Supplementary Information for

The full climate cost of agriculture and aquaculture including foregone land carbon storage

Stefan Wirsenius*, Oliver James, Tim Beringer, Timothy D. Searchinger*

*Corresponding authors: stefan.wirsenius@chalmers.se; tsearchi@princeton.edu

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1. Methods and data

1.1 Main modeling tool

The main tool in this study for calculating climate impacts is the ClimAg model, which is a biophysical systems model that calculates the resource use and emissions of greenhouse gases (GHGs) and nitrogen pollutants from food, fiber, and biofuel production [11]. The primary application of ClimAg is to calculate the climate impact of food and biofuel production systems. In addition to recurring GHGs, the model calculates the climate impact of carbon stock changes in plants and soils caused by land use.

ClimAg models all major steps related to agriculture and aquaculture production and use of food, materials, and biofuels, including i) production of inputs (fertilizer, electricity, etc.); ii) crop, livestock, and seafood production; iii) processing into end-use-ready items; iv) end-use (consumption); and v) transportation between production and use nodes. The model also represents all major co-products and their use; see Fig. S1.

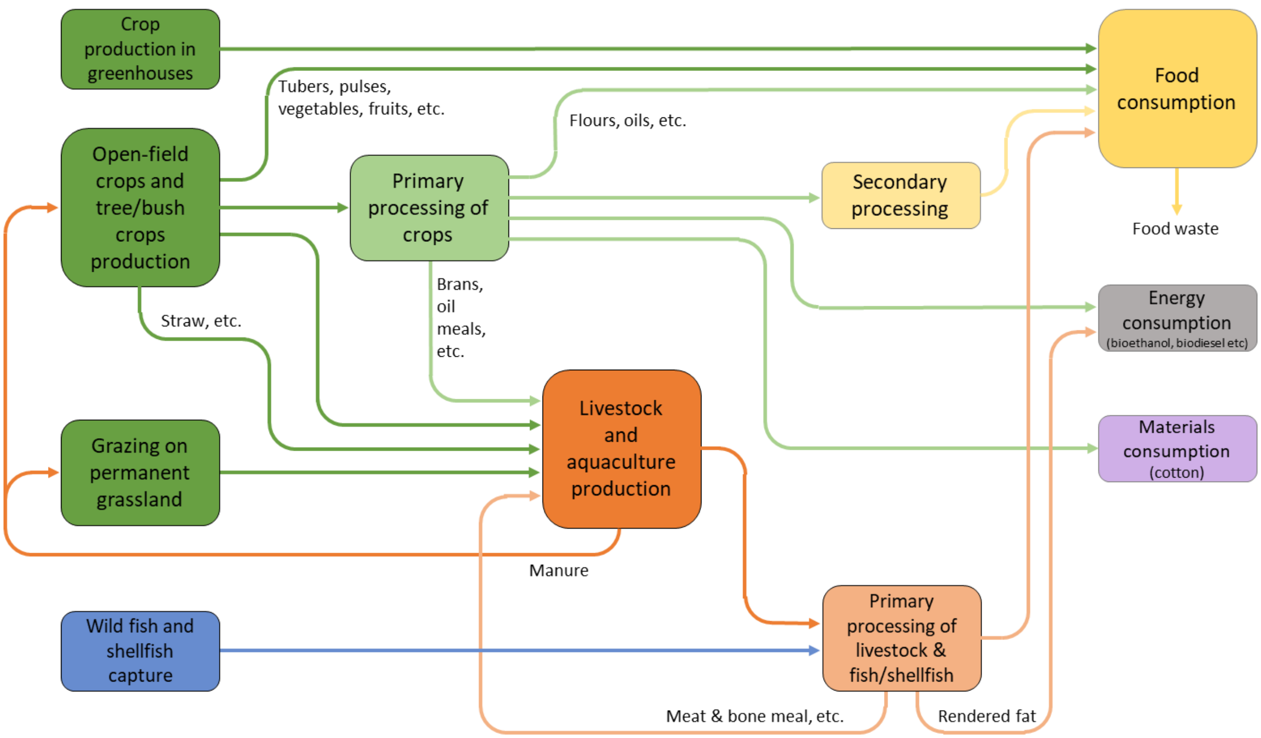

Fig. S1 Overview of the ClimAg model system: Sub-systems included and major product and co-product flows. Some flows are indicated for clarity. Emission flows are not shown. Sub-systems not shown are freight transport and production of fuels, electricity, fertilizer, and pesticides.

The model calculates land and energy use, and climate impacts and nitrogen emissions for approximately 400 products and co-products from agriculture, aquaculture, and fisheries and includes most GHG emission sources from agriculture and aquaculture (see full list in section 1.2). ClimAg does not include energy use and emissions from manufacturing and construction of machinery, buildings etc, except for greenhouse structures.

Key design features of the ClimAg model include:

- **Consistent accounting of upstream resource use and emissions** of all feeds and feedstocks used in production systems. The ClimAg model consistently calculates the land and energy use, and GHG and nitrogen (N) emissions that occur in the supply of all categories of feeds and feedstocks. This applies also to all flows generated as co-products, e.g., cereal brans and oil meals. Such upstream costs are also calculated for co-products, which are often considered free in other models and analyses. For example, straw used for bioenergy or manure used for organic crop production are typically assigned no upstream climate cost.
- **Physically consistent representation of the production and use of co-products** generated in crop and livestock systems, and related processing industries. Most co-products are useful as feedstock in other production processes. ClimAg calculates the production of co-products based on mass- and energy-balanced descriptions of the processes in which they originate. This ensures that the availability of co-products is correctly scaled to the production levels in the sub-systems that generate the co-products.
- **Endogenous representation of livestock herds** in terms of number of animals of different functions and ages, and the herd output of milk/egg and slaughter animals. Herd size and structure are calculated using herd dynamics parameters (e.g., reproduction and growth rates, and animal cohort descriptions, mainly age and liveweight). Endogenous representation enables calibration of key herd productivity parameters, such as calving and liveweight gain rates, to country statistics on production per number of livestock.
- **Endogenous estimates of feed energy intake per animal**, calculated using experiment-based equations that use various herd characteristic parameters as input data (e.g., liveweight, growth rate, and milk/egg production rate). Endogenous calculations of feed energy intake ensure fairly accurate feed use estimates even when feed basket data are incomplete. The benefit of this model feature applies particularly to systems with significant amounts of grazing since the grazed feed quantity is rarely known.
- **Description of nitrogen (N) flows on a mass balance basis**. The ClimAg model includes a highly detailed, mass-balance based representation of N flows in the food and agriculture system. Mass-balanced descriptions of N flows improve the accuracy of emission estimates for crop and livestock production, from which substantial amounts of N can escape as different gases and nitrate. Most of these losses are expensive to measure directly and rarely known with high certainty. Using mass balance ensures physically consistent results, and more accurate estimates overall of N flows.

1.2 Scope, base year, and emission sources of climate impact estimates

In this study, estimates of climate costs are calculated separately for ten world regions (see Table S22). Additional estimates are calculated for four countries: Brazil, China, India, and the USA. Russia is treated as a region distinct from Europe due to its vast size in terms of agricultural land and the lack of reliable data.

For each of these 14 regions and countries, we estimate the climate cost for 63 crop products, 24 livestock and fish/shellfish products, and about 70 products and 70 by-products from crop and livestock/fish processing. A complete list of all items treated is available in Tables 16-22 in the ClimAg model description.

The base year for all calculations is 2020. When compiling data from FAOSTAT and other statistical databases, we used the three-year average for 2019-21.

Total climate costs are divided into recurring emissions and carbon stock changes due to land use, the latter which we refer to as a product's "carbon opportunity cost" (COC) of land use (see section 1.9). The recurring emissions that result from production are referred to as "production emissions" (PEM). We estimate these production emission sources separately:

- Nitrous oxide (N_2O) from mineral soils, with separate representation of emissions from:
  - Plant residues left in field, including root mass
  - Fertilizer application, specific to crop type
  - Manure application, specific to crop type, manure type, and application technology
  - Manure excreted at grazing
- CO_2 and N_2O from drained organic soils
- Methane (CH_4) from flooded rice fields
- CH_4 from feed digestion ("enteric" fermentation) in ruminants and pigs
- N_2O and CH_4 from livestock manure in animal confinements and storage, respectively
- CH_4 from manure excreted at grazing
- CH_4 and N_2O from aquaculture facilities
- "Indirect" N_2O caused by ammonia and nitrate emissions from agriculture
- CO_2 from fuel and electricity use in crop production (e.g., for land preparation, irrigation, harvesting, and post-harvest crop drying).
- CO_2 from fuel and electricity use in livestock confinements, aquaculture facilities, and capture fisheries
- CO_2 from fuel and electricity use in crop, livestock, and fish/shellfish processing
- CO_2 and N_2O from production of mineral fertilizers and pesticides
- CO_2 from manufacturing of materials used in greenhouse structures
- CO_2 from transportation from production to use and end-use, including inter-regional trade

All climate impacts are expressed in emission terms, not temperature increases. To measure methane and nitrous oxide in CO_2 terms, we use the IPCC AR6 [42] GWP factors recommended for a 100-year horizon (27 and 273, respectively).

When vegetation changes from forest to agricultural land, and vice versa, changes occur in surface albedo and cloud formation which both influence regional and global temperatures. However, due to insufficient understanding and data, we do not include these factors in our assessment.

1.3 Core data for representing land use, and biomass and nitrogen flows

1.3.1 Spatial distribution of crops, pastures, and aquaculture ponds

Location of production needs to be factored in for accurately estimating the climate change impacts of land-based products. Location of production influences climate costs via three main factors:

- *Climate*, which affects in particular nitrous oxide emissions from mineral soils (see section 1.4.1), CO_2 and nitrous oxide emissions from drained organic soils (section 1.4.2), and methane emissions from manure (section 1.5.3) and aquaculture ponds (section 1.6.2).
- Carbon densities of *existing* and *potential native vegetation*, which affect emissions, and potential uptake, of CO_2 that occur because of land use (see section 1.9).
- *Soil properties*, in particular clay content, which influence nitrous oxide emissions from soils, existing and potential soil carbon stocks, and fuel use for tillage operations.

In this study, we control for regional climate and vegetation factors, but not for soils (due to insufficient regional soil data and unresolved process-based descriptions of soil dynamics, especially regarding nitrous oxide emissions and soil carbon stocks).

To spatially locate crops grown on cropland, we use the MapSPAM (Spatial Production Allocation Model) database 2020 v1 [23], which provides 5 arcminute resolution (≈10x10 km) global, gridded maps for 42 major crops in the year 2020. For grapes and forage crops, which are not included in MapSPAM, we use maps provided in [43]. The distribution of permanent and semi-permanent (≈10 years renewal rate) pastures is based on maps (at 5 arcminutes) from the HYDE database version 3.3 [24]. The distribution of aquaculture ponds is based on [25], who used 10-meter resolution satellite imagery to identify the location of clustered ponds in 2020.

Table S1 Global average distribution of agricultural open-field crops and aquaculture ponds across biomes. Numbers in percent of total for each crop or land use category. Sources: [23–25,43] in combination with biome map from [44].

	Trop. moist forest	**Trop. dry forest**[1]	**Temp broad-leaf forest**	**Temp. conif. forest**[2]	**Medi-terra-nean forest**	**Trop. grass & shrub**	**Temp. grass & shrub**	**Flood-ed grass-land**	**Mon-tane shrub**	**Xeric grass-land**	**Man-grove**
All agricult. land	11,1	4,5	10,5	2,2	4,0	23,2	15,5	1,2	6,2	21,3	0,1
All cropland	*18,8*	*7,7*	*20,5*	*1,9*	*5,4*	*15,5*	*19,7*	*1,0*	*1,4*	*7,4*	*0,3*
Cereals	16,1	7,1	22,8	1,5	5,0	16,0	19,8	1,3	1,8	7,8	0,3
Oil/protein crops	21,2	8,4	14,5	1,1	4,7	21,7	20,0	1,0	0,8	6,2	0,4
Starchy roots	31,5	5,1	12,1	1,0	0,8	39,7	3,4	0,9	2,5	2,1	0,9
Sugar crops	43,5	10,3	9,8	0,7	0,9	18,6	3,6	1,1	0,7	10,6	0,2
Vegetables	35,8	8,8	27,7	0,9	3,1	9,7	4,0	1,2	1,5	6,3	0,8
Fruits	25,8	7,1	24,5	1,4	10,8	11,1	5,5	1,1	2,6	9,7	0,2
Cocoa, coffee	48,7	11,1	4,5	0,3	0,0	32,0	0,0	0,3	1,4	1,0	0,7
Forage crops	5,0	3,7	37,5	7,4	5,3	1,6	30,2	0,6	0,9	7,7	0,0
All perm. pasture	*7,3*	*2,9*	*5,5*	*2,3*	*3,2*	*27,0*	*13,4*	*1,2*	*8,7*	*28,1*	*0,0*
Aquaculture ponds	42,5	5,9	26,2	0,0	1,4	0,2	0,9	9,1	0,0	4,6	9,4

[1] Including tropical coniferous forests, which make up 0.5% of all global agricultural land.
[2] Including boreal forests, which make 0.6% of all global agricultural land.

To validate the data on distribution of crops, pastures, and ponds, as well as carbon stock densities per hectare (section 1.9), we organize the distribution of the above land use data over a structure of 13 major biomes [44]. The estimated global average distribution is shown in Table S1.

1.3.2 Yield and net photosynthetic production of crops and pastures

We calculate regional average yields per physical area of all crops included in this study, except forage crops, by combining FAOSTAT [5] and MapSPAM data [23], see Table S23. FAOSTAT yield statistics refer to yield per *harvested* area. Since the annual average number of harvests on a unit of cropland can be less, or more, than one, this information is insufficient for calculating the annual production per unit of actual land, or *physical* area. To estimate yield per physical area, we use data in the MapSPAM database [23] on cropping intensities, that is, the ratio of harvested area per physical area. For Brazil and South America, cropping intensities are based also on [45].

Data availability of yield of grasses, legumes and other forage crops cultivated on cropland is generally poor; only a few countries compile yield statistics. Reliable forage yield data sources exist for only a few regions; yields for other regions are estimates of this study (see Table S23).

Crop yields in greenhouse production are typically several times higher than in open-field production. However, there are no national or international statistics available on yields in greenhouse production, nor on the quantity of production, or type of greenhouse production (e.g. heated or unheated). To estimate yields and magnitude and type of production, we combine data on yields in greenhouse with data on areas used for greenhouses, see Table S26. In this study, we limit the inclusion of greenhouse-produced crops to the four most common globally (tomato, cucumber, capsicum, and eggplant).

Using yields per physical area, we estimate total NPP per hectare and year for each crop using plant allometry data. To calculate total above-ground plant mass, we use equations that estimate the percentage harvested plant mass ('harvest index') as a function of the annual yield, when allometric equations were available. For most cereals, oil/protein crops and starchy root crops, we use the equations developed by [26]. For other crops, we use fixed values based on literature searches. For calculating root mass production, we use fixed percentages based on literature. For details, see in Table 25 in the ClimAg model description.

Herbage intake per hectare of permanent and semi-permanent pastures are estimates of this study, calculated as a function of estimated grazed intake in the ruminant feed baskets (section 1.3.3) and the pasture areas as reported in the HYDE database [24] and FAOSTAT. Annual above-ground herbage production per hectare on permanent pastures is estimated as the intake per hectare divided by 0.45; in other words, we assume that the annual average herbage intake as a fraction of above-ground production is 45 percent. To assess the feasibility of our regional estimates of herbage intake and above-ground production per hectare, we compare these estimates with the net primary production (NPP) of existing native vegetation (see Table S23). In regions where most pasture is native vegetation, such as Central Asia and Middle East/North Africa, our estimated NPP is close to the native NPP. (In contrast, and as expected, in regions where pre-existing vegetation is dominated by forests, such as Europe, native NPP is substantially larger than our estimated NPP of current grasslands.)

The main purpose of calculating the NPP of crops and pastures is to provide a basis for calculating the nitrogen flows associated with agricultural plant growth. This in turn is an important foundation for accurately estimating nitrogen inputs and emissions from cropland and pastures (see sections 1.3.4, 1.4.1, and 1.10).

1.3.3 Feed and land use in livestock production

Accurate and consistent calculation of feed use, specifically the efficiency of feed use, is a key condition for accurately estimating livestock's climate costs per kg of output, because feed use efficiency influences land use and emissions for feed production as well as emissions from livestock and their manure. Here, we constrain estimates of feed energy requirements by statistics on livestock productivity, and combine these estimates with detailed feed basket data, in turn constrained by statistics on feed use and availability of land used as feed.

First, we use the herd modules in the ClimAg model to represent the number of each type of animal that is needed to produce a unit of meat, milk, or egg. Main parameters in the herd modules include liveweights, birth/hatching rates, liveweight gain rates, mortality rates, and milk/egg production rates. Milk and egg production per female and year are based on FAOSTAT [5] data. The values of other parameters are based on literature in combination with FAOSTAT data on meat (carcass) production per number of animals. For each region, we calibrate birth rates, liveweight gain rates, and slaughter weights against the FAOSTAT values on carcass production per number of animals (see Table S28).

Second, we calculate feed energy intake per animal using experiment-based equations that use the before-mentioned herd characteristics as input data, in particular liveweight, growth rate, and milk/egg production rate (for details, see section 3.2 in the ClimAg model description). Endogenous calculations of feed energy intake ensure reasonably accurate feed use estimates, and hence emission estimates, even when feed basket data are scarce.

Use of pasture as feed incurs an additional energy cost for physical activity, calculated as a fraction (~10-25% depending on pasture quality) of the maintenance requirements. To accurately estimate the energy requirements for milk production, we control for the regional variation in milk composition (see Table S29).

Third, using the calculated feed energy intake as an input, we estimate feed matter intake per kg of meat, milk and egg, by determining feed baskets (percentage of individual feeds) separately for major animal categories (see Table S66-71). For pigs and poultry, feed basket options include ten different cereals, starchy roots, and protein crops and about 30 types of by-products from crop and livestock processing (e.g., cereal brans and oil meals). For ruminants, additional feeds include harvested and conserved (as silage or hay) grass-legume and whole-cereals forage crops, as well as grazing on cropland and permanent and semi-permanent pastures. Feed energy content and other key characteristics, such as nitrogen (protein) densities, are specified for all feedstuffs (forage crops given in Table S30; all others in in Tables 25-26, 29-30 in the ClimAg model description).

Using statistics and literature, we estimate feed baskets for each animal category based on productivity level, mainly liveweight gain rates, and milk/egg yields in the case of dairy and egg animals. For feedstuffs included in FAOSTAT (cereals, starchy roots, oil and protein crops, brans, oil meals, molasses, etc.), we calibrate the feed baskets for each animal category so that our total feed use in each region equals that in the FAOSTAT statistics. However, in the case of cereal brans, oil meals and other by-products, we constrain their use to the amounts available in each region, regardless of the FAOSTAT statistics. Using our ClimAg model, we calculate relatively robust regional production estimates of these feed by-products following detailed, mass-balance based model descriptions of the process from which they originate (e.g., cereal milling, oil extraction). For forage produced on cropland (grasses/legumes and whole cereals), we calibrate our calculations of forage use against data on forage area in [43] or to region and country data on forage areas and production, if available [46–50].

In most tropical and subtropical regions, ruminant production is mainly sustained by a combination of grazing on permanent grassland in the wet season and on crop residues (and poor quality pasture) in the dry season. We estimate these feed baskets by separately modeling feed energy intake in each season, using literature estimates in combination with calculated availability of crop residues (using ClimAg) and pasture land from HYDE [24] and FAOSTAT as calibration data. A key factor in these estimates is the forage energy content of permanent pasture. Since this factor is highly variable, we repeat our calculations using upper and lower bounds in our uncertainty analysis (see section 2.1).

The estimated feed energy requirements in the second step above combined with the feed basket percentages give estimates of feed intake in kg per kg of meat, milk, and egg output in each livestock system. Our endogenous estimates of feed requirements, in addition to being input data for the climate cost calculations, are standalone results of this study, and are shown in Table S66-71.

Fourth, given feed intake per kg of output, we calculate the cropland land use per unit of output using crop yields based on FAOSTAT and MapSPAM (see section 1.3.2). For by-products (e.g., cereal brans, oil meals, etc.) and crop residues, cropland area use per kg is calculated in ClimAg using allocation over co-products (see section 1.11). The total area of permanent and semi-permanent pasture in each region is calibrated against the pasture areas reported in the HYDE database and FAOSTAT. The quantity of grazed intake per hectare of pasture is assumed to be the same for all ruminant categories within the region. Hence, the use of permanent pasture per unit of meat and milk output is a result of the regional grazed intake per hectare and the quantity of grazed intake per kg of meat and milk in each ruminant system. Resulting land use per kg of output is shown in Table S72.

1.3.4 Nitrogen balances in crop and livestock systems

Accurate estimation of nitrogen flows in agricultural systems is crucial for accurately estimating emissions of nitrous oxide and other nitrogen species. Here, we estimate nitrogen flows by specifying the nitrogen content of all about 500 separate plant, animal and other mass flows in the ClimAg model system and by representing all processes on a nitrogen mass balance basis. Maintaining nitrogen balance means that for each sub-system (e.g., wheat production), all significant nitrogen inputs and outputs must be accounted for, and their sums equal. Using a mass balance approach ensures physically consistent results and increases the overall accuracy of modeled nitrogen flows estimates.

For each crop, we account for these nitrogen inputs: i) decomposing organic nitrogen in plant matter left in field from the preceding crop; ii) biological fixation, including non-symbiotic; iii) atmospheric deposition, and iv) manure applied and/or excreted; and v) fertilizer applied. Outputs included are i) harvested plant matter and ii) losses (emissions) of ammonia, nitric oxide, nitrous oxide, dinitrogen, and nitrate (for details on emission calculations, see sections 1.4.1 and 1.10.1).

The efficiency of different inputs in contributing to plant uptake of nitrogen is described by three different sets of parameters:

- Differences in ammonia losses from applied fertilizer and manure related to variation in type, climate, and application technology (section 1.10.1).
- Differences between crop species in uptake efficiency of soil nitrogen related to their varying density and depth of root systems (for details, see section 2.2 in the ClimAg model description).

- The degree of oversupply of nitrogen (for more details, see section 2.2 in the ClimAg model description).

In the crop nitrogen mass balance, the quantity of fertilizer input completes the balance after all outputs and all other inputs have been accounted for (i.e., the fertilizer application rate is an endogenous function of all other flows). To correctly represent fertilizer application rates in each region, we calibrate regional fertilizer usage against FAOSTAT [5] statistics by adjusting the oversupply factors. In this way, we also reflect regional variation in nitrogen use efficiency in crop production. In addition, we differentiate the degree of oversupply by crop category, to reflect the varying nitrogen use efficiency in different crop categories. We base these crop-specific adjustments on [27], who reported that global nitrogen use efficiencies are substantially lower for fruits, vegetables, and sugar crops. Estimated fertilizer rates are given in Table S63.

The nitrogen mass balance of inputs and outputs is also calculated for each animal category in each livestock system. The input is the nitrogen content of the feed intake, and the outputs are the nitrogen retained in animal mass and nitrogen in excreted feces and urine (manure). Manure nitrogen completes the nitrogen balance for each animal category. We calculate the nitrogen retained in body mass using the estimated liveweight growth in combination with a detailed representation of the allometry and nitrogen content of body parts (for details on the latter, see Table 28 in the ClimAg model description).

In animal confinements, the manure nitrogen input to storage is the amount of nitrogen remaining after ammonia and nitrous oxide losses in the confinement have been deducted. Nitrogen in feed waste occurring during feeding and nitrogen in bedding materials also constitute inputs to the manure storage stage. For feeding waste, we assume a waste rate of 2% for cereals and other concentrate feed and 7% for forages [51]. The quantity of nitrogen in manure after the storage phase equals the inputs minus the emissions of ammonia and nitrous oxide (for details on emission calculations, see sections 1.10.2 and 1.5.3). After storage, all manure is assumed to be applied on cropland, or to some extent burnt (see Table S31). In the case of grazing, the nitrogen entering the soil nitrogen pool is the excreted nitrogen minus emissions of ammonia and nitrous oxide (see sections 1.4.1 and 1.10.1). The estimated average rate of nitrogen input from manure application and excretion combined is given in Table S64.

1.3.5 Production, trade, food consumption and diets

To accurately depict the current scale of agriculture and aquaculture, we calibrate ClimAg calculations of production of crops, livestock products (carcass, milk, eggs, wool) and aquaculture products in each region against FAOSTAT [5] statistics. We do the same for some major processed products, including vegetable oils, sugars, starches, and liquid biofuels. For other key processed products, such as cereal flours, white rice, alcoholic beverages, and cheese and other dairy products, we calibrate our production numbers by calculating the food consumption of these items in each region using FAOSTAT statistics (further discussion below). Calibration ensures, among other things, accurate representation of the quantities produced of by-products and crop residues, which are key inputs for accurate estimation of the use of these products, particularly as feed (see section 1.3.3).

To factor in the climate impact of food, feed and feedstocks produced outside a region, we represent major trade flows in the ClimAg model based on FAOSTAT trade data. The production emissions (PEMs) and carbon opportunity costs (COCs) per kg of imported goods are calculated as the weighted average of the PEMs and COCs per kg of the exported quantities from exporting regions. Emissions from inter-regional transportation are included (see section 1.8).

ClimAg estimates the quantities of food consumed in each region, and the necessary production inside or outside the region to support this consumption, using FAOSTAT Food Balance Sheet (FBS) statistics. ClimAg adopts a food item structure similar to FAOSTAT FBS, but with a higher level of detail: for livestock and fish/shellfish, it includes about 45 items, and for crops and crop-based food about 85 items (for more details, see section 8 in the ClimAg model description). Table S47 presents aggregate data on food consumption per capita, for current regional diets and for alternative diets (the latter described in section 5.2).

1.4 Greenhouse gas emissions from crop production and pastures

1.4.1 Nitrous oxide from mineral soils

Nitrous oxide (N_2O) emissions from mineral soils are close to linearly scaled to the nitrogen flow rates in the soil. By using a detailed, mass-balance based description of nitrogen flows (see section 1.3.4), we constrain the estimates of N_2O emissions. More specifically, since nitrogen inputs to the soil must add up to the estimated nitrogen requirement of the crop, the N_2O contribution from each of these inputs is also fairly well constrained.

We calculate (N_2O) emissions as a fraction (emission factor) of different inputs of nitrogen (N). For consistency, the emission factors are applied to the quantity of N input remaining after losses of ammonia. Surface application without incorporation of urea fertilizer and most manure types can lead to very high losses (up to 50%) of the total N as ammonia. Since these ammonia emissions occur very soon after application (within 24 hours) the fraction lost does not induce significant N_2O emissions. For this reason, we apply the emission factors only to the remaining quantity.

For fertilizer and manure, we differentiate the emission factors by climate, based in particular on [28], who found that the average fertilizer emission factor is about three times higher in humid climates than in dry climates. To arrive at regional emission factors, we calculate the area percentages of humid vs. dry climates for all cropland in each region. (Humid climate in tropical biomes is defined as having an annual rainfall exceeding 1000 mm, and in temperate biomes as having a ratio of annual precipitation over annual potential evapotranspiration exceeding 0.65.) We then use the humid and dry emission factors in [28] to calculate regional averages (shown in Table S50). Our estimated global average factor for fertilizer nitrogen on all crops including irrigated rice is 1.2%.

For fertilizer, we use different emission factors for annual crops and perennial crops, following evidence that emission factors for grasses and other perennial crops are substantially lower [28], [52]. For manure, however, we are not able to make this differentiation due to insufficient data.

For manure, we do differentiate emission factors by manure type and manure application technology. Several studies have shown that emission factors for liquid manure are several times higher than for solid manure. Based mainly on [53], we assume that the emission factor for liquid manure is three times higher than for solid manure. Sub-surface application of liquid manure is known to increase emission factors, although the magnitude is uncertain. Based on [54], we assume that the emission factor for injected liquid manure is 50 percent higher than for surface application.

Furthermore, we factor in the increase in N_2O emissions following application of fertilizer and manure in combination. According to [53], the emission factors for organic inputs more than doubles when combined with fertilizer inputs. In addition, the emission factor for the fertilizer itself increases by about 20%. Based on data in [53], we assume that the emission factors of combined manure and fertilizer application are 90% and 20% percent higher than that for manure and fertilizer, respectively. We use an application rate of 25 kg N per hectare per year as a threshold for applying the higher emission factors.

For crop residues and other plant mass left in field, we differentiate the emission factors by type of plant mass, in particular its C:N ratio. According to [55], crop residues with a high C:N ratio, such as mature (dry) straw, generate much lower N_2O emissions than those with a low C:N ratio, such as fresh grass. Fresh residues high in nitrogen, such as vegetables and potato and sugar tops have particularly high emission rates per unit of nitrogen content. This was noted previously by [56], who proposed an emission factor for vegetables ten times higher than that for cereal straw. Based on these results, we coarsely differentiate emission factors across different crop categories (see Table S50). Crop residue nitrogen input rates are shown in Table S65.

Since N_2O from soils is a significant but highly uncertain emission source we re-run our calculations using lower and upper bounds for these emission factors in our uncertainty analysis (section 2.2).

1.4.2 CO_2 and nitrous oxide from drained organic soils

Based on the current distribution of agricultural land (see section 1.3.1), we estimate the extent of drained organic soils on cropland and permanent grassland. We overlay the maps of the distribution of agricultural land with the global map by [29] of the location of organic soils, or peatland. We assume that all peatland areas that overlap with agricultural areas are drained.

Emissions of CO_2 and N_2O are calculated using emission factors per hectare of drained peatland. We use differentiated emission factors for each of three climate zones: tropical, temperate, and boreal. The emission factors are based on data in [57], with a few exceptions: for oil palm, we use the emission factor derived by [58], who calculated an average of 78 Mg CO_2 eq. ha^{-1} $year^{-1}$ (incl. N_2O) from several sources. For CO_2 emissions in boreal areas, we use data in [59]. Emissions per hectare are higher in tropical zones than in temperate and boreal zones. The numbers given in Table S51 are averages that reflect the geographic structure of each crop and region.

There is considerable uncertainty with respect to both the extent of drained areas and the emissions per hectare of drained organic soils. Therefore, we include lower and upper bound emission factors in our uncertainty analysis (section 2.2)

1.4.3 Methane from flooded rice cultivation

Technically, our calculations of methane emissions from rice paddies follow the methodology defined by the IPCC [39]. Emissions per harvested area per year are calculated as a climate-specific default emission rate multiplied by three different scaling factors that reflect variations in management. These scaling factors reflect differences in i) water regime *during* the cultivation cycle, ii) water regime *before* the cultivation cycle, and iii) amount and type of organic matter added (e.g., manure) or left in the field (e.g., straw).

Water management schemes have a decisive influence on emission levels in flooded rice production [60]. Due to variation in management schemes and uncertainty in their specific effects, there is a very large spread in global emission estimates, ranging from 20 to 110 Tg methane per year [60]. Because of the large, spatially explicit data requirements that would be needed for accurate modeling of rice methane emissions, this study adopts previous estimates for two major rice-producing regions, East Asia, and South Asia, which between them account for 90%of global production of flooded rice.

For East Asia, we adjust our water management scaling factors so that our methane emission estimate per *harvested* hectare and year agrees with best available estimates for China, which accounts for c. half of rice production in East Asia. As a best available estimate, we choose [30], who estimates emissions at 270 kg methane ha^{-1} $year^{-1}$ using the DNDC model. For South Asia, we apply the same calibration approach using estimates for India. As a best estimate for India, we use India's Second National Communication to the UNFCCC, which estimated emissions at 78 kg methane ha^{-1} $year^{-1}$ using field measurements in combination with remote sensing [31].

As mentioned, there are very large uncertainties with respect to emissions per hectare of flooded rice. Therefore, we include lower and upper bound emission estimates in our uncertainty analysis (section 2.2)

1.4.4 Energy use in open-field crop production

To estimate the emissions from on-farm energy use in crop production, we include separate estimates of the energy use for:

- Land preparation (leveling, plowing, tilling etc.), sowing and planting
- Fertilizer and pesticides application
- Manure application
- Irrigation
- Pruning (of tree crops)
- Harvesting and transportation to storage
- Post-harvest drying before storage

For land preparation and irrigation, we calculate the energy use as a crop-specific fuel use rate per physical area. In the case of tree crops, we allocate the energy used for establishing the plantation over its estimated lifetime. For application of fertilizer, pesticides, and manure we calculate the energy use as a fuel use rate per number of applications and applied amount. For harvest and transportation of field crops, we calculate fuel use as a function of both area and harvested amount, based on [61].

In rainfed production, on-farm energy use is dominated by consumption of diesel fuel, mainly for tractors and other field equipment. Data sources and the sum of fuel use for the operations except drying are given in Table S24.

In irrigated crop production, energy use for pumping and distribution of water can greatly exceed other on-farm energy uses. Energy use and data sources are given separately in Table S25.

Due to large variation in fuel use and the lack of comprehensive and consistent data sources, we include lower and upper bound estimates of energy use in our uncertainty analysis (section 2.2).

1.4.5 Inputs and emissions in greenhouse crop production

To estimate the climate impact crop production in greenhouses, we include the energy use not only for operating the greenhouse but also for producing the greenhouse structures. To estimate materials use for greenhouse structures, we rely mainly on the comprehensive studies by [62] and [63]; see Table S26.

We rely on [62] and [63] also for data on the use of fertilizers, pesticides, and substrates, together with [64–73].

Energy use in greenhouses is substantial only in heated greenhouses, and those are common mainly in Europe; see Table S26 for numbers and sources.

To estimate nitrous oxide emissions, we use the emission factor 1.4%, based on [74]. Ammonia emissions are assumed to be small, and we use an emission factor of 2.5% for all fertilizer types.

1.4.6 Use and production of fertilizer and pesticides

As described in section 1.3.4, we estimate nitrogen fertilizer application rates from crop-specific calculations of nitrogen requirements and calibrate these estimates against FAOSTAT data on regional fertilizer use. These estimates are given in Table S63.

Estimated application rates of potassium, phosphorus and pesticides are also based on crop-specific requirements calibrated against FAOSTAT data on regional fertilizer use. However, in contrast to nitrogen, the estimated requirements of potassium and phosphorus are not based on an analysis that considers other inputs. Instead, these estimates are fixed quantities per unit of yield which are regionally adjusted via calibration against FAOSTAT, and thus indirectly capture regional variation in soil nutrient status and other factors.

To reflect increasing energy efficiency in the production of fertilizers and pesticides, we use the most recent data available on energy use. Data sources, energy use and greenhouse gas emissions from the production of fertilizers and pesticides are given in Table S46.

1.5 Greenhouse gas emissions from livestock production

1.5.1 Emissions from feed production and manure application and excretion

Methods and data for calculating emissions from production of crops used as livestock feed are described in section 1.4. Technically, all forages cultivated on cropland (i.e., grasses, legumes and grass-legume mixtures and whole cereals, and most of the cereals used as feed) are assumed to be produced on the livestock farm. All other feeds, including by-products such as cereal brans, oil meals, etc., are assumed to be purchased and transported to the farm. All upstream climate costs of purchased feed are tracked and added to the on-farm emissions. By-products and crop residues are allocated a part of the upstream climate costs based on their economic value (see section 1.11).

Stall manure (i.e., manure excreted in animal confinements), is assumed to be applied on the cropland areas used on the livestock farm for forage and/or cereals production. Calculations of the emissions from manure application are described in sections 1.4.1 and 1.4.4.

In the case of manure excreted by grazing animals, we include emissions of nitrous oxide and methane. Nitrous oxide emissions are described in section 1.4.1. Methane emissions are calculated as a function of the maximum methane production potential of excreted amounts of volatile solids, multiplied by a methane conversion factor. For all ruminant types and regions, we use the factor 0.5%, based on IPCC (2019).

1.5.2 Methane from feed digestion

The rate of methane produced in the digestive tract of animals is approximately linearly scaled to feed intake. We constrain our calculations of the methane production and emission rates with a detailed approach for estimating feed intake (see section 1.3.3).

We calculate the methane emissions from feed digestion in ruminants and pigs as a fraction of feed gross energy intake. Here, in contrast to most other studies, for ruminants this fraction is not an exogenous constant, but an endogenous variable calculated as a function of feed quality, daily feed intake, and animal liveweight. This reduces the prediction error compared to using fixed factors (a fixed factor approach is the standard approach recommended by the IPCC [39]).

For cattle and buffalo, we use predictive equations developed by Moraes et al. [32], based on an analysis of approximately 2,600 energy balance trials. Among the various equations derived by Moraes et al., we use those with the most detailed input data ("animal" level). For sheep and goats, we use equations from [33], who analyzed a database containing 270 measurements. The emission rates obtained are given in Table S52.

For pigs, we use fixed emission factors, based on [75] and [76] For sows, we use a factor of 0.80%, and for all other pigs a factor of 0.45%.

Since methane from feed digestion is by far the single largest greenhouse gas emission source from global agriculture and the variance in emission rates is large, we include lower and upper bound rates in our uncertainty analysis (section 2.2).

1.5.3 Methane and nitrous oxide from manure in livestock stalls and manure storage

Methane and nitrous oxide (N_2O) emissions from manure are proportional to the quantities of manure generated, and, therefore, also to the feed intake. We constrain these emission estimates by using a detailed approach for estimating feed intake (section 1.3.3). These constraints are incomplete, however, since manure methane emissions differ greatly depending on management technology and temperatures during storage. In general, manure with high water content (slurry, urine) promotes methane production, especially when temperatures are above 15°C. Under these conditions, emissions per unit of manure can be two orders of magnitudes greater than for manure with low water content.

For all types of manure, we calculate methane emissions as a function of the excreted quantity of volatile solids (VS), multiplied by an animal- and feed-specific factor that reflects the maximum potential methane production per unit of VS (denoted B_o) and a climate- and management-specific methane conversion factor (MCF) that reflects to what extent the maximum methane production is realized. Furthermore, we make separate estimates of the emissions that occur in the animal confinements (stalls, etc.) and those during the subsequent storage, if any. Apart from the methane generated from the manure itself, we also include calculations of methane produced from substrates added to the manure stream, mainly bedding materials and feeding waste. We apply the same MCFs as for the manure to these streams; B_o values are substrate specific.

For solid manure streams with low water content (feces, poultry manure, etc.) MCFs are generally low, both in the confinements and during storage, although factors increase with temperature. For the confinement phase, we assume the same MCFs in all regions, except for dry lots, which are more exposed to climatic variation in temperatures. For dry lots, and the storage phase, we assume MCFs slightly differentiated to regional temperature differences. Factors and sources are given in Table S53; B_o data in Table S54.

For liquid manure streams with high water content, we use a relatively detailed approach to reflect the large regional variation in methane emissions due to temperature differences. Since methane production is non-linearly related to temperature, calculating emissions using average temperatures over a long time period (e.g., a year) will underestimate emissions. In general, modeled estimates based on shorter time steps will provide more accurate emission estimates. This is particularly the case in cool regions where most annual methane production occurs during a few warm months when temperatures exceed 15 °C.

Here, we use monthly average temperatures to calculate the annual methane emissions during storage of liquid manure. We base these calculations on the predictive model presented in IPCC (2019, Annex 10A.3), which is itself based on a model developed by [77]. However, because several studies have shown that the IPCC model greatly overestimates methane emissions at temperatures at or below ≈15 °C [34,78,79 80], we make the following slight modifications to the model: For temperatures at 17 °C and below, we reduce the predicted methane production by a progressively large factor, which reaches 80% at temperatures below 10 °C. These reduction factors are determined by calibrating the model predictions against the measurements in [34], one of very few studies that report long-term, farm-scale measurements under cold conditions. We validate these adjustments by finding reasonable agreement between predicted emissions and those observed in [81], another rare farm-scale study that reports measurements in an area with low winter but high summer temperatures. Importantly, for the regions of analysis in our study, the downward corrective factors do not greatly reduce predicted emissions, and in some regions not at all. For example, in Europe, one the coldest regions, the adjusted MCF for slurry stored outdoors is 20%, whereas the unadjusted is 26%.

We use the adjusted model to estimate MCFs differentiated by regional climate for:

- Anaerobic lagoons
- Slurry pits indoors beneath animals; and
- Slurry and urine stored outdoors

For lagoons, MCFs are relatively high due to long residence times compared to pit and tank storage, which typically are emptied once or twice a year. For indoor pits, MCFs are higher than slurry stored outdoors because of higher indoor temperatures, which we assume never fall below 18 °C. For details see Table S53.

MCFs from liquid manure that is stored temporarily indoors before being transferred to outdoor storage are based on [82]. A residence time of ten days indoors is assumed for both dairy and pig systems.

As mentioned above, the type of manure management greatly influences emissions. We estimate the extent of use of different manure systems in each region based on an extensive literature review (see Table

S31). In general, dry manure management systems are prevalent in extensive ruminant systems, whereas liquid systems are common in intensive dairy and pork systems.

For N_2O, we calculate emissions as a function of the excreted total nitrogen, multiplied by an emission factor that reflects the degree of N_2O production depending on type of manure and management technology. As in the case of methane, we calculate emissions separately for the confinement and storage phases, respectively. We also include the nitrogen additions to the manure from bedding materials and feeding waste, applying the same N_2O factors as to the manure stream. Emission factors and sources are given in Table S53.

1.5.4 Energy use

For livestock farming activities except those for feed production, we calculate emissions from energy use separately for three categories (Note: energy use for crop production used as feed is covered in section 1.4.4.):

- Fuel for heating
- Electricity for milking
- Fuel and electricity for all other purposes (feeding, ventilation, manure management, etc.)

We calculate emissions for heating and general purposes by assuming systems- and region-specific energy use per unit of animal and time spent in confinement. Annual energy use is calculated by multiplying these factors by the percentage time of the year spent in confinement. In this way our estimates factor in the differences in energy use due to varying extent of grazing in ruminant systems. Emission factors and data sources are given in Table S32.

1.6 Greenhouse gas emissions from aquaculture production and wild fish capture

1.6.1 Feed use and yields in aquaculture

In aquaculture, feed use efficiency is typically quantified according to the "economic feed conversion ratio," which quantifies total feed input per total net output (actual harvest) of product. Hence, the ratio factors in losses of product by death, escapes, etc. and that of non-ingested feed. Here, in contrast to livestock feed, we do not make detailed estimates of the feed energy requirements in aquaculture. Instead, we assume species-specific feed conversion ratios based on the most recent data available. Due to lack of detailed regional data, we apply the same numbers across all regions. Data and sources are given in Table S71.

Several species common in aquaculture can feed on organic matter naturally present in the water body, such as plankton and detritus. Some filter-feeding species, such as certain carps (e.g., silver carp) and mollusks, feed exclusively on naturally occurring food, and their production uses no external feed. We calculate the use of external feed by assuming rates of intake of in-situ natural food based on [83] (see Table S33). For carps, we calculate the average for all carp species based on production data in Tacon (2020). About half of global carp production consists of filter-feeding species, which consume no external feed. For the other half of production, external feed makes up approximately 57% of total feed requirements. We therefore assume an overall, production-weighted average 28% external feed requirement for all global carp production.

There is little data available on the mix of different feed components in the external feed basket, and we rely on only a few studies [17,84,85]. Due to these data limitations, we apply the same species-specific feed baskets across all regions (see Table S33).

We assume all external feed is transported to aquaculture facilities from crop farms and compound-feed plants. Upstream climate costs of external feed that occur in crop production and processing are accounted for in the same way as in livestock production (section 1.5.1).

Aquaculture production of crustaceans and freshwater fish mainly occurs in artificial ponds, created at the expense of native vegetation or other land uses. Product yields per pond area vary greatly depending on species and production intensity; however, there are no international yield statistics currently available. Here, we base our yield estimates on data for China, by far the largest aquaculture producer. Using yield data in [35,84], we calibrate yields for crustaceans, carps, tilapia, and other freshwater fish against Chinese statistics on pond area [25] and production in FishStat [86]. Based on these estimates, we then calibrate yields in other regions (again using data on pond areas from [25] and production from FishStat; see Table S33).

1.6.2 Methane and nitrous oxide emissions from aquaculture

Large input of feed to aquaculture ponds in combination with poor aeration of the water mass stimulates substantial methane production. We estimate methane production per hectare of pond area based on Dong et al [35], who synthesized methane emission measurements for Chinese ponds, and [87], who report measurements of methane emissions from ponds and other water bodies in India. Data in Dong et al (2023) indicate that methane emissions rates are substantially higher in shrimp ponds (~880 kg CH_4 ha^{-1} $year^{-1}$) than in fishponds (≈220 kg CH_4 ha^{-1} $year^{-1}$). Fishponds in China are mainly used for carp production, and we therefore adopt the Dong et al fishpond emissions intensity figure as our base estimate for carp ponds. For crustacean ponds, we adopt the Dong et al shrimp pond figure. For tilapia, catfish, and other freshwater fishponds, we assume substantially higher emission rates compared to carp, because of the much greater input of external feed in those systems. To estimate emission rates in other regions, we scale the methane emission rates to the Chinese yields, based on the assumption that lower yields mean lower feed input per hectare and therefore lower emission rates. These regional figures are given in Table S57.

Because of the large input of reactive nitrogen in feed to aquaculture ponds, it is likely that nitrous oxide (N_2O) production in the water mass is larger than what it would be without the feed input. However, there currently exist no comprehensive N_2O emission measurement data for aquaculture ponds. It has been suggested that N_2O rates from wastewater treatment plants could be used as a proxy for aquaculture ponds [88]. Based on a recent comprehensive study on emission from wastewater treatment plants [89], we assume an N_2O-N emission factor of 1.6% of total nitrogen (average for all 376 observations in Song et al). We uniformly apply this emission factor to the amount of feed nitrogen input to the water mass that is not retained in animal mass, that is, feed nitrogen excreted in feces and feed not ingested.

Since methane according to the data above is a substantial emission source and the variance in emission rates is large, we include lower and upper bound rates in our uncertainty analysis (see section 2.2).

1.6.3 Energy use in aquaculture

In addition to energy use in feed production, we include emissions from the use of energy for the production of compound feed in feed mills, and for the operation of the aquaculture farm itself. There is little data available, and we rely on only a few sources. Due to the lack of detailed data, for each aquaculture product we assume the same energy use in all regions (see Table S34 for emission factors and sources).

