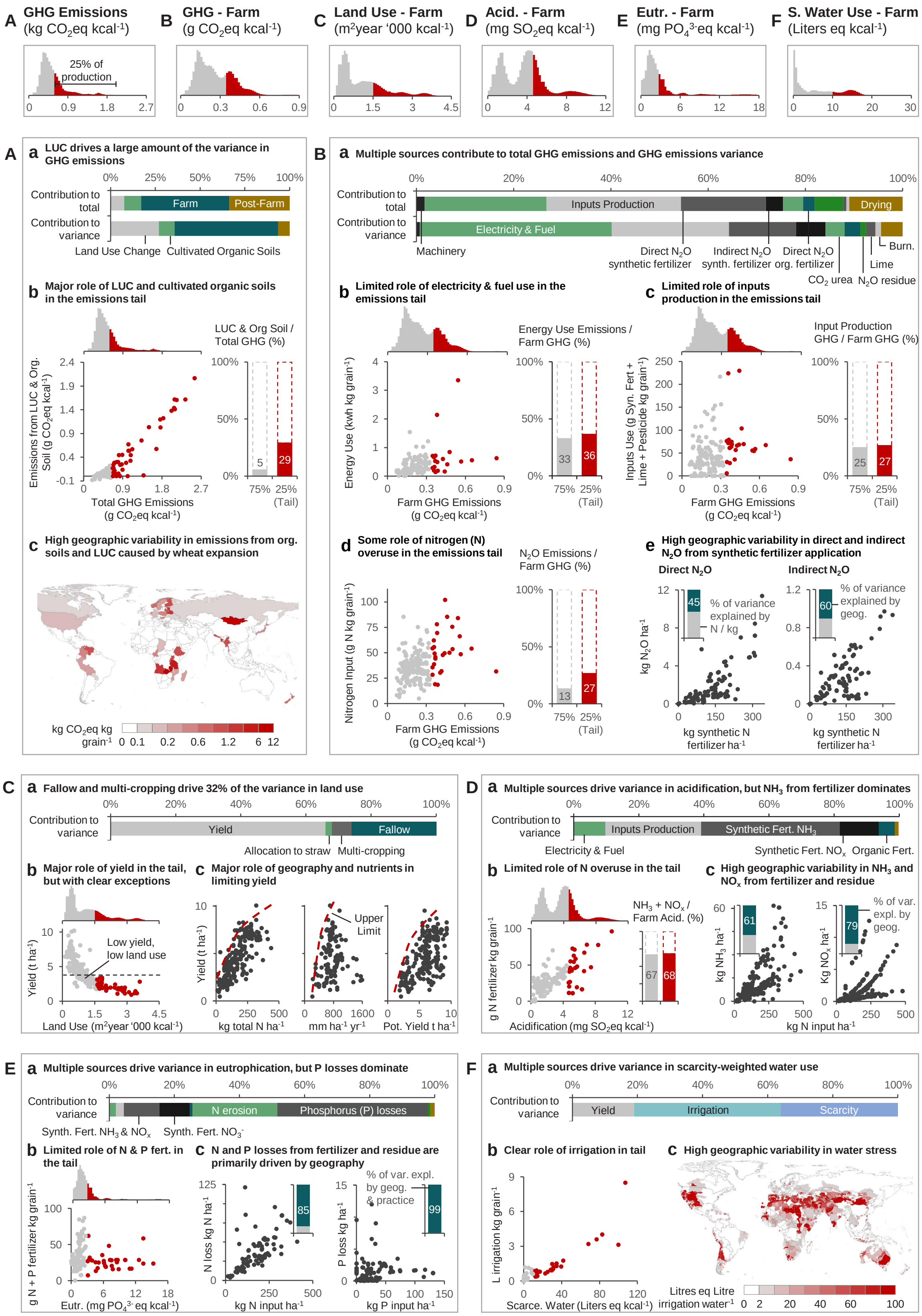


Fig. S9. Contributions of emission sources to total farm-stage eutrophication. Grey bars show 10th- and 90th-percentile contributions. Shaded bars represent the distribution. Density is estimated using a Gaussian kernel with bandwidth selection performed by biased cross-validation. (**A**) Wheat, rye, barley, and oats. (**B**) Maize. (**C**) Flooded rice. (**D**) Sunflower and rapeseed. (**E**) Soybeans and groundnuts. (**F**) Roots (potatoes, sugar beet, and root vegetables). (**G**) Sugar cane. (**H**) Vegetables (tomatoes, lettuce, cucumber, green beans, and green peas).



Land Use
GHG Emissions
GHG Emissions
Sct.-Wtd. Water Use
A Animal Products
Beef (beef herd)
Lamb & Mutton
Beef (dairy herd)
Milk
Crustaceans (farmed
Fish (farmed)
Pig Meat
Poultry Meat
Eggs
n/a
Arable
Temporary Pasture
Permanent Pasture
Land Use Change
Cultivated Organic Soils
Feed
Farm
Feed
Enteric Fermentation (CH_4)
Manure Management (CH_4)
Aquaculture (CH_4, N_2O)
Other (incl. energy use, pasture mgmt., and manure mgmt. N_2O)
Irrigation - Feed
Basin Stress - Feed
Water Use - Farm
Basin Stress - Farm
B Cereals
Rice (flooded)
Oats
Wheat & Rye
Maize
Barley
Roots
Cassava
Potatoes
Root Vegetables
Sugar Beet
0
Temporary Crops
Soybeans
Rapeseed
Sunflower
Groundnuts
Other Pulses
Peas
Tomatoes
Brassicas
Onions & Leeks
Permanent Crops
Berries
Wine grapes
Cocoa
Coffee
Bananas
Apples
Citrus
Olives
Palm
Nuts
Yield
Fallow
Allocation to Co-Prods
Non-Bearing Duration
Multi-Cropping
Land Use Change
Cultivated Organic Soils
Farm
Electricity & Fuel
Inputs Production
Direct and Indirect N_2O Emissions (Synthetic Fertilizer, Organic Fertilizer, & Crop Residue)
Other
Drying
Yield
Allocation to Co-Prods
Irrigation
Basin Stress

Fig. S10. Contribution of each impact source to variance among producers for the same product. Contributions are calculated using variance-based sensitivity analysis (supplementary text). (**A**) Animal products. 'Water Use – Farm' includes drinking water, service water, and pasture irrigation. (**B**) Crops.



A GHG Emissions (kg CO_2eq kcal^{-1})
25% of production
B GHG - Farm (g CO_2eq kcal^{-1})
C Land Use - Farm (m^2year '000 kcal^{-1})
D Acid. - Farm (mg SO_2eq kcal^{-1})
E Eutr. - Farm (mg PO_4^{3-}eq kcal^{-1})
F S. Water Use - Farm (Liters eq kcal^{-1})
A a LUC drives a large amount of the variance in GHG emissions
Contribution to total
Contribution to variance
Farm
Post-Farm
Land Use Change
Cultivated Organic Soils
b Major role of LUC and cultivated organic soils in the emissions tail
LUC & Org Soil / Total GHG (%)
Emissions from LUC & Org. Soil (g CO_2eq kcal^{-1})
Total GHG Emissions (g CO_2eq kcal^{-1})
75% 25% (Tail)
c High geographic variability in emissions from org. soils and LUC caused by wheat expansion
kg CO_2eq kg grain^{-1}
0 0.1 0.2 0.6 1.2 6 12
B a Multiple sources contribute to total GHG emissions and GHG emissions variance
Inputs Production
Drying
Electricity & Fuel
Machinery
Direct N_2O synthetic fertilizer
Indirect N_2O synth. fertilizer
Direct N_2O org. fertilizer
CO_2 urea
Lime
N_2O residue
Burn.
b Limited role of electricity & fuel use in the emissions tail
Energy Use Emissions / Farm GHG (%)
Energy Use (kwh kg grain^{-1})
Farm GHG Emissions (g CO_2eq kcal^{-1})
c Limited role of inputs production in the emissions tail
Input Production GHG / Farm GHG (%)
Inputs Use (g Syn. Fert + Lime + Pesticide kg grain^{-1})
d Some role of nitrogen (N) overuse in the emissions tail
N_2O Emissions / Farm GHG (%)
Nitrogen Input (g N kg grain^{-1})
e High geographic variability in direct and indirect N_2O from synthetic fertilizer application
Direct N_2O
Indirect N_2O
% of variance explained by N / kg
% of variance explained by geog.
kg N_2O ha^{-1}
kg synthetic N fertilizer ha^{-1}
C a Fallow and multi-cropping drive 32% of the variance in land use
Yield
Fallow
Allocation to straw
Multi-cropping
b Major role of yield in the tail, but with clear exceptions
Low yield, low land use
Yield (t ha^{-1})
Land Use (m^2year '000 kcal^{-1})
c Major role of geography and nutrients in limiting yield
Upper Limit
kg total N ha^{-1}
mm ha^{-1} yr^{-1}
Pot. Yield t ha^{-1}
D a Multiple sources drive variance in acidification, but NH_3 from fertilizer dominates
Inputs Production
Synthetic Fert. NH_3
Electricity & Fuel
Synthetic Fert. NO_x
Organic Fert.
b Limited role of N overuse in the tail
NH_3 + NO_x / Farm Acid. (%)
g N fertilizer kg grain^{-1}
Acidification (mg SO_2eq kcal^{-1})
c High geographic variability in NH_3 and NO_x from fertilizer and residue
% of var. expl. by geog.
kg NH_3 ha^{-1}
Kg NO_x ha^{-1}
kg N input ha^{-1}
E a Multiple sources drive variance in eutrophication, but P losses dominate
N erosion
Phosphorus (P) losses
Synth. Fert. NH_3 & NO_x
Synth. Fert. NO_3^-
b Limited role of N & P fert. in the tail
g N + P fertilizer kg grain^{-1}
Eutr. (mg PO_4^{3-} eq kcal^{-1})
c N and P losses from fertilizer and residue are primarily driven by geography
% of var. expl. by geog. & practice
N loss kg N ha^{-1}
P loss kg ha^{-1}
kg N input ha^{-1}
kg P input ha^{-1}
F a Multiple sources drive variance in scarcity-weighted water use
Yield
Irrigation
Scarcity
b Clear role of irrigation in tail
L irrigation kg grain^{-1}
Scarce. Water (Liters eq kcal^{-1})
c High geographic variability in water stress
Litres eq Litre irrigation water^{-1}
0 2 20 40 60 100

Fig. S11. Detailed case-study of wheat, showing: contributions to variance of each impact source; drivers of the impact distribution; and the role of geography in impacts. Here, contributions of geography/practice to variance in emissions represent the variance not explained by fertilizer quantity using linear regression. (**A**) Full supply chain GHG emissions. (**B**) Farm-stage GHG emissions. (**C**) Farm-stage land use. (**D**) Farm-stage acidifying emissions. (**E**) Farm-stage eutrophying emissions. (**F**) Farm-stage scarcity-weighted freshwater withdrawals.