1.6.4 Energy use in capture fisheries

Greenhouse gas emissions from the capture of wild fish and seafood are essentially limited to the quantities of fuel consumed by fishing vessels. This study does not aim to improve the current knowledge on this topic, but we include these emissions for enabling comparisons with other food items. As a basis for our emission numbers, we use the comprehensive study by [36]; see Table S35.

1.7 Greenhouse gas emissions from processing of crop, livestock, and fish products

1.7.1 Food products

In this study, we include comprehensive emission estimates of all major food commodities made from processing of crop products, including cereal flours & groats, rice, vegetable oils, sugars, starches, protein concentrates and isolates, and alcoholic beverages. For livestock and fish, we include processing into ready-to-eat items (cut meat, fish fillets, etc.). For dairy, we include processing into all major products, including milk/yogurt, cream, cheese, butter, and milk powder.

We describe the production of these processes on a mass and energy balance basis, with separate balances for nitrogen (protein). Hence, for each of these processes, we estimate the yield of the main product as well as that of all significant co-products. We also estimate the use of energy in each process, with separate estimates for process steps with significant energy use, such as drying.

All upstream climate costs of the process feedstock are tracked and added to the emissions from the processing plant. For each process, we calculate the climate cost of the main product and its co-products by allocating the sum of the upstream and on-site climate costs over the products based on their economic value (see section 1.11).

We base our estimates of process yields and energy use on an extensive literature review. Due to general lack of region-specific data, however, for most processes we apply the same factors across all regions (see Table S36-41). Our estimates still capture regional variation, since we make region-specific estimates of the climate cost of the production of the feedstock, which in all cases is several times larger than that of the processing itself.

For some products, we do make region-specific estimates of the process yields and energy use. Among crop-based products, these include palm oil, peanut oil, olive oil, cane sugar and beet sugar. For these products there is large variation in feedstock composition and extraction techniques, which both influence yields. We calculate the regional estimates by calibrating our process yields against FAOSTAT statistics on regional feedstock use and production of outputs.

For milk and yogurt, regional variation in average yield (Table S37) is due to regional differences in the consumption of milk fat in concentrated form (i.e., cream and butter). Since concentrated milk fat is produced by skimming fat from whole milk, the larger the consumption of the fat component, the lower the yield of the remaining fraction (i.e., milk and its derivatives, such as yogurt).

For meat, regional variation in average yield (Table S38) is due to variation in carcass yield (Table S28) and herd structure (e.g., cattle herds dominated by dairy cattle, as in Europe and South Asia, have lower average meat yield due to generally lower carcass yields of dairy breeds). We also provide estimates of the yields of separate meat cuts that better resemble the actual form at the point of consumption (see Table S39).

For offal and lard consumed as food, we estimate the liveweight fraction by calculating the regional consumption of these items (see section 1.3.5) and apportion these quantities over the regional liveweight production of ruminants and pigs.

1.7.2 Composite food products - plant based meat and dairy substitutes

Food commodities originating from the first stage of processing are often further processed and mixed with other ingredients before consumption. Here, we include estimates for one such category, plant-based meat and dairy substitutes, because of the potentially lower climate cost of these products compared to animal meat and dairy products.

Plant-based meat substitutes are currently marketed in many different forms. Products designed to closely resemble real animal meat are typically made from a combination of plant-based protein concentrates (and/or isolates) and vegetable oils, together with additives and other minor ingredients. Among the most used plant protein sources are from soybeans or peas. As a fat source, any vegetable oil may be used, except in certain products, such as patties, for which coconut fat is preferred for its high melting point.

We calculate the climate cost of four distinct but generalized ingredient configurations for plant-based meat products (see Table S41). These configurations use either soybean or peas as a plant protein source, either at a low or high fat content. In the high-fat configurations, coconut fat is used. We base these assumptions on information about chemical composition (protein, fat, carbohydrate content) and ingredients lists retrieved from back-of-package information for a large set of plant-based products currently on the market. Based on a few sources (see Table S41), we also estimate the energy use for the production process. As in the case of processed food, all upstream climate costs of the feedstock are tracked and added to the emissions from the production itself.

For plant based dairy products, we estimate ingredient mixes and energy use for the most common types of milk substitutes (soy, oat, almond, and rice-based; see Table S42). We also include three variants of plant-based butter substitutes which are based either on soy oil, palm oil or coconut oil, in addition to rapeseed and sunflower oil which we assume are included in all three variants. For cheese and cream substitutes, we include only one ingredient configuration each, reflecting the smaller variability within the ingredient composition of currently marketed products. We estimate the ingredient mixes and calculate the climate costs in the same way as for plant-based meat substitutes.

1.7.3 Cotton, biofuels

In addition to the food products mentioned above, we include estimates of the climate costs of cotton lint and related co-products, as well as of liquid biofuels made from agricultural feedstocks. We represent the production processes for these products in the same fashion as for processed food products, i.e., using a mass and energy balance approach. All upstream climate costs of the feedstocks are tracked and added to the emissions from the production process. For each process, we calculate the climate cost of the main product and its co-products, if any, by allocating the sum of the upstream and on-site climate costs over the products based on their economic value (see section 1.11).

For cotton products, estimated yields, energy use, and data sources are given in Table S43. Due to lack of detailed regional data, we apply the same assumptions across all regions. However, we do factor in the regional variation in processing cottonseed into oil and meals. For example, in South America, cottonseed is widely used as livestock feed, and a relatively smaller fraction of cottonseed is processed compared to other regions. We base these assumptions on FAOSTAT production statistics.

For liquid biofuels, factors and data sources are given in Table S44. Although we include data for several regions, our assumptions are representative primarily for those regions or countries that account for a majority of global biofuel production across feedstock types. For example, global maize ethanol production is dominated by US production, sugarcane ethanol by Brazil, and wheat ethanol by Europe. It should be noted that current global ethanol production from cereal straw is relatively very small, and process assumptions here may not hold if global production scales significantly in the future.

1.8 Greenhouse gas emissions from electricity production, fossil fuels and transportation

To account for regional variation in climate costs from energy use, we include estimates of the average CO_2 intensity of electricity supply in each region (see Table S45 for emission factors and data sources). For fossil fuels, we include estimates of upstream emissions related to the extraction and processing of the fuel feedstock (see Table S45).

For freight transport, we calculate the use of energy for transportation of all crop products from the farm or greenhouse to the processing plant, to food stores for direct consumption (e.g., in the case of vegetables and fruits), or to livestock and aquaculture farms for use as feed. For livestock and fish, we calculate the energy use for the transportation of live animals, whole fish, and whole milk to abattoirs and fish and dairy processing plants. We also calculate the energy used for the transportation of processed items for further use as feedstock or for consumption as food.

In addition to goods being transported within each region, we also calculate the emissions from transportation between regions. For inter-regional transport, we include dry crops (e.g., grains), dry processed commodities (e.g., flours, oils, milk powder, etc.), fresh/frozen vegetable and fruits, and fresh/frozen meat, dairy and fish products.

To factor in the influence of the properties of the cargo on energy use requirements, we estimate pallet density and the need for cold transport (see Table S48). For short-distance road transport, we calculate energy use for two different vehicle options, “small” and “large”. For long-distance road transport, we model three types, “bulk”, “semi-trailer”, and “trailer”, of which trailer has the lowest fuel consumption per cargo and kilometer. For long distance maritime transport, we model three types, “bulk”, “container”, and “reefer”; the latter is used for transport of chilled or frozen cargo. For more details, see section 7.2 in the ClimAg model description.

Within each region, we assume that all transportation occurs by road, as a one-leg trip (plus return). Depending on cargo and distance, we assume energy use requirements for the most likely transport vehicle.

For inter-regional transport, in addition to a maritime-transport stage, we also calculate the energy use for a long-distance stage by road, reflecting the need for transport from the point of production to the point of export (i.e., a port). In addition, we calculate the need for transport by road from the receiving port to the point of storage.

For capacity utilization, we assume 50% for most distribution within the region. This assumes full capacity utilization on the outbound trip, and zero (empty) on the return trip. For inter-regional transport, we assume somewhat higher capacity utilization, because trade is bidirectional.

All assumptions for transportation distances are provided in Table S48 and are estimates of this study. Because of the complexity of the global trade system, it is beyond the scope of this study to estimate freight transport distances of any one commodity with high accuracy. Here, we assume transport distances with sufficient accuracy to produce emission estimates to the correct order of magnitude.

1.9 Foregone carbon storage due to crop, livestock, and aquaculture production

1.9.1 Introduction

Since agricultural production mainly takes place on land that supports plant growth, most agricultural land use occurs at the expense of reduced carbon stored in forests and other native, carbon-rich vegetation. Therefore, agricultural land use has an inherent climate impact in the form of reduced land carbon stocks and, hence, higher atmospheric CO_2 levels. By some estimates, about half of the carbon people have added to the atmosphere is due to land use change[90]. Conceptually, this effect can be described as the "carbon opportunity cost" (COC) of land: when we use a parcel of land for agricultural production, we forego the opportunity to store carbon in the native vegetation and soils that otherwise could exist on that land. (Note, however, that irrigating dry lands may, in contrast, increase carbon storage.)

Reductions in land carbon stocks resulting from the conversion of natural lands to agriculture and aquaculture are one-off fluxes. For example, when forests, grasslands and other native vegetation is cleared for agriculture or aquaculture, most of the carbon stored in the vegetation is converted to CO_2 essentially instantly, mainly via burning, representing a one-off pulse emission of CO_2. In contrast, if agricultural land spared from use regains its native vegetation, reaching a steady-state carbon stock will take decades or more. Yet, despite the longer time horizon, the total carbon stock increase following restoration is still a one-off change in a carbon stock: after a certain time period, there is no additional growth in the carbon stock.

In contrast to these carbon stock changes, the use of cleared land for production of agricultural goods can proceed, in theory, indefinitely. The distinction presents a non-trivial calculation problem in how to apportion the climate impact from the one-off carbon stock change (decrease or increase) over a recurring, indefinite output of agricultural goods.

Here, we present two primary approaches for addressing this calculation problem. The first approach, here called the "expansion" metric, estimates the CO_2 emissions that occur because of agricultural expansion (i.e. deforestation). This one-off emission can be understood conceptually as the investment cost, in units of carbon dioxide, of creating new agricultural land. The second approach, here called "regrowth" metric, estimates the uptake of CO_2 that would occur if land currently in agricultural use were spared and native vegetation allowed to regrow.

The expansion metric is based on the concept that cropland and pasture are fixed production inputs, like a factory, and the carbon emissions associated with their production must be assigned to a product. Even though fixed assets exist by the time they generate each product, the assumption is that each unit of a product will ultimately require more of an additional fixed asset. This is true of assets like factories that have fixed lifetimes. But it is also true of agricultural land in a world that has expanding agricultural land. In such a world, each hectare utilized requires a hectare more agricultural land all other things being equal.

For both the expansion and regrowth metrics, we calculate the difference between plant and soil carbon stored in potential native vegetation (sections 1.9.4 and 1.9.5) and the carbon stored in agricultural vegetation (sections 1.9.6 and 1.9.7). This difference is the foregone carbon storage due to land use and represents the amount of carbon emitted in the case of the "expansion" metric, and the amount of carbon uptake in the "regrowth" metric. For both metrics the cumulative carbon storage effect from land use is the same, the only difference between the methods being the dynamic of the carbon stock change, as detailed below.

We overlay maps of potential carbon stocks per hectare (see sections 1.9.4 and 1.9.5) with separate distribution maps of crops, grazing land, and aquaculture ponds (section 1.3.1), to calculate the average foregone carbon storage per ha for each crop, grazed intake and aquaculture output in each region. This quantity is the main input to both the regrowth and expansion metrics.

1.9.2 The "expansion" metrics: Quantifying the COC of land as the carbon emissions from conversion of native vegetation into agricultural land and aquaculture ponds

In the expansion metric, the calculation issue at hand is how to apportion the one-off CO_2 emission from the clearing of a parcel of land (i.e., the carbon "investment cost") over the future benefits in the form of agricultural (or aquaculture) outputs from that parcel of land. Here, we use two different approaches:

A. Discounted expansion metric

As discussed more below, due to the lack of certainty regarding the future damage costs from continued greenhouse gas emissions, particularly those linked to tipping points in the climate system, many studies have found that immediate rather than delayed emission reductions are more cost-effective for achieving a specified temperature target [91–94]. This finding implies that the benefit of reducing emissions by one unit is greater today than it will be tomorrow. One way of reflecting these differential values is to use a discount rate applied to both changes carbon fluxes over time (see section 1.9.9 for further details). For consistency, we also discount the future production on the land.

As mentioned, in the process of agricultural expansion by destruction of native vegetation, a major fraction of the plant matter is burnt, leading to instant emissions of carbon. However, a substantial amount of plant carbon is not completely burnt, but instead decomposes exponentially at a rate that depends mainly on climate. Hence, not all of the one-off CO_2 emission pulse occurs at year 0, but instead takes place over several years. We apply a discount rate to these emissions from decay to calculate an aggregate present value (see Eq. 1).

We estimate the fraction of plant carbon emitted by burning from [95]; see Table S2. Rates of decay are estimated from [96], who developed an equation for estimating decay rates as a function of mean annual temperature (see Table S62).

Soil carbon stock change following natural land conversion to agriculture also occurs gradually; it may take many decades to reach a new, lower soil carbon equilibrium level. Here, we assume that the percent loss of soil carbon (see section 1.9.7), takes place over a period of 20 to 60 years depending on the regional climate (Table S61). This is partly based on [97], who reported equilibrium times of 17 and 23 years for grassland to cropland and forest to cropland, respectively, in temperate regions. However, these factors are valid for topsoil carbon changes only. Since our study also includes subsoil carbon, which has slower response rates, we choose more conservative numbers, based on [98]. The soil carbon losses are discounted to an aggregate present value assuming a linear change in soil carbon levels (see Eq. 1).

Table S2 Burning rates in the expansion COC metrics and parameters in Chapman-Richards function in the regrowth COC metrics. Sources: [95,99].

Biome	**Fraction of plant matter burnt at deforestation (at year zero)**		**Parameter values in Chapman-Richards growth function**	
	Of above-ground	Of entire plant including roots	k	m
Tropical moist forest	52%	43%	0,070	0.6
Tropical dry forest	52%	43%	0,065	0.6
Tropical coniferous forest	52%	43%	0,050	0.5
Temperate broadleaf forest	51%	42%	0,065	0.5
Temperate coniferous forest	51%	42%	0,060	0.4
Boreal forest & taiga	59%	52%	0,040	0.4
Tropical grass- & shrubland	75%	36%	0,075	0.6
Temperate grass- & shrubland	83%	44%	0,065	0.5
Flooded grassland	75%	36%	0,070	0.5
Montane grass- & shrubland	59%	40%	0,060	0.5
Mediterranean forest & shrub	75%	40%	0,065	0.5
Deserts	75%	20%	0,060	0.5

In summary, in the discounted expansion metric, the carbon opportunity cost for product (e.g., crop) p, $COC_p^{exp,dis}$ (kg CO_2 kg^{-1}), equals the aggregate, time-discounted carbon lost from native vegetation on land used in the region to produce the crop, divided by the aggregate, time-discounted annual production in the region for that crop:

$$COC_p^{exp,dis} = \frac{44}{12} \times \frac{C_p^{burnt,nat} + \int_0^{T_{dis}} C_p^{unburnt,nat} \times \left(e^{d}-1\right) \times e^{-(d+r)t} - C_p^{plant,prod} + \int_0^{T_{dis}^{soil}} \frac{C_p^{soil,nat} - C_p^{soil,pr}}{T^{soil}} \times e^{-rt}}{\int_0^{T_{dis}} Y_p \times e^{-rt}} \quad \text{Eq. 1}$$

where:

$C_p^{burnt,nat}$ (Mg C ha^{-1}) is the burned amount of native vegetation plant carbon for product p.

$C_p^{unburnt,nat}$ (Mg C ha^{-1}) is the remaining, unburnt amount of native plant carbon for product p.

$C_p^{plant,prod}$ (Mg C ha^{-1}) is the amount of plant carbon in the production system for product p.

$C_p^{soil,nat}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) under native vegetation for product p.

$C_p^{soil,prod}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) in the production system for product p.

T_{dis} (years) is the discounting period.

T^{soil} (years) is the time required for soil carbon to reach a new steady state level.

T_{dis}^{soil} (years) is the discounting period for soil carbon loss (equals T^{soil} unless $T_{dis}^{soil} > T_{dis}$, then T_{dis}^{soil} is set to the value of T_{dis}).

r (dimensionless) is the discount rate.

d (dimensionless) is the decay rate for plant matter remaining after burning.

Y_p (Mg ha^{-1} year^{-1}) is the annual yield of product *p* (constant value over the calculation period).

The same equation applies to grazing land; in this case, grazed intake of plant matter per hectare is equivalent to yield per hectare. For aquaculture ponds, we assume that all pre-existing plant and half of the soil carbon is lost instantly. In this case, the numerator in Eq. 1 becomes $C_p^{plant,nat} + 0.5 \times C_p^{soil,nat}$.

B. Amortized expansion metric

A crude, but also more straightforward, approach is to amortize the total one-off carbon emission, including all cumulative soil carbon losses, evenly over a set period of years. The amortized carbon opportunity cost for product *p*, $COC_p^{exp,amor}$ (kg CO_2 kg^{-1}), is calculated as:

$$COC_p^{exp,amort} = \frac{44}{12} \times \frac{C_p^{plant,nat} + C_p^{soil,nat} - C_p^{plant,prod} - C_p^{soil,prod}}{T_{amort} \times Y_p} \qquad \text{Eq. 2}$$

where:

$C_p^{plant,nat}$ (Mg C ha^{-1}) is the amount of plant carbon in native vegetation for product *p*.

$C_p^{soil,nat}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) under native vegetation for product *p*.

$C_p^{plant,prod}$ (Mg C ha^{-1}) is the amount of plant carbon in the production system for product *p*.

$C_p^{soil,prod}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) in the production system for product *p*.

T_{amort} (years) is the amortization period.

Y_p (Mg ha^{-1} year^{-1}) is the annual yield of product *p* (constant value over the calculation period).

This metric is equivalent to straight-line amortization in accounting; it is also the approach recommended for accounting for carbon stock changes in the 2019 IPCC guidelines for National Inventory Reports [39]. As a default, we use a 30-year amortization period. The IPCC default is 20 years. We believe 30 years is more appropriate, primarily because most countries and regions (e.g., the EU), use 2050 (i.e., 30 years from the base year in this study) as the primary reference year for their national climate targets. According to most climate models, 30 years is also roughly the maximum time available for stabilizing the climate at 2°C or less.

It should be noted that, although not explicit, amortization, too, implies a discounting of future costs and benefits, as the discounting method above also does. After the amortization period, future costs and benefits are assigned no value. During the amortization period the discount rate is zero, i.e. costs and benefits remain the same over the time period.

1.9.3 The "regrowth" metrics: Quantifying the COC of land as the carbon uptake from regrowth of potential native vegetation.

In the regrowth metric, the carbon opportunity cost is measured as the CO_2 uptake that would occur if the land were, contra factually, not used, but instead allowed to regain its native vegetation. For a parcel of land, this quantity is divided by the output from the current use of that land. As for the expansion metric, we calculate two different variants:

A. Discounted regrowth metric

As mentioned above, discounting is appropriate when valuing future emissions and uptake of CO_2. As in the expansion metric we discount the CO_2 uptake that would occur over time through regrowth of vegetation, and the future production that takes place through continued use of the land.

Here, we model regrowth of native vegetation using the Chapman-Richards growth function, which is widely used in forestry [100]:

$$c(t)_p^{plant,nat} = C_p^{plant,nat} \times (1 - e^{-kt})^{\frac{1}{m}} \qquad \text{Eq. 3}$$

where:

$c(t)_p^{plant,nat}$ (Mg C ha^{-1}) is the amount of plant carbon <u>at time *t*</u> in potential native vegetation on land where product *p* is produced.

$C_p^{plant,nat}$ (Mg C ha^{-1}) is the amount of plant carbon <u>at steady state</u> in potential native vegetation on land where product *p* is produced (equals $C_p^{plant,nat}$ in Eq. 2).

t is time in years.

k and *m* (functionless) are parameters that determine the shape of the growth curve (see Table S2 for numbers).

By fitting the Chapman-Richard growth function to the dataset in Cook-Patton et al [99], we estimate parameter values specific for the biomes included in this study (see Table S1). We use these growth curves to calculate the gain of carbon in the plant component of the regrowing vegetation, as shown in Eq. 3. The gain in plant carbon over time is discounted to an aggregate present value (see Eq. 4).

For soil carbon, we calculate carbon gains in the equivalent way as carbon losses following the "expansion" method. We assume a linear gain of soil carbon back to the native, steady-state, level over a time period that varies depending on the climate in the region (Table S62). The soil carbon gains are discounted to an aggregate present value (see Eq. 4).

In summary, for the discounted regrowth metric, the carbon opportunity cost for product *p*, $COC_p^{regr,dis}$ (kg CO_2 kg^{-1}), equals the aggregate, time-discounted carbon gain from regrowth of native vegetation on land used in the region to produce the crop, divided by the aggregate, time-discounted annual production in the region for that crop:

$$COC_p^{regr,dis} = \frac{44}{12} \times \frac{\int_0^{T_{dis}} \left[c(t)_p^{plant,nat} - c(t-1)_p^{plant,nat}\right] \times e^{-rt} - C_p^{plant,prod} + \int_0^{T_{dis}^{soil}} \frac{C_p^{soil,nat} - C_p^{soil,prod}}{T^{soil}} \times e^{-rt}}{\int_0^{T_{dis}} Y_p \times e^{-rt}} \quad \text{Eq. 4}$$

where:

$c(t)_p^{plant,nat}$ (Mg C ha^{-1}) is the amount of plant carbon at time *t* in potential native vegetation on land where product *p* is produced (see Eq. 3).

$C_p^{soil,nat}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) under potential native vegetation on land where product *p* is produced.

$C_p^{plant,prod}$ (Mg C ha^{-1}) is the amount of plant carbon in the production system for product *p*.

$C_p^{soil,prod}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) in the production system for product *p*.

T_{dis} (years) is the discounting period.

T^{soil} (years) is the time required for soil carbon to reach a new steady state level.

T_{dis}^{soil} (years) is the discounting period for soil carbon gain (equals T^{soil} unless $T_{dis}^{soil} > T_{dis}$, then T_{dis}^{soil} is set to the value of T_{dis}).

r (dimensionless) is the discount rate.

Y_p (Mg ha^{-1} year^{-1}) is the annual yield of product *p* (constant value over the calculation period).

As with the expansion metric, we use as default a 4% discount rate over 80 years for calculating the discounted regrowth carbon opportunity cost.

B. Undiscounted regrowth metric

A more straightforward variant is to calculate the cumulative, undiscounted gain in carbon on a parcel of land over a set period of time, which is 30-years in our principal regrowth metric, and divide this quantity by the cumulative, undiscounted output from the land over this time period. One benefit of this approach is that it is less sensitive to the assumed shape of the growth curve (Table S2), since only the cumulative growth matters. The formula for calculating the undiscounted regrowth carbon opportunity cost for product *p*, $COC_p^{regr,undis}$ (kg CO_2 kg^{-1}), can be written as:

$$COC_p^{regr,undis} = \frac{44}{12} \times \frac{c(T_{regr})_p^{plant,nat} - C_p^{plant,prod} + \varepsilon \times \left(C_p^{soil,nat} - C_p^{soil,prod}\right)}{T_{regr} \times Y_p} \quad \text{Eq. 5}$$

where:

$c(T_{regr})_p^{plant,nat}$ (Mg C ha^{-1}) is the amount of plant carbon at the end of the regrowth period (T_{regr}) in potential native vegetation on land where product *p* is produced (see Eq. 3).

$C_p^{plant,prod}$ (Mg C ha^{-1}) is the amount of plant carbon in the production system for product *p*.

$C_p^{soil,nat}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) under potential native vegetation on land where product p is produced.

$C_p^{soil,prod}$ (Mg C ha^{-1}) is the amount of soil carbon (top 1 m) in the production system for product p.

T_{regr} (years) is the regrowth period.

T^{soil} (years) is the time required for soil carbon to reach a new steady state level.

ε (dimensionless) is the fraction of soil carbon gain that occurs during the regrowth period (equals 1 unless $T^{soil} > T_{regr}$, then $\varepsilon = \frac{T_{regr}}{T^{soil}}$).

Y_p (Mg ha^{-1} year^{-1}) is the annual yield of product p (constant value over the calculation period).

For the same reasons as in amortization in the expansion metric, we use 30 years as default period for calculating the undiscounted regrowth carbon opportunity cost.

1.9.4 Potential plant carbon stocks of native vegetation

Estimates of carbon density per hectare in the plant component of potential native vegetation were taken from Erb et al. [37], who used an ecozone approach to allocate typical plant carbon densities per hectare across a 5 arc-minute grid (~10x10 km). Erb et al. present five separate spatially explicit estimates of potential carbon stocks, using different data and methodology. For our main COC estimates, we use the average of all these five maps.

Overlaying the Erb et al maps with the current distribution of crops, permanent grassland and ponds (section 1.3.1), we produce crop- and region-specific estimates of potential plant carbon stocks per hectare on the land currently in use for agriculture and aquaculture (see Table S58). These data represent our estimates of the parameter $C_p^{plant,nat}$(see above).

Because of the decisive influence of these potential carbon density data on the magnitude of the calculated carbon opportunity cost of land use, we use lower and upper data in Erb et al. in our uncertainty analysis, see section 2.3.

1.9.5 Potential soil carbon stocks of native vegetation

To estimate soil carbon stocks under potential native vegetation on land currently used for agricultural and aquaculture, we use the LPJmL dynamic global vegetation model [38,101]. LPJmL builds on process-based representations of key ecosystem processes (e.g., photosynthesis, plant and soil respiration, carbon allocation, evapotranspiration, and phenology) in nine generic plant functional types (e.g., temperate broadleaf deciduous tree, tropical broadleaf evergreen tree) to represent natural terrestrial ecosystems at the level of biomes. Competition between different plant functional types for light, space, and water determines vegetation composition within a grid cell. The model takes as inputs monthly data of temperature, precipitation, cloud cover and number of wet days. Individual processes in LPJmL have been validated extensively (e.g., for carbon cycling and plant geography of natural vegetation, for permafrost, carbon and water fluxes). The model has also been successfully evaluated against various biome-specific observational data, such as net primary production and forest carbon stocks.

We use the LPJmL model to create a 0.5° resolution (≈50x50 km) map of carbon stocks per hectare in the top 1 meter of soil under potential native vegetation at current climate conditions. By overlaying this map with the current distribution of crops, permanent grassland and ponds (section 1.3.1), we produce crop- and region-specific estimates of potential soil carbon stocks per hectare on land currently in use for agriculture and aquaculture (see Table S59). These data represent our estimates of the parameter $C_p^{soil,nat}$(see above).

1.9.6 Current plant carbon stocks on agricultural land

With a few exceptions, crops on arable land contain little plant carbon per hectare relative to potential native vegetation. For arable crops we estimate the annual average plant carbon stocks as 25% of the peak amount (the time of harvest).

Tree and bush crops, and sugarcane do store substantial amounts of plant carbon. We estimate the plant carbon stocks of these crops based on a comprehensive literature search (see Table S60). The validity of reported yields was cross-checked in the ClimAg model, which represents the turnover and production of plant mass in tree and bush crops.

Grazed land typically retains significant presence of trees, bushes, and other native vegetation. We estimate the current plant carbon on permanent and semi-permanent grassland (Table S60) from [102] who harmonized maps of current land carbon densities on global grasslands at a 300 meter resolution.

1.9.7 Current soil carbon stocks on agricultural land

In general, soil carbon per hectare at steady state is significantly lower in agricultural soils than in soils under native vegetation. However, the magnitude of difference is uncertain, largely because most measurements to date have only sampled the top horizons of the soil (to ~30 cm) across relatively short time horizons (up to ~20 years) following conversion of native vegetation to agricultural land. Since substantial soil carbon exists beneath 30 cm depth, and new equilibrium levels are thought to be reached only after >50 years, most existing data do not provide a reliable basis for estimating the full, long-term effects of land-use change on soil carbon stocks.

Here, we estimate soil carbon stock in agricultural land as a percent loss of soil carbon stocks in soil under potential native vegetation (section 1.9.5). These loss factors were based on several recent meta-analyses, notably [103], see Table S61 for details.

We apply different loss factors depending on the type of potential native vegetation (biome-specific) and agricultural land use. For conversion from forest and grassland biomes to arable land used for annual non-grass crops we assume these losses:

- tropical forest: 25%,
- temperate forest: 30%
- tropical and temperate shrub- and grassland: 20%
- montane and other grassland: 15%

For conversion of dryland vegetation, we assume gains in soil carbon, based on [104]:

- mediterranean forest and shrub:40%
- deserts: 80%.

For conversion of forests and grasslands to permanent tree and bush crops, and perennial grass crops on arable land, we assume that the loss factors are 20% lower than those for annual crops. For conversion of forests and grasslands to permanent and semi-permanent grassland, we assume that the loss factors are 50% lower than those for annual crops. For Mediterranean forest/shrub and deserts converted to permanent and semi-permanent grassland, we assume no change in soil carbon. Note that the numbers in Table S61 show the average crop- and region-specific losses depending on biome structure for each crop and region.

Because of the large uncertainties surrounding soil carbon changes, we analyze the influence of lower and upper bound soil carbon loss factors on our carbon opportunity cost calculations in our uncertainty analysis (see section 2.3).

1.9.8 Carbon stock changes from grazing in forest land

In India, and the broader South Asian region, there is extensive grazing in areas categorized as forest land. Virtually all forests in India are grazed to some extent. Due to grazing, wood harvest, and other human interference, current forest carbon stocks in India and South Asia are substantially lower than the native, potential levels. Potential native plant carbon stock of Indian forests is estimated to the order of 110 Mg C ha^{-1}, according to [37]. Current plant carbon stocks in Indian forests are much lower, approximately 45 Mg C ha^{-1}, according to recent assessments [105].

In our main results, we assume that 50% of this forest carbon loss in India and South Asia is due to grazing. Due to lack of reliable data, this assumption is purely conjecture. We therefore include lower and upper bounds in our uncertainty analysis (see section 2.3).

1.9.9 Factoring in time

Both the cost in terms of foregone carbon storage from land use and the benefits in terms of goods (which in the case of bioenergy are also climate benefits) occur over time. The costs and benefits, however, occur at different times. In general, carbon costs are concentrated up-front, while production can occur in theory indefinitely. It is a question of policy how to value these costs and benefits over time. Policymakers have had to confront these questions most directly in determining how to factor land use change emissions into biofuel production. The European Commission has used 20 years, while the U.S. Environmental Protection Agency and the State of California have used 30 years [106]. Our central approach uses 30 years for several reasons: this is a policy decision for which actual regulatory decisions can be cited as an example; the mechanism makes the work simple for others to use; and it generates results similar to those that could be provided by a more intellectually rigorous approach.

Such a more rigorous approach would use discount rates. That is because the 30-year approach technically values all emissions or mitigation and agricultural production equally whenever it occurs within those 30-years while assigning no value to what occurs after 30 years. Discount rates more closely reflect the reality that time matters both within and outside the 30-year period.

Both the effect and the rationale for such a discount rate differ from the role of discount rates in evaluating the social cost of carbon (SCC). (The SCC is a dollar value placed on the damages from a one-ton pulse of CO_2 emissions, which is conversely the dollar value placed on a ton of mitigation. Here we use the language of mitigation.) In SCC calculations, the discount rate determines the value society places on whatever year the emissions occur, to avoid future damages resulting from that year’s emissions. This includes the value society places on avoiding damage to future generations. A larger discount rate means a lower SCC because it means less value is assigned to avoiding future climate damages. By contrast, when a discount rate is used to value future mitigation, a higher discount rate places a more substantial value on present mitigation because one ton of future mitigation is worth less tomorrow relative to one ton of mitigation today. If people in 2025 are for mitigation, they would be willing to pay less for mitigation that only occurs in 2050 than they would be willing to pay for mitigation that occurs in 2025. The discount rate in this context represents the size of the discount in the amount they would pay. This represents how much less they would pay per ton for mitigation that only occurs in the future, or conversely, how much more mitigation they would require for the same amount of money if it only started in 2050 rather than in 2025.

One basic reason to understand why discount rates produce contrary results in the two contexts is that the SCC provides a measurement of the value assigned to mitigation to people in the year in which the payment is made. In other words, if an SCC model claims that the SCC will be worth 25% more in 2050 than the SCC in 2025, that is because 1 ton of mitigation in 2050 is worth more to the people in 2050 who will pay for it than one ton of mitigation in 2025 is worth to people in 2025. In some models, the SCC rises because people in 2050 are wealthier, and damages are higher because of higher cumulative emissions. By contrast, the discount rate question for COCs does not involve how much mitigation is valued if paid for in different years. Instead, it involves how much more money people in 2025 are willing to pay for mitigation that occurs in 2025 versus in 2050.

There is little direct literature on how to value earlier versus later mitigation. The closest related literature involves the valuation of temporary mitigation. This is informative, although not the same, as the question for this paper is how to value a permanent stream of emissions, mitigation, or economic benefits that occur in different years. We see two possible ways of doing this estimate.

One would be to directly calculate the discount rate using the factors that should influence policymakers. A higher value for earlier mitigation is supported by many factors, including:

- Avoiding damages that occur in the interim. Examples include all the immediate damages from heat waves, floods, increased hurricane intensity, and droughts. Later mitigation does nothing to address the damages that occur before the mitigation.
- Avoiding long-term damages that occur from even short-term warming, such as melting glaciers.
- Reducing the potential for adverse feedback effects that occur from earlier warming. In early SOC papers, the assumption was that the future warming effects of present CO_2 emissions were lower than those that occurred in future years because much of the emitted carbon would have been removed by the ocean and enhanced forest growth. (Joos et al. [107] includes a discussion of how different representations of this decay rate influence SCC calculations). Since the seminal paper in Allen et al. [108], however, the more accepted scientific view is that when factoring in various feedback effects, CO_2 emissions emitted in earlier years have the same warming effect in later years as later emissions. In the modeling, this result is primarily due to the feedback effects of warming oceans. There is a risk, however, of additional feedback effects not built into these analyses, such as significant methane releases from permafrost, forest dieback, or more enhanced soil respiration than typically estimated from warmer temperatures built into the typical modelling. Some of these feedback effects can be considered tipping points [109]. Whether called tipping points or not, reducing the risk of any additional adverse feedback effects places a higher value on earlier mitigation.

- Providing insurance and option value (reflected in Daniel et al. [110]). Mitigating emissions earlier provides more time to determine what climate effects will be and therefore provides opportunity to implement more aggressive mitigation.
- Providing more time for technological improvements to reduce climate costs (as also reflected in Daniel et al. [110]). Earlier mitigation postpones even more harmful damages and allows time for cheaper mitigation technologies to occur.
- Providing time for political evolution. Earlier mitigation extends the time for political will to develop to take advantage of these technologies.

As typically modeled, the SCC cannot fully evaluate all these advantages of earlier mitigation because the SCC in any given year is generally based on an estimated, overall emission pathway. This means that the value of mitigation in any one year is a function of how much mitigation has occurred and will occur in the future, and these emissions are typically based on an estimated low-cost pathway. But merely because there is a low-cost pathway does not mean that the world will in fact follow the path. In general, the world is not meeting mitigation targets [111]. Earlier mitigation therefore has particular value in extending the time at which the world can get on low-cost pathways.

An alternative means of estimating the relative value of earlier versus later mitigation does not seek to answer these questions directly but starts from the acknowledgement that governments and private parties have decided to make efforts to mitigate at least some emissions today. Because waiting to provide the same mitigation in future years will be cheaper, this method asks what higher value must be placed on earlier rather than later mitigation to justify not waiting. For reasonable public policy, the relative value of mitigation today versus mitigation that only occurs in the future should equal the relative difference in cost of achieving that same mitigation at the different times.

Two factors will make future mitigation cheaper than present mitigation. The first is the time value of money, which can also be called the social cost of capital. Any mitigation postponed can be achieved in the future using money that has been invested and increased in size in real terms. This means it would always make sense to postpone mitigation if its real value were the same in the future and if it could be provided at the same cost.

The second factor is that mitigation costs are likely to decline for the same unit of mitigation. There has been a consistent pattern of declining mitigation costs [110,112,113]. If mitigation were worth the same in the future as in the present, it would always make sense to postpone mitigation and pay for it at less cost using cheaper technology in the future. (For similar reasons, it would generally not make sense to pay for a cell phone today rather than wait for the future unless the purchaser placed a higher value on having a cell phone right away than waiting.)

Considering the two factors together, any mitigation today must have a higher value than future mitigation based on the sum of both factors. In other words, the value of future mitigation must be discounted by a discount rate that equals the sum of the rate of the real social cost of capital plus the rate of the declining costs of mitigation. This approach is similar to the approach recommended in Parisa et al. [114] for evaluating temporary carbon reductions, except that paper recommends discounting by the sum of the cost of capital minus the rate of a rising SCC. While this might be appropriate for temporary carbon storage, the rate of change in the SCC is not appropriate for our purpose because it is based on future valuations of mitigation while for COC purposes, the question is how to evaluate future changes in emissions and mitigation that will result from actions taken in a base year. The SCC also values mitigation based on a long-term pathway of emissions while our formula just depends on declining costs of mitigation.

Economists debate whether the social cost of capital should be based on equity returns or riskless bonds. As a result, estimates can vary substantially. The U.S. Office of Management and Budget use for the return on private capital, and 3% for the broader social time preference, which should reflect all uses of capital [115]. However, real rates of return on bonds appear to have been falling, perhaps justifying a lower rate [116]. For guidance on declining mitigation costs, the costs in recent years for solar and wind technologies have been declining at very rapid rates [112,113]. However, these may be technology-specific, and they also reflect investments probably motivated not just by mitigating emissions today but also to spur technological change, and in that way may be thought of as reflecting investments in technology-forcing like research and development funding. To estimate declining mitigation costs, Daniel et al. [110] used an exogenous rate of productivity gains of 1.5%.

Overall, a range of discount rates could be justified, but a discount rate of at least 4% would appear to be required to capture both the rate of return on capital and the declining mitigation costs. In our calculations, a 4% rate of return does not produce results that greatly diverge from the 30-year amortization.

1.10 Ammonia, nitrate, and indirect N_2O emissions from crop and livestock production

1.10.1 Ammonia from agricultural land, livestock stalls and manure storage

We base our estimates of indirect nitrous oxide emissions induced by other nitrogen emissions on estimations of agricultural ammonia and nitrate emissions.

We calculate ammonia emissions by applying emission factors to all nitrogen flows in agriculture systems that are known to generate significant emissions. In addition to fertilizer and manure nitrogen, we also include ammonia emissions from decomposing plant mass left in field after harvest.

The assumed emission factors for fertilizer and manure reflect differences between regions in terms of management, technology, and climate. We constrain our emission estimates by basing them on a detailed, mass-balance description of nitrogen flows (see section 1.3.4). More specifically, by accounting for all inputs and all other major outputs and calibrating the largest input (fertilizer nitrogen) against statistics, we ensure that our ammonia estimates are of the correct order of magnitude. The global average emission factor of fertilizer in this study is 12% (Table S55), which is very close to the figure (12.6%) reported in [117]. Our total ammonia emissions from manure represent approximately 26% of excreted total nitrogen, which is lower than the figure (30%) assumed in [118], but higher than that (19%) in [119].

1.10.2 Nitrate from agricultural land

Nitrate emissions are calculated as a percentage of the nitrogen surplus over the soil-plant profile for each crop and region. The surplus is the nitrogen inputs to the soil remaining after ammonia (and N_2O and NO) losses minus the nitrogen in removed (harvested or grazed) plant mass. This surplus leaves the soil-plant system either in the form of dinitrogen (N_2) or nitrate. For more details, see section 2.2 in the ClimAg model description.

For annual crops, we assume that the percentage lost as nitrate is 50% of the surplus, and for perennial grass crops and permanent crops, 30%. Our estimated global nitrate emissions are about 23% as a fraction of all fertilizer and manure inputs to agricultural land. This is close to the figure (22%) in [120], and the default factor (24%) in the IPCC guidelines [39] (Table 11.3).

1.10.3 Nitrous oxide emission factors for ammonia and nitrate emissions

To calculate nitrous oxide emissions caused by ammonia and nitrate emissions, we use the emission factors in the IPCC guidelines [39] (Table 11.3). For ammonia, we differentiate the emission factor by climate, using 0.5% in dry climates, and 1.4% in wet, and use the same climate definitions as in section 1.4.1. For nitrate, we use the factor 1.1% in all regions.

1.11 Allocation of climate costs over co-products

Almost all systems in agriculture, aquaculture and their processing industries produce more than one output, i.e., co- or by-product(s) in addition to the primary product, the latter of which may be defined as the output with the largest economic value. To arrive at an estimate of the climate cost per kg of main product, a method is needed to apportion the total climate cost of the system over the main product and its co-product(s).

In this study, we use economic allocation, i.e., the climate cost of the system is allocated over all outputs based on their relative economic value. As a measure of economic value, we use prices received by producers, where available (see Table S49).

Another common alternative to economic allocation is substitution. Instead of economic value, the substitution method assigns the co-product(s) a physical value in terms of displaced emissions, based on an assumption of the production of some other product the co-product displaces. By relying on a specific assumption of displacement the climate benefit of the co-product may appear more tangible. A key drawback of this method is the inherent sensitivity to the selection and design of the displacement assumption. Economic allocation, in contrast, is not sensitive to assumptions. In fact, it may be considered superior to substitution, because the market value reflects the aggregate benefit of all possible substitutions that exist at any one point in time.

Almost all the price data in Table S49 are the same across all regions. This is partly due to lack of detailed data, yet for most products treated in this study this assumption is defensible, as most of these products are traded on global markets.

A major exception to this assumption is whole milk, which is not traded over long distances in its unprocessed form. Here, we use regional price data. Another exception is sheep wool, whose market value can vary by a factor of ten depending on quality and demand. A third important exception is cereal straw; the market value of cereal straw is higher in regions with large demand for use as ruminant feed.

For allocation over outputs from whole-milk processing, e.g. yogurt, cheese and butter, we use the allocation method in [121]. This method uses the protein and fat content of the different outputs as a basis for allocation. Based on prices received by producers of whole milk, the method values protein 40% higher than fat while carbohydrate has zero value.

2. Uncertainty and sensitivity analyses

In contrast to most previous estimates of the regional and global greenhouse gas emissions from agriculture, here we carry out a comprehensive uncertainty analysis, based on statistical evidence where possible. We also estimate the uncertainties of the foregone carbon storage caused by land use.

2.1 Feed intake

As mentioned in section 1.3.3, accurate estimates of feed efficiencies are fundamental to the accurate estimation of livestock's climate costs per kg of output. The variance of feed intake by ruminants is much greater compared to pig and poultry, because of a larger diversity of breeds and a very large variation in feed quality, particularly with respect to grazed herbage on permanent grasslands. For this reason, here, we include a conservative uncertainty assessment of ruminant feed intake.

Several studies suggest that the feed energy requirements for maintenance may vary on the order of 10% depending on the type of breed; see, e.g., [122]. Therefore, in our uncertainty analysis we set lower and upper bounds of a ±10% increase or decrease around the main estimate of the energy requirements for maintenance (as given by equations 18-20 in the ClimAg model description).

The feed energy value of herbage on permanent grassland varies greatly, especially intra-annually. Typically, a high feed value is exhibited at the onset of the wet (or warm) season and gradually decreases into a very poor feed value by the end of the dry season. There exist no comprehensive data on the average feed value across seasons and regions. To reflect this uncertainty, we assume a ±5% variation in our main estimates of the digestible energy of herbage on permanent grassland (Table S30). Our assumed variance of ±5% may appear small, but it should be noted that the effect of this variation on net energy value is much greater because of its non-linear relationship to digestibility.

In our main estimate, global feed intake by ruminants amounts to about 5.6 Pg of dry matter per year. In our lower estimate, feed intake is about 8% lower, and in our upper estimate it is about 13% higher. The asymmetric range is explained by the large dominance of permanent grassland in regions with generally poorer feed value, in combination with the non-linear drop in net energy value when digestibility decreases.

The variance in feed intake directly influences several emission sources, in particular methane from feed digestion and methane and nitrous oxide from manure. The sensitivity (i.e., range) of estimated aggregate global emissions due to estimated uncertainty in feed intake is shown in Table S3. When compared to the sensitivity due to uncertainty in other emission sources, the sensitivity of estimated aggregate emissions due to variance in feed intake ranks third after methane from feed digestion (i.e., variance in methane emissions at a given feed intake) and CO_2 from drained peatlands.

2.2 Production emissions including drained organic soils

In this study, we assess the uncertainty of all emission sources, except two: CO_2 from energy use for drying of crops after harvest, and CO_2 and nitrous oxide from production of inputs (fertilizers and pesticides). In addition to being a small source of global emissions (≈2% of global total), energy use for drying is unlikely to vary greatly because energy use is strongly correlated with the water content of the crop and, therefore, the overall output, which is well established. As to emissions from fertilizer and pesticide production (≈8% of total), we assume that variance in our data is low because we use recent data and because of convergence in regional industrial performance over time.

Wherever possible, as a basis for our calculated uncertainty ranges, we use studies that report variance in the form of 95% confidence intervals or standard deviation. When a standard deviation is reported, we use double that value as a proxy for a 95% confidence interval. For most emission sources and their determining variables (e.g., emission factors), there exist sufficient measurement data to produce uncertainty ranges based on 95% confidence intervals. These sources include: i) nitrous oxide from mineral soils; ii) "indirect" nitrous oxide emissions induced by ammonia and nitrate emissions; iii) methane from flooded rice production; iv) methane from feed digestion; v) nitrous oxide from manure management; vi) methane from aquaculture ponds; and vii) CO_2 and nitrous oxide from drained peatlands. Together, these sources account for about 73% of all global production emissions from agriculture and aquaculture.

Applied uncertainty ranges and literature sources are shown in Table S3. In general, the applied uncertainty ranges for most determining variables are in the order of ±35% around the main estimate. For some emission sources, uncertainty ranges are skewed towards the upper bounds. This is the case for nitrous oxide from mineral soils, methane from flooded rice, and drained peatland, where the upper bound is about 50% greater than the mean.