Processing

GHG Emissions ($g\ CO_2eq$)

			n	10th pctl.	Mean	90th pctl.
A	**100 g protein**					
	Beef	Slaughter	25	110	1,120	2,550
	Mutton & Lamb	Slaughter	11	280	710	1,120
	Cheese	Caseiculture	20	100	340	840
	Pig Meat	Slaughter	27	31	300	610
	Fish	Processing	14	1	60	210
	Poultry Meat	Slaughter	17	140	450	800
	Tofu	Production	3	180	490	700
	Groundnuts	Deshelling, Roasting	7	60	170	270
B	**1 liter**					
	Milk	Pasteurisation, Sterilization	77	9	87	290
	Soymilk	Production	2	69	160	260
C	**1000 kcal**					
	Rice	Dehulling, Milling, Polishing	10	7	16	41
	Oatmeal	Peeling, Rolling	6	13	22	34
	Wheat & Rye	Milling, Bread Making	24	50	77	130
	Maize (Meal)	Dry Milling	4	17	28	32
D	**1 liter**					
	Palm Oil	Milling & Refining	36	1,050	-	-
	Soybean Oil	Crushing & Refining	15	120	200	340
	Olive Oil	Pressing	16	1,280	-	-
	Rapeseed Oil	Milling & Refining	17	140	190	260
	Sunflower Oil	Milling & Refining	15	120	200	340
E	**1 kg**					
	Cane Sugar	Milling	25	24	26	27
	Beet Sugar	Milling	14	66	280	440
F	**1 unit**					
	Beer (5% ABV)	Malting, Mashing, Brewing	16	15	23	36
	Wine (12.5% ABV)	Vinification	42	3	5	12
G	**1 serving**					
	Dark Chocolate (50g)	Roasting, Grinding, Blending	5	11	12	13
	Coffee (15g, 1 cup)	Wet/Dry Proc., Grind., Roast.	4	5	27	68

Mean
10th 90th

Packaging

		n	Min	Mean	Max
H	**1 kg / liter of retail weight**				
	Bread	8	28	84	250
	Oatmeal, Nuts, Rice, Sugar, Other	8	7	90	330
	Beans, Pulses	6	7	360	890
	Fresh Fruit, Vegetables, Roots (Durable)	9	10	45	92
	Fresh Fruit, Vegetables, Roots (Delicate)	12	80	210	440
	Coffee	3	240	1,250	3,230
	Chocolate	3	250	750	1,190
	Oil, Wine	15	230	790	2,200
	Beer	27	19	510	2,570
	Milk	38	44	100	200
	Meat, Fish, Crustaceans	26	58	410	2,330
	Cheese, Tofu	13	38	180	440
	Eggs	3	100	180	300

Retail

		n	Min	Mean	Max
I	**1 kg / liter of retail weight**				
	Fresh: Fruit and Vegetables	24	0	17	100
	Chilled: Meat, Fish, Cheese, Tofu, Beer	22	20	270	1,190
	Ambient: Bread, Nuts, Roots, Eggs, Oils, Other	12	1	40	190

Mean
Min Max

Fig. S12. Variation in GHG emissions for different post-farm processes, pack types, and retail types. Not shown: post-farm processes with negligible emissions. Bars represent 10th- and 90th-percentiles for processing, and the minimum and maximum for packaging and retail. (**A**) Processing emissions of protein-rich products. (**B**) Milk processing. (**C**) Starch-rich product processing. (**D**) Oil processing. (**E**) Sugar processing. (**F**) Alcoholic beverage processing (1 unit = 10 ml alcohol; ABV, alcohol by volume). (**G**) Stimulant processing. (**H**) Packaging. (**I**) Retail.