Due to lack of data, we are unable to apply an uncertainty range to the determining variables of, and thus fully assess the uncertainty of our model estimates for, methane emissions from manure management. In our main model estimate, these emissions account for about 6% of global production emissions. The variance associated with methane from manure management is likely to be greater than for all other major emission sources of methane. There are three main contributing factors to the expected variance. First, the methane production potential, B_o, (see section 1.5.3) varies not only between species but also with feed diets. Second, and more importantly, due to a lack of data, there is uncertainty regarding the methane production rate response to temperature. It is well established that production rates increase with temperature, but the shape of this relationship is not otherwise well established. Finally, the timing and frequency of emptying manure from confinements and storage facilities greatly influences methane production rates (i.e., the longer the duration between emptying, the larger the emissions).

Due to the scarcity of methane measurements under farm-scale conditions, there exists, to the best of our knowledge, no basis for estimating confidence intervals of the temperature effect on manure emission rates. However, based on literature, we do make assumptions on the potential variability of the methane production potential (see Table S3 for numbers and sources).

In our main model estimate, energy use except for drying and production of inputs accounts for about 10% of global emissions. Because there are no statistics on energy use in agriculture, we are unable to constrain these estimates. (We are aware that FAOSTAT produces statistics; however, their numbers are very aggregated and include energy use also in aquaculture, fisheries, forestry, as well as fuel use for electricity production off-farm and were therefore not deemed useful in this study.) In addition, there exists little published data on energy use in agriculture, particularly for regions outside Europe and North America.

Table S3 Uncertainty analyses of production emissions for agriculture and aquaculture. The table shows the applied uncertainty intervals of main determining variables and their corresponding global averages as well as effects on global emissions. For data sources, see table footnotes.

	Relative change in main determining variable		Global aggregate main variable			Global emissions (Tg CO_2 eq/year)		
	Lower	*Upper*	*Main*	*Lower*	*Upper*	*Main*	*Lower*	*Upper*
N_2O minerals soil (% of N inputs)								
Fertilizer application						490	-144	+194
Annual crops excl rice[1]			1,3%	0,95%	1,6%			
Wet climate	-25%	+25%						
Dry climate	-40%	+60%						
Rice – flooded[2]	-75%	+300%	0,40%	0,10%	1,6%			
Perennial crops[3]	-40%	+50%	0,86%	0,52%	1,3%			
Manure application[4]			1,3%	0,65%	2,2%	110	-55	+86
Wet climate	-50%	+80%						
Dry climate	-50%	+60%						
Manure excretion[5]	-50%	+100%	0,44%	0,23%	0,90%	91	-44	+98
Crop residues[6] (including root mass)	-25%	+25%	0,37%	0,28%	0,46%	320	-80	+80
N_2O indirect (% of NH_3-N and NO_3-N emitted)[7]								
Ammonia						200	-70	+70
Wet climate	-21%	+21%	1,4%	1,1%	1,7%			
Dry climate	-80%	+120%	0,5%	0,1%	1,1%			
Nitrate	-82%	+82%	1,1%	0,2%	2,0%	200	-160	+160
CH_4 flooded rice production (kg CH_4 per ha land area per year)								
All regions[8]	-33%	+48%	240	160	360	770	-255	+371
CH_4 feed digestion (% of gross energy feed intake)								
Dairy cows & replacers[9]	-30%	+30%	6,6%	4,7%	8,6%	970	-292	+292
Beef cattle and buffalo[10]	-27%	+27%	6,6%	4,8%	8,4%	1600	-461	+442
Sheep and goats[11]	-25%	+25%	5,9%	4,4%	7,4%	430	-108	+106
CH_4 manure (change in maximum CH_4 production potential, B_o)[12]						530	-75	+68
Dairy cows	-35%	+30%						
Other cattle, sheep & goats	-15%	+15%						
Pigs	-25%	+20%						
Poultry	-25%	+25%						
N_2O manure management (% of N inputs to shed and storage)				153	390	260	-97	+100
Drylot[13]	-40%	+40%	2,0%	1,2%	2,8%			
Deep bedding; storage of solids[13]	-40%	+40%	1,0%	0,6%	1,4%			
Storage of slurry, urine[14]	-100%	+100%	0,25%	0,0%	0,5%			
CH_4 aquaculture ponds (kg CH_4 per ha land area per year)[15]								
All regions	-30%	+30%	490	340	640	81	-24	+24
CO_2 and N_2O emissions from drained peatland[16] (per ha land area per year)								

	Relative change in main determining variable		Global aggregate main variable			Global emissions (Tg CO_2 eq/year)		
	Lower	*Upper*	*Main*	*Lower*	*Upper*	*Main*	*Lower*	*Upper*
CO_2 (Mg C)								
Annual crops except flooded rice	-31%	+44%	9,3	6,4	13	360	-112	+160
Flooded rice	-100%	+112	9,4	0,0	20	31	-31	+35
Perennial crops except grass, oil palm	-49%	+79	13	6,6	23	42	-21	+33
Grasses/legumes crops on cropland	-27%	+29%	6,1	4,5	7,9	53	-16	+20
Oil palm	-48%	+50%	21	11	32	270	-131	139
Permanent/semi-perm. grassland	-38%	+47%	5,9	3,6	8,6	160	-62	+75
N_2O (kg N_2O) – average all	-42%	+43%	11	6,4	16	77	-33	+34
Energy use per ha in crop production (GJ per ha land area per year)[17]								
Field operations except irrigation	-25%	+25%	2,9	2,1	3,6	380	-88	+78
Irrigation	-35%	+35%	1,3	0,86	1,8	320	-110	+110
Energy use in livestock sheds and on aquaculture farms[18]	-25%	+25%				170	-38	+38
Sources not included in the analysis								
CO_2 energy use for crop drying						180		
CO_2 energy use from production of fertilizer and pesticides						680		
Total excl. effects from feed use							-2520	+2820
Aggregate effects of feed use							-190	+470
Total including feed use effects	-30%	+37%				8910	-2720	+3290

1 Confidence intervals (95%) in [28] Table 2
2 Based on uncertainty range in [39] Table 11.1.
3 Confidence intervals (95%) in [28] Table 2
4 Confidence intervals (95%) in [28] Table 2
5 Based on uncertainty range in [39] Table 11.1.
6 Author estimate.
7 Uncertainty ranges in IPCC 2019 Table 11.3.
8 Confidence interval (95%) in [123] Table 4, who reported the same relative change to lower and upper value for all regions.
9 Double the standard deviation in [32]
10 Double the standard deviation in [32]
11 Uncertainty range in [33].
12 Based on [34,79,124 80,125–127].
13 Double the standard deviation for solid storage in [128].
14 Based on [39,80,126].
15 Confidence interval (95%) in [35].
16 Confidence intervals (95%) in [57] Table 2.5.
17 Author estimate.

Here, based on the variation observed in data collected, and the plausible variation from factors like soil type (e.g., heavy clay-rich soils require more diesel for plowing), we assume an uncertainty range of ±25% for all energy use except that for irrigation. The variance of energy use for irrigation is likely to be larger, because of the large variation in type of water source (i.e., surface water to deep groundwater) and in conveyance and application method (e.g., gravity based, as is often the case in rice fields, to pumping and application with high-pressure nozzles). For irrigation we therefore assume a larger uncertainty range of ±35%; see Table S3.

2.3 Carbon opportunity costs

As described in section 1.9.4, our main model estimate of plant carbon stocks in potential native vegetation represents the average of all five maps in [37]. To assess uncertainty in carbon opportunity cost factors, we apply an uncertainty range corresponding to the lowest and highest plant carbon stock estimates in potential native vegetation across all the five maps. More specifically, we identify the lowest and highest numbers for each biome in each region. Although this applied uncertainty range does not represent a statistically-derived confidence interval, the applied range provides a plausible upper- and lower-bound estimate of potential carbon stocks.

Table S4 Uncertainty ranges of global potential native plant carbon stocks on agricultural land. Data are not shown for minor biomes but are included in the total. Numbers in Pg C for total stocks, and Mg C ha^{-1} for area-scaled stocks. Source: [37]. For details, see text.

	TOTAL	Trop. moist forest	Trop. dry forest	Temp broad-leaf forest	Medi-terra-nean forest	Trop. grass & shrub	Temp. grass & shrub	Mon-tane shrub	Xeric grass-land
All agricultural land									
Main estimate									
Total stocks	280	85	21	48	8,1	71	15	7,6	12
Per hectare	61	164	112	94	41	66	19	26	12
Lower (% of main)	-23%	-13%	-17%	-35%	-33%	-16%	-31%	-71%	-35%
Upper (% of main)	+27%	+13%	+33%	+21%	+62%	+25%	+39%	+62%	+44%
Cropland									
Main estimate									
Total stocks	130	48	13	32	4,4	19	7,4	1,1	3,1
Per hectare	87	166	117	93	45	77	20	51	27
Lower (% of main)	-22%	-15%	-21%	-34%	-29%	-16%	-31%	-55%	-24%
Upper (% of main)	+22%	+12%	+37%	+21%	+68%	+22%	+34%	+62%	+20%
Permanent pasture									
Main estimate									
Total stocks	150	36	7,9	16	3,7	52	7,5	6,5	8,7
Per hectare	48	162	106	95	37	63	18	24	10
Lower (% of main)	-23%	-11%	-12%	-35%	-38%	-15%	-31%	-73%	-38%
Upper (% of main)	+31%	+15%	+28%	+26%	+56%	+26%	+43%	+120%	+52%

As shown in Table S4, the global average uncertainty range for estimated potential native plant carbon stocks on all agricultural land is -23% and +27% around the main model estimate. Note that, for some biomes, the uncertainty range is much larger, e.g. Mediterranean forests and xeric grasslands.
We make no uncertainty analysis of the variance in potential, native soil carbon stocks. Instead, we estimate the uncertainty of the loss (or gain) of soil carbon that occurs due to agricultural or aquacultural land use (section 1.9.7). For this analysis, we use the 95% confidence interval in [103], who reported a ±36% range for the carbon loss at conversion of forest to cropland. We apply this same range as an uncertainty range for soil carbon stock changes, as shown in Table S61.

2.4 Sensitivity of carbon opportunity costs to choices of time horizon and discount rate

The choice of discount rate and time horizon used to annualize changes in land carbon stocks when calculating the carbon opportunity cost factor (kg CO_2 eq per kg product) for a given product is inherently a matter of policy. In this section, we demonstrate the impact of these policy choices by presenting the annualized carbon opportunity costs for four products calculated using a wider range of time horizons and discount rates than those underlying the main data presented in this study (as described in section 1.9).

Fig. S2 shows the carbon opportunity cost for suckler beef for different time horizons and discount rates; Fig. S3, Fig. S4 and Fig. S5 shows the same for cattle milk, chicken meat, and maize grains, respectively.

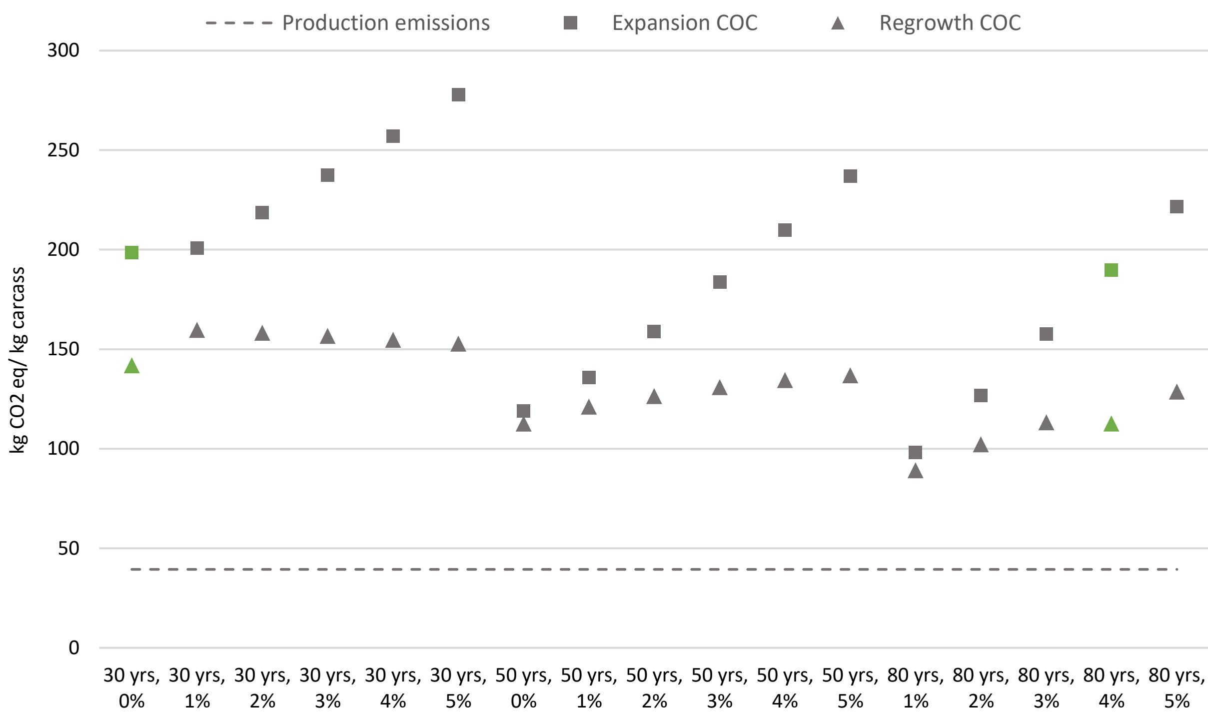

Fig. S2 Sensitivity of carbon opportunity costs to time horizon and discount rate. Analysis of beef. The graph shows the global average carbon opportunity costs (COC) per kg of suckler beef for the two principal types of metrics in this study (see 1.9) at different time horizons and discount rates. Green markers show the variants included in the output data in this study. Undiscounted metrics for the 80-year time horizon are not included. Production emissions include drained organic soils.

From Fig. S2-5, it is evident that as the time horizon increases, the annual carbon opportunity cost per unit of output decreases. This is because the one-off carbon stock change at land conversion is distributed over a larger amount of output, resulting in a smaller annual carbon cost per kg of output. Furthermore, the carbon opportunity cost per kilogram increases with a higher discount rate, as a higher rate indicates a lower present value of future output.

Even when a long time horizon (80 years) and a low discount rate (1%) are chosen, the carbon opportunity cost per kilogram remains considerably higher than the respective recurring production emissions. In the case of beef, the carbon opportunity cost is about 2.4 times greater than the production emissions of beef (Fig. S2). For chicken, milk, and maize, the carbon opportunity costs per kg are 1.5, 1.3, and 2 times higher than the respective production emissions (Fig. S3, Fig. S4 and Fig. S5). If a 2% discount rate is chosen, i.e., the current discount rate used by the US EPA [129], and a 50-year time period is utilized (representing a relatively more policy-relevant planning horizon), the carbon opportunity costs per kg for beef, chicken, milk, and maize are 3.6, 2.2, 2 and 3 times higher than the respective production emissions.

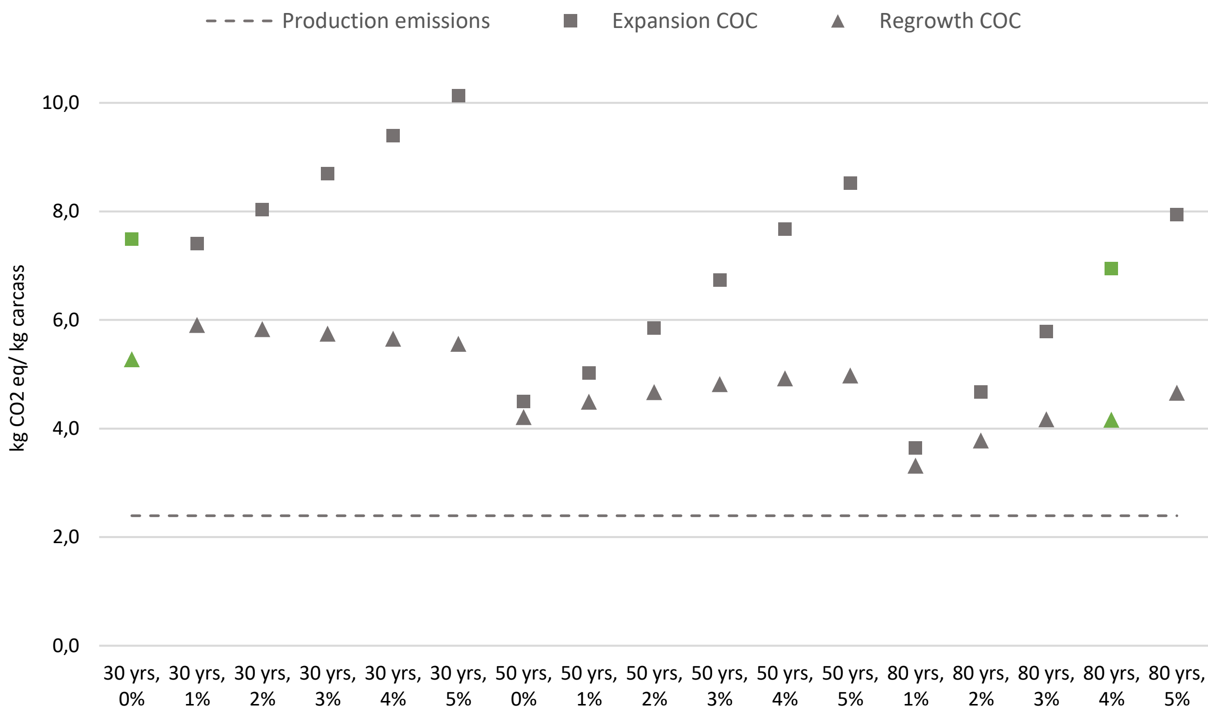

Fig. S3 Sensitivity of carbon opportunity costs to time horizon and discount rate. Analysis of chicken. The graph shows the carbon opportunity costs (COC) per kg of chicken meat for the two principal types of metrics in this study (see 1.9) at different time horizons and discount rates. Green markers show the variants included in the output data in this study. Undiscounted metrics for the 80-year time horizon are not included. Production emissions include drained organic soils.

While the magnitude by which the carbon opportunity cost of a product exceeds its production emission varies by product and region of production, the relationship holds overall (i.e., within the range of time horizons and discount rates presented). Hence, a major conclusion that can be drawn from this analysis is that, irrespective of the COC metric and the discount rate and time horizon used, the climate impact of foregone carbon stocks attributed to the production of a given product will invariably be significantly larger compared to the emissions generated during the production of that product.

From Fig. S2-5 it can also be observed that the “regrowth” COC metric consistently produces lower COC factors than the “expansion” metric. This pattern arises from the differing assumptions underlying how the two metrics are calculated (see section 1.9). In the case of the expansion metric, the opportunity cost is calculated as the carbon emissions due to loss of native carbon stock: the entire plant carbon stock of native vegetation is assumed to be lost and emitted to the atmosphere relatively quickly (i.e., the majority of the emissions occur in the first 5-10 years of the time horizon). In contrast, the regrowth metric calculates the carbon opportunity cost as the foregone carbon sequestration that would occur over the time horizon if agricultural production were to cease, and native vegetation restored. In other words, the regrowth metric accounts for the accumulation of plant carbon stock over the specified time.

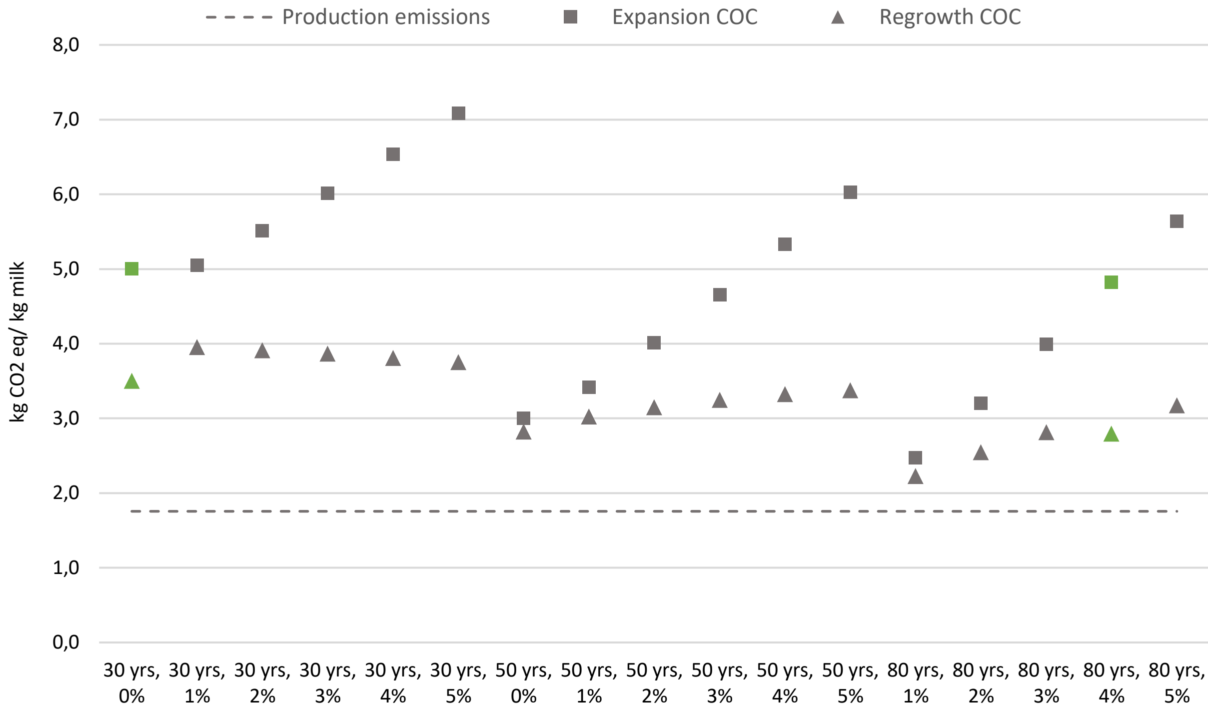

Fig. S4 Sensitivity of carbon opportunity costs to time horizon and discount rate. Analysis of milk. The graph shows the global average carbon opportunity costs (COC) per kg of cattle milk for the two principal types of metrics in this study (see 1.9) at different time horizons and discount rates. Green markers show the variants included in the output data in this study. Undiscounted metrics for the 80-year time horizon are not included. Production emissions include drained organic soils.

Therefore, the pattern that arises can be attributed to the interaction between the carbon loss or gain equation as a function of time and the choice of the discount rate and time horizon. If the time horizon were sufficiently long (>100 years, e.g.) and the discount rate were set to a very low value, the regrowth COC metric would yield almost the same result as the expansion COC metric.

Another conclusion that can be drawn from this analysis is that the 30-year undiscounted regrowth metric is an accurate representation of the average across the combinations of time horizons and discount rates shown in Fig. S2-5. Analysis of more products at regional and global levels not shown here reveals that this holds generally. Therefore, this metric is used as the principal basis for the graphical and tabular representations of the results in this study.

Fig. S6 shows estimates of the annual foregone carbon storage of global agriculture for varying time horizons and discount rates. In this analysis, we only include the regrowth metric, that is, the chart shows the global uptake of CO_2 that could occur from regrowth of native vegetation on all agricultural land currently in use. This is the true opportunity cost of current agricultural land use from the perspective of carbon storage. The expansion metric is formally not a measure of this opportunity cost, as mentioned in section 1.9.1. Instead, it is rather a measure of the of the investment cost, in units of carbon dioxide, of creating new agricultural land. For this reason, it is less suitable for measuring the foregone carbon storage caused by continual use of current agricultural land.

As shown in Fig. S6, depending on time horizon and discount rate, global foregone carbon storage spans from 16 to 29 Pg CO_2 eq per year, with an average of 23 CO_2 eq per year. Adding the production emissions gives a total of 25 to 38 Pg CO_2 eq per year. This is of the same order of magnitude as the emissions from fossil fuel combustion, which were 35 Pg CO_2 in year 2020 [130].

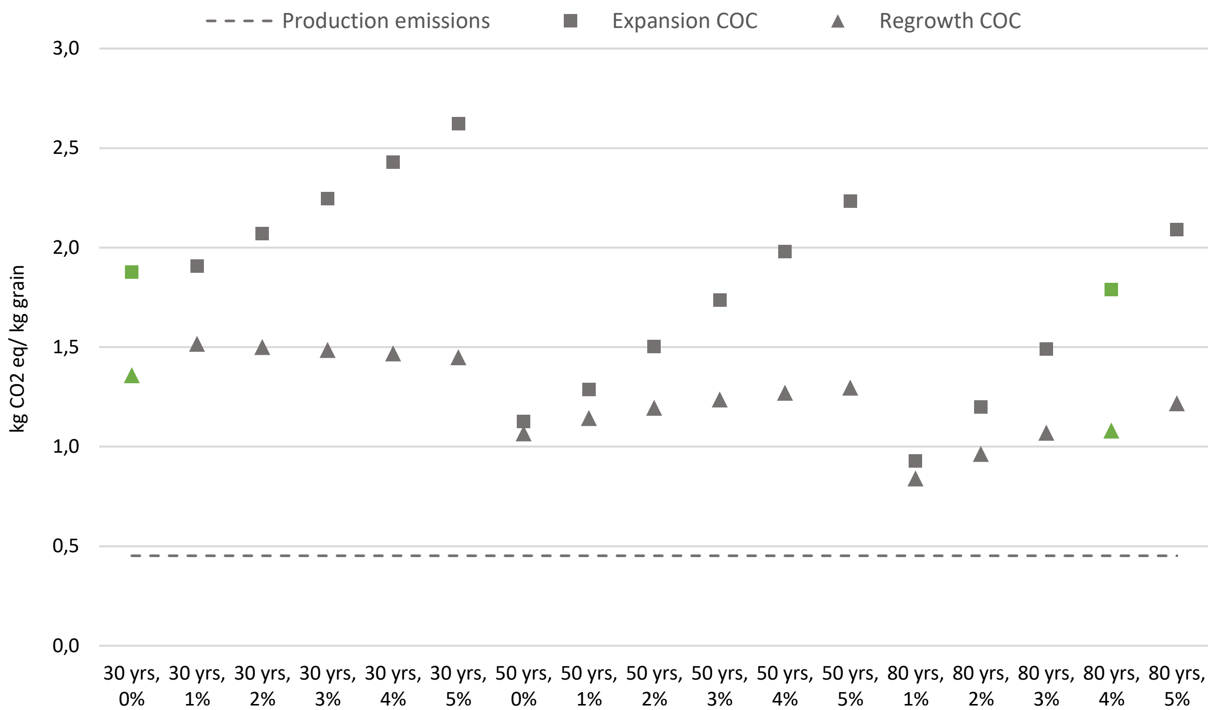

Fig. S5 Sensitivity of carbon opportunity costs to time horizon and discount rate. Analysis of maize. The graph shows the global average carbon opportunity costs (COC) per kg of maize grains for the two principal types of metrics in this study (see 1.9) at different time horizons and discount rates. Green markers show the variants included in the output data in this study. Undiscounted metrics for the 80-year time horizon are not included. Production emissions include drained organic soils.

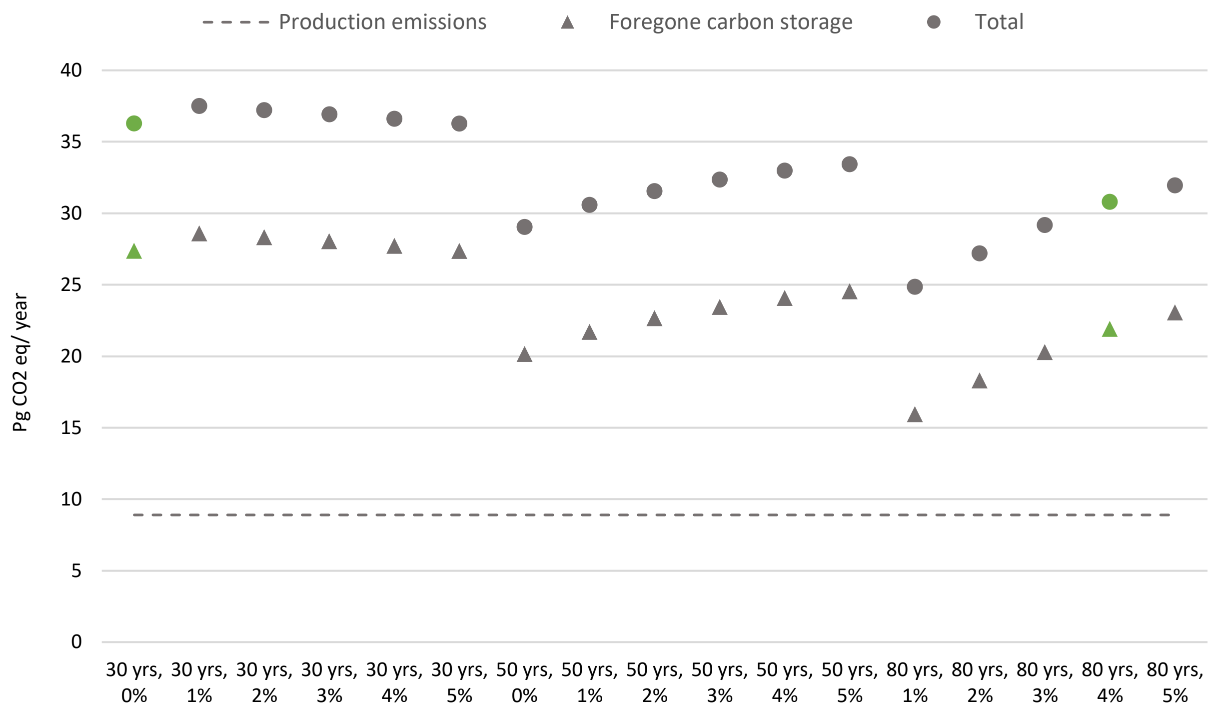

Fig. S6 Sensitivity of carbon opportunity costs to time horizon and discount rate. Analysis of global totals. The graph shows the global foregone carbon storage in regrowth (see 1.9) under different time horizons and discount rates. Green markers show the variants included in the output data in this study. Undiscounted metric for the 80-year time horizon is not included. Production emissions include drained organic soils.

3. Comparisons with previous studies

3.1 Global emissions

To date, very few previous global estimates of agricultural emissions have included most major emission categories. In this section, we compare our main model results with those that do exist [2,5,6]; see Table S5. We ruled out comparing with the recent papers by [131] and [132] because these efforts mainly relied on FAOSTAT [5] data for estimating production emissions, making their contribution in terms of original estimates negligible. Similarly, we do not include comparison with [133] because this paper reported data from an older version of the EDGAR [6] database.

For **nitrous oxide from mineral soils**, our estimates are much lower than FAOSTAT and EDGAR, except for crop residues. However, compared to GLEAM, our estimates of livestock-related emissions are higher, by about 20%. The difference compared to FAOSTAT and EDGAR is likely due to the fact that we use recent, revised understanding of the emission factors (EFs) of nitrous oxide. In the now outdated 2006 IPCC guidelines [134], the default EF for applied nitrogen was 1%, regardless of nitrogen type (mineral or organic) or climate. For manure nitrogen excreted on pastures, the EF was 2% for cattle and buffalo and 1% for sheep. As described in section 1.4.1, current understanding shows a much greater variation in EF numbers depending on nitrogen type and climate. For manure excreted on pastures, EFs are now believed to be four to five times lower than in the IPCC 2006 guidelines; our global average EF for cattle and buffalo is 0.46 (see Table S50), or 4.3 times lower than the 2006 factor. We believe this may explain why our estimate for nitrous oxide from excreted manure is much lower than in FAOSTAT and EDGAR, whose numbers seem to be based on outdated high EFs. A recent study by [135] that used updated EFs, confirms this lower level of emissions from excreted manure; their estimate is about 120 Tg CO_2 eq per year, which is close to our main estimate of 90 Tg.

For nitrous oxide from crop residues on cropland, our number is higher than that of FAOSTAT. However, the FAOSTAT figure includes emissions from only 11 crops (see foot note in Table S5), and therefore does not constitute a comprehensive global estimate of crop residue emissions.

In contrast to most previous studies, we include estimates of nitrous oxide from litter decomposition on permanent and semi-permanent grasslands. Among the very few attempts that have been made to quantify such emissions at global level are Song et al. [136], who reported about 0.35 Tg N_2O-N year^{-1} for “residual” grassland emissions for the 2010s. Residual emissions are dominated by litter decomposition. Our main estimate is 0.25 Tg N_2O-N year^{-1}, fairly in line with that of Song et al.

For emissions from **drained organic soils**, our estimates are similar to those of FAOSTAT, EDGAR, and [58], but much lower than [137], who reported a global total emission of about 1.9 Pg CO_2 eq. year^{-1}, from a drained area of 51 million ha. We use the most recent global peatland map available [29], together with most recent maps of distribution of crops and pastures [23,24]. Our estimate of global drained area is 26 million ha with an average emission of 39 Mg CO_2 eq. ha^{-1} year^{-1}. This is similar to the 24 million ha and emission of 35 Mg CO_2 eq. ha^{-1} year^{-1} in [58]. One reason, although likely minor, for the larger drained area and emissions in [137] is that the study included drained forestry land; however, the authors did not report forestry area and emissions separately.

Table S5 Comparison with previous studies: Global emissions. Numbers in Tg CO_2 eq year^{-1} (GWPs: N_2O: 273, CH_4: 27). Blank cells mean that emission source is not estimated or reported.

	This study (yr 2020)	**GLEAM v3 (scaled to 2020)**[1]	Difference from this study	**FAOSTAT (yr 2020)**	Difference from this study	**EDGAR v8/7 (yr 2020)**	Difference from this study
N_2O mineral soils	**1010**			**1380**	37%	**1690**	67%
Livestock only, incl. indirect[2]	770	621	-19%				
N_2O crop residues	320						
Cropland only	210			161[3]	-23%		
N_2O fertilizer application	490			474	-3%		
N_2O manure application	110			117	6%		
N_2O manure excretion	90			629	599%		
N_2O indirect emissions	**400**			**435**	9%	**407**	2%
CO_2, N_2O organic soils	**1000**			**930**			
CO_2 organic soils	920			830	-10%	1157	26%
N_2O organic soils	80			95	19%		
CH_4 rice	**770**			663	-14%	1005	31%
CH_4, N_2O livestock and manure	**3850**	**3690**		**3160**		**3460**	
CH_4 feed digestion	3030	2932	-3%	2773	-8%	3020	0%
CH_4 stables & manure storage	540	447	-12%	271	-50%	341	-37%
N_2O stables & manure storage	260	316	22%	120	-54%	103	-60%
CH_4 grazing manure	20						
CH4, N_2O aquaculture	**94**						
N_2O aquaculture	13						
CH_4 aquaculture ponds	81						
CO_2 energy and infrastructure	**1850**						
Crop and livestock farms	1020						
Livestock farms only	300	172	-43%				
Aquaculture farms	73						
Fisheries	170						
Agric, forestry, aquacult., fisheries[4]				929			
Prod. of fertilizer and pesticides	590[5]			500	-15%		

[1] Global averages per kg of production for 2015 from [2] scaled to global emissions by multiplying with production levels in 2020.
[2] Includes emissions from all feed produced both on and off livestock farms, as well as indirect N_2O emissions induced by emissions of ammonia and nitrate.
[3] Includes emissions only from crop residues for wheat, maize, rice, barley, sorghum, millet, oats, rye, soybean, beans, and potatoes.
[4] FAOSTAT reports emissions from energy use only at highly aggregated level.
[5] Does not include CO_2 captured in urea which is emitted after application on field. We estimate this quantity to about 100 Tg CO_2 per year.

For **methane from flooded rice**, our estimate is between those of FAOSTAT and EDGAR, but much lower than in [1] who reported an emission more than twice as large as ours, and [8] whose estimate is 50% higher than ours. For further details, see sections 3.2 and 3.5.

For **methane from feed digestion** ("enteric" methane), our estimates are close to all other recent global estimates, but much higher than those in [7], who reported about 30% lower emissions (scaled to 2020 production levels). There are also differences compared to GLEAM between livestock categories; for further details, see section 3.3.

For **methane from manure**, our numbers are consistently higher, particularly compared to FAOSTAT and EDGAR. One strength of our estimates is that we use monthly temperature data to estimate emission factors in combination with statistics-constrained estimates of feed intake and manure excretion. As mentioned in section 1.5.3, using annual average temperatures instead of monthly (the approach taken by most other studies) underestimates the emission rates.

For **nitrous oxide from manure** management, our estimate is lower than that of GLEAM but much higher than those of FAOSTAT and EDGAR. The recent study by [135] that used updated EFs, estimated these emissions at about 270 Tg CO_2 eq per year, very close to our estimate of 260 Tg.

Emissions from **aquaculture** are not included in FAOSTAT or EDGAR, and the only global estimate we are aware of is that of MacLeod et al. [17], who reported global emissions of 260 Tg CO_2 eq. year^{-1}. This is close to our main global estimate of 240 Tg CO_2 eq. year^{-1} (of which about 80 Tg CO_2 eq. year^{-1} comes from production and transportation of feed; not displayed separately in Table S5). However, MacLeod et al. did not include methane from aquaculture ponds, which we estimate at 80 Tg CO_2 eq. year^{-1}. In addition, we believe that MacLeod et al. greatly overstated the nitrous oxide emissions from aquaculture; for further details, see section 3.3.

For **CO_2 from energy use**, lack of disaggregation in FAOSTAT prevents us from comparing with their estimates. Compared to GLEAM, our number is much higher, but this may partly be due to different system boundaries.

One rare instance of global energy use estimates for agriculture is that of Qin et al. [138], who estimated energy use for irrigation. Qin et al. estimated global energy use at 1.9 EJ of fuel and electricity combined, and a total emission of 220 Tg CO_2 year^{-1}. Our estimate of energy use is similar, 2.0 EJ, but we find emissions to be higher, 310 Tg CO_2 year^{-1}. It seems that the CO_2 intensity of energy in Qin et al. is too low, although we cannot say with certainty, because Qin et al. did not report energy use separately for electricity and diesel. For China, their average estimated intensity is 117 CO_2 MJ^{-1}. Assuming the CO_2 intensities of electricity and diesel in this study (290 and 95, see Table S45), to arrive at the 117 average in Qin et al., the fraction of electricity in irrigation must be as low as 11%. This is not credible, and much lower than the reported fraction in Qin et al. (55%, which we apply for China).

3.2 Crop products

To our knowledge, Carlson et al. [8] is the only previous assessment at global level of GHG intensities for a larger selection of crops. Carlson et al. estimated emissions for as many as 172 different crops. However, their coverage of emissions was limited, and included only nitrous oxide from fertilizer and manure application, methane from rice, and emissions from drained peatland (organic soils). They excluded nitrous oxide from crop residues, and all energy related emissions, including that from production of fertilizer and pesticides; in our study, these sources constitute 45% of all emissions from global crop production.

Table **S6** shows a comparison for major crops of our estimates with those in Carlson et al. In general, their numbers for **drained organic soils** are much higher than ours, consistently so for all vegetables and fruits.

Table S6 Comparison with previous studies: Crop products. Global averages. Nitrous oxide from fertilizer and manure includes indirect emissions caused by ammonia and nitrate emissions. Numbers in kg CO_2 eq per MJ metabolizable energy[1] (GWPs: N_2O: 273, CH_4: 27).

	This study (year 2020)				**Carlsson et al 2017 (year 2000)**					
	Total all sources in this study[2]	**Total equiv. sources in Carlsson**	**N_2O fert. & manure**	**CO_2/N_2O drained peatland**	**Total**	Diff. from this study	**N_2O fert. & manure**	Diff. from this study	**CO_2/N_2O drained peatland**	Diff. from this study
Cereals, roots, sugar										
wheat	0.039	0.013	0.010	0.003	0.015	13%	0.009	-10%	0.006	88%
maize	0.031	0.016	0.013	0.003	0.011	-34%	0.007	-44%	0.003	2%
rice	0.103	0.081	0.0028	0.005	0.122[3]	50%	0.006	99%	0.006	13%
barley	0.034	0.015	0.008	0.007	0.026	69%	0.006	-20%	0.019	161%
sorghum	0.022	0.008	0.007	0.001	0.006	-26%	0.005	-34%	0.001	59%
cassava	0.017	0.010	0.004	0.006	0.008	-16%	0.001	-72%	0.007	16%
potato	0.039	0.018	0.010	0.008	0.029	62%	0.010	3%	0.018	141%
sweetpotato	0.046	0.023	0.011	0.012	0.014	-38%	0.010	-8%	0.004	-68%
sugarcane	0.028	0.009	0.009	0.001	0.014	51%	0.005	-38%	0.009	934%
sugarbeet	0.030	0.014	0.009	0.005	0.011	-25%	0.005	-49%	0.006	17%
Oil, protein crops										
soybean	0.032	0.014	0.004	0.010	0.011	-21%	0.003	-18%	0.008	-22%
rapeseed	0.055	0.028	0.018	0.010	0.030	10%	0.017	-5%	0.013	38%
groundnut	0.032	0.007	0.004	0.003	0.025	248%	0.006	55%	0.019	451%
sunflower	0.040	0.016	0.014	0.002	0.014	-12%	0.008	-38%	0.006	141%
oilpalm	0.108	0.092	0.007	0.085	0.043	-53%	0.003	-60%	0.040	-52%
coconut	0.140	0.097	0.016	0.081	0.105	9%	0.001	-93%	0.104	29%
olive	0.045	0.011	0.007	0.004	0.018	67%	0.017	153%	0.002	-64%
cashew	0.071	0.019	0.010	0.009	0.225	1063%	0.003	-68%	0.222	2293%
almond	0.197	0.035	0.028	0.006	0.020	-42%	0.016	-42%	0.004	-43%
Vegetables, fruits										
tomato	0.317	0.054	0.048	0.006	0.069	26%	0.049	2%	0.019	236%
cabbage	0.218	0.089	0.081	0.008	0.088	-1%	0.047	-42%	0.040	437%
cucumber	0.428	0.098	0.083	0.015	0.151	54%	0.085	2%	0.066	349%
cauliflower	0.639	0.250	0.240	0.010	0.119	-53%	0.102	-57%	0.017	65%
onion	0.079	0.028	0.023	0.005	0.053	91%	0.027	16%	0.026	472%
carrot	0.097	0.033	0.028	0.005	0.040	21%	0.019	-31%	0.021	310%
grape	0.077	0.013	0.010	0.002	0.019	49%	0.015	45%	0.004	65%
mango	0.166	0.059	0.037	0.022	0.097	65%	0.049	34%	0.048	116%
plantain	0.031	0.015	0.002	0.013	0.022	46%	0.002	-1%	0.020	54%
banana	0.052	0.020	0.012	0.008	0.055	179%	0.027	123%	0.028	268%
apple	0.074	0.010	0.004	0.006	0.042	312%	0.028	605%	0.014	129%
orange	0.087	0.025	0.019	0.006	0.078	215%	0.030	59%	0.048	701%

[1] To convert to g CO_2 eq per kcal, multiply by 4.18.
[2] Includes all sources in Carlson et al plus N_2O from crop residues, CO_2 from on-farm energy use, and CO_2 and N_2O from production of fertilizer and pesticides.
[3] Includes methane emissions in addition to N_2O from fertilizer/manure and CO_2 and N_2O from drained organic soils.

As mentioned already, we use the most recent global peatland map available [29], together with recent (year 2020) maps of the distribution of crops and pastures [23,24]. Carlson et al. created their own peatland map, based on the Harmonized World Soil Database (HSWD), and overlayed that map with year 2000 cropland distribution maps from [139]. According to [29], HWSD overestimates peatland extent in temperate areas and underestimates it in tropical regions. To some extent, this seems to be reflected in the Carlson et al. estimates. For major temperate crops, such as wheat, barley, potatoes, rapeseed, and sunflower, the Carlson et al. numbers are significantly higher than ours, and for crops grown in the tropics, such as soybean and oil palms their numbers are lower. However, the pattern is not consistent; for example, for all tropical fruits the opposite is the case.

Instead, a major factor behind the high numbers in Carlson et al. seems to be an error in their calculations. The authors state that they use emission factors from [57], which we do as well. According to [57], the highest emissions per hectare occur in the tropics, where they are about 53 Mg CO_2 eq ha^{-1} $year^{-1}$ for CO_2 and nitrous oxide combined. However, in their supplement the authors report emissions per hectare much higher than this for many crops, up to 170 Mg CO_2 eq ha^{-1} $year^{-1}$, which is not possible unless the calculations are flawed. Even their global average, 61 Mg CO_2 eq ha^{-1} $year^{-1}$, is higher than the maximum possible level. For most vegetable and fruits, groundnut and sugarcane, the inexplicably high emissions per hectare in Carlson et al. are two to three times higher than ours, which explains about half of the differences per metabolizable energy shown in

Table **S6**. For cashew, the Carlson et al. estimate is as much as 23 times higher than ours. Their emission factor per hectare is three times higher, but also the percentage drained area is much larger, 0.83% against our 0.17%.

For **nitrous oxide**, the Carlson et al. numbers are mainly lower than ours. This is not unexpected, because we use more recent understanding of emission rates, which for fertilizer are significantly higher than previously thought, by up to 60% in humid climates. In the case of rice, however, the Carlson et al. number is larger than ours, by a factor of more than two. This may be due to several factors, one being that we use a global data set, MapSPAM [23], on the percentages and distribution of different rice systems, which were not available when Carlson et al. completed their study. According to MapSPAM data, low input and subsistence rice systems makes up about 30% of global rice area (physical, not harvested), and has a global average yield of only 2 Mg ha^{-1} $year^{-1}$. These areas receive very little nitrogen fertilizer or manure inputs. Correctly factoring in this distinction is key for producing an accurate global average for all types of rice production.

For **methane from rice**, the Carlson et al. number is about 50% higher than ours. For irrigated rice, we used national methane emission data for China and India to calibrate emission rates per hectare of harvested area (see section 1.4.3). Assuming that the national estimates are correct, this ensures our main emission estimates are reasonably accurate. However, Carlson et al. seem to have used a similar approach. One reason for the unexpected difference may therefore be that national emission estimates have been reduced downwards owing to better understanding. Another explanation could be the differences in the percentages of different rice systems mentioned above.

3.3 Livestock products

For livestock products we compare our results mainly with the output from the GLEAM model [2], which to date, offers by far the most sophisticated global estimates of GHG emissions from livestock. The ClimAg model and the key modules in the GLEAM model are in most regards similar. However, the ClimAg model is more detailed in terms of emission sources , and by including detailed, mass-balance based descriptions of nitrogen flows also in the soil-crop component. The ClimAg model also includes emissions from drained organic soils, which GLEAM does not. For the comparison, we also include the study by Herrero et al. [7], another major global estimate of the climate impact of livestock.

When comparing the **totals** per kg of all equivalent sources, the largest discrepancies with GLEAM exist for **dairy herd beef** (≈50% lower than this study) and **milk** (≈30% higher), see Table S7. These differences may partly be due to differences in allocation; it seems that GLEAM allocates more of the dairy herd emissions to milk than we do. For consistency, we use economic allocation throughout our entire dataset (see section 1.11). In contrast, GLEAM uses protein content as a basis for allocation. An additional reason for the higher total CO_2 eq per kg for cattle/buffalo milk in GLEAM is that their feed use per kg of milk is about 50% higher (see Table S8), which means that some emission sources, in particular enteric methane emissions, should also be higher to the same order of magnitude. Indeed, the GLEAM enteric methane estimate is about 40% higher than ours. The methodology for calculating feed energy requirements and intake is very similar to ours, which suggests that the likely reason for the differences in feed efficiencies is divergent assumptions about herd characteristics and feed baskets. However, since no such data have been published for GLEAM v3, we are unable to explore this difference in greater detail. Although our feed efficiency for milk is higher than in GLEAM, it is much lower than in Herrero et al.

Our numbers are significantly lower than in GLEAM also for **pork** and **chicken meat**. This seems to be due to larger feed use per kg in GLEAM (Table S8) in combination with the fact that the emission source "CO_2 energy incl. fertilizer" for GLEAM includes also CO_2 emissions from deforestation linked to soybean production. Unfortunately, the latter is not reported separately, so we cannot factor out this emission source in the comparison. Our number for pork is lower compared to Herrero et al, which is most likely due to an outdated, much higher estimate of the feed use per kg in Herrero et al, ≈60% higher than ours. Our feed efficiency estimates for both pork and poultry reflect the fast growth in herd productivity that has occurred in low- and middle-income regions since 2000 (the base year in Herrero et al).

For **nitrous oxide from mineral soils**, our numbers are somewhat higher than in GLEAM in aggregate (Table S5), although for individual products our numbers are substantially higher (e.g., beef) but also lower in some instances (e.g., cattle/buffalo milk). The reason for the generally higher numbers may be due to our assumption of higher emission factors for fertilizer and manure applied in combination (see section 1.4.1 and Table S50); however, we are unable to say with certainty since there are no published emission factor data published for GLEAM v3. The numbers in Herrero et al. are much higher than ours. This is because Herrero et al. used outdated, much higher emission factors for applied and excreted manure; compared to our emission factors, those in Herrero et al. are two to three times higher.

For **methane from feed digestion**, in aggregate, our numbers are almost equal to those in GLEAM (Table S5), but for both types of milk, their numbers are substantially higher and for average beef their numbers are lower. As mentioned above, this may be due to differences in allocation and feed efficiencies. However, for sheep/goat milk, and sheep/goat meat, GLEAM feed use per kg is 20-25% larger than our numbers. This suggests that the methane production rates per kg of feed intake for sheep/goats are higher in GLEAM, by around 25%. Our global average methane production rate for sheep/goats is 5.8% of feed energy intake (see Table S52), and we estimate that the GLEAM equivalent would need to be about 7.2%, which is higher than typically believed (see, e.g., Table 10.13 in [39]). Unfortunately, the magnitude of the GLEAM methane emission factor cannot be confirmed, since there are no such methane data published for GLEAM v3. In Herrero et al., enteric methane per kg for beef and cattle/buffalo milk are much lower than in this study and in GLEAM. This is mainly due to much lower feed use per kg compared to both our numbers and those of GLEAM (Table S8). However, the methane emission factors in Herrero et al. are

Table S7 Comparison with previous studies: Livestock products. Global averages. Numbers in kg CO_2 eq per kg fresh weight (GWP N_2O: 273, CH_4: 27). Blank cells mean that emission source is not estimated.

	This study (year 2020)	**GLEAM v3.0 (year 2015)**	Diff. from this study	**Herrero et al 2013 (yr 2000)**	Diff. from this study
Beef carcass, avg. beef & dairy					
Total this study	**34.6**				
Total for equivalent sources in GLEAM	**31.3**	**26.3**	**-16%**		
N2O soil + indirect	4.00	2.6	-34%		
CH4 feed digestion (enteric methane)	23.04	19.4	-16%		
CH4 grazing manure	0.16				
N2O stables & manure storage	1.21	1.6	35%		
CH4 stables & manure storage	1.23	0.83	-32%		
CO2 energy incl. fertilizer production	1.79	1.9[1]	5%		
CO2/N2O organic soils	2.26				
Beef carcass - beef herd					
Total this study	**39.4**				
Total for equivalent sources in GLEAM	**35.4**	**37.1**	**5%**		
Total for equivalent sources in Herrero et al	**30.4**			**25.9**	**-15%**
N2O soil + indirect	4.93	3.6	-27%		
N2O manure applic. & excretion	1.43			4.9	246%
CH4 feed digestion (enteric methane)	26.8	27.9	4%	18.0	-33%
CH4 grazing manure	0.23				
N2O stables & manure storage	1.12	2.2	97%	1.8	62%
CH4 stables & manure storage	1.08	0.87	-19%	1.2	8%
CO2 energy incl. fertilizer production	1.50	2.6[1]	71%		
CO2/N2O organic soils	3.02				
Beef carcass - dairy herd[2]					
Total this study	**28.2**				
Total for equivalent sources in GLEAM	**25.7**	**13.5**	**-48%**		
N2O soil + indirect	2.77	1.5	-46%		
CH4 feed digestion (enteric methane)	18.0	9.2	-49%		
CH4 grazing manure	0.07				
N2O stables & manure storage	1.33	1.0	-28%		
CH4 stables & manure storage	1.42	0.79	-44%		
CO2 energy incl. fertilizer production	2.18	1.1[1]	-52%		
CO2/N2O organic soils	1.24				
Sheep/goat carcass - avg. meat & dairy					
Total this study	**23.7**				
Total for equivalent sources in GLEAM	**21.8**	**21.4**	**-2%**		
Total for equivalent sources in Herrero et al	**18.6**			**25.9**	**40%**
N2O soil + indirect	2.60	2.0	-24%		
N2O manure applic. & excretion	0.65			3.4	423%
CH4 feed digestion (enteric methane)	16.8	16.8	0%	20.7	23%
CH4 grazing manure	0.14				
N2O stables & manure storage	0.64	0.93	44%	0.93	45%
CH4 stables & manure storage	0.54	0.44	-18%	0.92	73%
CO2 energy incl. fertilizer production	1.31	1.3[1]	-1%		
CO2/N2O organic soils	1.12				
Pig carcass					
Total this study	**5.22**				
Total for equivalent sources in GLEAM	**4.52**	**5.1**	**14%**		
Total for equivalent sources in Herrero et al	**2.32**			**2.3**	**-1%**

	This study (year 2020)	GLEAM v3.0 (year 2015)	Diff. from this study	Herrero et al 2013 (yr 2000)	Diff. from this study
N2O soil + indirect	1.02	0.72	-30%		
N2O manure applic. & excretion	0.20			0.36	80%
CH4 feed digestion (enteric methane)	0.16	0.18	10%		
N2O stables & manure storage	0.19	0.36	89%	0.29	54%
CH4 stables & manure storage	1.93	2.0	3%	1.7	-14%
CO2 energy incl. fertilizer production	1.21	1.9[1]	56%		
CO2/N2O organic soils	0.36				
Chicken carcass					
Total this study	**2.39**				
Total for equivalent sources in GLEAM	**1.93**	**2.6**	**35%**		
N2O soil + indirect	0.61	0.54	-11%		
N2O stables & manure storage	0.42	0.11	-74%		
CH4 stables & manure storage	0.18	0.09	-49%		
CO2 energy incl. fertilizer production	0.72	1.9[1]	158%		
CO2/N2O organic soils	0.25				
Cattle/buffalo milk (whole)					
Total this study	**1.76**				
Total for equivalent sources in GLEAM	**1.58**	**2.1**	**32%**		
Total for equivalent sources in Herrero et al	**1.24**			**0.91**	**-27%**
N2O soil + indirect	0.19	0.23	16%		
N2O manure applic. & excretion	0.048			0.12	146%
CH4 feed digestion (enteric methane)	0.96	1.4	40%	0.66	-31%
CH4 grazing manure	0.004				
N2O stables & manure storage	0.063	0.13	107%	0.06	-5%
CH4 stables & manure storage	0.17	0.13	-19%	0.07	-58%
CO2 energy incl. fertilizer production	0.19	0.24[1]	25%		
CO2/N2O organic soils	0.10				
Sheep/goat milk (whole)					
Total this study	**4.48**				
Total for equivalent sources in GLEAM	**4.12**	**5.2**	**27%**		
Total for equivalent sources in Herrero et al	**3.36**			**4.3**	**27%**
N2O soil + indirect	0.50	0.4	-11%		
N2O manure applic. & excretion	0.025			0.70	2733%
CH4 feed digestion (enteric methane)	3.04	3.7	22%	3.2	4%
CH4 grazing manure	0.021				
N2O stables & manure storage	0.17	0.25	46%	0.28	62%
CH4 stables & manure storage	0.12	0.11	-14%	0.12	1%
CO2 energy incl. fertilizer production	0.28	0.72[1]	155%		
CO2/N2O organic soils	0.20				
Egg					
Total this study	**2.88**				
Total for equivalent sources in GLEAM	**2.28**	**2.1**	**-8%**		
N2O soil + indirect	0.79	0.50	-37%		
N2O stables & manure storage	0.20	0.12	-41%		
CH4 stables & manure storage	0.22	0.28	25%		
CO2 energy incl. fertilizer production	1.07	1.2[1]	11%		
CO2/N2O organic soils	0.28				

[1] Includes emissions from deforestation for soybeans, oil palm and pasture.

[2] Average for meat from dairy cows and all surplus dairy calves, female not used as replacements and males.

lower as well, although we cannot determine the exact difference because Herrero et al. did not disclose these figures.

For **methane from manure**, most of our estimates are higher than GLEAM, by about 20%. This may partly be due to that for liquid manure types we use monthly temperature data to estimate emission factors. As mentioned in section 1.5.3, using monthly average temperatures gives more accurate and consistently higher emission rates compared to annual averages, which most other studies have used. However, we are unable to identify the exact differences, because no data on methane potentials (B_o) or methane conversion factors (MCF) have been published for GLEAM v3.

Table S8 Comparison with previous studies: Feed efficiencies in livestock production. Global averages. Numbers in feed dry matter intake per output in fresh weight.

	This study (year 2020)	**GLEAM v3 (year 2015)**	Difference from this study	**GLEAM 2013 (year 2005)**	Difference from this study	**Herrero et al 2013 (year 2000)**	Difference from this study
Beef carcass (beef herd)	51,8	50,7	-2%	58,3	+13%	40,0	-23%
Sheep/goat carcass (meat herd)	51,5	38,2	-26%	38,4	-25%	48,6	-6%
Pig carcass	3,7	4,2	+14%	4,8	+30%	5,9	+59%
Chicken carcass	2,7	3,9	+44%	3,3	+20%	not estim.	
Cattle/buffalo whole milk	2,0	3,0	+50%	3,0	+50%	1,4	-30%
Sheep/goat whole milk	11,1	8,9	-20%	9,0	-19%	8,3	-25%
Egg (whole)	2,9	3,4	+17%	3,3	+14%	not estim.	

For **nitrous oxide from manure** management, our numbers are lower than GLEAM, except for poultry where the opposite is the case. While GLEAM includes very detailed representation of different manure systems, for nitrous oxide emissions, GLEAM uses a relatively reduced number of factors for each livestock species. For ruminants, GLEAM uses a factor of 2% N_2O-N for all solid manure types [140], p 71). We differentiate between solid types and use a 1% factor for solids in separate solid-liquid systems as well as deep bedding, and a 2% factor for drylots (Table S53). Since separate solid-liquid systems according to our collected data sources are about as common as drylots (Table S31), we obtain lower emission rates. Also, for milk, the much higher feed requirement per kg in GLEAM contributes to an even larger difference.

For poultry, GLEAM uses a factor of 0.2% N_2O-N for all manure types. Based on an extensive literature review, we use 1% except for manure stored below layer cages for which we use 0.25% (Table S53). We therefore obtain much higher emission rates. The GLEAM number is close to the default emission factor in the IPCC guidelines [39], which is 0.1 % for all manure types (Table 10.21). This number is based on expert judgement citing no references. After reviewing the available literature, we believe this judgment is erroneous.

3.4 Aquaculture products

For aquaculture products, we compare our results with the only two studies we are aware of that have made global estimates for a wide range of products, Gephart et al [16] and MacLeod et al [17]; see Table S9.

Across taxa, our estimates of total emissions per kg for tilapia and catfish are relatively close to both Gephart et al. and MacLeod et al., and for other non-freshwater fish and mollusks to Gephart et al. The largest differences exist for **crustaceans**, for which our total per kg is about twice as large, mainly because we include **methane emissions from ponds**, which Gephart et al. and MacLeod et al. did not. Pond methane emissions are significant also for freshwater fish, but not to the same extent as for crustaceans, and therefore do not contribute to large differences in totals per kg compared to Gephart et al. and MacLeod et al.

Nitrous oxide emissions from aquaculture farms were included in MacLeod et al., but not Gephart et al. However, MacLeod used a simplistic approach for estimating these emissions, assuming a flat emission per kg, without any link to the quantity of feed nitrogen added to the water body. To the extent that there is an elevated production of nitrous oxide in aquaculture water bodies, this quantity is almost certainly correlated with the amount of external nitrogen added through feed (see 1.6.2). By ignoring this, MacLeod et al. greatly overstated the nitrous oxide emissions, particularly for carp production, which largely relies on in-site feed and mollusks which feed exclusively on in-situ feed.

For **CO_2 from on-farm energy use**, our numbers agree fairly well with those of MacLeod et al., except for salmonids and other non-freshwater fish for which the MacLeod number is only about a fifth of ours. For salmonids, we use data from a recent comprehensive study of salmon production in Norway [141], who conducted detailed assessments of electricity use at feed barges and fuel use for service vessels and well boats. Norway is a top tier producer in terms of energy and feed efficiency, and we therefore believe that the energy use reported in [141] is unlikely to overestimate the global average. That the energy use number for salmonoids in Gephart et al. is close to the one in [141] supports this assumption.

Some other energy use numbers in Gephart et al., however, deviate greatly from ours: their number for carp is five times larger than ours and for other non-freshwater, twice as large. We are unsure how Gephart et al. arrived at their energy use assumption for carp production (which is higher than other freshwater fish, and even higher than salmon farming which tends to be intensive), given that carp production is generally less intensive.

For **emissions from feed** production, our estimates agree with those of MacLeod et al., except for salmon and non-freshwater fish. Most of the differences are due to divergent feed baskets and emission intensities of feeds, and much less to differences in feed conversion efficiencies. For salmon, our feed emission intensity is about 1.7 kg CO_2 eq kg feed^{-1} (fresh weight), which is the same as in [141] and close to the 1.8 average in [142]. In MacLeod et al., the emission intensity of salmon feed is only about 1.1 kg CO_2 eq per kg. Strangely, the emission intensity of feed for non-freshwater fish in MacLeod et al is as high as 2.3 kg CO_2 eq per kg feed, even though the feed basket is similar to that of salmon. The feed emission intensities in MacLeod et al. were taken from unreported data in the GLEAM model [2], so we are unable to investigate this difference further. In Gephart et al., emissions from off-farm feed production are much higher than

Table S9 Comparison with previous studies: Aquaculture products. Global averages. Numbers in kg CO_2 eq per kg whole product fresh weight (GWP N_2O: 273, CH_4: 27). Blank cells mean that emission source is not estimated.

	This study (year 2020)	Gephart et al 2021 (year 2018)[1]	Diff. from this study	MacLeod et al 2020 (year 2017)	Diff. from this study
Carp[2]					
Total	**1.24**	**2.13**	**72%**	**1.68**	**36%**
On-farm	0.64	0.63	-2%	0.98	53%
Of which energy use	0.12	0.63	434%	0.26	122%
Of which aquatic N2O	0.05			0.73	1503%
Of which pond CH4	0.48				
Off-farm (feed production)	0.60	1.50	152%	0.70	17%
Tilapia					
Total	**3.30**	**3.26**	**-1%**	**3.11**	**-6%**
On-farm	1.58	0.48	-69%	1.29	-18%
Of which energy use	0.56	0.48	-14%	0.56	0%
Of which aquatic N2O	0.33			0.73	117%
Of which pond CH4	0.68				
Off-farm (feed production)	1.72	2.77	62%	1.82	6%
Catfish & other freshwater fish[3]					
Total	**3.13**	**3.21**	**3%**	**3.56**	**14%**
On-farm	1.27	0.32	-75%	1.03	-19%
Of which energy use	0.23	0.32	38%	0.30	32%
Of which aquatic N2O	0.28			0.73	156%
Of which pond CH4	0.75				
Off-farm (feed production)	1.86	2.89	56%	2.53	36%
Salmonoids[4]					
Total	**3.05**	**1.85**	**-39%**	**2.13**	**-30%**
On-farm	0.72	0.58	-21%	0.81	12%
Of which energy use	0.45	0.58	27%	0.08	-81%
Of which aquatic N2O	0.27			0.73	169%
Off-farm (feed production)	2.33	1.27	-45%	1.32	-43%
Other non-freshwater fish[5]					
Total	**3.15**	**3.22**	**2%**	**4.80**	**52%**
On-farm	0.87	1.08	24%	0.81	-7%
Of which energy use	0.45	1.08	141%	0.08	-81%
Of which aquatic N2O	0.42			0.73	71%
Off-farm (feed production)	2.27	2.14	-6%	3.99	75%
Crustaceans					
Total	**10.1**	**4.45**	**-56%**	**5.99**	**-41%**
On-farm	8.04	2.40	-70%	3.78	-53%
Of which energy use	2.96	2.40	-19%	3.06	3%
Of which aquatic N2O	0.31			0.73	131%
Of which pond CH4	4.76				
Off-farm (feed production)	2.09	2.05	-2%	2.20	6%
Molluscs					
Total	**0.44**	**0.62**	**42%**	**1.07**	**145%**
On-farm	0.44	0.62	42%	1.07	145%
Of which energy use	0.44	0.62	42%	0.35	-20%
Of which aquatic N2O	0.00			0.73	

[1] Emissions from feed production are based on factors from Agri-Footprint 5.0 and include CO_2 from land use change (deforestation). Gephart et al did not report this quantity separately, why the feed use numbers are not fully comparable.
[2] For Gephart et al, production weighted averages between "silver/bighead" and "misc. carps". For MacLeod et al, production weighted averages between "Indian major carps" and "Cyprinids".
[3] For Gephart et al, "catfish". For MacLeod et al, production weighted averages between "catfish" and "freshwater fish, general".
[4] For Gephart et al, production weighted averages between "salmon" and "trout".
[5] For Gephart et al, production weighted averages between "milkfish", "misc. diadromous fish", and "misc. marine fish".

ours for carp, tilapia, and catfish, and lower than ours for salmon (close to the MacLeod et al. figure for salmon). One possible explanation for the higher numbers in Gephart et al. is that their emissions from feed production are based on factors from Agri-Footprint 5.0 and include CO_2 from land use change (deforestation). Unfortunately, Gephart et al. did not report the deforestation component separately, nor the assumed feed conversion efficiencies, so we are unable to investigate these differences further.

3.5 Processed food and other food products

To date, one of the most comprehensive global analysis of the climate impact of food is from Poore & Nemecek [1], who compiled results from a large meta-analysis and produced a dataset on GHG emissions and other environmental impacts for 52 food items. We compare our results for 44 of these items, excluding minor ones and items not included in this study (tofu, aquatic plants); see Extended DataTable 10.

The methodologies of this study and that of Poore & Nemecek differ fundamentally. Here, we use a regional-scale systems model to obtain consistent estimates of GHG emissions and other impacts. A key feature of our model-based approach is that we constrain model estimates by calibrating major physical features (such as production, land use, fertilizer use, feed use, livestock productivity, etc.) against global and regional statistics and datasets (see sections 1.3-7). Poore & Nemecek compiled data from 570 individual studies and, after applying different techniques and additional data to fill data gaps and standardize their dataset, make assumptions about the relative contribution of production systems in the dataset to arrive at national, and ultimately global, weighted-average emission factors. Still, the data in Poore & Nemecek are not constrained in an equally systematic and comprehensive way as in this study.

For **rice**, Poore & Nemecek's emission factor is more than twice as large as ours. This is mainly because their methane emission per kg rice is almost twice as large (2.4 kg CO_2 eq kg^{-1} compared to our 1.3;for methane GWP = 34). As mentioned in section 3.2, for irrigated rice, we use national methane emission data for China and India to calibrate emission rates per hectare of harvested area. Importantly, methane emissions per hectare are much lower in South Asia and India, amounting to only 0.7-0.8 kg CO_2 eq kg of $rice^{-1}$. To explain this difference, it could be that Poore & Nemecek did not include as part of their meta-analysis studies sufficiently representative of the lower emission intensities in South Asia.

For **tomato**, Poore & Nemecek report a very high number, 0.71 kg CO_2 $eqkg^{-1}$, which is three times larger than our main figure. Previous studies have shown that for open-field tomatoes, emission intensities in rainfed production are well below 0.1 kg CO_2 eq kg^{-1}, see, e.g., [143]), but may in irrigated production reach 0.3 kg CO_2 eq kg^{-1} [144]. Only in heated greenhouse production do emission intensities surpass the number in Poore & Nemecek; for example, the emission intensity of Dutch greenhouse tomatoes is estimated at 2.0 kg CO_2 eq per kg [62]. However, the global production of tomatoes in heated greenhouses is very small, occurring almost only in Europe, and contributes only 1-2% of overall global production, and therefore does not significantly influence the global average. To explain this difference, it could be that the selection of studies in Poore & Nemecek was skewed towards heated greenhouse production.

For **fruits,** Poore & Nemecek also report very high numbers, two to three times higher than ours. To arrive at such high numbers, it is likely that fertilizer and/or energy use would have to be much higher than typically reported, possibly in combination with higher emission intensities in fertilizer production. For example, for grape production in Europe, the use of energy and fertilizer would have to be four times larger than what we assume to arrive at the 0.72 kg CO_2 eq kg^{-1} figure in Poore & Nemecek,corresponding to about 1,000 liters of diesel and 220 of kg nitrogen per hectare and year. This is much more than reported in studies of European grape production, which suggest typical levels at about 200-400 liters of diesel and 25-50 kg of nitrogen [145–147]. It may be that, for fruit production, Poore & Nemecek relied on studies with particularly high use of energy and fertilizers, or other specific conditions associated with high emissions. However, for fruits, or any other product in their dataset, we cannot assess these differences further as Poore & Nemecek do not report data on the physical flows that underpin their climate impact estimates.

For **coffee**, the Poore & Nemecek number is even more extreme, as high as 10 kg CO_2 eq per kg for the farm phase only, excluding roasting and transportation. This is more than 10 times larger than our estimate, and the reported magnitude, 0.5-1.0 kg, in several recent studies [148–150]. Again, due to the lack of underlying data in Poore & Nemecek we are unable to identify a plausible explanation for their very high number.

Other products where Poore & Nemecek numbers are significantly higher than ours include **peanut**, **cassava**, **oats**, and **olive oil**. As illustrated in the case of fruits, these differences may be due to that Poore & Nemecek included as part of their meta-analysis studies with unusually high energy use and fertilizer use. The number for oats is particularly high: for instance, and we do not understand how the emission intensity for oats can be almost twice that of wheat in Poore & Nemecek. Oats cultivation is less intensive than wheat, receiving less nitrogen inputs per kg of grain, and the global percentage of irrigated production (which uses more energy) is much lower than wheat. These fundamental differences suggest that the emission intensity of oat grains should not be significantly higher than wheat, but rather the opposite.

Among major crop products, only two are estimated to have substantially lower emission intensities in Poore & Nemecek than our study, palm oil and cane sugar. For **palm oil**, we believe that the lower value in Poore & Nemecek can be explained by their sample of studies not reflecting the expansion in oil palm cultivation on drained peatland that has occurred over the past 20 years. Based on recent maps of peatland and crop distribution (see section 1.3.1), we estimate that the global average area-fraction of oil palm production on drained peatland now is about 14%, and that this portion of production alone adds 3.1 kg CO_2 eq kg oil^{-1} to the global average emission intensity. This figure almost equals the palm oil total including all other sources in Poore & Nemecek.

For **cane sugar**, the Poore & Nemecek number seems to represent well the emission intensities in Brazil and South America, which have been extensively documented, particularly in Brazil. Our estimate for cane sugar in South America is 0.55 CO_2 eq kg $sugar^{-1}$, almost identical to the number in Poore & Nemecek. However, a great fraction of cane sugar production, almost 50%, occurs in East Asia and South Asia. Those regions are characterized by large over-supply of nitrogen fertilizer, particularly for sugar crops, vegetables, and fruits [27] and large reliance on irrigation, including for sugar cane. For these reasons, we find that the emission intensity of cane sugar in South Asia is about 0.93 kg CO_2 eq per kg sugar. For this reason, it appears that Poore & Nemecek may not have included studies that are sufficiently representative of conditions in South Asia.

For **meat** and **dairy** products, our estimates are relatively close to those of Poore & Nemecek. However, as is observed in section 3.3, these similarities could be coincidental, concealing differences for individual emission sources. Unfortunately, we are unable to investigate any differences further since Poore & Nemecek did not report separate details about major emission sources.

For **dairy beef,** the Poore & Nemecek number is much lower than ours, by 35%. As discussed in section 3.3, this could be due to larger emission allocation to milk than in our study. However, in the Poore & Nemecek dataset, the emissions for milk are also lower overall than ours, by about 20%, which does not support this explanation. One reason why our global average for dairy beef is relatively high, 41 kg CO_2 eq kg^{-1}, is that a large fraction, about 30%, of the production occurs in South Asia and Sub-Saharan Africa. It is well established that the emission intensities of beef production in these regions are very high (see e.g. [7]), because of very low calving rates and liveweight gain rates (in our dataset the average for dairy beef in these regions is 78 kg CO_2 eq kg^{-1}, see also Extended Data Fig. 3.) To arrive at the Poore & Nemecek figure, the emission intensity of the rest of the global dairy beef production would need to be as low as 5.1 kg CO_2 eqkg^{-1}, which is an unfeasibly low number. To explain this difference, it seems possible that the sample studies included in the meta-analysis of Poore & Nemecek did not represent the global average, and in particular could have lacked studies that reflected the higher emission intensities in South Asia and Sub-Saharan Africa.

Skewness in the sample of studies in Poore & Nemecek towards high productive systems may also explain why their numbers for **milk** and **sheep/goat meat** are significantly lower than ours. In other words, it may be that their sample of studies was not representative of low-productivity systems with higher emission intensities.

For **chicken meat**, the Poore & Nemecek number is significantly higher than ours, by nearly 20%. For **pork**, the difference is smaller. However, our higher (and as explained elsewhere, likely more accurate) estimates of methane from manure for pork means that our numbers for other emission sources are substantially lower in comparison. To explain this difference, we believe that Poore & Nemecek may not have included relatively recent studies that reflect the fast growth in poultry and pork productivity that has occurred in low- and middle-income regions over the past two decades.

For **crustaceans**, the Poore & Nemecek number is very close to ours. This is surprising since most previous studies have ignored pond methane emissions (see section 3.4), which we estimate at 10.5 kg CO_2 eq kg shell-free $meat^{-1}$ (for methane GWP = 34), or more than half of our total overall emission estimate. However, we are unable to investigate this unexpected similarity with the Poore & Nemecek number since they did not report any separate details about major emission sources.

Finally, for **farmed fish**, the Poore & Nemecek number is almost twice as large as ours. We predict that this is almost certainly because of a skewed sample of studies that is not representative of the global average for farmed fish production. More than half of farmed fish production consists of carp, which have generally low emission intensities, as shown in this study and in others [16,17]. The Poore & Nemecek number for farmed fish fillet approximately corresponds to about 5 kg CO_2 eq kg of $liveweight^{-1}$. This estimate is much higher than not only our estimate for carp but all other major fish categories as well, as shown in Table S9.

4. Supplementary notes on methodology compared to life cycle assessment

In the Life Cycle Assessment (LCA) method, descriptive information known as "inventory" data is gathered for the product or system being analyzed. The data is typically collected from existing plants, farms, or other production facilities. For agricultural products, this data may include the use of energy, fertilizer, and other inputs, as well as crop yields, feed use, and herd productivity data. Environmental impacts are then quantified by applying various emission and impact factors to the inventory data. The result is a detailed, numerically precise description of the environmental effects of the products from the studied farms. However, the results apply only to the farms studied and do not necessarily reflect the national or regional averages. Because, by design, the LCA method produces data valid only for individual farms.

The methodology of this study is specifically designed to address the issue of representativeness at both the national and regional (multi-country) levels. Using the ClimAg model, this study depicts all production, resource use, and emissions at country and region scales. This enables the calibration of key data against country and region statistics and other country-level data (e.g. maps), such as land use, fertilizer and pesticide use, livestock herd productivity, and feed use (see section 1.3). By doing so, we generate data sets comparable to the inventory data used in LCA, with the key difference that our inventory data are calibrated against country and regional information. These constrained inventory data sets provide a foundation for country- and region-representative estimates of greenhouse gas emissions.

Crucially, we create these constrained inventory data sets without sacrificing the level of detail necessary to capture variation in climate impacts. The ClimAg model includes a high level of detail, equivalent or even superior to a standard LCA regarding factors that influence climate impacts. For example, in the ClimAg model, energy use in crop production is estimated separately for nine different activities, and in livestock and aquaculture production, it is estimated for six activities and energy types. Energy use is also greatly detailed in the processing of crop, livestock, and aquaculture outputs, with separate representations of particularly energy-demanding steps such as drying and rendering. More importantly, key inventory data, such as nitrogen and feed use, are described in a high level of detail and are based on mass and energy balances. For example, for the eight livestock systems included, feed intake is detailed using 44 separate feed baskets, each including up to 32 explicit feed items. Manure excretion is linked to feed use, calculated from intake and energy and nitrogen retention in animal tissue. In crop systems, nitrogen inputs and usage are represented by ten distinct flows, while eleven flows represent nitrogen outputs and emissions. All nitrogen flows are calculated based on a mass balance approach.

In summary, the method used in this paper combines the thoroughness of Life Cycle Assessment with national statistics to produce estimates that are valid at regional and country levels. Compared to previous studies, such as those by Poore & Nemecek [1], our approach is more likely to yield estimates that accurately represent specific countries and regions. As illustrated in section 3.5, our estimates for about half of the 52 items included in Poore & Nemecek differ by at least 25%, with some cases showing even larger discrepancies. We believe the primary reason for these differences is that our estimates are constrained by national data, while those of Poore & Nemecek are not.

5. Supplementary results and findings

This section presents additional and more comprehensive results data than in the main text. As in the main text, data on the climate costs are divided into i) production emissions excluding drained organic soils (see section 1.2 for a list of emission categories), ii) drained organic soils, and iii) foregone carbon storage. Unless otherwise stated, the carbon opportunity cost quantity refers to the 30-year undiscounted expansion metric.

Section 5.1 includes additional results and findings on global emissions, and climate cost per kg of output for major products. Section 5.2 and 5.3 give more details on the climate benefits of alternative human diets and increased efficiency, respectively. Section 5.4 gives more details on the variation in climate cost for different car, bus, and truck powertrains. Section 5.5 includes condensed data tables on total climate costs and climate cost per output at regional levels. More detailed climate impact data per unit of output are available in the supplementary file Data S1.

5.1 Climate cost of agriculture and aquaculture

5.1.1 Findings on global emissions

Below are some comments on our estimates of global emissions for major categories. For more details on differences compared to previous estimates, see section 3.1.

For global **nitrous oxide emissions from manure excretion**, we find that they are about 80% lower than previously estimated, because changed understanding towards much lower emission factors (see section 1.4.1).

We find that global **nitrous oxide emissions from crop residues** and litter are substantially higher than previously estimated, mainly because we factor in the emissions from grassland, but also because we use differentiated, higher emission factors for some crops (see section 1.4.1).

For estimating CO_2 and nitrous oxide **emissions from drained peatland**, we use the most global peatland map available in combination with recent maps of the distribution of crops and pasture (see section 1.4.2). We find global emissions to be at the order of 1.0 Pg CO_2 eq per year, which is similar to estimates by [5,6,58]. The much higher 1.9 Pg estimate by Leifeld & Menichetti [137] seems inaccurate.

For estimating **methane emissions from enteric fermentation**, we used statistically-derived methane-prediction models in combination with detailed feed basket data (see section 1.5.2). We find that global emissions are about 110 Tg CH_4 per year, which is similar to estimates by [2,5,6]. The 30% lower estimate by Herrero et al [7] seems inaccurate.

For estimating **methane emissions from manure**, we use a detailed approach, based on monthly temperature averages rather than annual (see section 1.5.3). We also include in-barn emissions, which no previous global study has estimated separately. We find that global methane emissions from manure are 50% to 100% higher than most prior estimates.

We find that global **methane emissions from fish and shrimp ponds**, which have not been estimated previously, are larger than those from energy use in aquaculture, and make up a third of the aquaculture sector's production emissions (Table S11; see section 1.6.2 for method and data).

5.1.2 Differences between products

Because of limited space in the main text, we present additional comments on the results regarding the climate cost per unit of output here.

Climate costs of capture **fish and seafood** are several times lower than those of farmed (Extended Data Fig. 6). However, about 40% of all wild fish stocks are overfished [151] and some fishing techniques damage habitats and reduce marine biodiversity.

Mollusks and carps are among the major aquaculture products with substantially lower climate costs. Since mollusks obtain their feed in situ from the surrounding water mass, no external feed is needed, and only the use of energy on-farm contributes to their climate impact. Similarly, carp production relies largely on in-situ feed, and external feed is comparatively small.

The climate cost of irrigated, flooded **rice** production is only 35% of that of low-input upland rice production, despite high methane emissions in irrigated production (Fig. S7A) The reason is that irrigated production yields are four times larger (global average), resulting in much lower foregone carbon storage per kg of rice.

Except for sweet potato and yams, the global average climate costs of different **starch-rich crops except rice** are similar, varying by only about 15% around the global average (Fig. S7B). The climate costs of sweet potato and yams are higher mainly because of much lower yields than cassava and white potato.

The variation among **fruits and nuts** is relatively small (Fig. S8A) except for cashew nuts, which have relatively low yields and are cultivated in tropical biomes with carbon-rich potential vegetation.

For **vegetables**, the climate cost of different types varies around the global average by about 50% (Fig. S8B), except for okra, which has a climate cost about three times the average for all vegetables because of its very low yields. Cauliflower and broccoli have the second-highest climate cost among vegetables, mainly because of their high protein content and large oversupply of nitrogen fertilizer.

The climate cost of **greenhouse-produced vegetables** is not significantly higher than that of open-field production, despite the use of energy-demanding greenhouse structures (Fig. S8B). The reason is the much higher yields in greenhouse production, which result in much lower foregone carbon storage per unit of output.

Sugar has lower climate costs than other pure carbohydrates, such as **starch** (Extended Data Fig. 7B). The main reason is the higher yields for sugar beet and sugarcane crops.

5.1.3 Regional differences for major livestock products

Here follow some complementary comments in addition to those in the main text:

The climate cost of **beef** in different regions and countries varies greatly, with that in North Africa & Middle East being 80% lower than the global average and that of Brazil being 50% higher, and Sub-Saharan Africa as much as 170% higher (Fig. 2A in the main text). A major factor that determines the climate cost of beef is the percentage of meat coming from dairy herds, which, because of its higher productivity of milk and meat combined, results in a lower climate cost of the meat output. A high fraction (70% or more) of meat from dairy herds contributes to low numbers for Central Asia, Europe, North

Africa & Middle East, Russia, and South Asia/India. In addition, for Central Asia and North Africa & Middle East, low native carbon stocks, particularly on grassland, contribute to low aggregate climate cost, despite herd productivities at low to intermediate levels. Despite a significant fraction of beef from dairy in Sub-Saharan Africa (67%), its average is very high because of extremely low productivity in dairy and suckler herds. In East Asia, North America/USA, Oceania, and South America/Brazil, about 70-80% of the beef is produced in suckler herds. Apart from Africa, the climate cost of suckler beef is particularly high in South America/Brazil (Extended Data Fig 1A), because of carbon-rich native vegetation and relatively low herd productivity.

For **pork**, the regional variation in climate cost is much smaller than for beef, varying by about 30% around the global average (Fig. 2B in the main text). Herd productivity is similar in Europe, North America, and the US. The main reason for the lower numbers for North America and the USA is lower potential native carbon stocks on cropland, which, on average, are only about half of those in Europe.

For **chicken** meat, the regional variation is slightly lower than that of pork (Fig. 2C in the main text). The distinctly lower numbers for North America/USA (40-50% lower than the global average) is due to lower potential native carbon stocks on cropland, not higher herd productivity.

Except for Sub-Saharan Africa, for **sheep/goat meat**, the regional variation is relatively small, being 20-50% lower than the global average in all major regions (Extended Data Fig 2). The global average is higher than in almost all other regions except Sub-Saharan Africa because of the very high climate cost combined with a large share of the global production (18%) in this region.

For **cattle & buffalo milk**, the regional variation is substantial (Extended Data Fig 3A), because of very large differences in milk yield combined with varying native carbon stocks. Milk yields span from about 600 kg cow-1 year-1 in Sub-Saharan Africa to over 10,000 kg in the US. Carbon stocks in potential native vegetation on current grasslands span from less than 10 Mg C ha-1 in Central Asia to 130 in Brazil.

For **sheep & goat milk**, too, the regional variation is substantial (Extended Data Fig 3B), for the same reasons as in the case of cattle & buffalo milk.

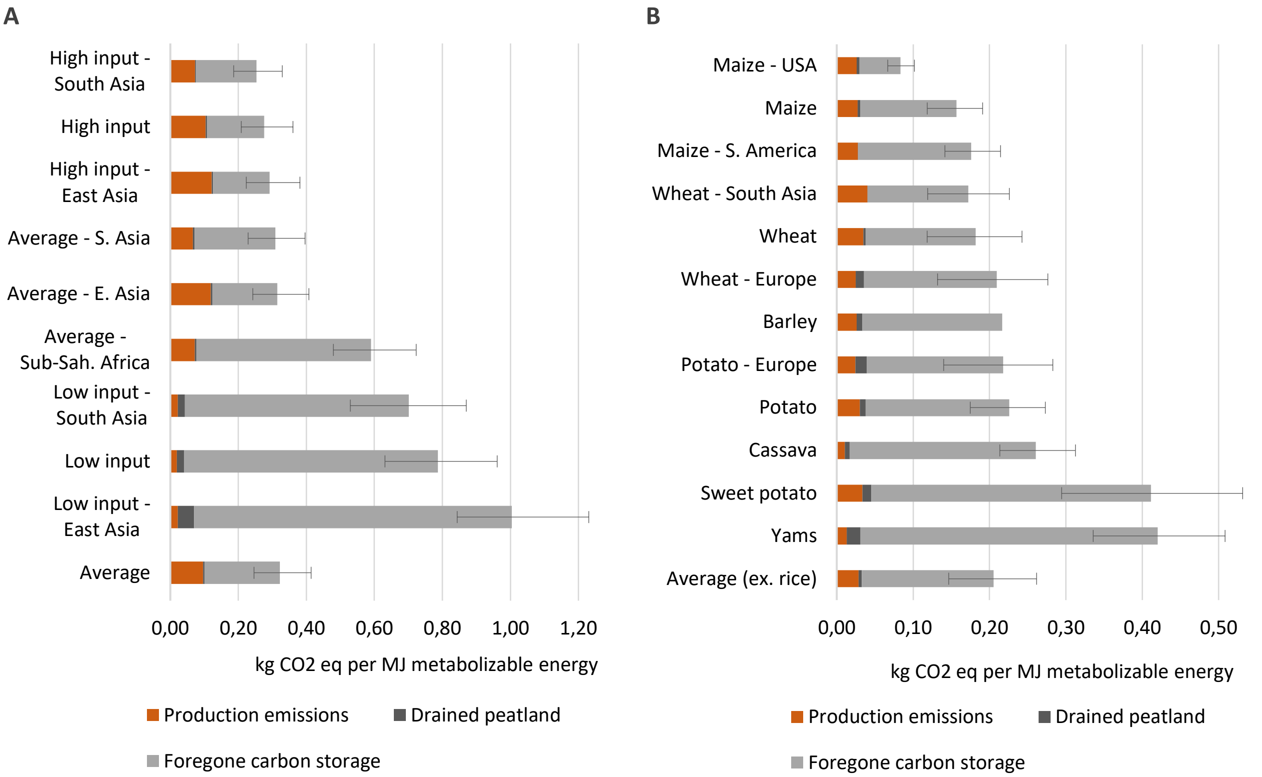

Fig. S7 Climate impact per unit of energy for cereals and starchy crops. World averages except where indicated. (**A**) Rice, (**B**) Other cereals and starchy tubers. Average refers to the average for all tubers and cereals except rice.

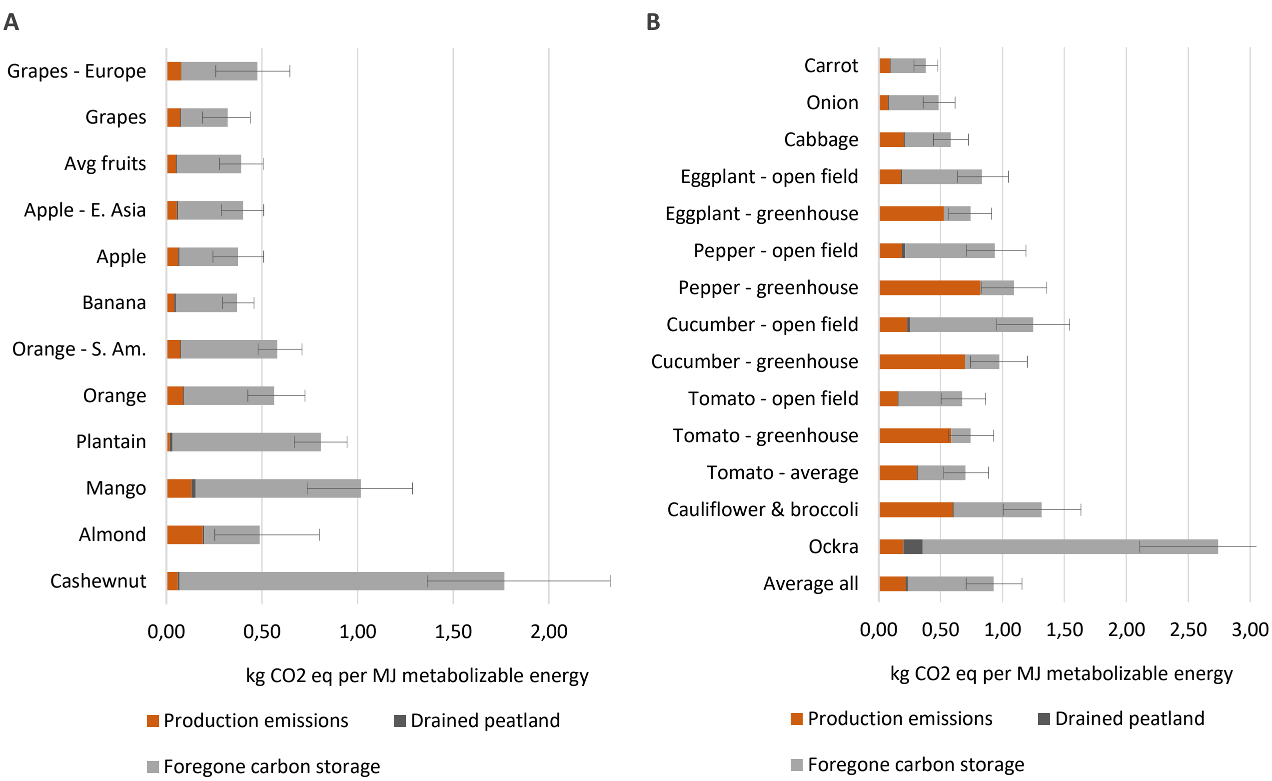

Fig. S8 Climate impact per unit of energy for fruits, nuts and vegetables. (**A**) Fruits and nuts, (**B**) Vegetables. World averages except where indicated.

5.2 Climate benefits of human dietary changes

Fig. 4 in the main text shows emissions and foregone carbon stocks caused by food consumption, with panel A showing the climate cost of current diets and panel B that of three alternative diets. Data on all diets are available in Table S47.

As mentioned in the main text, the data in Fig. 4 is based on the global average supply's climate cost for highly traded products. Those include meat, milk powder (but not other dairy products), fish/seafood, wheat and rice, vegetable oils, sugar, coffee, cocoa, tea, and alcoholic beverages. For comparison, in Extended Data Fig 8 we present equivalent estimates using regional/national supply for all products.

The alternative diets in Fig. 4 (and Extended Data Fig. 8) are included mainly to illustrate the aggregate climate intensity of different types of food. They are not intended to be realistic in terms of viability or entirely desirable. For example, consumption of some types of fish has beneficial health effects. Furthermore, a certain degree of ruminant production is needed to preserve biodiversity-rich grasslands, for example, in Europe.

The "No suckler beef" diet assumes a level of beef consumption corresponding to the amount of beef supplied from the rearing of dairy surplus calves and culled dairy cows. This entails a significant reduction in beef consumption in regions with a high current beef consumption and relatively low dairy consumption, for example, South America (see Table S47). In contrast, in regions with relatively low beef consumption and high dairy consumption, for example, Europe, the reduction in beef consumption is small. Total meat consumption in this diet is the same as in the current (on a carcass fresh weight basis). Any reduction in beef consumption is compensated by an increase in pork and chicken consumption (assuming the same pork-chicken proportions as in the current diet).
gh per capita consumption of meat.

The "No ruminant" diet assumes no beef, sheep/goat meat, or dairy product consumption. Pork and chicken consumption are increased (assuming the same pork-chicken proportions as in the current diet) to keep total meat consumption at the same level as in the current diet (on a carcass fresh weight basis). Current consumption of milk/yogurt, cheese, butter, and cream is fully replaced, on a calorie basis, by plant-based milk/yogurt, cheese, butter, and cream substitutes.