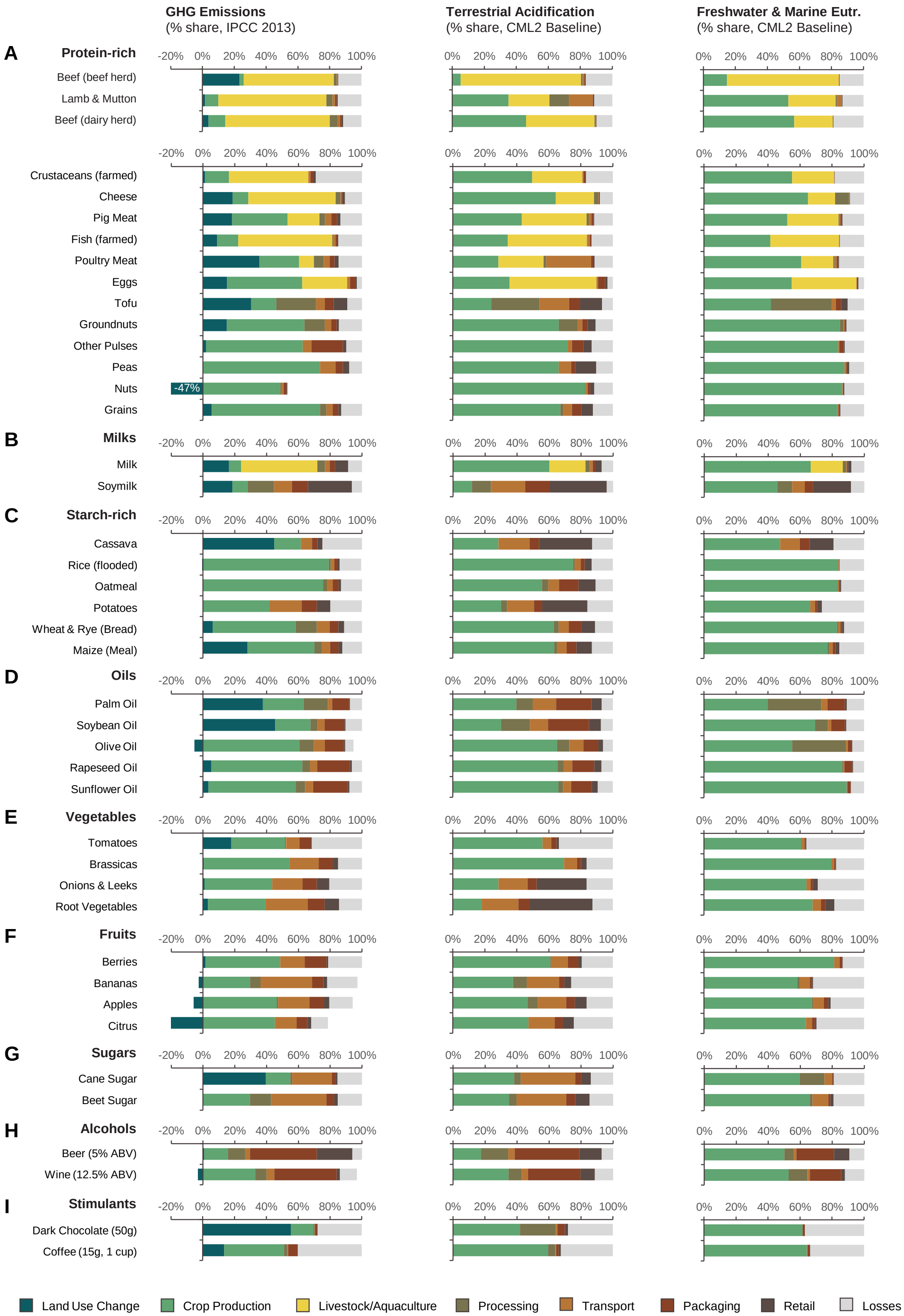
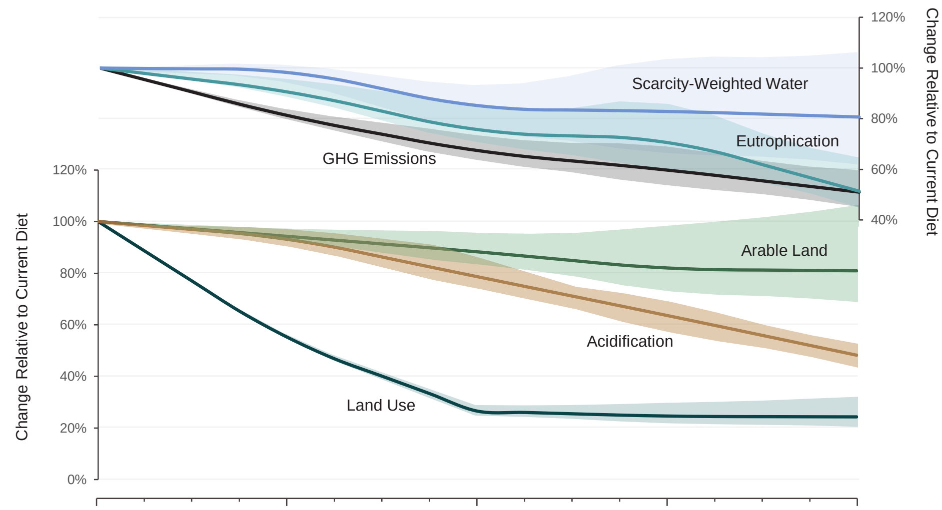