The "Plant based" diet assumes no meat, dairy, egg, or fish consumption. Plant-based substitutes replace dairy products in the same way as in the "No ruminant" diet. Meat, egg, and fish are replaced, on a protein basis, by plant-based meat substitutes, and a significant increase in the consumption of pulses and beans. One half of the replaced protein comes from meat substitutes, and the other half from pulses.

Importantly, a global diet without ruminant products, with pork and poultry substituting for ruminant meat, results in almost as large emissions reductions as a pure plant-based diet. The "No ruminant" diet gives a 52% reduction compared to the current diet; the plant-based diet gives an additional decrease by only 6 percentage points. Hence, the same amount of meat as today can be consumed and still achieve emission reductions close to a pure plant-based diet. The reason for this is the relatively low climate costs of pork and poultry, which in absolute terms are not much larger than those of beans and plant-based meat substitutes (see Fig. 3 in the main text).

5.3 Climate benefits of increased efficiency and high-yield production forms

Increased land and feed efficiency in the production of crops and livestock products is widely considered crucial for meeting the increasing global food demand while minimizing adverse environmental effects [152,153]. With a few exceptions [154], however, most assessments to date have ignored the climate benefits from reductions in foregone carbon storage that follow from higher efficiencies. Here, using two examples, we illustrate the magnitude of the effects on carbon storage from higher crop yields and increased feed efficiency.

Fig. S9A shows how emissions and foregone carbon stocks per kg of beef vary with efficiency, in this example based on data for Brazilian beef [155]. System 1 represents a low-efficiency system with no inputs and no grass management. The systems with higher beef output per hectare rely on fertilizer inputs, frequent pasture renewal, and the use of concentrate feed. Because of lower feed use per kg of beef in the more efficient systems, production emissions per kg of beef, mainly enteric methane, are lower. But the reduction in foregone carbon storage per kg, due to the lower land use per kg, is much larger, by about a factor of ten.

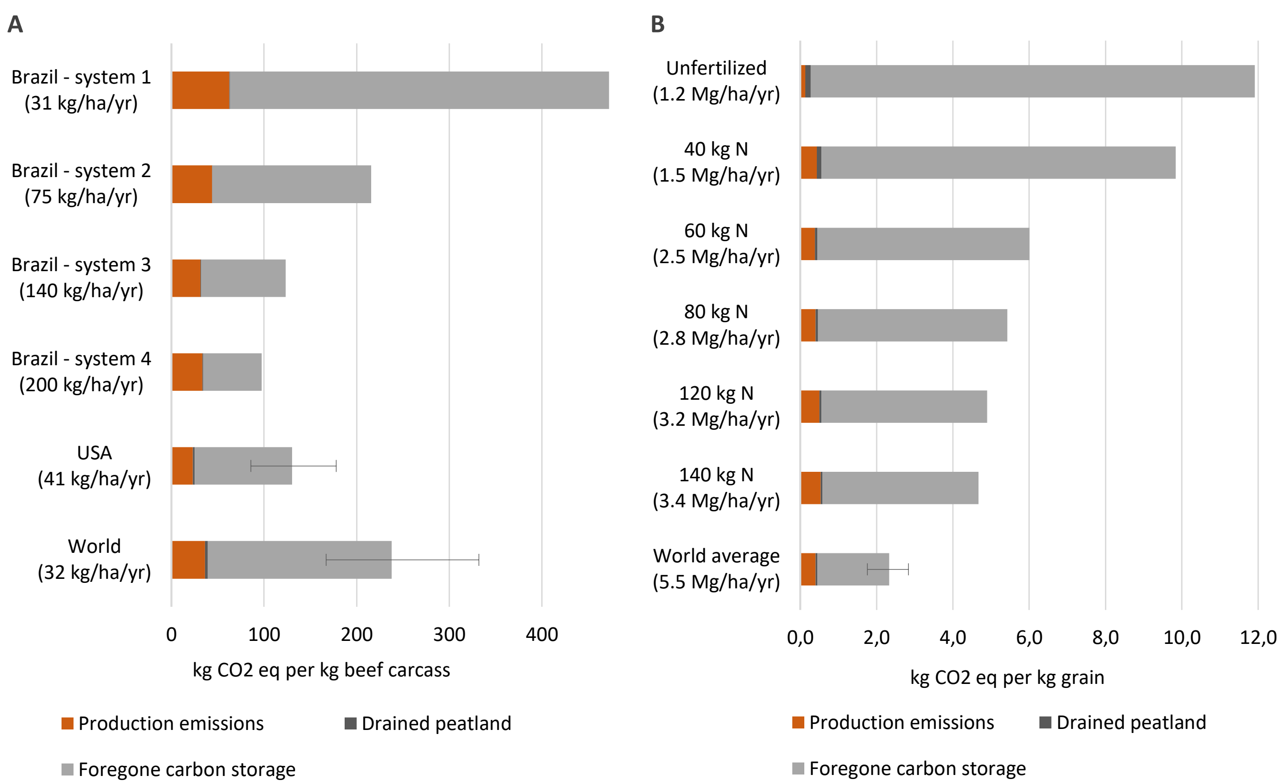

Fig. S9 Climate benefits of increased feed and land efficiency in crop and livestock production. Example data for (A) Brazilian beef production, (B) East African maize production. In (A), production emissions from [155]; foregone C storage calculated from land use data in [155]. In (B), nitrogen inputs and yields from [156]; emissions and foregone C storage calculated from the data above in [156]; for other parameters, the example assumes the data for maize in Sub-Saharan Africa as reported in this study.

Fig. S9B shows emissions and foregone carbon storage per kg of maize grains at different yields per hectare, based on data for East Africa [156]. According to this dataset, maize that receives no fertilizer yields 1.2 Mg ha^{-1} year^{-1}. Since no inputs are used, production emissions per kg of maize are very low. In cases with nitrogen fertilizer inputs, production emissions per kg are higher than in the unfertilized case, because of the emissions associated with the production and application of fertilizer. Hence, if only considering the production emissions, increasing the yields by using fertilizer results in a higher climate cost per kg of maize. However, when factoring in the lower land requirement and therefore lower forgone carbon storage that results from higher yields, using fertilizer results in a net reduction of the total climate cost that is about 15 times larger than the increase in production emissions.

In the EU, targets of increased organic farming have been set under the Green Deal's Farm to Fork strategy; at least 25% of the EU's agricultural land shall be under organic farming by 2030 (up from the current fraction of 9.1%, of which about 60% is grassland [157]). The purported aim is to produce high-quality food with a low environmental impact. While organic methods are less environmentally harmful due to their reduced reliance on pesticides, their greater land requirements hurt carbon storage and native ecosystem biodiversity. Here, using data for the EU, we illustrate the differences in climate impacts between organic and conventionally produced products.

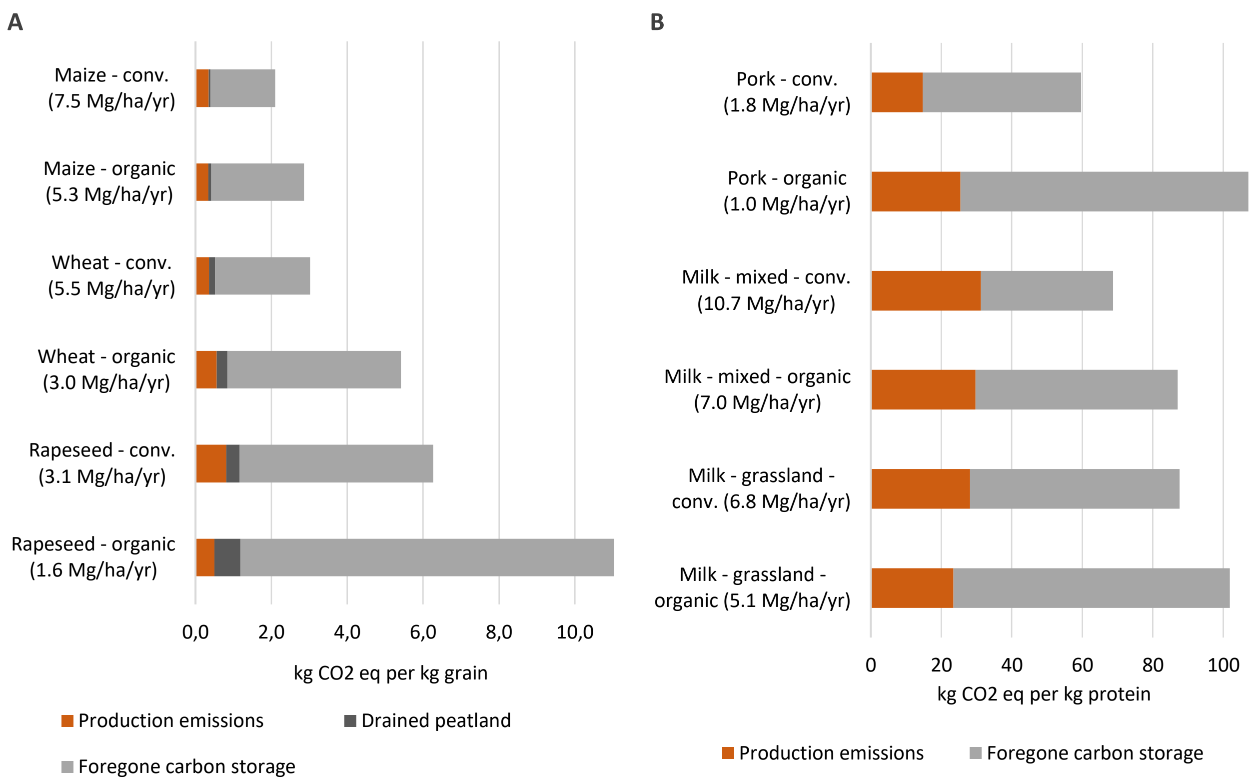

Fig. S10 Climate benefits of high-yield production per unit of land. (A) Conventional and organic crop production. (B) Conventional and organic pork and cattle milk production. Organic crop yields in (A) based on [157–159]; conventional yields are those for Europe in this study. In (B), both organic and conventional yields from [160,161]. Production emissions of organic crops in (A) are estimated using the ClimAg model, assuming that cattle slurry is used instead of mineral fertilizer. The percentage of drained organic soils, and the yields of conventional crops, are those for Europe as reported in this study. Production emissions in (B) are those reported in [160,161].

Fig. S10A compares the climate cost of organic and conventional crop production. According to these numbers, production emissions of organic crops are somewhat lower than those of conventional. However, this comparison understates the production emissions of organic crops, because it follows the widespread practice in analyses of organic farming of ignoring the opportunity cost of manure, that is, manure is treated as a free resource without any upstream costs. In reality, manure has a significant opportunity cost for several reasons. For example, a livestock farm selling manure to an organic crop farm must compensate for the nutrient export from its soils by purchasing more fertilizer or setting aside more land for green manure. Also, the carbon exported in the manure lowers soil carbon stocks at the livestock farm. If the opportunity cost of manure is included, the production emissions of the organic crops in Fig. S10A would be significantly higher. Still, regardless of the differences in production emissions, the lower yields in organic crop production mean that the climate cost from foregone carbon storage is much higher than in conventional production.

Fig. S10B compares the climate cost of organic and conventional pork and dairy production. Production emissions from organic pork are higher than conventional pork, mainly because of the lower liveweight gain rates in organic production, which leads to higher feed use per unit of meat. However, because of the much lower pork output per hectare, the difference in foregone carbon storage is much larger. The differences between organic and conventional are more minor for dairy, mainly for two reasons. First, milk yields per cow in organic production can be, and often are, as high as in conventional. Second, in both conventional and organic dairy production, most feed consists of grass, which in organic production has nearly as high yields as in conventional. Yet, for these two examples, the foregone carbon storage is significantly higher in organic production.

5.4 Climate cost of biofuels and transportation

Fig. 5 in the main text shows the climate costs of major biofuels as well as those of different powertrains for a medium-sized car. In this comparison, fuel use for the gasoline/diesel combustion car is assumed to be 0.51 kWh per km, and that of the electric car 0.15 kWh per km, both numbers based on [162]. As explained in the main text, the data in Fig. 5 are based on the climate cost of the global average supply of biofuel feedstocks.

The numbers in Fig. 5 do not include emissions from the manufacturing of the car (which corresponds to about 25 g CO_2 per km) except for the electric vehicle battery. The electric car is assumed to have a 65 kWh battery, with a CO_2 emission intensity in manufacturing of 80 kg CO_2 per kWh, based on [163]. The lifetime mileage of the car is assumed to be 200,000 km, which gives an emission of 26 g CO_2 per km from the battery manufacturing.

The carbon intensity of electricity in the EU is assumed to be 230 g CO_2 per kWh [164]; that in the US is given in Table S45. The carbon intensity of wind power is assumed to be 12 g CO_2 per kWh [165].

Extended Data Fig. 9 shows examples of the climate costs for different powertrains in buses and trucks. As in the car example in Fig. 5, the data are based on the climate cost of the global average supply of biofuel feedstocks. The electric bus example represents a 12-meter bus, based on the Volvo “7900 Electric” model, which has a 470 kWh battery and a power consumption of 1.6 kWh per km (average consumption). Fuel consumption of the diesel/biodiesel bus is assumed to be 4 kWh per km [166].

The electric truck example represents a 40-tonne semi-trailer, based on the Mercedes “eActros 600” model, which has a 621 kWh battery and a power consumption of 1.2 kWh per km (consumption when fully loaded with the maximum payload of 22 tonnes). The diesel/biodiesel-powered truck's fuel consumption is assumed to be 3 kWh per km, based on [167].

Battery type in both the bus and truck example is assumed to be LFP (lithium iron phosphate), with a CO_2 emission intensity in manufacturing of 55 kg CO_2 per kWh [163]. The lifetime mileage of the bus is assumed to be 900,000 km, and that of the truck is 1,300,000 km, both based on [167].

In the bus example, the carbon intensity of travelling in the electric bus with electricity supplied by wind power is 0.50 g CO_2 per person per km, about 99% lower than that of an internal-combustion bus fueled by rapeseed or animal-fat biodiesel. In the truck comparison, the carbon intensity of freight with the electric truck is 1.8 g CO_2 per tonne per km, about 98% lower than that of an internal-combustion truck fueled by rapeseed or animal-fat biodiesel.

5.5 Condensed data tables on total climate costs and climate cost per output at regional levels

Table S10 Summary of emissions and foregone carbon stocks by major products: Global totals and averages. Data on impact per output are allocated data (see 1.11). COC data for the undiscounted regrowth metric (see 1.9.3). Food crop by-products used as feed include crop residues (straw) and processing co-products (e.g. brans, oil meals). The climate cost allocated to these by-products is deducted from the total for the category "Crops used as food", but not for the individual specified crops. Production in energy terms for cotton and biofuels refers to gross energy.

	Production			**Climate impact per output**					**Total climate impact**				
				PEM	**Org. soils**	**COC**	**ALL**		**PEM**	**Org. soils**	**COC**	**ALL**	
	Tg fresh/ year	EJ edible ME/ year	Tg edible protein/ year	kg CO2 eq/ kg fresh	kg CO2 eq/ kg fresh	kg CO2/ kg fresh	kg CO2 eq/ MJ edible ME	kg CO2 eq/ kg edible protein	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	% of total
Animal products		**5.92**	**95.2**						**5588**	**377**	**15780**	**21745**	**61.4%**
Beef (carcass)	72.0	0.55	10.89	32.3	2.3	128.6	21.2	1078.7	2327	162.5	8579	11069	31.2%
Sheep/goat meat (carcass)	15.9	0.14	2.11	26.3	1.3	107.0	15.4	1019.7	420	21.0	1595	2036	5.7%
Pork (carcass)	114.7	0.95	17.92	4.9	0.4	6.9	1.45	77.6	558	41.3	736	1334	3.8%
Poultry meat (carcass)	129.6	0.96	17.92	2.1	0.2	5.5	1.06	56.9	278	31.9	662	972	2.7%
Cattle/buffalo milk (whole)	848.2	2.60	29.42	1.66	0.10	3.8	1.80	159.6	1408	81.7	2969	4458	12.6%
Sheep/goat milk (whole)	31.1	0.10	1.36	4.27	0.20	18.8	7.40	531.5	133	6.3	546	685	1.9%
Egg	88.0	0.45	9.64	2.59	0.28	5.6	1.66	77.7	228	24.9	461	714	2.0%
Fish - farmed (whole)	86.1	0.16	5.98	2.7	0.1	2.9	3.16	83.1	235.9	7.5	233	476	1.3%
Crops used for food	**6832.5**	**45.19**	**330.3**						**1624**	**400**	**5750**	**7773**	**21.9%**
Food crop by-products used as feed									-714	-89	-2146	-2949	-8.3%
Wheat	622.7	8.97	70.46	0.50	0.04	1.46	0.14	17.4	312.5	27.4	850	1190	3.4%
Maize	211.3	3.14	16.90	0.40	0.05	1.45	0.13	23.7	85.1	10.4	287	382	1.1%
Rice	767.1	10.49	46.79	1.32	0.07	2.45	0.28	62.9	1010.6	51.9	1703	2765	7.8%
Other cereals	137.3	1.98	13.66	0.33	0.10	3.23	0.25	36.8	45.1	13.9	419	478	1.4%
Soybean	255.6	4.38	88.96	0.36	0.17	3.32	0.22	11.0	91.7	42.2	794	927	2.6%
Oil palm	333.1	2.63	6.06	0.17	0.67	1.42	0.29	124.3	57.7	223.4	424	705	2.0%
Other oil/protein-rich crops	277.2	4.20	41.17	0.57	0.19	4.65	0.36	36.5	159.3	53.4	1190	1403	4.0%
Starchy root crops	422.9	1.84	6.85	0.09	0.04	0.88	0.23	62.3	39.9	16.2	343	398.9	1.1%
Sugar crops	1723.0	3.63	14.94	0.05	0.00	0.18	0.11	27.3	94.4	6.1	281	381.9	1.1%
Vegetables	1180.5	1.36	13.43	0.25	0.020	0.63	0.78	78.4	298.5	23.3	685	1006	2.8%
Fruits	863.4	2.06	6.07	0.12	0.014	0.61	0.31	105.7	104.1	12.2	481	597	1.7%
Tree nuts	17.0	0.35	2.16	1.74	0.11	9.04	0.53	85.3	29.4	1.8	139	171	0.5%
Cocoa, coffee, tea	21.6	0.16	2.80	0.44	0.30	15.2			9.4	6.6	301	317	0.9%
Other		**5.68**							**895**	**267**	**4745**	**5907**	**16.7%**
Seed cotton	70.6	1.34		0.80	0.03	2.85			57	2	187	245	0.7%
Biofuels	133.6	4.33		1.58	0.56	3.96			212	75	491	778	2.2%
Crop products lost or used for non-food									202	129	1260	1590	4.5%
Animal by-products (wool, leather, etc)									425.1	22.4	1925	2372	6.7%
Fallow									0.0	38.7	883	922	2.6%

Table S11 Production emission details by sub-systems: Global totals. All numbers in Tg CO_2 eq. per year. For uncertainty ranges, see section 2.

	On-farm[1]												Processing	Transport
	Production emissions													
	ALL	N2O soils	CH4 enteric ferm. or flooded rice	N2O confine-ments & manure mgmt	CH4 confine-ments & manure[2]	N2O aqua-culture	CH4 aqua-culture	CO2 energy on farm or from fisheries	CO2/ N2O fert. & pesticides prod.	CO2 green-house structures	N2O indirect from NH3/NO3 emissions	CO2/ N2O drained organic soils	CO2 process energy use	Of feed/ feedstock to farm or processing plant
Animal systems[3]	**5610**	**461**	**3034**	**261**	**557**	**13**	**81**	**541**	**113**		**240**	**309**		**117**
Cattle/buffalo - suckler beef	1648	129	1176	49	57			27	8		75	126		17
Cattle/buffalo - dairy beef[4]	581	32	434	33	25			12	3		19	21		20
Sheep/goats - meat herd	311	21	242	8	9			4	2		11	14		4
Pigs	524	73	20	24	239			75	36		32	26		12
Poultry - meat flock	206	37		54	22			38	21		22	13		10
Cattle/buffalo - dairy cows[5]	1552	107	974	63	173			79	20		53	83		36
Sheep/goats - dairy herd	247	15	187	11	9			4	1		10	11		5
Poultry - egg flock	207	47		20	22			61	22		19	14		6
Fish - farmed	167					13	81	73						6
Fish - captured	168							168						
Crop systems[6]	**3392**	**556**	**772**					**688**	**569**	**36**	**157**	**614**		
Wheat	376	90.6						140.1	92.9		22.6	30.2		
Maize	262	85.9						60.1	68.6		18.6	28.3		
Rice	1066	33.7	772.3					121.7	73.5		12.6	52.0		
Other cereals	93	23.3						26.3	16.1		5.5	21.4		
Soybean	176	36.7						38.6	33.2		12.0	55.6		
Oil palm	345	22.4						9.0	33.3		6.0	274.2		
Pulses ex. soybean, peanut	64	11.9						18.5	6.9		4.8	22.3		
Other oil/protein-rich crops	221	58.2						54.2	47.1		15.6	45.4		
Starchy root crops	108	27.3						15.1	24.6		7.3	33.4		
Sugar crops	133	39.3						39.6	36.0		11.0	7.2		
Vegetables	308	80.9						72.4	72.3	35.7	26.8	19.4		
Fruits	121	16.9						48.1	36.5		5.3	14.2		
Tree nuts	31	5.4						15.7	6.9		1.3	1.8		
Cocoa, coffee, tea	30	7.6						1.9	11.8		2.4	6.8		
Seed cotton	59	15.9						26.9	9.6		4.7	1.8		
Processing systems													**854**	**324**
Abattoirs													95.0	161.5

	On-farm[1]												Processing	Transport
	Production emissions													
	ALL	N2O soils	CH4 enteric ferm. or flooded rice	N2O confine-ments & manure mgmt	CH4 confine-ments & manure[2]	N2O aqua-culture	CH4 aqua-culture	CO2 energy on farm or from fisheries	CO2/ N2O fert. & pesticides prod.	CO2 green-house structures	N2O indirect from NH3/NO3 emissions	CO2/ N2O drained organic soils	CO2 process energy use	Of feed/ feedstock to farm or processing plant
Fish/shellfish plants													24.6	11.7
Dairies													245.0	62.7
Cereal flour plants													211.9	41.2
Vegetable oil plants													98.9[7]	21.0
Sugar plants													23.8	12.8
Alcoholic beverages plants													50.0	1.2
Starch, protein concentrates													29.4	1.9
Cotton processing plants													2.9	1.6
Biofuel plants (liquid fuels)													72.6	8.7
TOTAL	**9002**	**1017**	**3806**	**261**	**557**	**13**	**81**	**1230**	**682**	**36**	**397**	**923**	**854**	**441**

[1] Includes upstream emissions from production of fuels, electricity, fertilizer and pesticides.
[2] Includes methane emissions from manure excreted on pastures during grazing (globally 19 Tg CO_2 eq. per year).
[3] Includes emissions and foregone carbon stocks from crops cultivated for direct use as feed, but not that of co-products from crop, livestock, and fish/shellfish processing.
[4] Excluding dairy cows and dairy cow replacements.
[5] Including dairy cow replacements.
[6] Excluding crops cultivated for direct use as livestock and aquaculture feed.
[7] Includes methane emissions from oil palm processing (globally 79 Tg CO_2 eq. per year).

Table S12 Summary of emissions and foregone carbon stocks by major products: East Asia. Data on impact per output are allocated data (see 1.11). COC data for the undiscounted regrowth metric (see 1.9.3). Food crop by-products used as feed include crop residues (straw) and processing co-products (e.g. brans, oil meals). The climate cost allocated to these by-products is deducted from the total for the category "Crops used as food", but not for the individual specified crops. Production in energy terms for cotton and biofuels refers to gross energy.

	Production			**Climate impact per output**					**Total climate impact in region**				
				PEM	**Org. soils**	**COC**	**ALL**		**PEM**	**Org. soils**	**COC**	**ALL**	
	Tg fresh/ year	EJ edible ME/ year	Tg edible protein/ year	kg CO2 eq/ kg fresh	kg CO2 eq/ kg fresh	kg CO2/ kg fresh	kg CO2 eq/ MJ edible ME	kg CO2 eq/ kg edible protein	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	% of total
Animal products		**1.37**	**27.3**						**1206**	**118**	**2459**	**3783**	**47.5%**
Beef (carcass)	9.4	0.07	1.42	34.2	4.4	104.8	18.3	943.9	321	41.0	912	1274	16.0%
Sheep/goat meat (carcass)	5.2	0.05	0.69	18.0	1.3	66.3	9.8	646.7	94	6.8	322	423	5.3%
Pork (carcass)	60.1	0.50	9.36	5.2	0.4	7.3	1.53	82.4	309	22.5	406	738	9.3%
Poultry meat (carcass)	35.4	0.26	4.88	2.5	0.4	5.7	1.17	62.9	89	14.8	188	293	3.7%
Cattle/buffalo milk (whole)	49.7	0.15	1.67	1.47	0.17	4.1	1.98	171.9	73	8.5	191	273	3.4%
Sheep/goat milk (whole)	2.0	0.01	0.10	5.33	0.39	17.9	6.73	478.2	11	0.8	33	45	0.6%
Egg	44.9	0.23	4.92	3.02	0.39	6.0	1.84	85.9	136	17.4	250	403	5.1%
Fish - farmed (whole)	63.5	0.11	4.23	2.7	0.1	2.7	3.27	82.1	172.4	6.2	155.1	334	4.2%
Crops used as food		**14.31**	**77.0**						**942**	**262**	**2056**	**3260**	**40.9%**
Food crop by-products used as feed									-229	-44	-633	-905	-11%
Wheat	110.4	1.59	12.42	0.75	0.01	1.18	0.13	16.9	82.7	1.3	124	208	2.6%
Maize	32.7	0.49	2.62	0.62	0.10	1.73	0.16	30.5	20.2	3.2	53	76	1.0%
Rice	425.7	5.82	25.97	1.62	0.07	2.11	0.28	62.4	689.4	31.7	814	1535	19.3%
Other cereals	3.6	0.05	0.36	0.67	0.11	3.80	0.32	45.7	2.4	0.4	13	15	0.2%
Soybean	13.4	0.23	4.68	0.70	0.92	7.10	0.51	25.0	9.4	12.4	90	112	1.4%
Oil palm	289.8	2.29	5.27	0.18	0.73	1.29	0.28	120.9	52.3	212.0	334	598	7.5%
Other oil/protein crops	77.9	1.00	9.70	0.58	0.35	5.22	0.48	49.4	45.5	27.4	370	443	5.6%
Starchy root crops	127.0	0.54	2.05	0.12	0.02	0.75	0.21	55.0	15.7	2.4	86	104.6	1.3%
Sugar crops	318.7	0.65	2.84	0.07	0.00	0.26	0.16	37.7	21.3	1.2	76	98.0	1.2%
Vegetables	646.1	0.74	7.37	0.28	0.005	0.65	0.82	81.3	177.9	3.5	388	570	7.2%
Fruits	318.7	0.76	1.97	0.12	0.020	0.80	0.39	151.3	37.8	6.4	232	277	3.5%
Tree nuts	5.4	0.10	0.48	0.94	0.12	3.21	0.23	47.7	5.0	0.6	16	22	0.3%
Cocoa, coffee, tea	6.8	0.06	1.27	1.73	0.44	15.0			11.7	3.0	92	107	1.3%
Other		**1.21**							**203**	**65**	**651**	**919**	**11.5%**
Seed cotton	18.2	0.35		0.76	0.02	0.78			14	0	13	28	0.3%
Biofuels	22.4	0.86		2.44	2.16	5.88			55	48	119	223	2.8%
Crop products lost or used for non-food									19	8	191	219	2.7%
Animal by-products (wool, leather, etc)									115.2	8.1	327	450	5.7%
Fallow										0.0	0	0	0.0%

Table S13 Summary of emissions and foregone carbon stocks by major products: Europe. Data on impact per output are allocated data (see 1.11). COC data for the undiscounted regrowth metric (see 1.9.3). Food crop by-products used as feed include crop residues (straw) and processing co-products (e.g. brans, oil meals). The climate cost allocated to these by-products is deducted from the total for the category "Crops used as food", but not for the individual specified crops. Production in energy terms for cotton and biofuels refers to gross energy.

	Production			**Climate impact per output**					**Total climate impact in region**				
				PEM	**Org. soils**	**COC**	**ALL**		**PEM**	**Org. soils**	**COC**	**ALL**	
	Tg fresh/ year	EJ edible ME/ year	Tg edible protein/ year	kg CO2 eq/ kg fresh	kg CO2 eq/ kg fresh	kg CO2/ kg fresh	kg CO2 eq/ MJ edible ME	kg CO2 eq/ kg edible protein	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	% of total
Animal products		**1.05**	**15.6**						**568**	**114**	**1261**	**1943**	**66.5%**
Beef (carcass)	9.0	0.07	1.35	17.1	5.3	51.8	9.5	495.7	155	47.6	440	642	22.0%
Sheep/goat meat (carcass)	1.0	0.01	0.13	15.1	4.3	77.0	11.0	731.6	15	4.3	73	93	3.2%
Pork (carcass)	25.6	0.21	4.01	3.9	0.4	6.2	1.26	67.0	99	10.7	150	260	8.9%
Poultry meat (carcass)	17.3	0.13	2.39	1.7	0.3	4.9	0.92	49.5	29	4.9	79	113	3.9%
Cattle/buffalo milk (whole)	196.1	0.56	6.28	1.17	0.20	2.2	1.24	110.5	230	38.7	399	668	22.9%
Sheep/goat milk (whole)	6.1	0.02	0.28	2.80	0.70	12.5	4.82	344.6	17	4.3	71	93	3.2%
Egg	8.3	0.04	0.91	1.86	0.34	5.3	1.46	68.1	16	2.9	41	60	2.0%
Fish - farmed (whole)	2.9	0.01	0.23	2.2	0.2	2.7	1.65	65.0	6.5	0.5	7.4	14	0.5%
Crops used as food		**3.55**	**23.7**						**87**	**26**	**250**	**363**	**12.4%**
Food crop by-products used as feed									-43	-8	-164	-216	-7.4%
Wheat	88.6	1.28	9.84	0.36	0.16	1.73	0.16	19.5	31.6	13.8	145	190	6.5%
Maize	18.0	0.27	1.44	0.35	0.05	1.18	0.11	19.7	6.2	0.9	20	27	0.9%
Rice	2.9	0.04	0.18	1.33	0.01	1.02	0.17	38.6	3.9	0.0	3	7	0.2%
Other cereals	19.1	0.27	1.87	0.33	0.20	2.31	0.20	29.1	6.3	3.8	42	52	1.8%
Soybean	3.7	0.06	1.28	0.55	0.07	4.00	0.27	13.3	2.0	0.2	14	16	0.6%
Oil palm	0.0	0.00	0.00	0.14	0.00	0.17	0.04	16.8	0.0	0.0	0	0	0.0%
Other oil/protein crops	46.0	0.84	6.02	0.66	0.15	1.97	0.15	21.2	30.2	6.7	85	122	4.2%
Starchy root crops	40.4	0.14	0.73	0.08	0.05	0.43	0.16	31.4	3.4	2.1	16	21.9	0.7%
Sugar crops	135.8	0.36	0.94	0.06	0.02	0.17	0.09	35.9	7.6	2.6	22	32.5	1.1%
Vegetables	79.8	0.09	0.86	0.31	0.019	0.32	0.57	59.2	24.5	1.5	24	50	1.7%
Fruits	76.5	0.18	0.39	0.14	0.017	0.54	0.30	138.0	11.0	1.3	39	51	1.7%
Tree nuts	1.2	0.02	0.15	2.69	0.36	5.10	0.40	67.0	3.2	0.4	5	9	0.3%
Cocoa, coffee, tea	0.0	0.00	0.00	0.69	0.00	7.7			0.0	0.0	0	0	0.0%
Other		**0.69**							**91**	**40**	**485**	**616**	**21.1%**
Seed cotton	0.3	0.01		0.61	0.31	6.37			0	0	2	2	0.1%
Biofuels	17.5	0.69		2.12	1.07	5.97			37	19	98	154	5.3%
Crop products lost or used for non-food									19	7	147	174	5.9%
Animal by-products (wool, leather, etc)									34.2	5.5	110	150	5.1%
Fallow										8.8	128	137	4.7%

Table S14 Summary of emissions and foregone carbon stocks by major products: North America. Data on impact per output are allocated data (see 1.11). COC data for the undiscounted regrowth metric (see 1.9.3). Food crop by-products used as feed include crop residues (straw) and processing co-products (e.g. brans, oil meals). The climate cost allocated to these by-products is deducted from the total for the category "Crops used as food", but not for the individual specified crops. Production in energy terms for cotton and biofuels refers to gross energy.

	Production			**Climate impact per output**					**Total climate impact in region**				
				PEM	**Org. soils**	**COC**	**ALL**		**PEM**	**Org. soils**	**COC**	**ALL**	
	Tg fresh/ year	EJ edible ME/ year	Tg edible protein/ year	kg CO2 eq/ kg fresh	kg CO2 eq/ kg fresh	kg CO2/ kg fresh	kg CO2 eq/ MJ edible ME	kg CO2 eq/ kg edible protein	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	% of total
Animal products		**0.84**	**13.7**						**671**	**52**	**1174**	**1897**	**61.2%**
Beef (carcass)	15.6	0.12	2.38	23.3	2.1	62.9	11.5	579.6	364	32.8	920	1316	42.4%
Sheep/goat meat (carcass)	0.2	0.00	0.03	23.9	2.0	90.5	13.3	880.7	5	0.4	17	22	0.7%
Pork (carcass)	15.7	0.13	2.46	5.1	0.2	3.3	1.04	55.3	80	3.8	49	133	4.3%
Poultry meat (carcass)	27.5	0.20	3.80	1.7	0.2	2.5	0.59	31.6	46	5.2	66	117	3.8%
Cattle/buffalo milk (whole)	120.3	0.33	3.85	1.31	0.07	0.9	0.82	69.6	157	8.3	96	262	8.4%
Sheep/goat milk (whole)	0.2	0.00	0.01	4.32	0.35	17.2	5.59	399.6	1	0.1	4	5	0.2%
Egg	10.1	0.05	1.11	1.54	0.17	2.2	0.77	36.1	16	1.7	22	39	1.3%
Fish - farmed (whole)	0.9	0.00	0.06	3.3	0.1	1.7	2.56	69.0	2.8	0.1	1.3	4	0.1%
Crops used as food		**4.21**	**44.2**						**76**	**23**	**247**	**345**	**11.1%**
Food crop by-products used as feed									-59	-9	-120	-188	-6.1%
Wheat	74.9	1.08	8.57	0.41	0.08	1.08	0.11	13.7	30.9	6.3	77	114	3.7%
Maize	53.1	0.79	4.25	0.36	0.05	0.64	0.07	13.2	19.0	2.6	33	54	1.7%
Rice	7.3	0.10	0.44	0.79	0.00	1.26	0.15	33.7	5.7	0.0	9	14	0.5%
Other cereals	10.9	0.15	1.08	0.39	0.13	1.24	0.13	17.8	4.2	1.4	13	18	0.6%
Soybean	65.4	1.12	22.77	0.35	0.19	2.14	0.16	7.7	22.7	12.7	134	169	5.5%
Oil palm	1.0	0.01	0.02	0.15	0.03	1.26	0.18	79.0	0.2	0.0	1	1	0.0%
Other oil/protein crops	21.6	0.40	4.30	0.69	0.21	2.11	0.16	15.1	14.8	4.5	43	62	2.0%
Starchy root crops	17.4	0.06	0.31	0.08	0.01	0.12	0.06	11.7	1.4	0.2	2	3.5	0.1%
Sugar crops	119.8	0.26	1.02	0.05	0.02	0.15	0.10	26.4	6.5	2.6	16	25.4	0.8%
Vegetables	60.0	0.07	0.65	0.23	0.021	0.24	0.44	44.5	14.0	1.3	13	28	0.9%
Fruits	45.5	0.10	0.30	0.15	0.010	0.35	0.23	79.4	6.9	0.4	15	22	0.7%
Tree nuts	3.3	0.07	0.51	2.41	0.07	1.00	0.16	22.8	8.0	0.2	3	11	0.4%
Cocoa, coffee, tea	0.2	0.00	0.01	0.89	0.36	53.8			0.2	0.1	9	10	0.3%
Other		**1.79**							**156**	**38**	**664**	**858**	**27.7%**
Seed cotton	9.9	0.19		0.75	0.11	2.22			7	1.1	21	29	0.9%
Biofuels	53.5	1.60		1.45	0.14	2.05			77	7.3	104	189	6.1%
Crop products lost or used for non-food									26	2.8	65	94	3.0%
Animal by-products (wool, leather, etc)									45.4	2.8	138	186	6.0%
Fallow										23.9	337	361	11.6%

Table S15 Summary of emissions and foregone carbon stocks by major products: South America. Data on impact per output are allocated data (see 1.11). COC data for the undiscounted regrowth metric (see 1.9.3). Food crop by-products used as feed include crop residues (straw) and processing co-products (e.g. brans, oil meals). The climate cost allocated to these by-products is deducted from the total for the category "Crops used as food", but not for the individual specified crops. Production in energy terms for cotton and biofuels refers to gross energy.

	Production			**Climate impact per output**					**Total climate impact in region**				
				PEM	**Org. soils**	**COC**	**ALL**		**PEM**	**Org. soils**	**COC**	**ALL**	
	Tg fresh/ year	EJ edible ME/ year	Tg edible protein/ year	kg CO2 eq/ kg fresh	kg CO2 eq/ kg fresh	kg CO2/ kg fresh	kg CO2 eq/ MJ edible ME	kg CO2 eq/ kg edible protein	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	% of total
Animal products		**0.65**	**10.8**						**943**	**14**	**4087**	**5044**	**75.4%**
Beef (carcass)	17.2	0.13	2.62	39.5	0.6	200.9	31.8	1580.4	678	10.8	3161	3849	57.5%
Sheep/goat meat (carcass)	0.3	0.00	0.04	31.9	0.3	190.7	25.4	1688.1	10	0.1	57	67	1.0%
Pork (carcass)	6.8	0.06	1.07	5.7	0.1	10.4	1.94	103.2	39	0.4	65	105	1.6%
Poultry meat (carcass)	23.6	0.18	3.27	2.0	0.0	7.1	1.23	65.9	48	0.5	155	203	3.0%
Cattle/buffalo milk (whole)	84.7	0.24	2.71	1.61	0.02	7.4	3.19	283.3	136	2.0	577	715	10.7%
Sheep/goat milk (whole)	0.7	0.00	0.04	5.37	0.05	32.1	9.60	686.2	4	0.0	19	23	0.3%
Egg	7.1	0.04	0.78	1.88	0.02	5.9	1.52	71.0	13	0.1	39	52	0.8%
Fish - farmed (whole)	3.5	0.01	0.28	4.2	0.0	4.5	3.70	106.8	14.5	0.1	14.5	29	0.4%
Crops used as food		**4.96**	**54.7**						**86**	**5**	**695**	**786**	**11.7%**
Food crop by-products used as feed									-56	-1	-255	-313	-4.7%
Wheat	22.7	0.33	2.59	0.41	0.00	2.58	0.21	26.0	9.4	0.1	55	65	1.0%
Maize	29.8	0.44	2.39	0.41	0.01	1.79	0.15	27.7	12.3	0.2	50	62	0.9%
Rice	26.3	0.36	1.60	0.94	0.03	2.28	0.24	53.1	24.6	0.7	55	80	1.2%
Other cereals	7.5	0.10	0.74	0.37	0.00	2.24	0.19	26.4	2.8	0.0	16	19	0.3%
Soybean	108.6	1.86	37.78	0.30	0.01	3.44	0.22	10.8	32.7	0.9	347	380	5.7%
Oil palm	20.9	0.16	0.38	0.10	0.05	1.17	0.17	72.1	2.1	0.9	22	25	0.4%
Other oil/protein crops	16.8	0.23	2.40	0.53	0.03	6.14	0.50	47.0	9.0	0.5	95	105	1.6%
Starchy root crops	22.6	0.10	0.36	0.11	0.01	0.92	0.23	65.1	2.6	0.3	19	21.7	0.3%
Sugar crops	512.7	1.03	4.61	0.04	0.00	0.22	0.13	29.0	21.5	0.2	103	125.0	1.9%
Vegetables	35.9	0.04	0.38	0.21	0.004	0.80	0.87	94.6	7.6	0.1	26	34	0.5%
Fruits	109.0	0.27	0.97	0.12	0.012	0.64	0.32	87.2	13.3	1.3	63	78	1.2%
Tree nuts	0.7	0.02	0.10	1.31	0.19	15.37	0.80	122.9	1.0	0.1	10	12	0.2%
Cocoa, coffee, tea	6.4	0.02	0.36	0.64	0.12	15.2			4.1	0.8	88	93	1.4%
Other		**1.24**							**115**	**2**	**747**	**863**	**12.9%**
Seed cotton	8.2	0.16		0.60	0.00	2.87			5	0	22	27	0.4%
Biofuels	35.7	1.08		1.01	0.01	4.77			36	0	158	194	2.9%
Crop products lost or used for non-food									2	0	20	22	0.3%
Animal by-products (wool, leather, etc)									71.5	0.9	399	471	7.0%
Fallow										0.4	148	148	2.2%

Table S16 Summary of emissions and foregone carbon stocks by major products: South Asia. Data on impact per output are allocated data (see 1.11). COC data for the undiscounted regrowth metric (see 1.9.3). Food crop by-products used as feed include crop residues (straw) and processing co-products (e.g. brans, oil meals). The climate cost allocated to these by-products is deducted from the total for the category "Crops used as food", but not for the individual specified crops. Production in energy terms for cotton and biofuels refers to gross energy.

	Production			**Climate impact per output**					**Total climate impact in region**				
				PEM	**Org. soils**	**COC**	**ALL**		**PEM**	**Org. soils**	**COC**	**ALL**	
	Tg fresh/ year	EJ edible ME/ year	Tg edible protein/ year	kg CO2 eq/ kg fresh	kg CO2 eq/ kg fresh	kg CO2/ kg fresh	kg CO2 eq/ MJ edible ME	kg CO2 eq/ kg edible protein	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	% of total
Animal products		**1.04**	**13.2**						**864**	**9.8**	**1308**	**2182**	**58.9%**
Beef (carcass)	5.1	0.04	0.76	45.8	0.4	97.0	18.4	964.7	235	1.8	445	681	18.4%
Sheep/goat meat (carcass)	1.8	0.02	0.24	27.3	0.2	53.5	9.2	613.7	50	0.3	88	139	3.7%
Pork (carcass)	0.4	0.00	0.06	7.7	0.2	11.7	2.36	125.6	3	0.1	4	7	0.2%
Poultry meat (carcass)	6.1	0.05	0.84	2.2	0.1	6.1	1.13	60.5	13	0.5	33	47	1.3%
Cattle/buffalo milk (whole)	238.9	0.85	9.22	2.01	0.02	2.8	1.37	125.9	481	5.9	605	1092	29.5%
Sheep/goat milk (whole)	10.2	0.03	0.38	3.05	0.02	5.6	3.15	229.4	31	0.2	50	82	2.2%
Egg	7.2	0.04	0.79	2.92	0.09	6.9	1.93	90.3	21	0.7	45	66	1.8%
Fish - farmed (whole)	11.4	0.02	0.87	2.5	0.0	3.7	3.05	81.8	29.0	0.3	38.0	67	1.8%
Crops used as food		**8.01**	**50.3**						**281**	**21**	**893**	**1195**	**32.3%**
Food crop by-products used as feed									-156	-6	-471	-633	-17%
Wheat	124.3	1.79	14.23	0.58	0.00	1.48	0.14	17.9	72.0	0.3	166	238	6.4%
Maize	17.6	0.26	1.41	0.47	0.03	1.66	0.15	27.0	8.3	0.5	26	35	1.0%
Rice	251.3	3.44	15.33	0.91	0.06	2.63	0.26	59.1	228.3	16.3	594	839	22.7%
Other cereals	18.1	0.27	1.90	0.34	0.01	2.35	0.18	25.6	6.2	0.1	38	44	1.2%
Soybean	6.1	0.10	2.11	0.58	0.01	6.21	0.40	19.6	3.5	0.1	34	37	1.0%
Oil palm	0.0	0.00	0.00	0.16	0.00	0.17	0.04	18.0	0.0	0.0	0	0	0.0%
Other oil/protein crops	48.7	0.61	6.80	0.50	0.07	4.65	0.42	37.4	24.5	3.3	202	230	6.2%
Starchy root crops	45.3	0.17	0.80	0.11	0.03	0.69	0.23	47.2	5.1	1.3	28	34.5	0.9%
Sugar crops	416.0	0.84	3.74	0.07	0.00	0.09	0.08	18.0	29.7	0.1	33	62.9	1.7%
Vegetables	171.5	0.22	2.26	0.21	0.015	0.88	0.86	81.9	36.3	2.5	136	175	4.7%
Fruits	120.0	0.27	1.02	0.14	0.024	0.68	0.37	98.5	16.3	2.9	73	92	2.5%
Tree nuts	0.8	0.02	0.15	1.68	0.08	19.87	0.92	122.3	1.4	0.1	15	17	0.5%
Cocoa, coffee, tea	2.1	0.02	0.59	2.31	0.04	9.5			4.9	0.1	18	23	0.6%
Other		**0.50**							**75**	**1.7**	**248**	**325**	**8.8%**
Seed cotton	21.3	0.40		0.94	0.00	4.16			20	0.1	80	100	2.7%
Biofuels	3.4	0.09		1.24	0.02	1.77			4	0.1	5	10	0.3%
Crop products lost or used for non-food									7	1.3	56	65	1.7%
Animal by-products (wool, leather, etc)									43.8	0.3	107	151	4.1%
Fallow										0.0	0	0	0.0%

Table S17 Summary of emissions and foregone carbon stocks by major products: Sub-Saharan Africa. Data on impact per output are allocated data (see 1.11). COC data for the undiscounted regrowth metric (see 1.9.3). Food crop by-products used as feed include crop residues (straw) and processing co-products (e.g. brans, oil meals). The climate cost allocated to these by-products is deducted from the total for the category “Crops used as food”, but not for the individual specified crops. Production in energy terms for cotton and biofuels refers to gross energy.

	Production			Climate impact per output					Total climate impact in region				
				PEM	Org. soils	COC	ALL		PEM	Org. soils	COC	ALL	
	Tg fresh/ year	EJ edible ME/ year	Tg edible protein/ year	kg CO2 eq/ kg fresh	kg CO2 eq/ kg fresh	kg CO2/ kg fresh	kg CO2 eq/ MJ edible ME	kg CO2 eq/ kg edible protein	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	% of total
Animal products		**0.27**	**4.3**						**710**	**33**	**4229**	**4972**	**64.8%**
Beef (carcass)	6.3	0.05	0.94	63.4	3.2	379.9	58.9	2969.6	398	20.0	2238	2655	34.6%
Sheep/goat meat (carcass)	2.8	0.02	0.37	35.9	1.0	300.5	38.3	2560.7	100	2.9	787	890	11.6%
Pork (carcass)	1.6	0.01	0.25	4.3	0.4	20.3	3.01	159.7	7	0.6	31	39	0.5%
Poultry meat (carcass)	5.1	0.04	0.70	2.5	0.2	14.7	2.35	125.8	13	1.0	70	84	1.1%
Cattle/buffalo milk (whole)	32.2	0.11	1.32	4.49	0.20	25.6	8.54	739.0	145	6.3	775	926	12.1%
Sheep/goat milk (whole)	5.7	0.02	0.24	6.37	0.18	53.3	19.48	1402.6	36	1.1	286	323	4.2%
Egg	2.5	0.01	0.27	2.43	0.17	12.8	3.00	140.3	6	0.4	30	36	0.5%
Fish - farmed (whole)	2.2	0.00	0.17	2.8	0.1	6.4	5.07	121.5	6.2	0.2	13.4	20	0.3%
Crops used as food		**4.58**	**28.5**						**75**	**36**	**1447**	**1558**	**20.3%**
Food crop by-products used as feed									-49	-6	-364	-419	-5.5%
Wheat	16.9	0.24	1.92	0.38	0.00	1.17	0.11	13.5	6.4	0.0	19	25	0.3%
Maize	58.9	0.87	4.71	0.29	0.06	4.10	0.30	55.6	17.0	3.7	227	248	3.2%
Rice	37.7	0.52	2.30	0.99	0.06	5.82	0.50	112.6	37.2	2.2	204	243	3.2%
Other cereals	46.7	0.69	4.62	0.20	0.02	5.54	0.39	58.3	9.6	0.8	248	258	3.4%
Soybean	1.5	0.02	0.51	0.44	0.03	6.39	0.40	19.7	0.6	0.0	9	10	0.1%
Oil palm	21.5	0.17	0.39	0.13	0.31	3.87	0.55	236.7	2.7	6.6	76	86	1.1%
Other oil/protein crops	40.3	0.66	8.55	0.47	0.13	9.75	0.63	48.7	18.9	5.2	372	396	5.2%
Starchy root crops	135.8	0.72	1.98	0.07	0.06	1.44	0.30	107.7	9.0	8.6	183	200.2	2.6%
Sugar crops	99.1	0.21	0.87	0.04	0.00	0.10	0.07	15.4	3.6	0.1	9	12.7	0.2%
Vegetables	82.2	0.10	0.87	0.09	0.122	1.28	1.28	138.8	7.6	10.0	98	115	1.5%
Fruits	99.2	0.27	0.90	0.07	0.017	1.40	0.55	164.2	6.7	1.7	129	137	1.8%
Tree nuts	2.6	0.06	0.44	1.02	0.13	33.66	1.50	203.2	2.6	0.3	79	82	1.1%
Cocoa, coffee, tea	5.7	0.05	0.45	0.41	0.50	30.2			2.3	2.8	159	164	2.1%
Other		**0.11**							**91**	**12**	**1036**	**1139**	**14.9%**
Seed cotton	4.6	0.09		0.52	0.03	10.47			2	0	46	48	0.6%
Biofuels	1.0	0.03		0.96	0.08	5.52			1	0	5	6	0.1%
Crop products lost or used for non-food									12	8	356	376	4.9%
Animal by-products (wool, leather, etc)									75.8	2.9	593	672	8.8%
Fallow										0.6	37	37	0.5%

Table S18 Summary of emissions and foregone carbon stocks by major products: Brazil. Data on impact per output are allocated data (see 1.11). COC data for the undiscounted regrowth metric (see 1.9.3). Food crop by-products used as feed include crop residues (straw) and processing co-products (e.g. brans, oil meals). The climate cost allocated to these by-products is deducted from the total for the category "Crops used as food", but not for the individual specified crops. Production in energy terms for cotton and biofuels refers to gross energy.

	Production			Climate impact per output					Total climate impact in region				
				PEM	Org. soils	COC	ALL		PEM	Org. soils	COC	ALL	
	Tg fresh/ year	EJ edible ME/ year	Tg edible protein/ year	kg CO2 eq/ kg fresh	kg CO2 eq/ kg fresh	kg CO2/ kg fresh	kg CO2 eq/ MJ edible ME	kg CO2 eq/ kg edible protein	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	% of total
Animal products		**0.33**	**5.7**						**554**	**5.7**	**2302**	**2862**	**78.5%**
Beef (carcass)	10.0	0.08	1.53	42.7	0.5	207.4	33.2	1640.1	429	4.6	1892	2326	63.8%
Sheep/goat meat (carcass)	0.1	0.00	0.02	33.5	0.2	185.0	24.9	1657.4	4	0.0	22	26	0.7%
Pork (carcass)	3.9	0.03	0.62	6.3	0.1	9.9	1.95	103.7	25	0.3	36	61	1.7%
Poultry meat (carcass)	14.3	0.11	1.98	2.0	0.0	6.6	1.16	62.1	28	0.3	87	116	3.2%
Cattle/buffalo milk (whole)	35.3	0.10	1.13	1.64	0.01	7.4	3.18	282.4	58	0.5	237	295	8.1%
Sheep/goat milk (whole)	0.3	0.00	0.02	5.81	0.03	31.8	9.63	688.6	2	0.0	9	10	0.3%
Egg	3.3	0.02	0.36	1.94	0.02	5.8	1.52	71.2	6	0.1	18	24	0.7%
Fish - farmed (whole)	0.6	0.00	0.05	3.0	0.0	4.5	4.60	104.1	1.9	0.0	2.6	5	0.1%
Crops used as food		**2.33**	**27.7**						**29**	**0.7**	**302**	**332**	**9.1%**
Food crop by-products used as feed									-30	-1.3	-139	-171	-4.7%
Wheat	3.7	0.05	0.42	0.44	0.02	5.00	0.38	47.4	1.6	0.1	17	19	0.5%
Maize	10.5	0.16	0.84	0.43	0.01	1.84	0.15	28.5	4.6	0.1	18	23	0.6%
Rice	11.0	0.15	0.67	0.76	0.01	2.14	0.21	47.7	8.3	0.2	22	30	0.8%
Other cereals	1.0	0.01	0.09	0.39	0.01	6.32	0.49	69.4	0.4	0.0	6	6	0.2%
Soybean	59.5	1.02	20.72	0.30	0.01	3.31	0.21	10.4	17.7	0.6	182	200	5.5%
Oil palm	1.7	0.01	0.03	0.11	0.00	0.72	0.10	45.4	0.2	0.0	1	1	0.0%
Other oil/protein crops	7.3	0.07	0.88	0.41	0.10	6.32	0.70	56.4	3.0	0.7	42	46	1.3%
Starchy root crops	6.9	0.04	0.11	0.11	0.01	0.91	0.20	67.3	0.7	0.1	6	6.5	0.2%
Sugar crops	351.3	0.71	3.16	0.04	0.00	0.21	0.12	27.9	12.7	0.0	70	82.4	2.3%
Vegetables	13.7	0.02	0.14	0.20	0.001	0.81	0.90	97.6	2.8	0.0	10	13	0.4%
Fruits	38.3	0.08	0.35	0.11	0.004	0.65	0.37	83.7	4.2	0.2	22	27	0.7%
Tree nuts	0.6	0.01	0.06	1.17	0.02	29.72	1.61	305.6	0.7	0.0	17	18	0.5%
Cocoa, coffee, tea	3.5	0.01	0.20	0.62	0.04	9.1			2.1	0.1	29	31	0.9%
Other		**1.05**							**74**	**1.3**	**378**	**454**	**12.4%**
Seed cotton	7.3	0.14		0.63	0.00	2.81			5	0.0	20	24	0.7%
Biofuels	30.9	0.91		0.92	0.03	4.51			28	0.8	129	158	4.3%
Crop products lost or used for non-food									2	0.1	18	20	0.6%
Animal by-products (wool, leather, etc)									39.3	0.4	212	251	6.9%
Fallow										0.0	0	0	0.0%

Table S19 Summary of emissions and foregone carbon stocks by major products: China. Data on impact per output are allocated data (see 1.11). COC data for the undiscounted regrowth metric (see 1.9.3). Food crop by-products used as feed include crop residues (straw) and processing co-products (e.g. brans, oil meals). The climate cost allocated to these by-products is deducted from the total for the category "Crops used as food", but not for the individual specified crops. Production in energy terms for cotton and biofuels refers to gross energy.

	Production			**Climate impact per output**					**Total climate impact in region**				
				PEM	**Org. soils**	**COC**	**ALL**		**PEM**	**Org. soils**	**COC**	**ALL**	
	Tg fresh/ year	EJ edible ME/ year	Tg edible protein/ year	kg CO2 eq/ kg fresh	kg CO2 eq/ kg fresh	kg CO2/ kg fresh	kg CO2 eq/ MJ edible ME	kg CO2 eq/ kg edible protein	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	% of total
Animal products		**1.00**	**20.0**						**818**	**65.1**	**1675**	**2558**	**59.4%**
Beef (carcass)	6.5	0.05	0.99	26.6	3.8	97.3	16.5	840.8	173	25.1	592	790	18.3%
Sheep/goat meat (carcass)	4.8	0.04	0.63	16.4	1.3	73.4	10.4	688.1	79	6.2	328	413	9.6%
Pork (carcass)	49.2	0.41	7.68	4.9	0.3	5.6	1.29	69.2	242	13.0	257	512	11.9%
Poultry meat (carcass)	20.7	0.15	2.86	2.5	0.2	4.6	1.00	53.6	53	4.6	90	147	3.4%
Cattle/buffalo milk (whole)	34.7	0.10	1.11	1.49	0.20	5.2	2.44	214.0	52	6.9	167	225	5.2%
Sheep/goat milk (whole)	1.5	0.01	0.08	4.57	0.35	18.7	6.41	454.3	7	0.5	26	33	0.8%
Egg	32.6	0.17	3.57	2.89	0.22	4.3	1.44	67.6	94	7.2	131	233	5.4%
Fish - farmed (whole)	48.9	0.08	3.13	2.4	0.0	1.9	2.65	67.2	117.6	1.6	84.9	204	4.7%
Crops used as food		**7.61**	**50.7**						**506**	**11.0**	**724**	**1241**	**28.8%**
Food crop by-products used as feed									-138	-17.3	-399	-555	-13%
Wheat	110.2	1.59	12.46	0.76	0.01	1.08	0.13	16.0	83.3	0.9	113	197	4.6%
Maize	12.0	0.18	0.96	0.64	0.07	1.03	0.12	21.7	7.6	0.8	12	20	0.5%
Rice	212.4	2.90	12.95	1.37	0.04	1.32	0.20	44.6	290.7	7.4	260	558	13.0%
Other cereals	4.5	0.06	0.44	0.68	0.09	2.36	0.22	32.0	3.0	0.4	10	13	0.3%
Soybean	12.7	0.22	4.42	0.70	0.92	6.08	0.45	22.2	8.9	11.7	73	94	2.2%
Oil palm	1.1	0.01	0.02	0.19	0.00	1.10	0.16	70.9	0.2	0.0	1	1	0.0%
Other oil/protein crops	37.8	0.76	7.81	0.87	0.09	4.40	0.27	26.0	32.9	3.3	155	191	4.4%
Starchy root crops	85.6	0.31	1.46	0.13	0.01	0.63	0.21	44.9	10.7	0.9	49	61.0	1.4%
Sugar crops	120.6	0.25	1.06	0.07	0.00	0.22	0.14	32.2	8.0	0.1	23	31.3	0.7%
Vegetables	568.8	0.64	6.54	0.28	0.002	0.48	0.67	65.5	160.2	1.3	249	410	9.5%
Fruits	247.4	0.57	1.33	0.11	0.004	0.59	0.31	131.4	27.8	1.1	135	164	3.8%
Tree nuts	4.8	0.09	0.38	0.85	0.02	0.69	0.09	19.7	4.1	0.1	3	7	0.2%
Cocoa, coffee, tea	2.8	0.04	0.87	2.44	0.01	15.8			6.8	0.0	40	47	1.1%
Other		**0.61**							**136**	**8.8**	**365**	**510**	**11.8%**
Seed cotton	17.9	0.34		1.11	0.02	0.60			20	0.4	10	30	0.7%
Biofuels	8.3	0.27		2.16	0.17	3.17			18	1.4	25	44	1.0%
Crop products lost or used for non-food									21	2.1	61	85	2.0%
Animal by-products (wool, leather, etc)									77.3	5.0	268	351	8.1%
Fallow										0.0	0	0	0.0%

Table S20 Summary of emissions and foregone carbon stocks by major products: India. Data on impact per output are allocated data (see 1.11). COC data for the undiscounted regrowth metric (see 1.9.3). Food crop by-products used as feed include crop residues (straw) and processing co-products (e.g. brans, oil meals). The climate cost allocated to these by-products is deducted from the total for the category "Crops used as food", but not for the individual specified crops. Production in energy terms for cotton and biofuels refers to gross energy.

	Production			**Climate impact per output**					**Total climate impact in region**				
				PEM	**Org. soils**	**COC**	**ALL**		**PEM**	**Org. soils**	**COC**	**ALL**	
	Tg fresh/ year	EJ edible ME/ year	Tg edible protein/ year	kg CO2 eq/ kg fresh	kg CO2 eq/ kg fresh	kg CO2/ kg fresh	kg CO2 eq/ MJ edible ME	kg CO2 eq/ kg edible protein	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	% of total
Animal products		**0.76**	**9.5**						**568**	**6.9**	**809**	**1384**	**52.8%**
Beef (carcass)	2.5	0.02	0.38	46.1	0.4	85.9	16.4	897.0	117	0.9	195	313	11.9%
Sheep/goat meat (carcass)	0.8	0.01	0.11	33.6	0.2	60.3	10.7	714.2	27	0.2	43	70	2.7%
Pork (carcass)	0.4	0.00	0.06	5.4	0.2	11.5	6.13	109.5	2	0.1	4	6	0.2%
Poultry meat (carcass)	4.2	0.03	0.57	2.2	0.1	7.0	1.25	67.2	9	0.4	26	36	1.4%
Cattle/buffalo milk (whole)	181.4	0.64	6.93	1.97	0.02	2.8	1.36	124.9	357	4.5	452	814	31.0%
Sheep/goat milk (whole)	6.3	0.02	0.24	2.97	0.02	4.9	2.87	207.9	19	0.1	27	46	1.8%
Egg	5.5	0.03	0.60	2.78	0.10	7.4	2.00	93.5	15	0.5	36	52	2.0%
Fish - farmed (whole)	8.6	0.02	0.66	2.6	0.0	3.2	2.84	76.4	22.1	0.2	25.3	48	1.8%
Crops used as food		**6.17**	**40.0**						**184**	**17.9**	**797**	**1000**	**38.1%**
Food crop by-products used as feed									-112	-4.2	-351	-468	-17.8%
Wheat	97.1	1.40	11.12	0.60	0.00	1.66	0.16	19.7	58.8	0.1	144	203	7.7%
Maize	11.9	0.18	0.95	0.49	0.03	1.83	0.16	29.4	5.9	0.4	20	26	1.0%
Rice	176.1	2.41	10.74	0.82	0.07	2.74	0.27	59.5	144.2	11.9	437	593	22.6%
Other cereals	17.2	0.26	1.81	0.37	0.01	2.28	0.18	25.1	6.3	0.1	35	41	1.6%
Soybean	5.7	0.10	2.00	0.52	0.01	7.75	0.48	23.8	3.0	0.1	40	43	1.6%
Oil palm	0.0	0.00	0.00	0.17	0.00	0.51	0.09	37.3	0.0	0.0	0	0	0.0%
Other oil/protein crops	42.0	0.54	6.16	0.56	0.08	5.83	0.50	44.1	23.4	3.6	218	245	9.3%
Starchy root crops	32.7	0.12	0.57	0.11	0.03	0.66	0.22	45.8	3.7	1.1	19	24.0	0.9%
Sugar crops	352.1	0.71	3.17	0.08	0.00	0.10	0.09	19.7	26.5	0.1	31	57.9	2.2%
Vegetables	147.8	0.19	1.99	0.04	0.014	0.84	0.70	64.6	5.4	2.0	112	120	4.6%
Fruits	103.3	0.23	0.90	0.14	0.024	0.68	0.37	96.7	14.1	2.5	63	80	3.1%
Tree nuts	0.8	0.02	0.14	1.79	0.08	21.25	0.98	128.4	1.4	0.1	15	17	0.6%
Cocoa, coffee, tea	1.7	0.02	0.45	2.45	0.11	8.6			4.1	0.2	13	17	0.7%
Other		**0.42**							**50**	**1.6**	**188**	**239**	**9.1%**
Seed cotton	17.7	0.34		0.87	0.00	4.83			15	0.1	77	92	3.5%
Biofuels	3.0	0.08		1.30	0.02	2.05			4	0.1	5	9	0.4%
Crop products lost or used for non-food									6	1.3	54	61	2.3%
Animal by-products (wool, leather, etc)									24.0	0.2	52	76	2.9%
Fallow										0.0	0	0	0.0%

Table S21 Summary of emissions and foregone carbon stocks by major products: USA. Data on impact per output are allocated data (see 1.11). COC data for the undiscounted regrowth metric (see 1.9.3). Food crop by-products used as feed include crop residues (straw) and processing co-products (e.g. brans, oil meals). The climate cost allocated to these by-products is deducted from the total for the category "Crops used as food", but not for the individual specified crops. Production in energy terms for cotton and biofuels refers to gross energy.

	Production			**Climate impact per output**					**Total climate impact in region**				
				PEM	**Org. soils**	**COC**	**ALL**		**PEM**	**Org. soils**	**COC**	**ALL**	
	Tg fresh/ year	EJ edible ME/ year	Tg edible protein/ year	kg CO2 eq/ kg fresh	kg CO2 eq/ kg fresh	kg CO2/ kg fresh	kg CO2 eq/ MJ edible ME	kg CO2 eq/ kg edible protein	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	Tg CO2 eq/ year	% of total
Animal products		**0.67**	**10.8**						**484**	**36.8**	**845**	**1366**	**63.6%**
Beef (carcass)	12.3	0.09	1.88	20.8	1.8	58.1	10.7	527.7	256	22.3	670	948	44.1%
Sheep/goat meat (carcass)	0.1	0.00	0.01	21.4	1.7	89.2	12.9	849.4	2	0.1	7	9	0.4%
Pork (carcass)	11.9	0.10	1.87	4.8	0.2	2.8	0.94	50.1	57	2.9	32	92	4.3%
Poultry meat (carcass)	22.8	0.17	3.15	1.6	0.2	2.3	0.55	29.6	37	4.4	50	91	4.2%
Cattle/buffalo milk (whole)	98.8	0.27	3.16	1.23	0.06	0.8	0.76	64.5	122	5.9	72	200	9.3%
Sheep/goat milk (whole)	0.0	0.00	0.00	3.80	0.30	16.4	5.25	375.1	0	0.0	0	0	0.0%
Egg	6.6	0.03	0.72	1.51	0.17	2.0	0.72	33.6	10	1.1	13	24	1.1%
Fish - farmed (whole)	0.4	0.00	0.03	2.3	0.0	1.4	2.55	66.1	1.0	0.0	0.6	2	0.1%
Crops used as food		**2.86**	**33.5**						**51**	**15.5**	**145**	**211**	**9.8%**
Food crop by-products used as feed									-42	-7.3	-92	-141	-6.6%
Wheat	46.3	0.67	5.29	0.45	0.07	1.06	0.11	13.7	20.8	3.1	47	71	3.3%
Maize	35.2	0.52	2.82	0.39	0.05	0.55	0.07	12.4	13.7	1.9	19	34	1.6%
Rice	6.6	0.09	0.40	0.80	0.00	1.24	0.15	33.4	5.3	0.0	8	13	0.6%
Other cereals	4.4	0.06	0.43	0.48	0.06	1.04	0.11	15.9	2.1	0.3	4	7	0.3%
Soybean	62.0	1.06	21.57	0.36	0.19	2.07	0.15	7.6	22.5	12.0	123	158	7.3%
Oil palm	0.0	0.00	0.00	0.16	0.00	0.19	0.04	19.2	0.0	0.0	0	0	0.0%
Other oil/protein crops	6.1	0.11	1.22	0.60	0.20	2.02	0.16	14.0	3.7	1.2	12	17	0.8%
Starchy root crops	13.1	0.05	0.23	0.09	0.01	0.09	0.05	10.4	1.1	0.1	1	2.4	0.1%
Sugar crops	58.1	0.13	0.46	0.06	0.04	0.09	0.09	25.0	3.7	2.4	5	11.3	0.5%
Vegetables	40.1	0.04	0.43	0.21	0.031	0.19	0.39	40.3	8.6	1.2	7	17	0.8%
Fruits	24.9	0.06	0.14	0.14	0.014	0.23	0.17	69.1	3.6	0.4	5	9	0.4%
Tree nuts	2.9	0.07	0.47	2.71	0.07	2.06	0.22	30.4	8.0	0.2	6	14	0.6%
Cocoa, coffee, tea	0.0	0.00	0.00	0.73	0.00	21.5			0.0	0.0	0	0	0.0%
Other		**1.72**							**133**	**25.2**	**413**	**571**	**26.6%**
Seed cotton	9.2	0.17		0.80	0.12	2.37			7	1.1	21	29	1.4%
Biofuels	51.6	1.54		1.53	0.14	1.98			79	7.1	97	184	8.5%
Crop products lost or used for non-food									17	1.2	30	49	2.3%
Animal by-products (wool, leather, etc)									29.1	1.8	88	119	5.5%
Fallow										14.0	176	190	8.9%

6. Appendices

A1. Regional structure

Table S22 Regional structure of this study.

Central Asia (CAS)	East Asia (EAS)	Europe (EUR)	Middle East & N. Africa (MEA)	North America (NAM)	Oceania (OCE)	Russia (RUS)	South America (SAM)	South Asia (SAS)	Sub-Saharan Africa (SSA)
Afghanistan	Cambodia	Albania	Algeria	Canada	Australia	Russian Federation	Argentina	Bangladesh	Angola
Kazakhstan	China	Austria	Armenia	Mexico	New Zealand		Bolivia	India	Benin
Kyrgyzstan	Indonesia	Belarus	Azerbaijan	Puerto Rico			Brazil	Nepal	Botswana
Mongolia	Japan	Belgium	Bahrain	USA			Chile	Pakistan	Burkina Faso
Tajikistan	Laos	Bosnia and Herzegovina	Egypt				Colombia	Sri Lanka	Burundi
Turkmenistan	Malaysia	Bulgaria	Georgia				Costa Rica		Cameroon
Uzbekistan	Myanmar	Croatia	Iran				Cuba		Central African Republic
	North Korea	Cyprus	Iraq				Dominican Republic		Chad
	Papua New Guinea	Czechia	Israel				Ecuador		Congo
	Philippines	Denmark	Jordan				El Salvador		Côte d'Ivoire
	South Korea	Estonia	Kuwait				Guatemala		Democratic Republic of the Congo
	Singapore	Finland	Lebanon				Haiti		Equatorial Guinea
	Thailand	France	Libya				Honduras		Eritrea
	Timor-Leste	Germany	Morocco				Jamaica		Eswatini
	Viet Nam	Greece	Oman				Nicaragua		Ethiopia
		Hungary	Palestine				Panama		Gabon
		Ireland	Qatar				Paraguay		Gambia
		Italy	Saudi Arabia				Peru		Ghana
		Latvia	Syria				Trinidad and Tobago		Guinea
		Lithuania	Tunisia				Uruguay		Guinea-Bissau
		Netherlands	Turkey				Venezuela		Kenya
		North Macedonia	United Arab Emirates						Lesotho
		Norway	Yemen						Liberia
		Poland							Madagascar
		Portugal							Malawi
		Moldova							Mali
		Romania							Mauritania
		Serbia							Mauritius
		Slovakia							

Central Asia (CAS)	East Asia (EAS)	Europe (EUR)	Middle East & N. Africa (MEA)	North America (NAM)	Oceania (OCE)	Russia (RUS)	South America (SAM)	South Asia (SAS)	Sub-Saharan Africa (SSA)
		Slovenia							Mozambique
		Spain							Namibia
		Sweden							Niger
		Switzerland							Nigeria
		Ukraine							Rwanda
		United Kingdom							Senegal
									Sierra Leone
									Somalia
									South Africa
									South Sudan
									Sudan
									Togo
									Uganda
									Tanzania
									Zambia
									Zimbabwe

A2. Exogenous input data: Crop and pasture production

Table S23 Crop yields and grazed intake per ha. Numbers in Mg dry matter per ha physical land area per year. Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per year (0.05 Tg DM limit for vegetables, fruits and stimulants). For sources, see table footnotes.

Crop Category[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cereals															
Wheat	3.5	1.4	7.5	4.8	2.1	3.3	1.8	2.6	2.8	3.6	3.6	2.3	7.8	4.4	3.2
Maize	5.7	5.3	6.3	6.5	6.6	8.9	6.7	4.9	6.0	3.4	1.9	7.0	8.1	3.0	10.1
Rice – irrigated/high input	7.1	3.2	8.3	6.0	5.7	7.5	8.7	4.9	8.0	6.2	3.7	10.0	10.7	6.5	7.6
Rice – low input	1.7		1.6		3.7				3.1	2.2	1.1	3.0		2.3	
Barley	2.6	1.3	2.7	4.2	1.6	3.4	2.1	2.1	3.3	2.3	3.5	2.9	3.1	2.3	3.7
Sorghum	1.3		3.1	4.3	0.89	3.4	3.1		2.7	0.71	1.0	2.5	4.1	0.7	4.2
Millet	0.8		2.1					1.2		1.1	0.62		2.5	1.1	
Oats	2.2	1.2	3.0	2.6	1.5	3.0	1.4	1.6	2.3		1.4	1.9	3.1		2.0
Rye	3.0		2.7	3.2	2.4	2.2		1.7					3.2		
Other	2.4	1.3	1.9	3.1	2.4	2.4		0.65	2.3		1.9		2.3		
Oil and protein field crops															
Soybean	2.7	1.9	1.5	2.4	2.7	3.0		1.4	3.3	1.1	1.3	4.1	1.6	1.1	3.0
Rapeseed	2.0	1.2	1.9	2.8	2.1	2.2	1.3	1.3	1.9	1.3	1.3		1.9	1.3	1.8
Peanut (pods)	1.6		3.1		3.1	4.2			2.8	1.5	1.0	3.6	3.6	1.4	4.3
Sunflower (in hull)	1.7	1.2	2.4	3.5	2.5	1.8		1.7	2.0	0.76	1.0	1.5	2.6	0.65	1.9
Sesame	0.5		0.64							0.46	0.47		1.5	0.45	
Common bean	0.8	1.1	1.4	2.0	2.0	1.1			1.0	0.37	1.0	1.0	1.5	0.37	1.9
Faba bean	1.7		1.8	2.4	0.91				1.0		2.0		1.8		
Cowpea	0.6										0.63				
Chickpea	2.3														
Peas	1.2		1.3	2.2	0.87	2.1		1.8	1.6	0.90	1.0		1.3	0.92	1.8
Pigeon pea	1.1									0.77	1.1				
Lentil	1.1	0.90	2.2		1.0	1.3				0.91	1.6		2.3	0.87	1.2
Other	0.8	1.3	1.0	1.5	1.1	0.83		1.5		0.54	0.62		1.9	0.43	
Oil tree crops and tree nuts															
Oil palm (fruit bunches)	7.2		9.0			7.0			7.6		2.1	7.6	6.9		
Coconut palm (nut in husk)	2.7		2.8	5.4	5.4	3.4			5.4	3.3	0.90	5.4	5.8	3.5	3.5
Olive	1.0			1.2	0.62				1.7		1.2				
Cashewnut (kernels)	0.4		0.57						0.22	0.53	0.37	0.19		0.51	
Almond (kernels)	0.6			0.21	0.37	1.5			0.21						1.5
Other tree nuts	1.8	2.4	3.2	1.6	1.1	2.2			2.1		1.5	2.1	4.1		0.77
Starchy root crops															
Cassava	4.6		8.8			5.1			5.4	9.9	3.8	6.1	6.8	10.4	
White potato	4.6	3.9	3.3	4.6	5.3	8.3	7.7	3.1	3.5	4.0	2.4	5.7	3.4	4.2	9.1
Sweet potato	3.1		4.6			5.3			2.5	2.5	1.8	3.2	5.0	2.6	5.3
Yams	2.8		5.4						2.7		2.8				

Crop Category[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Sugar crops															
Sugar cane	21.6		20.9		24.1	22.8	34.0		21.9	21.5	18.6	22.4	22.8	22.5	24.5
Sugar beet	13.6	6.7	12.9	15.7	13.7	16.0		10.2	17.8		11.4		12.4		16.0
Vegetables															
Tomato - average	2.4	1.7	4.7	4.0	3.6	4.4		1.7	2.5	1.3	0.84	3.8	5.1	1.4	5.4
Open field	1.8	1.7	2.8	3.0	2.9	4.2		1.7	2.3	1.3	0.84	3.7	3.6	1.4	5.4
Greenhouse	6.8		6.5	8.2	6.5	7.6							6.5		
Cucumber – average	1.5	1.1	1.8	1.7	1.7	1.1		1.3					2.7		0.65
Open field	1.0	1.1	1.3	1.3	1.2	1.0		1.3					2.3		0.64
Greenhouse	4.0		4.0	5.0	4.0								4.0		
Pepper (capsicum) – average	2.2		2.9	4.3	2.9	1.8					0.43		3.7		
Open field	1.3		1.4	2.8	2.2	1.6					0.43		2.2		
Greenhouse	5.4		5.3	6.5	5.3								5.3		
Eggplant - average	2.7		4.9	4.2	2.8					1.3			5.5	1.3	
Open field	1.7		3.0	2.4	2.0					1.2			3.9	1.3	
Greenhouse	6.7		6.7	8.1	6.7								6.7		
Okra	0.5								0.70	1.3	0.22			1.3	
Peas (green)	1.6		1.6	1.1	1.1					2.1			1.9	2.1	
Cabbage	3.3	3.3	4.7	2.6	2.2			3.3	2.3	2.2	1.5	2.3	3.7	2.2	4.2
Cauliflower & broccoli	1.8		1.8	1.6		1.9				1.9			2.2	1.9	2.0
Onion	2.2	3.1	2.2	3.1	3.0	5.2		3.0	2.8	1.9	1.5	3.4	2.9	2.0	7.3
Carrot	3.7	4.8	3.8	3.8	3.0	5.1		3.1	2.5		2.1		6.1		5.9
Other above-ground veg.	1.4	2.1	1.6	1.6	1.5	1.6	1.2	1.6	1.0	1.2	0.86	1.1	1.9	1.3	2.1
Other below ground veg.	1.3		1.3												
Fruits															
Grape	2.0	2.2	3.3	1.4	1.7	3.0	2.2	1.6	2.4	3.5	3.2	2.4	3.4	2.0	3.1
Mango	1.4		1.4			1.5			1.8	1.4	1.2	1.8	1.8	1.3	
Plantain	2.0		3.5						3.1	3.7	1.7				
Banana	4.7		6.5		7.4	6.4	5.7		5.3	7.1	2.3	5.3	6.8	7.5	
Apple	2.3	1.1	2.7	2.6	2.0	4.2	3.9	1.2	3.9	1.0	3.7	3.9	2.7	1.1	5.3
Orange	3.3		3.3	3.9	3.6	3.0	3.3		4.1	2.2	3.4	4.1	3.0	2.3	3.8
Other - Temperate	2.1	2.4	2.5	2.1	2.0	3.0	3.1	1.5	2.6	1.6	1.5	2.6	2.7	1.7	4.0
Other - Tropical	2.5		1.6		2.8	6.1			6.5	3.6	2.2	6.5	1.0	4.2	
Stimulants															
Cocoa (dried beans)	0.4		0.38						0.45		0.40	0.45			
Coffee	0.8		1.1			0.23			1.1	0.68	0.39	1.1	0.87	0.68	
Tea (dried leaves)	1.3		1.0		3.4					1.8	1.7		0.86	2.1	
Forage (harvested amount)[2]															
Whole cereals	12.2		12.0	12.0	12.0	12.9	12.0		12.0			12.0	12.0		12.9

Crop Category[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Grass/legumes – Dairy farms	6.5	4.2	4.8	7.0	4.0	6.1	8.9	4.2	5.6	6.4	4.8		4.8	6.4	6.1
Grass/legumes – Beef cattle	5.1	3.3	3.8	5.6		4.9	5.8	3.3	4.5	5.1	3.8	4.5	3.8		4.9
Grass/legumes – Sheep	4.1	3.3	3.8	5.6	3.2		5.8	3.3	4.5	5.1	3.8		3.8	5.1	
Fiber crops															
Seed cotton	2.0	2.3	4.8	0.74	3.5	2.5	3.7		3.5	1.3	0.93	3.9	5.0	1.2	2.5
Permanent & semi-perm. pasture (grazed amount)[3]															
Grazed intake per ha															
Dairy cattle	1.0	0.4	1.4	1.7	0.4	0.6	9.0	0.5	2.3	3.0	0.9	3.2	0.9	2.9	0.6
Beef cattle	1.2	0.4	1.4	1.7		0.6	0.4	0.5	2.3		0.9	3.2	0.9		0.6
Sheep	0.8	0.4	1.4	1.7	0.4		0.4	0.5	2.3	3.0	0.9		0.9	2.9	
Above-ground production of native potential vegetation[4]	4.3	1.5	3.4	6.8	1.1	4.5	3.3	4.6	7.8	4.5	5.3	9.3	3.1	5.8	4.6

[1] Yields calculated from FAOSTAT [5] and [23], except for forage and permanent grasslands.
[2] Whole cereals yield estimated from corresponding grain yield, with an upper limit of 12 Mg DM/ha/yr, except for NAM/USA which were based on [50]. Grass-legume yields based on [48] (EUR), [50] (NAM/USA), and [49] (OCE), [168] (SAS/India). Grass-legume yields in all other regions were estimates of this study.
[3] Based on [48] (EUR), [169,170] (NAM/USA), [49] (OCE), [171] (SAM/Brazil), and [168] (SAS/India). In all other regions, intake per hectare are estimates of this study.
[4] Net primary production of native potential vegetation estimated in the LPJ model (see section 1.9.5). Above-ground production assumed to be half of total production.

Table S24 Energy use for field operations excluding irrigation in open-field crop production. Numbers in liter of diesel per ha physical land area per year. Energy use includes leveling, plowing, tilling, sowing/planting, fertilizer & manure application, harvest, and transport from field. Energy use for irrigation is shown in Table S25. Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per. For sources, see table footnotes[1].

Crop Category[2]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cereals															
Wheat[3]	70	58	94	77	60	65	59	61	66	76	75	64	93	84	65
Maize[3]	88	83	114	102	119	105	102	87	101	102	22	112	128	99	104
Rice[4,3] (avg high/low input)	119	109	150	116	97	124	134	111	96	117	34	90	178	117	126
Barley	70	58	71	76	64	65	62	66	66	69	80	66	63	70	65
Sorghum	29		88	95	59	79	77		80	29	15	79	91	29	76
Millet	19		32					29		27	14		33	28	
Oats	64	59	68	63	60	63	59	67	67			59	67		62
Rye	61		63	62	62	59		58					65		
Other	46	57	58	62	61	60		55	61		25		63		
Oil and protein field crops															
Soybean[5]	58	52	53	55	56	57		51	62	63	59	68	53	54	57
Rapeseed	63	57	63	66	64	62	59	57	61	69		59	63	61	61
Peanut[6,7]	131		207		208	214			206	103	106	211	213	101	213
Sunflower[8]	126	114	128	138	127	121		119	125	113	121	119	131	110	122
Sesame[9]	32		26							28	35		33	27	
Common bean	37	57	58	60	62	57			57	27	16	58	61	27	60
Faba bean	48		59	62	56				57		17		60		
Cowpea	16										16				
Chickpea	48														
Peas	52	57	58	61	56	61		60	59	29	16		58	27	61
Pigeon pea	28									29	16			27	
Lentil	45	56	60		56	58				29	17		61	27	58
Other	33	58	57	58	57	56		59		28	16		60	27	56
Oil tree crops and tree nuts															
Oil palm[10]	105		113			113			113		67	114	114		
Coconut palm	30		36	36	36	36			36	21	20	36	36	20	36
Olive[11]	148			162	122				162		110				
Cashewnut[12]	59		101						101	50	50	101		50	
Almond[13]	407			339	339	451			451						451
Other tree nuts	162	163	162	162	162	162			162		163	162	163		162
Starchy root crops															
Cassava	26		67			58			61	38	16	64	65	37	
White potato	125	123	122	129	133	153	153	119	123	127	117	139	122	130	159
Sweet potato	72		123			127			113	59	30	118	128	60	127
Yams	16		35						31		16				
Sugar crops															
Sugar cane[14]	256		249		280	266	396		258	267	175	263	269	278	295

Crop Category[2]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Sugar beet[15]	164	130	161	171	163	175		146	183		159		160		169
Vegetables															
Tomato[16]	183	248	255	255	254	255		248	253	130	132	256	256	132	255
Okra	38									57	27			57	
Peas (green)	93		103	103	104					53			104	53	
Cabbage[17]	255	291	295	292	291			291	294	152	153	296	297	152	
Cucumber[18]	155		158	160	156	158							165		
Pepper (capsicum)	221		263	265	264	263					129		266		
Eggplant	176		265	265	262					134			266	137	
Cauliflower & broccoli[19]	278		336	334		336				174			337	175	336
Onion[20]	79	104	95	104	106	129		103	103	49	56	113	110	50	150
Carrot[21]	387	440	395	394	355	462		357	328		179		532		505
Other above-ground veg.	139	156	158	156	156	158	159	156	156	82	87	158	163	82	158
Other below ground veg.	88		85												
Fruits															
Grape[22]	308	315	314	314	316	314	316	316	315	189	186	315	316	189	315
Mango[23]	122		191			191			191	96	94	191	191	96	
Plantain	62		101						101	51	50			51	
Banana[24]	73		101		102	101			101	51	50	102	102	51	
Apple[25]	400	430	420	420	420	420	420	420	420	210	210	420	420	210	420
Orange[26]	240		290	290	290	290			290	140	140	290	290	140	290
Other - Temperate	180	200	200	200	200	200	200	200	200	110	110	200	200	110	200
Other - Tropical	170		200	200	200	200			200	100	100	200	200	100	
Stimulants															
Cocoa[27]	6,3		10						10		5	10			
Coffee[28]	18		20			20			20	20	10	20		20	
Tea[29]	19		20		20					20	10		20	20	
Forage															
Grass/legumes – Grazed[30]	39	34		44	56	36		30		114	60			110	38
Grass/legumes – Harvested[30]	88	64	71	84	91	73		62	145	163	100	119	72	158	72
Whole cereals	110		104	86		105	108		171			139	109		104
Fiber crops															
Seed cotton	57	57	73	51	64	60	67		64	53	51	68	74	53	60
Perm. & semi-perm. pasture		0	0	0	0	0	0	0	0	0	0	0	0	0	0

[1] It should be noted that FAOSTAT produces statistics on energy use. However, their numbers are very aggregated and include energy use also in aquaculture, fisheries, forestry, as well as fuel use for electricity and heat production off-farm and were therefore not deemed useful in this study.

2 172 61

3 173

4 174,175

5 176

6 177
7 178
8 179,180
9 181–183
10 184,185
11 186–188
12 189
13 190
14 191,192
15 61,193
16 144
17 70
18 69,194
19 70,195
20 70
21 70
22 145,146,196
23 197
24 198
25 190,199,200
26 199,201
27 202–204
28 150,205
29 206
30 61

Table S25 Energy use for irrigation of open-field crops. Numbers in GJ of electricity or diesel per ha irrigated area per year. Averages for entire crop areas are per physical area. For sources, see table footnotes.

Crop Category[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cereals excluding rice															
Per irrigated area															
Electricity	4.3		6.0	2.5	4.0	5.0				4.0			6.0	4.0	5.0
Diesel	5.8	20	4.0		11	11	9.0	9.0	9.0	1.8	9.0	9.0	4.0	1.8	11
Per entire crop area															
Electricity	0.74		2.3	0.11	1.0	0.68				2.3			3.5	2.3	0.69
Diesel	1.0	4.6	1.2		2.8	1.5	0.60	0.18	0.32	1.1	0.41	0.07	2.8	1.0	1.5
Rice – high input[2]															
Per irrigated area															
Electricity	1.4		1.0	2.5	1.0					1.0			1.0	1.0	
Diesel	0.71	9.0				9.0	2.7	2.7	9.0		2.7	9.0			9.0
Per entire crop area															
Electricity	0.74		1.1	2.0	0.60					0.76			1.1		
Diesel	0.39	8.4				8.8	2.7	2.7	4.3		0.73	2.9		0.75	8.9
Oil and protein field crops															
Per irrigated area															
Electricity	4.3		6.0	2.5	4.0	5.0				4.0			6.0	4.0	5.0
Diesel	5.4	20	4.0		11	11	9.0	9.0	9.0	1.8	9.0	9.0	4.0	1.8	11
Per entire crop area															
Electricity	0.28		0.83	0.09	1.5	0.34				0.53			0.99	0.51	0.43
Diesel	0.35	2.2	0.54		4.0	0.73	0.0	0.06	0.08	0.24	0.17	0.05	0.65	0.23	0.92
Oil tree crops and tree nuts															
Per irrigated area															
Electricity	4.3		6.0	2.5	4.0	5.0				4.0			6.0	4.0	5.0
Diesel	11		4.0		11	11	9.0	9.0	9.0	1.8	9.0	9.0	4.0	1.8	11
Per entire crop area															
Electricity	0.19		0.0	0.0	0.82	3.0				0.0			0.0	0.0	3.3
Diesel	0.46		0.0		2.2	6.5	0.0	0.0	0.14	0.0	0.0	0.0	0.0	0.0	7.2
Starchy root crops															
Per irrigated area															
Electricity	3.1		6.0	2.5	4.0	5.0				4.0			6.0	4.0	5.0
Diesel	6.3	20	4.0		11	11	9.0	9.0	9.0	1.8	9.0	9.0	4.0	1.8	11
Per entire crop area															
Electricity	0.19		0.36	0.35	2.8	0.41				0.92			0.23	0.51	0.0
Diesel	0.39	10	0.24		7.6	0.88	4.7	0.01	1.1	0.41	0.10	0.28	0.15	0.23	0.0
Sugar crops															
Per irrigated area															
Electricity	2.2		6.0	2.5	4.0	5.0				4.0			6.0	4.0	5.0

Crop Category[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Diesel	4.9	20	4.0		11	11	9.0	9.0	9.0	1.8	9.0	9.0	4.0	1.8	11
Per entire crop area															
Electricity	0.81		0.94	0.31	4.0	1.9				2.3			0.91	2.7	1.9
Diesel	1.8	11	1.3		11	4.0	7.0	1.6	1.2	1.6	5.1	0.49	0.85	1.5	4.0
Vegetables															
Per irrigated area															
Electricity	4.1		6.0	2.5	4.0	5.0				4.0			6.0	4.0	5.0
Diesel	6.1	20	4.0		11	11	9.0	9.0	9.0	1.8	9.0	9.0	4.0	1.8	11
Per entire crop area															
Electricity	1.4		1.8	0.82	2.4	4.7				1.1			2.2	1.0	4.4
Diesel	2.1	20	1.2		6.5	10	8.4	2.9	5.1	0.48	2.0	6.1	1.4	0.43	9.3
Fruits															
Per irrigated area															
Electricity	2.3		6.0	2.5	4.0	5.0				4.0			6.0	4.0	5.0
Diesel	7.9	20	4.0		11	11	9.0	9.0	9.0	1.8	9.0	9.0	4.0	1.8	11
Per entire crop area															
Electricity	0.32		0.06	0.39	1.4	1.9				0.48			0.0	0.0	1.7
Diesel	1.1	5.2	0.04		3.6	4.0	7.6	0.67	2.8	0.22	1.1	0.16	0.0	0.0	3.6
Stimulant crops															
Per irrigated area															
Electricity	2.2		6.0							4.0			6.0	4.0	
Diesel	7.9		4.0						9.0	1.8	9.0	9.0	4.0	1.8	
Per entire crop area															
Electricity	0.05		0.11							0.06			0.0	0.07	
Diesel	0.17		0.07						0.38	0.03	0.05	0.29	0.0	0.03	
Seed cotton															
Per irrigated area															
Electricity	3.8		6.0	2.5	4.0	5.0				4.0			6.0	4.0	5.0
Diesel	6.5	20	4.0		11	11	9.0	9.0	9.0	1.8	9.0	9.0	4.0	1.8	11
Per entire crop area															
Electricity	1.6		5.2	1.3	3.4	2.0				1.6			5.4	1.1	1.9
Diesel	2.8	19	3.4		9.0	3.8	7.4	0.63	0.54	0.69	0.85	0.16	3.6	0.50	4.0

[1] Assumed range from 2.0 GJ ha^{-1} electricity for regions with only surface-drawn water (mainly based on [144]) to 10 GJ ha^{-1} electricity for regions with a high degree with groundwater-sourced water (mainly based on [207]). Additional sources are [138,208–212]. Diesel pumps are assumed to use three times more energy compared to electric for providing the same pump work.
[2] In regions with a significant degree of gravity-fed irrigation of rice (East Asia and China), we assume 50% of the energy use in surface-fed irrigation (1.0 GJ ha^{-1} electricity).

Table S26 Greenhouse production: extent and type of production, yields, and energy and materials use. Yields are net amounts after discarded produce. Data is not shown for regions and crops with a production of less than 0.05 Tg dry matter per year. For sources, see table footnotes. For details on methodology, see sections 1.3.2 and 1.4.5.