GHG Emissions
(% share, IPCC 2013)
Terrestrial Acidification
(% share, CML2 Baseline)
Freshwater & Marine Eutr.
(% share, CML2 Baseline)
-20% 0% 20% 40% 60% 80% 100%
A Protein-rich
Beef (beef herd)
Lamb & Mutton
Beef (dairy herd)
Crustaceans (farmed)
Cheese
Pig Meat
Fish (farmed)
Poultry Meat
Eggs
Tofu
Groundnuts
Other Pulses
Peas
Nuts
-47%
Grains
B Milks
Milk
Soymilk
C Starch-rich
Cassava
Rice (flooded)
Oatmeal
Potatoes
Wheat & Rye (Bread)
Maize (Meal)
D Oils
Palm Oil
Soybean Oil
Olive Oil
Rapeseed Oil
Sunflower Oil
E Vegetables
Tomatoes
Brassicas
Onions & Leeks
Root Vegetables
F Fruits
Berries
Bananas
Apples
Citrus
G Sugars
Cane Sugar
Beet Sugar
H Alcohols
Beer (5% ABV)
Wine (12.5% ABV)
I Stimulants
Dark Chocolate (50g)
Coffee (15g, 1 cup)
Land Use Change
Crop Production
Livestock/Aquaculture
Processing
Transport
Packaging
Retail
Losses

Fig. S13. GHG emissions, acidification, and eutrophication by stage of the supply chain by product. Emission contributions are shown for the eight supply chain stages: 1) land use change (burning, above and below ground carbon stock change, amortized over 20 years from conversion, excluding savannah burning for management), which can be negative from carbon sequestration; 2) crop production (inputs production, field emissions, drying and grading) and for feed crops, transport; 3) livestock/aquaculture (pasture irrigation and fertilization, manure management, aquaculture emissions, enteric fermentation and energy use); 4) processing; 5) transport (farm to processor, processor to retailer); 6) packaging; 7) retail; 8) losses (storage and transport, processing and packaging, wholesale and retail). (**A**) Protein-rich products. Grains are an average of wheat, maize, oats, and flooded rice, and are included under protein-rich products given their high contribution to global protein intake, despite their lower protein content per kilogram. (**B**) Milks. (**C**) Starch-rich products. (**D**) Oils. (**E**) Vegetables. (**F**) Fruits. (**G**) Sugars. (**H**) Alcoholic beverages. (**I**) Stimulants.