	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Greenhouse type[1] (% of production; average all crops)															
Heated				29%		3.0%	20%	25%							20%
Unheated		100%	100%	71%	100%	97%	80%	75%	100%	100%	100%	100%	100%	100%	80%
Share greenhouse production (% of all crop production)															
Tomato	36%	15%	65%	50%	30%	20%	80%	25%	20%	1.0%	5.0%	5.0%	65%	1.0%	0.9%
Cucumber	36%	15%	65%	65%	30%	20%		25%					65%		2.0%
Pepper (Capsicum)	51%		65%	65%	30%	20%	80%		20%		5.0%		65%		
Eggplant	47%		65%	65%	30%					1.0%			65%	1.0%	
Net yield[1] (kg fresh m^{-2} $year^{-1}$)															
Heated type															
Tomato				46		40									
Cucumber				65											
Pepper (Capsicum)				25											
Eggplant				35											
Unheated type															
Tomato			13	12	13	11			13				11		
Cucumber			12	12	12								12		
Pepper (Capsicum)			7.0	7.0	7.0								7.0		
Eggplant			10	10	10								10		
Energy use[2] (MJ m^{-2} $year^{-1}$)															
Heating (fossil gas)				1,470		1,260									
Lighting (heated type only)				36		18									
Irrigation (electricity)			1.8	3.6	1.8	3.6			1,8				1.8		
Materials use[3]															
Heated type															
Concrete															
Amount (kg m^{-2})				60		60									
Lifetime (years)				40		40									
Glass															
Amount (kg m^{-2})				12		12									
Lifetime (years)				40		40									
Steel															
Amount (kg m^{-2})				11		11									
Lifetime (years)				40		40									
Aluminum															
Amount (kg m^{-2})				2.8		2.8									

	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Lifetime (years)				40		40									
Plastic – long lasting															
Amount (kg m^{-2})				0.26		0.26									
Lifetime (years)				20		20									
Plastic – short lasting															
Amount (kg m^{-2})				0.08		0.08									
Lifetime (years)				3.0		3.0									
Unheated type															
Concrete															
Amount (kg m^{-2})			45	45	45	45			45				45		45
Lifetime (years)			40	40	40	40			40				40		40
Steel															
Amount (kg m^{-2})			8.0	8.0	8.0	8.0			8.0				8.0		8.0
Lifetime (years)			40	40	40	40			40				40		40
Plastic – long lasting															
Amount (kg m^{-2})			0.33	0.33	0.33	0.33			0.33				0.33		0.33
Lifetime (years)			20	20	20	20			20				20		20
Plastic – short lasting															
Amount (kg m^{-2})			0.68	0.68	0.68	0.68			0.68				0.68		0.68
Lifetime (years)			3.0	3.0	3.0	3.0			3.0				3.0		3.0

[1] Extent of production and yields estimated from [213–215] (all regions); [216] (EAS/China); [62,63,65,217] (EUR); [66,67] (MEA); [218] (NAM/USA); [68] (OCE); [69] (SAM/Brazil); [219] (SAS/India).
[2] Based on [62,63,65–68].
[3] Based on [62,63,67].

Table S27 Use of drained organic soils in crop and pasture production. Numbers in percent drained organic soils of total physical land area occupied by each crop. Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per year. Sources: Estimates of this study (see 1.4.2) based on sources shown in table footnotes.

Crop Category[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cereals															
Wheat	0.65	0.15	0.29	2.5	0.01	0.99	0.06	0.31	0.04	0.02	0.01	0.10	0.21	0.02	0.72
Maize	1.0	0.02	1.9	1.1	0	1.4	0.25	1.2	0.09	0.33	0.33	0.10	1.9	0.34	1.7
Rice – irrigated/high input	1.1	0.69	1.5	0.13	2.6	0.04	0.42	3.8	0.33	0.70	0.17	0.17	1.2	0.67	0.02
Rice – low input	1.2		2.6		0				0.47	1.4	0.30	0.24		1.4	
Barley	0.97	0.02	0.32	2.8	0	1.3	0.04	0.44	0.03	0.01	0.01	0.02	0.35	0.01	0.31
Sorghum	0.07		1.5	0.58	0	0.05	0.03	0.56	0.02	0.01	0.04	0	1.6	0.01	0
Millet	0.44		0.86							0.03	0.03		1.0	0.03	0
Oats	1.4	0.02	1.1	2.0	0	2.8	0.53	0.9	0.11		0.09	0.07	0.66		1.6
Rye	1.6		1.1	2.0	0	2.8		0.9					0.66		
Other	1.0	0.02	1.1	2.0	0	2.8		0.9	0.11	0.44	0.09	0.07	0.66	3.3	1.6
Oil and protein field crops															
Soybean	1.5	0.03	4.6	0.53	0.01	1.9		21.1	0.06	0.04	0.07	0.08	4.9	0.04	1.9
Rapeseed	1.4	0.01	0.28	3.2	0.01	1.9	0.04	0.75	0.07	0.67		0	0.28	0.72	0.25
Peanut	0.28		0.53		0.0	3.8			0.05	0.04	0.15		0.39	0.03	4.2
Sunflower	0.33	0	0.9	0.69	0.01	0.45		0.11	0	0.11	0.14	0	1.1	0.15	0.36
Sesame	0.09		0.25		0.23					0.13	0.03		0.13		
Common bean	0.73	0	2.8	6.1	0.19	0.60			0.08	0.11	0.08	0.05	2.9	0.11	1.7
Faba bean	2.0		2.8	6.1	0.19	0.60	0.15	11.0	0.08	0.11	0.08		2.9		1.7
Cowpea	0.36		6.5								0.31				
Chickpea	0.13		0.24												
Peas	1.5	0.01	3.4	3.0	0.07	1.4	0.02	0.93	0.09	0.32	0.06		4.0	0.10	0.18
Pigeon pea	0.02		0.09								0.08				
Lentil	0.17	0	1.1		0.03						0		1.2	0.32	0.01
Other	0.72	0.01	2.5	0.30	0	0.50		0.49		0.15	1.3		1.3	0.13	0.12
Oil tree crops and tree nuts															
Oil palm	12.5		16.2			0.47			0.84		1.6	0	0		
Coconut palm	3.2		5.5			0.09			0.82	0.47	0.10	3.9		0.57	
Olive	0.26			0.55	0.01		0.02	0.14	0.03						
Cashewnut	0.17								0.37	0.08	0.10			0.08	
Almond	0.29	0.03	0.68	0.55	0.01	0.36			0.37						0.39
Other tree nuts	0.32	0.03	0.68	0.55	0.01	0.36			0	0.08	0.10	0.02	0.30	0.08	0.39
Starchy root crops															
Cassava	0.96		0.42			0.87			0.68	0.36	1.1	0.73	0	0.39	
White potato	1.5	0.27	1.0	3.8	0	1.1	0.2	2.3	0.11	1.3	0.20	0.05	0.92	1.6	1.1
Sweet potato	1.1		0.90	0		2.5			0.13	1.3	1.3	0.08	0.07	1.3	2.6
Yams	1.7		8.3						0.82		1.6	0.73			
Sugar crops															
Sugar cane	0.32	0	0.35		0.06	5.0	0.11		0.05	0.04	0.10	0.01	0.01	0.04	15.4

Crop Category[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Sugar beet	2.3	0	3.7	3.8	0.23	3.5		0.16	0.43	0	0		1.7		3.5
Vegetables	0.7	0.36	0.30	1.5	0.04	1.5	0.40	0.67	0.13	0.43	2.2	0.05	0.19	0.42	2.9
Fruits															
Grape	0.22	0	0.50	0.24	0.01	0.26	0.20	0.69	0.15	0.08	0	0.04	0.48	0.10	0.28
Mango	0.67		0.54		0.03	0.71			1.5	0.81	0.12	0.57	0.21	0.81	
Plantain	0.63		2.2		0				0.63	0.07	0.52				
Banana	0.80		1.9		0	0.13	0.01		0.55	1.3	0.19	0.22	0	1.3	
Apple	0.50	0	0.54	1.0	0	0.35	0.05	0.52	0.75	0.12	0.10	0.12	0.19	0.08	0.48
Orange	0.37		0.21	0.13	0.06	1.07	0.10		0.15	0.76	0.04	0.07	0.10	0.82	3.2
Other - Temperate	0.38	0	0.54	1.0	0	0.35	0.05	0.52	0.18	0.12	0.10	0.12	0.19	0.08	0.48
Other - Tropical	0.52		0.54		0.03	0.71	0.06		0.61	0.81	0.12	0.57	0.21	0.81	
Stimulants															
Cocoa	0.65		1.9						0.46		0.48	0.41	0		
Coffee	0.45		1.2			0.16			0.17	0.14	0.43	0.01	0.01	0.14	
Tea	0.08		0.07		0				0.21	0.10	0.12	0.01	0.03	0.44	
Forage															
Grass/legumes	2.0	0.40	1.2	4.1	0.02	2.1	0.30	2.0		0.36	0		0.59	0.36	1.2
Whole cereals	0.84		1.9	1.0	0	1.4	0.25		0.06			0.10	1.9		1.7
Fiber crops															
Seed cotton	0.15	0	0.25	0.73	0	0.89	0.59		0	0.01	0.06	0	0.26	0.01	0.93
Perm. & semi-perm. pasture	0.24	0.06	0.59	3.8	0	0.18	0.01	0.76	0.08	0.20	0.10	0.06	0.50	0.28	0.91
Originally forest	0.92	0.06	0.87	4.9	0	0.64	0.07	1.2	0.16	0.43	0.78	0.10	0.48	0.45	0.16
Orig. trop./sub-trop. grass-/woodland	0.08	0.0	10.8	0.06	0	0.15	0	7.1	0.04	0.50	0.03	0.01	11.0	0.93	0.13
Orig. temp. & montane grassl.	0.23	0.17	0.52	0.13	0	0.12	0.01	0.06	0	0	0	0	0.53	0	0.1
Originally xeric grassland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

[1] Organic soil distribution from [29]. Crop and pasture distribution from [220] (permanent and semi-permanent pastures), [43] (grapes and forage crops), and [23] (all other crops).

A3. Exogenous input data: Livestock and aquaculture production

Table S28 Herd characteristics and productivity of livestock systems. Data is not shown for regions with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes.

Parameter[1]	**CAS**	**EAS**	**EUR**[2]	**MEA**	**NAM**[3]	**OCE**[4]	**RUS**	**SAM**[5]	**SAS**	**SSA**[6]	**Brazil**[7]	**China**	**India**	**USA**[8]
Liveweight adults (kg)														
Dairy cows	350	500	650	500	700	470	550	500	300	300	470	500	300	700
Beef cows	500	500	600		650	550	550	420		300	450	500		650
Ewes/does	45	55	55	50		70		40	35	35		55	35	
Sows		250	250		250	250	250	200	120	120	200	250	120	250
Laying hens	1.7	1.6	1.7	1.6	1.7	1.7	1.7	1.7	1.7	1.5	1.7	1.6	1.7	1.7
Reproduction rates (live born or hatched/female/year)														
Dairy calves	0.77	0.80	0.87	0.84	0.87	0.87	0.89	0.66	0.61	0.60	0.66	0.80	0.61	0.91
Beef calves	0.85	0.85	0.93		0.93	0.93	0.95	0.70		0.58	0.70	0.85		0.97
Lambs/kids	1.26	1.62	1.35	1.35		1.53		0.99	1.08	0.90		1.85	0.90	
Piglets		24	31		26	37	37	18	13	13	18	24	13	31
Chicks (meat-type)	120	130	180	120	210	210	210	140	140	80	140	140	160	220
Age first birth (months)														
Dairy cows	33	32	28	31	26	26	26	34	36	42	34	31	36	25
Beef cows	29	30	27		25	25	25	38		40	38	29		24
Ewes/does	18	16	18	18		18		24	24	24		14	24	
Replacement rates														
Dairy cows	0.15	0.28	0.35	0.25	0.35	0.30	0.30	0.20	0.10	0.10	0.20	0.28	0.12	0.35
Beef cows	0.15	0.15	0.20		0.20	0.20	0.20	0.15		0.10	0.15	0.15		0.20
Ewes/does	0.20	0.15	0.20	0.20		0.20		0.15	0.15	0.15		0.15	0.15	
Sows		0.50	0.50		0.50	0.5	0.50	0.35	0.20	0.20	0.35	0.50	0.20	0.50
Milk/egg yield (kg delivered/female/year)[9]														
Dairy cows	1,550	3,510	7,010	2,960	9,030	5,230	4,710	2,620	2,220	630	2,290	2,940	2,370	10,200
Dairy ewes/does	27	33	160	52					120	38		32	140	
Laying hens	11.5	9.9	13.1	10.4	16.0	15.8	15.8	13.4	12.5	5.8	13.4	10.7	11.8	16.6
Wool yield (kg/ewe/year)[10]	2.8	1,7	1,5	3,3		7,0		3,5	0,5	0,3		1,9	0,4	
Liveweight at slaughter (kg)														
Dairy bulls/steers	430	260	500	480	630	410	420	530	240	380	660	330	100	660
Beef bulls/steers	460	270	530		670	430	440	570		410	720	390		690
Dairy lambs/kids	33	30	27	37					20	23		29	20	
Meat lambs/kids	41	36	33	45		43		37	25	28		35	24	
Hogs		106	128		132	108	127	124	54	70	127	109	54	135

Parameter[1]	CAS	EAS	EUR[2]	MEA	NAM[3]	OCE[4]	RUS	SAM[5]	SAS	SSA[6]	Brazil[7]	China	India	USA[8]
Chickens (meat-type)	2.6	1.8	2.2	1.8	2.7	2.5	2.4	3.0	1.9	1.9	3.2	2.0	2.1	2.8
Slaughter age (months/days)														
Cattle bulls/steers/heifers	16	12	18	16	21	13	11	53	95	83	65	12	95	17
Lambs/kids	17	3.0	9.1	12		8.5		31	10	16		3.0	12	
Hogs (days)		182	175		200	135	170	290	280	390	280	178	260	190
Chickens (days)	130	55	43	72	57	45	39	82	44	106	69	62	49	57
Carcass yield (of whole body)[11]														
Dairy cows	47%	47%	47%	47%	47%	47%	47%	46%	44%	44%	46%	47%	43%	47%
Beef cows	50%	50%	50%		50%	50%	50%	48%		46%	48%	50%		50%
Dairy bulls/steers	52%	52%	52%	52%	52%	52%	52%	51%	46%	46%	51%	52%	46%	54%
Beef bulls/steers	55%	55%	55%		55%	55%	55%	53%		51%	53%	55%		57%
Lambs/kids	47%	47%	47%	47%		47%		45%	45%	45%		47%	45%	
Hogs		70%	70%		70%	70%	70%	68%	65%	65%	69%	70%	65%	70%
Broilers	70%	73%	77%	70%	77%	77%	77%	75%	76%	70%	77%	73%	76%	77%
Mortality rates – Adults (% per year of stock)														
Dairy cows	1.1%	1.8%	1.3%	1.3%	1.3%	1.1%	1.1%	1.4%	1.7%	1.1%	1.4%	1.4%	1.5%	1.3%
Beef cows	0.6%	0.7%	0.5%		0.5%	0.5%	0.5%	0.7%		0.8%	0.7%	0.5%		0.5%
Ewes/does	3.0%	3.0%	3.0%	3.0%		3.0%		3.0%	3.0%	3.0%		3.0%	3.0%	
Sows		7.0%	7.0%		7.0%	7.0%	7.0%	7.0%	3.5%	3.5%	7.0%	7.0%	3.5%	7.0%
Laying hens	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
Mortality rates – Young (% of born or hatched)														
Cattle/buffalo calves	10.0%	14.0%	7.5%	7.5%	7.5%	7.5%	7.5%	15.0%	30%	19.0%	15.0%	10.0%	30%	7.5%
Cattle/buffaloes, weaned	4.0%	5.5%	3.0%	3.0%	3.0%	3.0%	3.0%	6.0%	8.5%	7.5%	6.0%	4.0%	8.5%	3.0%
Lambs/kids, newborn	16.0%	12.0%	12.0%	12.0%		12.0%		18.0%	18.0%	20.0%		12.0%	18.0%	
Lambs/kids, weaned	4.0%	3.0%	3.0%	3.0%		3.0%		4.5%	4.5%	5.0%		3.0%	4.5%	
Pigs, piglets		15.0%	15.0%		15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%
Pigs, weaners/hogs		3.5%	3.5%		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Chickens, broilers	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	6.8%	4.5%	4.5%	4.5%	4.5%
Liveweight gain from birth to slaughter (kg/head/day)														
Dairy bulls/steers	0.84	0.61	0.83	0.93	0.94	0.94	1.15	0.30	0.076	0.14	0.32	0.82	0.027	1.19
Beef bulls/steers	0.89	0.63	0.88		0.98	0.99	1.20	0.33		0.15	0.35	0.98		1.23
Dairy lambs/kids	0.056	0.28	0.084	0.093		0.12		0.027	0.057	0.039		0.27	0.045	
Meat lambs/kids	0.070	0.35	0.11	0.12		0.15		0.034	0.071	0.049		0.33	0.057	
Hogs		0.58	0.72		0.65	0.78	0.75	0.43	0.19	0.18	0.45	0.61	0.20	0.71
Chickens (meat type) [12]	0.020	0.032	0.051	0.024	0.047	0.055	0.060	0.036	0.043	0.018	0.046	0.032	0.042	0.048
Aggregate meat productivity (kg carcass/head/year)														

Parameter[1]	CAS	EAS	EUR[2]	MEA	NAM[3]	OCE[4]	RUS	SAM[5]	SAS	SSA[6]	Brazil[7]	China	India	USA[8]
All cattle & buffaloes	59.8	56.1	88.5	73.8	108	86.4	88.3	44.3	11.8	18.3	46.0	73.3	8.4	128
Beef cattle & buffaloes	80.2	56.9	94.4		110	91.1	99.1	44.8		20.7	47.1	77.9		130
All sheep & goats	7.0	14.5	8.3	8.9		12.9		3.8	4.5	3.7		16.2	3.7	
Pigs		128	160		147	174	170	93.8	38.0	38.2	100	134	38.0	159
Chickens (meat type)	4.8	8.0	13.4	6.0	12.5	14.5	15.8	9.4	11.0	4.3	12.1	8.0	11.0	13.0

1 [221, 222, 223, 224, 225, 39]
2 [226, 227, 228, 229, 230]
3 [231, 232, 233, 234]
4 [49, 235, 236, 237]
5 [155, 238, 239, 240, 241]
6 [242,243]
7 [155,240,241]
8 [231–234]
9 FAOSTAT. Dairy cow yield converted to ECM using Eq. 20 in [244].
10 Estimate based on FAOSTAT data on wool production in each region.
11 [221, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256]
12 [257–259]

Table S29 Composition and energy value of whole milk from ruminant dairy herds. Numbers are regional production-weighted averages for cattle and buffalo, and sheep and goats, respectively. Data is not shown for regions with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes.

Parameter[1]	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cattle/buffalo whole milk														
Dry matter (% of fresh weight)	12.9%	12.9%	12.5%	12.9%	12.2%	13.5%	12.4%	12.5%	15.2%	14.9%	12.5%	12.9%	15.0%	12.2%
Crude protein (% DM)	27.1%	26.1%	25.6%	27.1%	26.2%	27.4%	25.8%	25.6%	25.5%	27.5%	25.6%	26.1%	25.5%	26.2%
Lipid (% DM)	31.8%	31.8%	32.0%	31.8%	30.3%	33.3%	31.5%	32.0%	36.6%	36.9%	32.0%	31.8%	36.4%	30.3%
Carbohydrate (% DM)	37.2%	36.6%	38.4%	37.2%	39.3%	35.6%	38.7%	38.4%	32.8%	36.2%	38.4%	36.6%	33.0%	39.3%
Sheep/goat whole milk														
Dry matter (% of fresh weight)	14.7%	15.6%	14.9%	15.6%					12.6%	13.9%		16.3%	12.6%	
Crude protein (% DM)	31.2%	31.6%	31.2%	31.5%					29.9%	30.7%		31.9%	30.0%	
Lipid (% DM)	30.2%	33.5%	33.0%	33.5%					30.8%	32.2%		34.0%	30.9%	
Carbohydrate (% DM)	30.2%	29.4%	30.1%	29.4%					32.8%	31.1%		28.7%	32.8%	

1 39,242,260,261

Table S30 Composition and energy value of forage crops and pasture. Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per year. Composition and energy value of other feeds are given in Tables 25, 26, 29-30 in the ClimAg model description.. For sources, see table footnotes.

Parameter[1]	**CAS**	**EAS**[2]	**EUR**[3]	**MEA**	**NAM**[4]	**OCE**[5]	**RUS**	**SAM**[6]	**SAS**	**SSA**[7]	**Brazil**[8]	**China**[9]	**India**	**USA**[10]
Protein (crude) content (% DM)														
Whole maize		7.5%	7.5%	7.5%	7.5%	7.5%		7.5%			7.5%	7.5%		7.5%
Grasses and/or legumes on cropland, harvested and conserved (silage, hay)	12.0%	12.0%	12.0%	12.0%	13.0%	12.0%	12.0%	12.0%	12.0%	12.0%	12.0%	12.0%	12.0%	13.0%
Grasses and/or legumes on cropland, grazed			13.0%		13.0%	13.0%	13.0%							13.0%
Permanent & semi-permanent pasture														
Dairy cows														
Wet/Warm season	10.5%	11.0%		11.5%		14.0%	12.0%	10.5%	11.5%	9.5%	10.5%	11.0%	11.5%	
Dry/Cold season	8.4%	8.8%		9.2%		11.2%		8.4%	9.2%	7.6%	8.4%	8.8%	9.2%	
Beef cattle, other dairy cattle, sheep														
Wet/Warm season	11.0%	10.5%	12.5%	11.0%	11.0%	11.5%	11.5%	10.0%	10.5%	10.0%	10.0%	10.5%	10.5%	11.0%
Dry/Cold season	8.8%	8.4%		8.8%	8.8%	9.2%		8.0%	8.4%	8.0%	8.0%	8.4%	8.4%	
Neutral detergent fiber (% DM)														
Permanent & semi-permanent pasture														
Dairy cows														
Wet/Warm season	65%	60%	55%	60%		50%	55%	65%	65%	70%	65%	60%	65%	
Dry/Cold season	78%	72%		72%		60%		78%	78%	84%	78%	72%	78%	
Beef cattle, other dairy cattle, sheep														
Wet/Warm season	65%	66%	60%	60%	65%	65%	65%	70%	70%	70%	70%	66%	70%	65%
Dry/Cold season	78%	79%		72%	78%	78%		84%	84%	84%	84%	79%	84%	
Digestible energy (MJ/ kg DM)														
Whole maize silage		12.5	12.5	12.5	12.5	12.5		12.5			12.5	12.5		12.5
Grasses and/or legumes on cropland, harvested and conserved (silage, hay)														
Dairy cows	11.5	12.0	12.5	12.0	13.0	13.0	12.0	12.0	12.0	11.0	12.0	12.0	12.0	13.0
Beef cows, beef/dairy replacers, sheep	10.5	10.5	11.0	10.5	11.0	11.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5	11.0
Growing cattle	11.0	11.0	11.5	11.0	11.5	11.5	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.5
Grasses and/or legumes on cropland, grazed			12.0		12.0	12.0	12.0							12.0
Permanent & semi-permanent pasture														
Dairy cows														
Wet/Warm season	10.0	11.0		11.0		13.5	11.5	10.5	10.5	9.5	10.5	11.0	10.5	
Dry/Cold/cold season	8.0	8.8		8.8		10.8		8.4	8.4	7.6	8.4	8.8	8.4	
Beef cows, other dairy cattle, sheep														
Wet/Warm season	10.5	10.5	11.0	10.5	11.0	11.0	11.0	10.0	10.0	10.0	10.0	10.5	10.0	11.0

Parameter[1]	CAS	EAS[2]	EUR[3]	MEA	NAM[4]	OCE[5]	RUS	SAM[6]	SAS	SSA[7]	Brazil[8]	China[9]	India	USA[10]
Dry/Cold season	8.4	8.4		8.4	8.8	8.8		8.0	8.0	8.0	8.0	8.4	8.0	
Forage on forest and other land														
Wet/Warm season									10.0				10.0	
Dry/Cold season									8.0				8.0	

1 [262], [39], [224], [221], [263]
2 [264]
3 [228]
4 [265,266]
5 [49]
6 [267]
7 [242]
8 [267]
9 [264]
10 [265,266]

Table S31 Manure management systems in livestock production. Numbers refer to percent of animals in different management systems excluding manure excreted on pastures. For broilers, deep bedding systems were assumed to be used in all regions. For sources, see table footnotes.

Parameter[1]	CAS[2]	EAS [4]	EUR[3]	MEA[4]	NAM[5]	OCE[6]	RUS[7]	SAM[8]	SAS[9]	SSA[10]	Brazil[11]	China[12]	India[13]	USA[14]
Dairy cows & replacement heifers														
Slurry with outdoor storage		5.0	53.0		4.0							5.0		4.0
Slurry stored below confinements					15.0									15.0
Anaerobic lagoon					42.0	100.0								42.0
Separate solid/liquid storage	28.0	42.5	34.0	28.0	28.0		100.0	12.0	2.0	40.0	10.0	40.0	2.0	28.0
Drylot	68.5	42.5		68.5	3.0			88.0	48.0	50.0	90.0	42.5	48.0	3.0
Deep bedding			5.0											3.0
Daily spread			1.0		3.0									
Anaerobic digester		5.0	8.0		5.0							7.5		5.0
Burnt as fuel	3.5	5.0		3.5					50.0	10.0		5.0	50.0	
Beef cattle & dairy bulls/heifers														
Slurry with outdoor storage			27.0		2.0		11.0							2.0
Anaerobic lagoon						2.0								
Separate solid/liquid storage	23.0	47.5	53.0		74.0		89.0	53.0	2.0	30.0	48.0	47.5	2.0	74.0
Drylot	70.0	47.5			24.0	98.0		47.0	48.0	60.0	52.0	47.5	48.0	24.0
Deep bedding			15.0											
Daily spread			2.0											
Anaerobic digester			3.0											
Burnt as fuel	7.0	5.0							50.0	10.0		5.0	50.0	
Sheep/goats														
Separate solid/liquid storage	6.0	92.0	95.0	6.0		50.0		85.0	15.0	50.0		92.0	15.0	
Deep bedding			5.0											
Drylot	94.0	8.0		94.0		50.0		15.0	85.0	50.0		8.0	85.0	
Pigs														
Slurry with outdoor storage		15.0	46.0		12.5		81.0	55.0	23.0	7.0	60.0	15.0	23.0	12.5
Slurry stored below confinements		10.0	23.0		76.0				2.0	1.0		10.0	2.0	76.0
Anaerobic lagoon		10.0			11.0	60.0		10.0	12.0		15.0	10.0	12.0	11.0
Separate solid/liquid storage		15.0	15.0			25.0	19.0	7.5	13.0	6.0	5.0	15.0	13.0	
Drylot		30.0						17.5	42.0	86.0	10.0	30.0	42.0	
Deep bedding			10.0			10.0								
Anaerobic digester		20.0	6.0		0.5	5.0		10.0	8.0		10.0	20.0	8.0	0.5
Laying hens														
Anaerobic lagoon	15.0			15.0										
Semi-solid, stored below confinements	67.0	100.0	25.0	67.0	75.0	100.0	100.0	60.0			60.0	100.0		75.0
Semi-solid, frequently removed to outdoor storage (manure belt)	13.0		25.0	13.0	15.0			40.0	75.0		40.0		75.0	15.0
Drylot									25.0	90.0			25.0	
Deep bedding (indoor cage free prod.)	5.0		50.0	5.0	10.0					10.0				10.0

[1] Based on [39] in addition to the sources mentioned for each region.
[2] Data for MEA used.
3 [268], [269], [270]
4 [221]
5 [271], pp 4–70; [272]
6 [273], [274]
7 [275]
8 [221], [240], [222]
9 [31], p. 62.; [222]
10 [221], [276]
11 [221,240,277], [222]
12 [278] [221]
13 [31], p. 62.; [222]
14 [271], pp 4–70

Table S32 Energy use for animal housing, milking and manure management. Numbers in MJ of energy per head per housing-year (see section 1.5.4 for details), except for milking which is in MJ per milk produced. For sources, see table footnotes.

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Dairy farms[1]														
Heating - *fuel*														
Per cow	0.0	0.0	600	0.0	600	600	600	0.0	0.0	0.0	0.0	0.0	0.0	600
Per young (ex. calves)	0.0	0.0	450	0.0	450	450	450	0.0	0.0	0.0	0.0	0.0	0.0	450
Feeding, ventilation, manure mgmt.														
Electricity														
Per cow	0.0	600	1.200	0.0	1.200	1.200	1.200	0.0	0.0	0.0	0.0	600	0.0	1.200
Per young (ex. calves)	0.0	450	900	0.0	900	900	900	0.0	0.0	0.0	0.0	450	0.0	900
Fuel														
Per cow	0.0	600	1.200	0.0	1.200	1.200	1.200	0.0	0.0	0.0	0.0	600	0.0	1.200
Per young (ex. calves)	0.0	450	900	0.0	900	900	900	0.0	0.0	0.0	0.0	450	0.0	900
Milking – *electricity – per milk produced*	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.09	0.0	0.18	0.18	0.09	0.18
Beef farms[2]														
Feeding, ventilation, manure mgmt.														
Electricity														
Per cow	300	300	300	300	300	300	300	150	0.0	0.0	150	300	0.0	300
Per young (ex. calves)	230	230	230	230	230	230	230	100	0.0	0.0	100	230	0.0	230
Fuel														
Per cow	500	500	500	500	500	500	500	250	0.0	0.0	250	500	0.0	500
Per young (ex. calves)	380	380	380	380	380	380	380	190	0.0	0.0	190	380	0.0	380
Sheep/goat farms[2]														
Feeding, ventilation, manure mgmt.														
Electricity														
Per ewe	0.0	50	50	0.0		50		0.0	0.0	0.0		50	0.0	
Per young (ex. lambs)	0.0	38	38	0.0		38		0.0	0.0	0.0		38	0.0	
Fuel														
Per ewe	0.0	50	50	0.0		50		0.0	0.0	0.0		50	0.0	
Per young (ex. lambs)	0.0	38	38	0.0		38		0.0	0.0	0.0		38	0.0	
Pig farms[3]														
Heating - *fuel*														
Per sow		520	520		520	520	520	520	0.0	0.0	520	520	0.0	520
Per piglets		29	29		29	29	29	29	0.0	0.0	29	29	0.0	29
Per weaners and hogs		7.2	7.2		7.2	7.2	7.2	7.2	0.0	0.0	7.2	7.2	0.0	7.2
Feeding, ventilation, manure - *electricity*														
Per sow		360	360		360	360	360	360	0.0	0.0	360	360	0.0	360
Per piglets		7.2	7.2		7.2	7.2	7.2	7.2	0.0	0.0	7.2	7.2	0.0	7.2

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Per weaners and hogs		36.0	36.0		36.0	36.0	36.0	36.0	0.0	0.0	36.0	36.0	0.0	36.0
Egg farms[4]														
Feeding, ventilation, manure - *electricity*	12.5	9.4	12.5	9.4	12.5	12.5	12.5	12.5	12.5	3.1	12.5	12.5	12.5	12.5
Chicken meat farms[5]														
Heating – *fuel*	0.0	1.4	2.8	0.0	2.8	2.8	2.8	2.8	2.8	0.0	2.8	1.4	2.8	2.8
Feeding, ventilation, manure - *electricity*	0.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.25	0.5	0.5	0.5	0.5

1 221, 224, 279
2 61
3 222, 279
4 279
5 280

Table S33 Feed baskets and yields per pond area in farmed fish and seafood production. Feed basket data in % of dry matter; yields in Mg whole fish ha^{-1} $year^{-1}$. Note that the feed basket numbers refer only to external feed, i.e. excluding feed naturally present in the water body (see section 1.6.1). Data is not shown for regions with a production of less than 0.05 Tg dry matter per year. For sources, see table footnotes.

Taxa[1]	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Carps[2]														
Cereal grains, cassava (meal)		14.9		14.9					14.9	14.8		14.9	14.9	
Soybeans, faba beans, peas														
Flour and starch, broken rice		30.5		30.5					30.4	30.3		30.5	30.5	
Vegetable oil														
Fish oil														
Brans		26.4		26.4					26.4	26.3		26.4	26.4	
Gluten meal														
Oil meal		19.8		19.8					19.9	20.2		19.8	19.8	
Livestock meal		7.4		7.4					7.4	7.4		7.4	7.4	
Fish and shrimp meal		1.1		1.1					1.1	1.1		1.1	1.1	
Protein content of basket		21.9		22.3					21.0	19.5		22.4	21.0	
Share external feed		28		28					28	28		28	28	
Yield per pond area		12.5		10.0					11.1	11.1		12.5	14.3	
Tilapias[3]														
Cereal grains, cassava (meal)		4.9						5.0	4.9	4.9	5.0	5.0		
Soybeans, faba beans, peas														
Flour and starch, broken rice		14.7						14.8	14.7	14.5	14.8	14.7		
Vegetable oil		2.3						2.3	2.3	2.2	2.3	2.3		
Fish oil		0.6						0.6	0.6	0.6	0.6	0.6		
Brans		9.4						9.4	9.4	9.3	9.4	7.4		
Gluten meal														
Oil meal		60.3						60.1	60.4	60.8	60.1	60.3		
Livestock meal														
Fish and shrimp meal		7.4						7.5	7.4	7.3	7.5	7.4		
Pigments, vitamins, etc.		0.3						0.3	0.3	0.3	0.3	0.3		
Protein content of basket		36.8						39.7	35.7	31.3	39.7	38.4		
Share external feed		92						92	92	92	92	92		
Yield per pond area		18.2						16.7	16.7	18.2	16.7	20.0		
Catfish and other freshwater fish[4]														
Cereal grains, cassava (meal)		12.8						12.9	12.8	12.7		12.8	12.8	
Soybeans, faba beans, peas														
Flour and starch, broken rice		12.7						12.7	12.7	12.6		12.7	12.7	
Vegetable oil														
Fish oil		2.2						2.2	2.2	2.2		2.2	2.2	

Taxa[1]	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Brans		25.2						25.3	25.2	25.0		25.2	25.2	
Gluten meal														
Oil meal		35.7						35.5	35.8	36.2		35.7	35.8	
Livestock meal		3.7						3.7	3.7	3.7		3.7	3.7	
Fish and shrimp meal		7.4						7.4	7.4	7.3		7.4	7.4	
Pigments, vitamins, etc.		0.3						0.3	0.3	0.3		0.3	0.3	
Protein content of basket		30.2						31.8	29.3	26.8		31.1	29.1	
Share external feed		81						81	81	81		81	81	
Yield per pond area		14.3						15.4	15.4	15.4		16.7	18.2	
Salmonids[5]														
Cereal grains, cassava (meal)														
Soybeans, faba beans, peas			5.5	5.5	5.5			5.5						
Flour and starch, broken rice			8.6	8.6	8.6			8.6						
Vegetable oil			21.5	21.5	21.5			21.5						
Fish oil			12.9	12.9	12.9			12.9						
Brans														
Gluten meal			9.7	9.7	9.7			9.7						
Oil meal			22.0	22.0	22.0			22.0						
Livestock meal														
Fish and shrimp meal			17.2	17.2	17.2			17.2						
Pigments, vitamins, etc.			2.7	2.7	2.7			2.7						
Protein content of basket			33.5	34.8	32.7			34.9						
Share external feed			100	100	100			100						
Other non-freshwater fish[6]														
Cereal grains, cassava (meal)														
Soybeans, faba beans, peas														
Flour and starch, broken rice		15.4							15.3	15.2		15.4	15.3	
Vegetable oil														
Fish oil		5.5							5.5	5.5		5.5	5.5	
Brans														
Gluten meal														
Oil meal		49.1							49.2	49.6		49.1	49.2	
Livestock meal		10.4							10.4	10.3		10.4	10.4	
Fish and shrimp meal		14.6							14.5	14.4		14.6	14.5	
Pigments, vitamins etc.		5.0							5.0	4.9		5.0	5.0	
Protein content of basket		42.9							41.3	37.9		44.1	41.1	
Share external feed		82							82	82		82	82	
Crustaceans[7]														
Cereal grains, cassava (meal)														

Taxa[1]	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Soybeans, faba beans, peas														
Flour and starch, broken rice		23.8			23.9			23.9	23.8			23.8	23.8	
Vegetable oil		8.2			8.3			8.2	8.2			8.2	8.2	
Fish oil		2.2			2.2			2.2	2.2			2.2	2.2	
Brans														
Gluten meal														
Oil meal		29.9			29.7			29.7	30.0			29.9	30.0	
Livestock meal														
Fish and shrimp meal		31.0			31.0			31.0	30.9			31.0	30.9	
Pigments, vitamins, etc.		4.9			5.0			4.9	4.9			4.9	4.9	
Protein content of basket		41.1			43.1			43.6	41.0			41.8	40.7	
Share external feed		86			86			86	86			86	86	
Yield per pond area		4.5			4.5			5.0	5.0			5.0	5.0	

[1] Share external feed from [83]. Yields are estimated from various sources, see section 1.6.1.
[2] Feed basket from [17].
[3] Feed basket from [84]
[4] Feed basket from [84]
[5] Feed basket from [85]
[6] Feed basket from [17]
[7] Feed basket from [84]

Table S34 Energy use in farmed fish and seafood production. Numbers in MJ per kg fresh weight of feed for the feed mills and MJ per kg fresh weight of whole fish/crustacean for the farms. Data is not shown for regions with a production of less than 0.05 Tg dry matter per year. For sources, see table footnotes.

Taxa	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Carps[1]														
Feed mill														
Electricity		0.52		0.52					0.52	0.52		0.52	0.52	
Fuel		0.95		0.95					0.95	0.95		0.95	0.95	
Farm														
Electricity		0.26		0.26					0.26	0.26		0.26	0.26	
Fuel		0.54		0.54					0.54	0.54		0.54	0.54	
Tilapias[2]														
Feed mill														
Electricity		0.50						0.50	0.50	0.50	0.50	0.50		
Fuel		2.0						2.0	2.0	2.0	2.0	2.0		
Farm														
Electricity		2.0						2.0	2.0	2.0	2.0	2.0		
Fuel		0.80						0.80	0.80	0.80	0.80	0.80		
Catfish and other freshwater fish[3]														
Feed mill														
Electricity		0.70						0.70	0.70	0.70		0.70	0.70	
Fuel		1.5						1.5	1.5	1.5		1.5	1.5	
Farm														
Electricity		0.60						0.60	0.60	0.60		0.60	0.60	
Fuel		0.80						0.80	0.80	0.80		0.80	0.80	
Salmonids[4]														
Feed mill														
Electricity			0.52	0.52	0.52			0.52						
Fuel			0.95	0.95	0.95			0.95						
Farm														
Electricity			0.05	0.05	0.05			0.05						
Fuel			5.0	5.0	5.0			5.0						
Other non-freshwater fish[5]														
Feed mill														
Electricity		0.52							0.52	0.52		0.52	0.52	
Fuel		0.95							0.95	0.95		0.95	0.95	
Farm														
Electricity		0.05							0.05	0.05		0.05	0.05	
Fuel		5.0							5.0	5.0		5.0	5.0	
Crustaceans[6]														
Feed mill														
Electricity		0.90			0.90			0.90	0.90			0.90	0.90	

Taxa	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Fuel		1.1			1.1			1.1	1.1			1.1	1.1	
Farm														
Electricity		10.0			10.0			10.0	10.0			10.0	10.0	
Fuel		4.5			4.5			4.5	4.5			4.5	4.5	
Mollusks[7]														
Farm														
Electricity		1.1	1.1		1.1	1.1		1.1				1.1		1.1
Fuel		1.8	1.8		1.8	1.8		1.8				1.8		1.8

[1] Farm energy use from [17]. Feed mill energy use from [141].
[2] Farm energy use based on [17,84]. Feed mill energy use from [141].
[3] Farm energy use and feed mill energy from [84].
[4] Farm energy use and feed mill energy use from [141].
[5] Data for salmonoids.
[6] Farm energy use based on [17,84]. Feed mill energy use from [141].
[7] Farm energy use from [17].

Table S35 Energy use in fish and seafood capture. Numbers in MJ fuel per kg fresh whole weight of item landed. Data for regions with a production of less than 0.05 Tg dry matter per year is not shown. Based on [36].

Taxa	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Freshwater fish		3.5					3.5	3.5	3.5	3.5	3.5	3.5	3.5	
Pelagic fish		34.0	11.3	11.3	10.3	26.0	11.3	12.0	21.5	10.7		64.1	21.5	10.3
Demersal fish		27.0	26.0	26.0	17.5		26.0	36.6	28.2	33.4	36.6	24.5	28.2	17.5
Crustaceans		96.0	57.7		53.4			107	90.1	97.7	107	96.0	90.1	53.4
Bivalves, other mollusks		30.5	36.1	36.1	16.4		36.1	29.3	32.3	32.3		27.3	32.3	16.4
Reduction fish		3.5	3.5	3.5	3.5		3.5	3.5	3.5	3.5		3.5	3.5	3.5

A4. Exogenous input data: Processing of crop, livestock, and aquaculture products

Table S36 Yields and energy use in processing of crops into food-type items. Yield numbers in percent of feedstock (dry matter basis), and energy use in MJ per kg (fresh weight) of main output. Data is not shown for regions with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes.