	Current (~2010) Diet	No Beef (beef herd) or Mutton	No Beef (dairy herd), Milk, or Cheese	No Pork or Poultry (Eggs and Fish only)	No Animal Products
Land Use (million ha)	**4,130**	**2,210**	**1,100**	**1,010**	**1,000**
Arable Land	1,240	1,170	1,100	1,010	1,000
Permanent Pasture	2,890	1,040	0	0	0
GHG Emiss. (Gt CO_2eq)	**13.65**	**10.98**	**9.08**	**8.13**	**7.04**
Land Use Change	2.67	1.84	1.54	1.05	1.02
Feed Production	1.10	1.09	0.98	0.52	0.00
Food Production	7.46	5.69	4.21	4.41	3.70
Processing	0.60	0.55	0.52	0.44	0.54
Packaging	0.80	0.79	0.80	0.74	0.78
Transport	0.63	0.63	0.63	0.61	0.62
Retail	0.39	0.39	0.40	0.36	0.38
Acidification (Mt SO_2eq)	**89.0**	**83.4**	**69.4**	**55.8**	**44.1**
Farm	72.3	66.8	52.3	41.7	29.4
Post-Farm	16.7	16.6	17.1	14.1	14.7
Eutr. (Mt PO_4^{3-}eq)	**64.7**	**58.8**	**48.3**	**46.6**	**32.7**
Farm	61.6	55.8	45.4	43.9	29.7
Post-Farm	3.1	3.0	2.9	2.7	3.0
Freshwater Withdr. (km^3)	**2,200**	**2,200**	**1,900**	**1,900**	**1,700**
Scarce-Wtd. Wtr. (km^3eq)	**74,300**	**73,800**	**62,300**	**61,600**	**59,900**
Food Losses (%)	**26.7%**	**26.6%**	**26.6%**	**26.4%**	**26.8%**
Farm to Distribution	4.9%	4.9%	4.8%	4.6%	4.8%
Distribution to Retail	13.8%	13.8%	14.2%	14.2%	14.4%
Consumer (not incl.)	10.5%	10.5%	10.2%	10.0%	10.2%
Food Miles (million tkm, farm to consumer)	**9,395**	**9,395**	**9,385**	**9,385**	**9,375**
Road	2,910	2,900	2,890	2,880	2,870
Rail	930	930	930	930	930
Water	5,540	5,550	5,550	5,560	5,560
Air	15	15	15	15	15

Stimulants 17%
Sugar Cane 17%
Palm 7%
Cereals 12%
Cassava 10%
Soy 33%

Reduction in food waste and food miles associated with changing from animal to vegetable proteins is offset by higher consumption of fresh fruit and vegetables

Fig. S14. Impacts of alternative diet change scenarios. Shading indicates total global impacts, assuming new production is produced with impacts at the 10th- and 90th-percentiles of existing production. Non-food agricultural impacts are excluded (e.g., textiles, processing co-products). Land use change in the 'No animal products' scenario reflects historical land use change from soy and other crops. Acidification and eutrophication do not include forest or savannah burning. Scarcity-weighted freshwater withdrawals are calculated using marginal characterization factors and current crop footprints. Consumer food losses are not included in totals but are shown here for reference and are included as a sensitivity (table S16). Food miles are based on current crop footprints and do not include transport of feed to farm.

Data S1. Additional reference lists. (separate file)

This file contains references for all studies used in the meta-analysis, all studies not used with justifications based on inclusion criteria, and the list of authors who contributed additional data to this study. Detailed notes on locations of data within each published study, how study data were supplemented with data provided by authors, and details of the recalculations performed, are provided in the ‘Notes’ column in the original model. This model is freely available for download from the link in this study.

Data S2. Data in spreadsheet format. (separate file)

This file contains randomized and resampled data by product at the 5th-, 10th-, 90th-, and 95th-percentiles, mean and median; data without randomization at the minimum and maximum; and GHG emissions under IPCC AR4 and AR5 characterizations. Data are provided under different functional units: Retail Weight; Nutritional Units (table S1); and food balance sheet equivalent weights (ref. 129). Sample sizes are provided for each indicator by *n* = observations and *n* = farm/regional inventories, where one observation is a line in the database and can represent multiple similar farms. This file also includes measures of skew by product, and R^2, *p*-values, and sample sizes from the regressions in figs. S4, and S5.

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