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cereal products														
Wheat milling														
Yields[1]														
Flour	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Bran	22.5%	22.5%	22.5%	22.5%	22.5%	22.5%	22.5%	22.5%	22.5%	22.5%	22.5%	22.5%	22.5%	22.5%
Germ	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
Energy use[2]														
Electricity	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Fuel	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Maize dry milling														
Yields[3]														
Grits	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%	80.5%
Oil	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Hominy feed	17.5%	17.5%	17.5%	17.5%	17.5%	17.5%	17.5%	17.5%	17.5%	17.5%	17.5%	17.5%	17.5%	17.5%
Energy use[4]														
Electricity	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Fuel	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Rice milling														
Yields[5]														
White whole rice	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%	55%
Broken rice	12%	12%	12%	12%	12%	12%	12%	12%	12%	12%	12%	12%	12%	12%
Bran, polishings	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%	13%
Hulls	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Energy use[6]														
Electricity	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Fuel	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Oats milling														
Yields														
Groats	67%	67%	67%	67%	67%	67%	67%	67%		67%	67%	67%		67%
Hulls	33%	33%	33%	33%	33%	33%	33%	33%		33%	33%	33%		33%
Energy use														
Electricity	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85		0.85	0.85	0.85		0.85
Fuel	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02		0.02	0.02	0.02		0.02
Steam produced on site	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94		0.94	0.94	0.94		0.94

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Vegetable oils														
Soybean oil extraction[7]														
Yields														
Oil		20.6%	20.6%	20.6%	20.6%		20.6%	20.6%	20.6%	20.6%	20.6%	20.6%	20.6%	20.6%
Meal		78.2%	78.2%	78.2%	78.2%		78.2%	78.2%	78.2%	78.2%	78.2%	78.2%	78.2%	78.2%
Energy use														
Electricity		0.23	0.23	0.23	0.23		0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Fuel		2.2	2.2	2.2	2.2		2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Palm oil extraction[8]														
Yields														
Palm oil		33.2%						40.5%		23.2%	33.2%	33.2%		
Palm kernel oil		3.6%						3.6%		3.2%	3.6%	3.6%		
Kernel meal		4.3%						4.3%		3.7%	4.3%	4.3%		
Kernel shell, mesocarp fiber		27%						27%		27%	27%	27%		
Empty fruit bunches		19%						19%		19%	19%	19%		
Energy use														
Electricity		0.63						0.60		0.66	0.63	0.63		
Fuel		0.37						0.36		0.37	0.37	0.37		
Steam produced on site		8.9						8.9		8.9	8.9	8.9		
Rapeseed oil extraction[9]														
Yields														
Oil		42.6%	42.6%	42.6%	42.6%	42.6%	42.6%	42.6%	42.6%		42.6%	42.6%	42.6%	42.6%
Meal		55.7%	55.7%	55.7%	55.7%	55.7%	55.7%	55.7%	55.7%		55.7%	55.7%	55.7%	55.7%
Energy use														
Electricity		0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31		0.31	0.31	0.31	0.31
Fuel		1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10		1.10	1.10	1.10	1.10
Sunflower oil extraction[10]														
Yields														
Oil	44.0%	44.0%	44.0%	44.0%	44.0%		44.0%	44.0%	44.0%	44.0%	44.0%	44.0%		44.0%
Meal	40.0%	40.0%	40.0%	40.0%	40.0%		40.0%	40.0%	40.0%	40.0%	40.0%	40.0%		40.0%
Hulls	15%	15%	15%	15%	15%		15%	15%	15%	15%	15%	15%		15%
Energy use														
Electricity	0.48	0.48	0.48	0.48	0.48		0.48	0.48	0.48	0.48	0.48	0.48		0.48
Fuel	0.0	0.0	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0		0.0
Steam produced on site	1.74	1.74	1.74	1.74	1.74		1.74	1.74	1.74	1.74	1.74	1.74		1.74
Peanut oil extraction[11]														
Yields														
Oil		20.1%			20.1%			20.1%	23.4%	12.1%		20.1%	23.4%	20.1%
Meal		57.8%			57.8%			57.8%	54.5%	66.0%		57.8%	54.5%	57.8%
Hulls		21.5%			21.5%			21.5%	21.5%	21.5%		21.5%	21.5%	21.5%

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Energy use														
Electricity		0.74			0.74			0.74	0.67	1.1		0.74	0.67	0.74
Fuel		1.1			1.1			1.1	1.2	1.1		1.1	1.2	1.1
Coconut oil extraction[12]														
Yields														
Oil		16.8%						16.8%	16.8%	16.8%	16.8%		16.8%	
Meal		8.2%						8.2%	8.2%	8.2%	8.2%		8.2%	
Husks, shells & parings		68%						68%	68%	68%	68%		68%	
Energy use														
Electricity		0.55						0.55	0.55	0.55	0.55		0.55	
Fuel		0.50						0.50	0.50	0.50	0.50		0.50	
Steam produced on site		4.7						4.7	4.7	4.7	4.7		4.7	
Olive oil extraction[13]														
Yields														
Oil			39.0%	28.6%										
Pomace oil			4.8%	13.1%										
Energy use														
Electricity			1.0	1.1										
Fuel			0.45	1.1										
Steam produced on site			12.4	17.9										
Sugars														
Cane sugar extraction														
Yields[14]														
White sugar		29.6%		28.4%	36.9%	44.2%		29.0%	26.2%	32.8%	29.0%	25.9%	25.2%	36.9%
Molasses		9.4%		9.4%	9.7%	9.9%		9.4%	9.3%	9.5%	9.4%	9.3%	9.3%	9.7%
Energy use[15]														
Electricity		1.1		1.2	0.90	0.75		1.1	1.3	1.0	1.1	1.3	1.3	0.90
Fuel		0		0	0	0		0	0	0	0	0	0	0
Steam produced on site		15.7		16.4	12.6	10.5		16.0	17.8	14.2	16.0	18.0	18.4	12.6
Beet sugar extraction[16]														
Yields														
White sugar	56.4%	63.8%	71.6%	63.8%	69.9%		55.5%		63.8%	63.8%		63.8%		69.9%
Molasses	8.3%	8.5%	8.8%	8.5%	8.7%		8.3%		8.5%	8.5%		8.5%		8.7%
Pulp	21.7%	21.7%	21.7%	21.7%	21.7%		21.7%		21.7%	21.7%		21.7%		21.7%
Energy use														
Electricity	1.3	1.2	1.2	1.2	1.2		1.3		1.2	1.2		1.2		1.2
Fuel	13.2	12.5	11.9	12.5	12.0		13.3		12.5	12.5		12.5		12.0
Alcoholic beverages														
Beer production (from barley)[17]														

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Yields														
Beer (4.5% alcohol)	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%	42%
Brewers' grains	26%	26%	26%	26%	26%	26%	26%	26%	26%	26%	26%	26%	26%	26%
Culms, yeast, etc.	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Energy use														
Electricity	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Fuel	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Spirits production (from barley)[17]														
Yields														
Spirits (40% alcohol)	33%	33%	33%	33%	33%		33%	33%	33%	33%	33%	33%	33%	33%
Distillers' grains	24%	24%	24%	24%	24%		24%	24%	24%	24%	24%	24%	24%	24%
Culms, pot ale syrup, etc.	8%	8%	8%	8%	8%		8%	8%	8%	8%	8%	8%	8%	8%
Energy use														
Electricity	1.3	1.3	1.3	1.3	1.3		1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Fuel	9.8	9.8	9.8	9.8	9.8		9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
Wine production (from grapes)[18]														
Yields														
Wine (13% alcohol)		45%	45%		45%	45%	45%	45%		45%		45%		45%
Pomace ("marc")		13%	13%		13%	13%	13%	13%		13%		13%		13%
Spent yeast ("lees")		3.0%	3.0%		3.0%	3.0%	3.0%	3.0%		3.0%		3.0%		3.0%
Energy use														
Electricity		1.3	1.3		1.3	1.3	1.3	1.3		1.3		1.3		1.3
Fuel		0	0		0	0	0	0		0		0		0
Starches														
Wheat starch														
Yields (of wheat flour)[19]														
Wheat starch		79.5%	79.5%	79.5%		79.5%	79.5%	79.5%				79.5%		
Wheat gluten feed		7.5%	7.5%	7.5%		7.5%	7.5%	7.5%				7.5%		
Wheat gluten 80% protein		13.0%	13.0%	13.0%		13.0%	13.0%	13.0%				13.0%		
Energy use[20]														
Electricity		0.60	0.60	0.60		0.60	0.60	0.60				0.60		
Fuel		3.9	3.9	3.9		3.9	3.9	3.9				3.9		
Maize starch														
Yields (of maize grains)[21]														
Maize starch		66.7%	66.7%	66.7%	66.7%		66.7%	66.7%	66.7%	66.7%		66.7%	66.7%	66.7%
Maize oil		1.94%	1.94%	1.94%	1.94%		1.94%	1.94%	1.94%	1.94%		1.94%	1.94%	1.94%
Maize gluten feed		19.4%	19.4%	19.4%	19.4%		19.4%	19.4%	19.4%	19.4%		19.4%	19.4%	19.4%
Maize gluten		6.2%	6.2%	6.2%	6.2%		6.2%	6.2%	6.2%	6.2%		6.2%	6.2%	6.2%
Maize germ meal		5.7%	5.7%	5.7%	5.7%		5.7%	5.7%	5.7%	5.7%		5.7%	5.7%	5.7%
Energy use[22]														

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Electricity		0.7	0.7	0.7	0.7		0.7	0.7	0.7	0.7		0.7	0.7	0.7
Fuel		9.2	9.2	9.2	9.2		9.2	9.2	9.2	9.2		9.2	9.2	9.2
Cassava starch[23]														
Yields (of cassava tubers)														
Cassava starch		46.2%						46.2%		46.2%				
Cassava starch extraction pulp		13.8%						13.8%		13.8%				
Cassava stumps & peel		40.0%						40.0%		40.0%				
Energy use														
Electricity		0.2						0.2		0.2				
Fuel		0.3						0.3		0.3				
Potato starch[24]														
Yields (of potato tubers)														
Potato starch		75.0%	75.0%							75.0%				
Potato protein concentrate		8.5	8.5							8.5				
Potato starch extraction pulp		16.5%	16.5%							16.5%				
Potato stumps & peel		0.0%	0.0%							0.0%				
Energy use														
Electricity		1.1	1.1							1.1				
Fuel		2.4	2.4							2.4				
Protein concentrates and isolates[25]														
Soy protein concentrate														
Yields (of soybean meal)														
Soy protein conc. 65% protein			66%		66%									66%
Soy carbohydrate/whey			34%		34%									34%
Energy use														
Electricity			3.1		3.1									3.1
Fuel			37		37									37
Soy protein isolate														
Yields (of soybean meal)														
Soy protein isolate 90% protein			45%		45%									45%
Soy carbohydrate/whey			55%		55%									55%
Energy use														
Electricity			4.6		4.6									4.6
Fuel			54		54									54
Pea protein concentrate														
Yields (of peas)														
Pea protein conc. 65% protein			29%		29%									29%
Pea carbohydrate/whey			71%		71%									71%
Energy use														
Electricity			5.5		5.5									5.5

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Fuel			36		36									36
Pea protein isolate														
Yields (of peas)														
Pea protein conc. 90% protein			20%		20%									20%
Pea carbohydrate/whey			80%		80%									80%
Energy use														
Electricity			8.1		8.1									8.1
Fuel			54		54									54

1 262
2 172; 281
3 282
4 283; 281
5 284
6 285; 281
7 185; 286
8 185; 184; 287
9 185
10 288; 289
11 290; 289; 291
12 292, 293; 294;
13 295 in 292; 296; 297
14 298; 191
15 299, 192
16 193; 172
17 300; 301
18 302; 196; 303
19 304
20 304,305
21 306
22 172,307
23 308
24 305
25 309–313

Table S37 Yields and energy use in processing of whole milk. Yield numbers in percent of whole milk (dry matter basis) except where stated, and energy use in MJ per kg (fresh weight) of main output. Data is not shown for regions with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes.

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cattle/buffalo milk, yogurt etc.														
Yields														
Milk, yogurt	96%	90%	86%	90%	90%	90%	90%	95%	82%	93%	97%	95%	82%	90%
Cream (40% fat)	4%	10%	14%	10%	10%	10%	10%	5%	18%	7%	3%	5%	18%	10%
Energy use[1]														
Electricity	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Fuel	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Cattle/buffalo cheese														
Yields														
Cheese (28% fat)		54%	54%	54%	54%	54%	54%	54%		54%				54%
Whey		46%	46%	46%	46%	46%	46%	46%		46%				46%
Energy use[2]														
Electricity		1.4	1.4	1.4	1.4	1.4	1.4	1.4		1.4				1.4
Fuel		7.0	7.0	7.0	7.0	7.0	7.0	7.0		7.0				7.0
Sheep/goat milk, yogurt etc.														
Yields														
Milk, yogurt		100%		100%					100%	100%		100%	100%	
Cream (40% fat)		0%		0%					0%	0%		0%	0%	
Energy use														
Electricity		1.3		1.3					1.3	1.3		1.3	1.3	
Fuel		1.5		1.5					1.5	1.5		1.5	1.5	
Sheep/goat cheese														
Yields														
Cheese (28% fat)		63%	63%	63%						63%				
Whey		37%	37%	37%						37%				
Energy use														
Electricity		1.4	1.4	1.4						1.4				
Fuel		7.0	7.0	7.0						7.0				
Cattle/buffalo butter[3]														
Yields (from cream 40% fat)														
Butter (80% fat)		84%	84%	84%	84%	84%	84%	84%	84%	84%	84%		84%	84%
Buttermilk		16%	16%	16%	16%	16%	16%	16%	16%	16%	16%		16%	16%
Energy use														
Electricity		3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8		3.8	3.8
Fuel		3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7		3.7	3.7
Cattle/buffalo skim-milk powder														

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Yields														
Skim milk powder (0.1% fat)			61%	61%	61%	61%	61%		61%				61%	61%
Cream (40% fat)			39%	39%	39%	39%	39%		39%				39%	39%
Energy use[4]														
Electricity			2.0	2.0	2.0	2.0	2.0		2.0				2.0	2.0
Fuel			12.7	12.7	12.7	12.7	12.7		12.7				12.7	12.7
Cattle/buffalo whole-milk powder														
Yields														
Whole milk powder		100%	100%	100%		100%	100%	100%	100%	100%	100%		100%	
Energy use[5]														
Electricity		1.4	1.4	1.4		1.4	1.4	1.4	1.4	1.4	1.4		1.4	
Fuel		12	12	12		12	12	12	12	12	12		12	

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2 314,315
3 316
4 317,318
5 317,318

Table S38 Yields and energy use in processing of slaughter animals. Yield numbers in percent of whole animal (live weight, fresh weight basis), and energy use in MJ per kg (fresh weight) of liveweight processed. The percentage bone of the meat quantity is the average for the percentages bone of separate meat cuts show in Table S39. Data is not shown for regions with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes.

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Beef														
Yields														
Meat (0% bone)[1]	37%	39%	37%	36%	39%	37%	37%	38%	34%	35%	38%	39%	33%	41%
Offal, lard consumed as food[2]	5.9%	6.8%	5.0%	8.7%	3.0%	2.6%	8.1%	4.7%	6.8%	10%	3.6%	5.9%	5.0%	1.8%
Rendered fat[3, 4]	10%	8.7%	8.4%	9.3%	9.0%	8.4%	7.2%	8.6%	10%	10%	8.7%	8.9%	12%	8.9%
Meat & bone meal[3]	11%	10%	11%	11%	11%	11%	11%	11%	11%	10%	11%	10%	11%	11%
Hide	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%
Energy use[5, 6]														
Electricity	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.2	0.1	0.4	0.4	0.2	0.4
Fuel[7]	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.05	0.2	0.2	0.1	0.2
Sheep/goat meat														
Yields														
Meat (7% bone)[8]	32%	33%	32%	32%		32%		31%	30%	30%		33%	30%	
Offal, lard consumed as food[2]	5.2%	5.6%	4.4%	8.1%		2.2%		4.0%	6.0%	8.9%		5.1%	4.5%	
Rendered fat[9]	13%	10%	11%	12%		14%		12%	13%	13%		12%	14%	
Meat & bone meal	12%	13%	13%	12%		13%		13%	13%	12%		12%	13%	
Hide[10]	10%	10%	10%	10%		10%		10%	10%	10%		10%	10%	
Energy use[6]														
Electricity	0.4	0.4	0.4	0.4		0.4		0.2	0.2	0.1		0.4	0.2	
Fuel[7]	0.2	0.2	0.2	0.2		0.2		0.1	0.1	0.05		0.2	0.1	
Pork														
Yields														
Meat (7% bone)[11]		54%	55%		55%	55%	55%	53%		51%	54%	54%		55%
Offal, lard consumed as food[2]		10%	7.0%		4.1%	3.5%	11%	6.3%		14%	4.9%	7.8%		2.3%
Rendered fat[12]		4.5%	2.1%		3.9%	5.5%	0.4%	3.4%		4.2%	3.5%	3.7%		4.6%
Meat & bone meal		8.4%	9.4%		9.8%	9.4%	8.6%	10%		8.1%	10%	8.8%		10%
Energy use[6]														
Electricity		0.6	0.6		0.6	0.6	0.6	0.6		0.15	0.6	0.6		0.6
Fuel[7]		0.2	0.2		0.2	0.2	0.2	0.2		0.05	0.2	0.2		0.2
Chicken														
Yields														
Meat (18% bone) [13]	56%	58%	61%	56%	61%	62%	61%	60%	60%	56%	61%	58%	60%	62%
Rendered fat[3]	5.6%	5.6%	5.7%	5.6%	5.7%	5.7%	5.7%	5.7%	5.7%	5.6%	5.7%	5.7%	5.7%	5.7%
Meat & bone meal[3]	11%	11%	9.6%	11%	9.6%	9.5%	9.6%	10%	10%	11%	9.6%	11%	9.9%	9.5%
Energy use[6]														
Electricity	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.15	0.1	0.3	0.3	0.15	0.3

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Fuel[7]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.2	0.1	0.4	0.4	0.2	0.4

1 245

[2] Consumption of offal, lard etc. as food was modeled as being sourced from cattle, sheep and pigs, but not chicken, see section 1.7.

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4 320

5 321, 322, 281, 323

6 324

[7] Excluding fuel use for rendering of 8 MJ per kg of rendered fat.

8 325, 326

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10 249, 236

11 325, 327

12 320

13 255

Table S39 Yield and relative market value of separate meat cuts. Yield numbers in percent of "meat" fraction in Table S38 (fresh weight basis). The same data were used in all regions. For sources, see table footnotes.

Parameter	Yield	Relative price
Beef[1]		
Fillet, sirloin	8.5%	3.50
Round, chuck roast (0% bone)	40%	1.75
Diced meat	10%	1.50
Ground meat (15% fat)	41.5%	1.00
Sheep/goat meat[2]		
Chops, leg boneless (on average 7,5% bone)	35%	2.0
Shoulder bone-in, shank (15% bone)	30%	1.0
Diced meat	20%	1.5
Ground meat (25% fat)	15%	1.0
Pork[3]		
Hams	25%	2.0
Chops, loin (10% bone)	25%	2.5
Shoulder bone-in (15% bone)	20%	1.5
Belly (bacon)	15%	2.0
Spare ribs (30% bone)	5.0%	3.0
Ground meat (20% fat)	10%	1.0
Chicken[4]		
Breast boneless, skin on	35%	3.0
Thigh (20% bone)	33%	2.0
Drumstick (30% bone)	19%	1.5
Wing (45% bone)	12%	1.0

[1] Yield data from [245]; price data from [328] and [329]
[2] Yield data from [326]; price data from [328]
[3] Yield data from [330] and [327]; price data from [331], [329] and [328]
[4255]; price data from [329]

Table S40 Yields in processing of fish and seafood. Yield numbers in percent of whole animal (fresh weight basis). Oil and meal yield numbers represent the case where the entire non-fillet part is processed. Data is not shown for regions with a production of less than 0.05 Tg dry matter per year. For sources, see table footnotes.

Parameter[1]	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Freshwater fish - capture														
Fillet		45.0					45.0	45.0	45.0	45.0	45.0	45.0	45.0	
Non-fillet		40.0					40.0	40.0	40.0	40.0	40.0	40.0	40.0	
Fish oil		3.0					3.0	3.0	3.0	3.0	3.0	3.0	3.0	
Fish meal		9.9					9.9	9.9	9.9	9.9	9.9	9.9	9.9	
Guts		15.0					15.0	15.0	15.0	15.0	15.0	15.0	15.0	
Pelagic fish - capture														
Fillet		50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0		50.0	50.0	50.0
Non-fillet		35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0		35.0	35.0	35.0
Fish oil		3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2		3.2	3.2	3.2
Fish meal		9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2		9.2	9.2	9.2
Guts		15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0		15.0	15.0	15.0
Demersal fish - capture														
Fillet		45.0	45.0	45.0	45.0		45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
Non-fillet		40.0	40.0	40.0	40.0		40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Fish oil		3.0	3.0	3.0	3.0		3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Fish meal		9.9	9.9	9.9	9.9		9.9	9.9	9.9	9.9	9.9	9.9	9.9	9.9
Guts		15.0	15.0	15.0	15.0		15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Crustaceans - capture														
Meat		50.0	50.0		50.0			50.0	50.0	50.0	50.0	50.0	50.0	50.0
Non-meat		50.0	50.0		50.0			50.0	50.0	50.0	50.0	50.0	50.0	50.0
Shrimp meal		12.8	12.8		12.8			12.8	12.8	12.8	12.8	12.8	12.8	12.8
Reduction fish- capture														
Fish oil		5.0	5.0	5.0	5.0		5.0	5.0	5.0	5.0		5.0	5.0	5.0
Fish meal		23.3	23.3	23.3	23.3		23.3	23.3	23.3	23.3		23.3	23.3	23.3
Carps - farmed														
Fillet		42.0		42.0					42.0	42.0		42.0	42.0	
Non-fillet		42.0		42.0					42.0	42.0		42.0	42.0	
Fish oil		3.2		3.2					3.2	3.2		3.2	3.2	
Fish meal		10.4		10.4					10.4	10.4		10.4	10.4	
Guts		16.0		16.0					16.0	16.0		16.0	16.0	
Tilapias - farmed														
Fillet		37.0						37.0	37.0	37.0	37.0	37.0	37.0	
Non-fillet		46.0						46.0	46.0	46.0	46.0	46.0	46.0	
Fish oil		3.5						3.5	3.5	3.5	3.5	3.5	3.5	
Fish meal		11.4						11.4	11.4	11.4	11.4	11.4	11.4	

Parameter[1]	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Guts		17.0						17.0	17.0	17.0	17.0	17.0	17.0	
Catfish and other freshwater fish - farmed														
Fillet		40.0						40.0	40.0	40.0		40.0	40.0	
Non-fillet		44.0						44.0	44.0	44.0		44.0	44.0	
Fish oil		3.3						3.3	3.3	3.3		3.3	3.3	
Fish meal		10.8						10.8	10.8	10.8		10.8	10.8	
Guts		16.0						16.0	16.0	16.0		16.0	16.0	
Salmonids - farmed														
Fillet			45.0	45.0	45.0			45.0						
Non-fillet			38.0	38.0	38.0			38.0						
Fish oil			5.7	5.7	5.7			5.7						
Fish meal			9.1	9.1	9.1			9.1						
Guts			17.0	17.0	17.0			17.0						
Other non-freshw. fish - farmed														
Fillet		45.0							45.0	45.0		45.0	45.0	
Non-fillet		39.0							39.0	39.0		39.0	39.0	
Fish oil		4.3							4.3	4.3		4.3	4.3	
Fish meal		10.0							10.0	10.0		10.0	10.0	
Guts		16.0							16.0	16.0		16.0	16.0	
Crustaceans - farmed														
Meat		57.0			57.0			57.0	57.0			57.0	57.0	
Non-meat		43.0			43.0			43.0	43.0			43.0	43.0	
Shrimp meal		11.0			11.0			11.0	11.0			11.0	11.0	

[1] Based on [16], [141], [85], [332]. Energy use is assumed to be the same in all processes: 0.4 MJ electricity and 0.1 MJ fuel per kg of processed liveweight, based on [85].

Table S41 Feedstock and energy use in production of plant-based meat substitutes. Feedstock use numbers in mass fraction of product (fresh weight basis), and energy use in MJ per kg of product. Only major feedstocks are shown. For sources, see table footnotes.

Parameter	**Soybean based, lean** (16% protein, 7% fat)	**Soybean based, fat** (17% protein, 19% fat)	**Pea based, lean** (16% protein, 7% fat)	**Pea based, fat** (17% protein, 19% fat)
Feedstock[1]				
Soy protein isolate (90% protein)	0.06	0.10		
Soy protein concentrate (70% protein)	0.19	0.15		
Pea protein isolate (90% protein)			0.040	0.11
Pea protein concentrate (70% protein)			0.22	0.14
Rapeseed oil	0.070	0.12	0.070	0.12
Coconut oil		0.070		0.070
Energy use[2]				
Electricity	1.0	1.0	1.0	1.0
Fuel	6.0	6.0	6.0	6.0

[1] Estimated from fat, protein and carbohydrate contents as well as ingredients specifications in food labels.
[2] Based on [333–335]. Additional estimates were based on reported emissions per kg of product in carbon footprint labels.

Table S42 Feedstock and energy use in production of plant-based dairy substitutes. Feedstock use numbers in mass fraction of product (fresh weight basis), and energy use in MJ per kg of product. Only major feedstocks are shown. For sources, see table footnotes.

Parameter	**Soy drink** (3,5% protein, 1,8% fat)	**Oat drink** (1,0% protein, 1,5% fat)	**Almond drink** (0,4% protein, 1,0% fat)	**Rice drink** (0,7% protein, 1,0% fat)	**Cheese subst.** (0% protein, 21% fat)	**Butter subst.** (70% fat) – 20% soy oil	**Butter subst.** (70% fat) – 20% palm oil	**Butter subst.** (70% fat) – 20% coconut oil	**Oat cream** (13% fat)
Feedstock[1]									
Soybean seeds	0.11								
Oat groats		0.11							0.11
Almond kernels			0.021						
Rice white				0.13					
Sugar white	0.015		0.020						
Soy oil						0.20			
Palm oil		0.009		0.010			0.20		0.125
Rapeseed oil						0.25	0.25	0.25	
Sunflower oil						0.25	0.25	0.25	
Coconut oil					0.21			0.20	
Starch					0.23				
Energy use[2]									
Electricity	0.78	0.55	0.64	0.55	0.65	0.40	0.40	0.40	0.55
Fuel	2.0	1.1	0.57	1.1	0.55	0.75	0.75	0.75	1.1

[1] Estimated from fat, protein and carbohydrate contents as well as ingredients specifications in food labels.
[2] Based on [336], [316,337]. Additional estimates were based on reported emissions per kg of product in carbon footprint labels.

A5. Exogenous input data: Production of cotton lint, fertilizers, electricity, and fuels

Table S43 Yields and energy use in processing of seed cotton into lint. Yield numbers in percent of feedstock (dry matter basis), and energy use in MJ per kg (fresh weight) of main output. Yields of oil, meal, hulls and linters are those if the entire cottonseed is processed. The extent of cottonseed processing varies by region and country. Data is not shown for regions with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes.

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Yields[1]														
Lint	33.4	33.4	33.4	33.4	33.4	33.4		33.4	33.4	33.4	33.4	33.4	33.4	33.4
Ginning waste	10.6	10.6	10.6	10.6	10.6	10.6		10.6	10.6	10.6	10.6	10.6	10.6	10.6
Cottonseed	56.0	56.0	56.0	56.0	56.0	56.0		56.0	56.0	56.0	56.0	56.0	56.0	56.0
Oil	8.8	8.8	8.8	8.8	8.8	8.8		8.8	8.8	8.8	8.8	8.8	8.8	8.8
Meal	27.1	27.1	27.1	27.1	27.1	27.1		27.1	27.1	27.1	27.1	27.1	27.1	27.1
Hulls	15.1	15.1	15.1	15.1	15.1	15.1		15.1	15.1	15.1	15.1	15.1	15.1	15.1
Linters	4.8	4.8	4.8	4.8	4.8	4.8		4.8	4.8	4.8	4.8	4.8	4.8	4.8
Energy use[2]														
Electricity	0.69	0.69	0.69	0.69	0.69	0.69		0.69	0.69	0.69	0.69	0.69	0.69	0.69
Fuel	0.61	0.61	0.61	0.61	0.61	0.61		0.61	0.61	0.61	0.61	0.61	0.61	0.61

1 338–340

2 Based on [338]

Table S44 Yields, energy use and CO_2 emissions in production of biofuels. Yield numbers in percent of gross energy (HHV) in feedstock unless otherwise stated, energy use in MJ per kg (fresh weight) of main output, and emissions in g CO_2 per MJ (LHV) of fuel produced. Data is not shown for regions with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes.

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Biodiesel from veg. oil or rendered fat[1]														
Yields														
HVO		98%	98%		98%			98%			98%	98%		98%
Energy use														
Electricity		0.36	0.36		0.36			0.36			0.36	0.36		0.36
Fuel		4.9	4.9		4.9			4.9			4.9	4.9		4.9
CO_2 emissions		9.8	8.3		8.6			9.1			8.9	10.1		8.6
Bioethanol from wheat[2]														
Yields														
Ethanol (anhydrous)														
Gross energy yield		57%	57%	57%	57%		57%	57%			57%	57%		57%
Liter per kg of feedstock		0.38	0.38	0.38	0.38		0.38	0.38			0.38	0.38		0.38
Distillers grains (dried)		33%	33%	33%	33%		33%	33%			33%	33%		33%
Energy use														
Electricity		1.4	1.4	1.4	1.4		1.4	1.4			1.4	1.4		1.4
Fuel (incl. for drying of distillers grains)		11.2	11.2	11.2	11.2		11.2	11.2			11.2	11.2		11.2
CO_2 emissions		29.6	18.8	25.8	20.9		20.0	24.0			22.6	30.4		20.9
Bioethanol from maize[3]														
Yields														
Ethanol (anhydrous)														
Gross energy yield		62%	62%		62%					62%		62%		62%
Liter per kg of feedstock		0.42	0.42		0.42					0.42		0.42		0.42
Distillers grains (dried)		29%	29%		29%					29%		29%		29%
Energy use														
Electricity		1.3	1.3		1.3					1.3		1.3		1.3
Fuel (incl. for drying of distillers grains)		10.2	10.2		10.2					10.2		10.2		10.2
CO_2 emissions		22.6	17.2		18.2					20.8		23.0		18.2
Bioethanol from sugarcane[4]														
Yields														
Ethanol (anhydrous)														
Gross energy yield		47%						47%	47%	47%	47%		47%	
Liter per kg of feedstock		0.10						0.10	0.10	0.10	0.10		0.10	
Electricity to grid		1.0%						1.0%	1.0%	1.0%	1.0%		1.0%	
Energy use														
Electricity		1.4						1.4	1.4	1.4	1.4		1.4	
Fuel (incl. bagasse used as fuel)		18.6						18.6	18.6	18.6	18.6		18.6	

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
CO_2 em. (excl. from bagasse used as fuel)		0						0	0	0	0		0	
Bioethanol from cereal straw[5]														
Yields[4]														
Ethanol (anhydrous)														
Gross energy yield			57%											
Liter per kg of feedstock			0.38											
Energy use														
Electricity			0.51											
Fuel (incl. straw used as fuel)			6.9											
CO_2 em. (excl. from straw used as fuel)			0											

1 Based on [319,341–344]
2 Based on [341,345]
3 Based on [341,346]
4 Based on [341,346,347]
5 Based on [341]

Table S45 Carbon dioxide emissions from production of electricity and fossil fuels. Emissions from fuel in g CO_2 per MJ LHV. For sources, see table footnotes.

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Electricity[1]														
kg CO_2 per MJ	0.27	0.27	0.064	0.20	0.10	0.21	0.086	0.16	0.28	0.20	0.12	0.29	0.28	0.10
g CO_2 per kWh	980	980	230	710	370	760	310	590	990	730	450	1000	990	370
Fossil gas[2]														
Tailpipe	56	56	56	56	56	56	56	56	56	56	56	56	56	56
Upstream	13	13	13	13	13	13	13	13	13	13	13	13	13	13
TOTAL	69	69	69	69	69	69	69	69	69	69	69	69	69	69
Fossil oil[3]														
Tailpipe	73	73	73	73	73	73	73	73	73	73	73	73	73	73
Upstream	10	10	10	10	10	10	10	10	10	10	10	10	10	10
TOTAL	83	83	83	83	83	83	83	83	83	83	83	83	83	83
Fossil coal[4]														
Tailpipe	98	98	98	98	98	98	98	98	98	98	98	98	98	98
Upstream	14	14	14	14	14	14	14	14	14	14	14	14	14	14
TOTAL	112	112	112	112	112	112	112	112	112	112	112	112	112	112
Diesel[5]														
Tailpipe	74	74	74	74	74	74	74	74	74	74	74	74	74	74
Upstream	21	21	21	21	21	21	21	21	21	21	21	21	21	21
TOTAL	95	95	95	95	95	95	95	95	95	95	95	95	95	95
Kerosene[6]														
Tailpipe	73	73	73	73	73	73	73	73	73	73	73	73	73	73
Upstream	15	15	15	15	15	15	15	15	15	15	15	15	15	15
TOTAL	88	88	88	88	88	88	88	88	88	88	88	88	88	88

1 348, 349,350

2 351

3 352

4 353, 354

5 341,351,355

6 341,351,355

Table S46 Energy use and greenhouse gas emissions in the production of fertilizers and pesticides. Energy use in MJ LHV per kg of output unless otherwise stated. For sources, see table footnotes.

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Feedstocks for nitrogen fertilizers[1]														
Ammonia														
Electricity	1.0	0.8	0.84	1.0	0.47	1.0	1.0	1.0	0.8	1.0	1.0	0.5	0.5	0.47
Fossil gas	42.8	16.8	34.0	35.7	34.9	32.1	39.5	41.4	42.8	36.7	41.4	16.8	42.8	34.9
Fossil oil		3.4										3.4		
Fossil coal		21.8										21.8		
Nitric acid														
Nitrogen yield from ammonia	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%	94%
Nitrous oxide emissions (g N_2O/kg)	4.5	7.4	0.7	6.5	5.4	5.2	5.6	4.7	4.5	4.7	4.7	7.4	4.5	5.4
Nitrogen fertilizers														
Ammonia, anhydrous														
CO_2 emissions (kg CO_2/ kg N)	3.9	4.9	2.9	3.2	3.0	3.0	3.4	3.7	3.8	3.3	3.7	4.9	3.8	3.0
Ammonium nitrate														
Feedstock use (kg/kg)														
Ammonia	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Nitric acid	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Energy use														
Electricity[2]	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fossil gas[3]	0.7	0.7	0.5	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
CO_2 & N_2O emissions (kg CO_2 eq/ kg N)	7.2	10.0	3.6	7.7	6.7	6.6	7.2	7.0	7.1	6.7	7.0	10.0	7.1	6.7
Ammonium sulphate														
Feedstock use (kg/kg)														
Ammonia	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Energy use														
Electricity	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fossil gas	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
CO_2 emissions (kg CO_2/ kg N)	4.4	5.4	3.3	3.7	3.4	3.4	3.9	4.1	4.2	3.8	4.1	5.4	4.2	3.4
Urea														
Feedstock use (kg/kg)														
Ammonia[2]	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Energy use														
Electricity[2]	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
Fossil gas[4]	4.6	4.6	4.0	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
CO_2 emissions (kg CO_2/ kg N)[5]	4.9	5.9	3.6	4.2	3.8	3.9	4.2	4.6	4.8	4.3	4.6	5.9	4.8	3.8
Urea ammonium nitrate														
Feedstock use (kg/kg)														
Urea	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Nitric acid	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
Energy use[2]														
Electricity	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Fossil gas	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
CO_2 & N_2O emissions (kg CO_2 eq/kg N) [6]	5.7	8.0	3.2	6.1	5.5	5.2	5.9	5.7	5.7	5.3	5.7	8.0	5.7	5.5
Other fertilizers, pesticides														
Phosphorous fertilizers[7]														
Fossil gas (MJ LHV/ kg P)	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
CO_2 emissions (kg CO_2 / kg P)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Potassium fertilizers[7]														
Fossil gas (MJ LHV/ kg K)	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
CO_2 emissions (kg CO_2/ kg K)	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Pesticides[8]														
Fossil gas (MJ LHV/ kg active subst.)	290	290	290	290	290	290	290	290	290	290	290	290	290	290
CO_2 emissions (kg CO_2/ kg active subst.)	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1

[1] Based on [356]; [357 358].
[2] [358]
[3] Europe: [359]; all else: [358]
[4] Europe adjusted to make total emissions agree with [356]. All else: [358].
[5] Includes CO_2 captured in product and which is emitted shortly after application on land. Amounts to about 1.6 kg CO_2 per kg N.
[6] Includes CO_2 captured in product and which is emitted shortly after application on land. Amounts to about 0.8 kg CO_2 per kg N.
[7] Calibrated to CO_2 intensity in [360]
[8] Based on [5,361]. Energy use adjusted to achieve equivalent GHG intensity.

A6. Exogenous input data: Food consumption

Table S47 Food consumption per capita: Current and alternative diets. Units in kg fresh weight per capita and year. Current diets are based on FAOSTAT [5]; assumption underlying the alternative diets are explained in section 5.2.

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Meat[1]														
All meat														
Current diet/No suckler beef/No ruminant	32,5	52,2	77,6	34,7	107	109	75,6	75,5	7,2	17,0	99,3	62,4	5,6	123
Plant based	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Beef														
Current diet	16,7	5,7	13,6	7,5	30,7	27,3	13,3	26,8	2,8	5,9	37,4	5,5	1,1	37,2
No suckler beef	15,8	0,69	10,0	5,6	6,5	25,2	7,8	8,1	2,8	3,4	10,3	1,1	1,1	7,8
No ruminant/Plant based	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sheep/goat														
Current diet/No suckler beef	7,8	2,3	1,8	5,2	0,68	10,0	1,4	0,62	0,87	2,0	0,60	3,5	0,53	0,54
No ruminant/Plant based	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pork														
Current diet	3,1	30,0	38,1	0,6	25,8	27,3	29,6	12,3	0,18	2,9	14,2	39,2	0,22	28,8
No suckler beef	3,4	33,3	40,4	0,7	34,1	28,1	32,3	17,1	0,18	3,7	20,5	42,5	0,22	38,7
No ruminant	12,7	35,4	47,6	1,0	36,5	44,7	36,9	19,3	0,37	5,5	23,0	45,8	0,38	41,5
Plant based	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chicken														
Current diet	4,9	14,2	24,0	21,4	49,7	44,9	31,3	35,8	3,4	6,2	47,1	14,2	3,0	56,6
No suckler beef	5,4	15,8	25,4	23,2	65,6	46,2	34,1	49,7	3,4	7,8	67,9	15,4	3,0	76,1
No ruminant	19,8	16,8	30,0	33,7	70,3	73,5	39,0	56,2	6,9	11,5	76,3	16,6	5,2	81,6
Plant based	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Egg, dairy, fish, offal/lard														
Egg														
Current diet/No suckler beef/No ruminant	4,6	15,8	12,1	12,1	17,1	8,8	16,5	10,6	3,3	1,9	10,7	19,7	3,3	16,2
Plant based	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dairy products[2]														
Current diet/No suckler beef	137	28,9	246	110	241	233	198	133	135	34,2	144	29,7	134	290
No ruminant/Plant based	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fish and shellfish[3]														
Current diet/No suckler beef/No ruminant	2,0	39,5	21,4	12,6	20,2	24,4	21,6	9,3	9,0	7,8	8,1	39,1	8,0	22,7
Plant based	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Offal, lard														
Current diet/No suckler beef/No ruminant	3,3	4,1	6,0	1,8	3,6	7,6	6,3	4,3	0,6	1,8	4,7	4,6	0,3	2,4

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Plant based	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plant-based meat and dairy substitutes														
Plant-based meat substitutes														
Current diet/No suckler beef/No ruminant	not estimated													
Plant based	16,5	39,1	43,4	23,2	54,9	60,6	44,9	37,4	6,5	10,9	45,8	42,5	5,4	61,0
Plant-based milk, cheese, cream substitutes														
Current diet/No suckler beef	not estimated													
No ruminant/Plant-based	196	33,5	153	114	150	176	173	120	148	40,8	178	37,0	145	177
Plant-based butter substitutes (margarine)														
Current diet/No suckler beef	1,3	0,2	5,4	2,7	9,8	4,2	3,7	2,1	1,9	0,47	2,9	0	0,9	14,0
No ruminant/Plant-based	2,2	0,5	9,7	4,7	12,0	9,6	6,5	2,7	6,0	0,93	3,6	0,2	5,5	16,7
Pulses														
Current diet/No suckler beef/No ruminant	4,5	6,2	3,3	1,9	6,9	1,0	3,2	10,1	9,5	15,1	14,2	5,7	10,7	5,3
Plant based	15,9	27,4	35,1	19,4	48,6	43,0	35,4	37,6	14,3	22,5	49,0	26,0	14,9	49,6
Other food[4]														
Cereal products	141	151	104	164	98,0	81,4	119	106	148	128	102	151	138	85,9
Starchy tubers	42,2	47,0	56,0	35,7	33,9	36,5	82,0	42,6	24,9	109	32,2	58,6	23,6	39,7
Vegetable oils and fats	9,3	8,8	18,5	15,7	25,1	22,1	15,6	15,0	10,2	8,4	20,2	8,4	10,3	29,6
Nuts and seeds	2,2	9,5	5,3	6,5	7,1	8,6	2,5	9,1	8,8	6,1	17,0	6,9	10,1	8,6
Vegetables	135	230	111	146	113	107	95,8	69,2	82,0	63,4	64,3	296	90,6	119
Fruits	57,5	71,8	79,1	111	81,7	66,0	52,9	77,1	45,2	52,7	71,7	81,6	50,5	85,4
Sugar	13,5	11,8	32,4	26,0	48,5	42,3	37,6	36,0	19,2	12,8	36,7	7,0	20,3	52,8
Cocoa, coffee, tea	3,1	1,9	7,6	4,0	5,5	8,9	3,8	5,8	0,77	1,1	8,2	1,4	0,81	7,1
Alcoholic beverages[5]	1,3	3,3	6,7	0,58	5,3	5,4	6,4	2,9	0,60	1,3	2,9	3,9	0,77	6,5

[1] In equivalent carcass weight.
[2] In equivalent whole milk weight.
[3] In equivalent whole fish/shellfish weight.
[4] For these items, consumption levels in the alternative diets are the same as in the current diet.
[5] In pure ethanol weight.

A7. Exogenous input data: Freight transport distances and energy use

Table S48 Energy use and CO_2 emissions from freight transport. For sources, see table footnotes.

Parameter	**Route and cargo description**[1]					**Transportation mode and fuel use per transported weight and distance**[2]									**Energy use and CO_2 emissions per cargo**	
	Long distribution		**Short distrib.**	**Pallet density**	**Temp.**	**Road – LONG**			**Road – SHORT**			**Sea**				
	Road (km)	Sea (km)	Road (km)	Mg/m^3		Type	Capacity utilization	Fuel (MJ/ Mg/km)	Type	Capacity utilization	Fuel (MJ/ Mg/km)	Type	Capacity utilization	Fuel (MJ/ Mg/km)	MJ LHV/ kg	kg CO_2 eq/ kg
Transport within region																
Feed to livestock farms																
Cereals, other grains	400			0.70	Amb.	Bulk	50%	1.2							0.48	0.046
Oil meals, brans	300			0.70	Amb.	Bulk	50%	1.2							0.36	0.034
Distillers/brewers grains	300			0.45	Amb.	Bulk	50%	1.9							0.56	0.054
Molasses, beet pulp	300			0.50	Amb.	Bulk	50%	1.7							0.51	0.048
Silage, hay	100			0.40	Amb.	Bulk	50%	2.1							0.21	0.020
Other to livestock farms																
Straw, baled	50			0.16	Amb.	Bulk	50%	5.3							0.48	0.046
Cattle calves[3]	100				Amb.				Large	40%	4.0				0.40	0.038
Feedstock to processing																
Cereals, other dry crops	200			0.70	Amb.	Bulk	50%								0.24	0.023
Oil palm fruit bunches[4]			80	0.40	Amb.				Small	50%	3.5				0.28	0.027
Olive fruits			80	0.40	Amb.				Large	50%	2.8				0.23	0.021
Sugarcane stems[5]			20	0.40	Amb.				Large	50%	2.8				0.11	0.011
Sugar beet roots	100			0.40	Amb.	Bulk	50%	2.1							0.21	0.020
Whole milk to dairy	150			1.00	Cold	Bulk	50%	1.1							0.17	0.016
Animals to slaughter			300		Amb.				Large	40%	4.0				1.2	0.11
Food to food stores																
Cereals, other dry items	500		60	0.60	Amb.	Trailer	50%	0.57	Large	25%	5.6				0.62	0.059
Vegetables, fruits	500		60	0.25	Cold	Trailer	50%	0.89	Large	25%	7.3				0.88	0.084
Beverages	500		60	0.80	Amb.	Trailer	50%	0.57	Large	25%	5.6				0.62	0.059
Meat, dairy, egg, fish	500		60	0.3-0.5	Cold	Trailer	50%	0.74	Large	25%	7.3				0.81	0.077
Imports from other regions																
Crops, processed crops																
Unprocessed dry crops	500	10000	50	0.70	Amb.	Semi	65%	0.73	Large	50%	2.8	Bulk	70%	0.054	1.1	0.091
Vegetables, fruits	500	10000	50	0.25	Cold	Semi	65%	1.1	Large	50%	3.7	Reefer	70%	0.53	6.0	0.51
Cereal products, cocoa, coffee, tea	500	10000	50	0.60	Amb.	Semi	65%	0.73	Large	50%	2.8	Container	70%	0.13	1.8	0.15
Sugar	500	10000	50	0.60	Amb.	Semi	65%	0.73	Large	50%	2.8	Bulk	70%	0.063	1.1	0.098

Vegetable oils	500	10000	50	0.70	Amb.	Semi	65%	0.73	Large	50%	2.8	Container	70%	0.13	1.8	0.15
Soymeal	1000	10000	50	0.70	Amb.	Semi	65%	0.73	Large	50%	2.8	Bulk	70%	0.054	1.4	0.12
Beverages	500	10000	50	0.70	Amb.	Semi	65%	0.73	Large	50%	2.8	Container	70%	0.13	1.8	0.15
Livestock products, fish																
Meat, fresh dairy, fish	500	10000	50	0.30	Cold	Semi	65%	0.95	Large	50%	3.7	Reefer	70%	0.44	5.1	0.43
Milk powder	500	10000	50	0.60	Amb.	Semi	65%	0.73	Large	50%	2.8	Container	70%	0.15	2.1	0.17

[1] Author estimates of transport distances. Pallet densities based on [362,363]. Additional fuel usage in chilled road transport based on [364].
[2] For details, see the ClimAg model description.
[3] Based on [365].
[4] Based on [287]
[5] Based on [366], [192]

A8. Exogenous input data: Price relations for economic allocation

Table S49 Price relations for economic allocation between co-products. Numbers in \$US kg^{-1}. For sources, see table footnotes.

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Rice and rice products														
Grain[1]	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Straw[2]	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
Rice white[3]	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
Broken rice[2]	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Rice bran[4]	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Cereals other than rice														
Wheat grains[3]	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Maize grains[3]	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Barley grains[3]	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Sorghum grains	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Straw[5]	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.070	0.070	0.055	0.055	0.070	0.055
Cereal products other than rice														
Wheat flour[6]	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Wheat bran[7]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Maize grits, meal & flour[8]	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Maize oil[9]	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Maize hominy feed[4]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Sorghum grits, meal & flour	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sorghum oil	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Sorghum hominy feed	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Rye flour	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Rye bran incl germ	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vegetable oils, etc.														
Soybean oil[10]	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
Soybean meal[10]	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Palm oil[11]	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Palm kernel oil[12]	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Palm kernel meal	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Sunflower oil[10]	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19
Sunflower meal[10]	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Rapeseed oil[10]	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Rapeseed meal[10]	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Peanut oil[10]	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60
Peanut meal	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Olive oil[3]	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60
Pomace oil	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Coconut oil[10]	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21
Coconut meal	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Cottonseed[10]	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cotton oil[10]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cotton meal[10]	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Sugars														
Cane white sugar[3]	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Cane molasses	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Beet white sugar[3]	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Beet molasses[13]	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Beet pulp (dried)[14]	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Alcoholic beverages, biofuels														
Beer	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Barley brewers' grains (dried)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Spirits	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Barley distillers' grains (dried)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Fuel ethanol[13]	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Wheat distillers' grains	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Maize distillers' grains[13]	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Starch, protein concentrates and isolates														
Wheat starch[15]	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Wheat gluten feed (with liquor solids)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Wheat gluten 80% protein[16]	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Maize starch[17]	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Maize gluten feed (with liquor solids)[18]	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Maize gluten meal[19]	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Maize germ meal	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Cassava starch	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Cassava pomace	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Potato starch[14]	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Potato protein concentrate[20]	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90
Potato starch extraction pulp, wet[20]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Soy protein isolate 90% protein[21]			0.80		0.80									0.80
Soy protein concentrate 65% protein[22]			0.65		0.65									0.65
Soy carbohydrates/whey[22]			0.10		0.10									0.10
Pea protein isolate 90% protein[22]			0.80		0.80									0.80
Pea protein concentrate 65% protein[22]			0.65		0.65									0.65
Pea carbohydrates/whey[22]			0.10		0.10									0.10
Livestock products and by-products														
Cattle/buffalo														
Whole milk[23]	0.38	0.53	0.42	0.52	0.41	0.39	0.41	0.42	0.51	0.41	0.38	0.53	0.51	0.41
Weaned calves - male[24]	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82
Weaned calves – female[25]	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12
Carcass – cows[26]	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05
Carcass - bulls/steers[27]	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
Carcass – heifers[28]	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.28	4.28
Sheep/goat														

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Sheep wool[29]	3.0	7.0		1.5		7.5						7.0		
Whole milk[30]	0.75	1.0	0.82	0.83				0.82	0.68	0.68		1.0	0.68	
Carcass - ewes/does[31]	1.1	1.1	1.1	1.1		1.1		1.1	1.1	1.1		1.1	1.1	
Carcass - lambs/kids[32]	3.2	3.2	3.2	3.2		3.2		3.2	3.2	3.2		3.2	3.2	
Pig														
Pig carcass (crude carcass) [3]		1.80	1.80		1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Poultry														
Whole eggs	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Chicken carcass - broiler[3]	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
Slaughter by-products														
Offal for human cons.	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Fat for human cons. - beef & lamb[33]	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Fat for human cons. - pork[33]	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Fat for human cons. - chicken	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Rendered fat - beef & lamb[33]	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Rendered fat - pork[33]	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Rendered fat - chicken[33]	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Meat & bone meal[33]	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Blood meal[33]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cattle hides[34]	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Sheep hides[35]	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Fish/shellfish products and by-products														
Skin & boneless fillets / shell-free meat														
Freshwater fish	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Pelagic fish	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Demersal fish	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Carps	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Tilapias[2]	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Catfish & oth. farmed freshwater fish[2]	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Salmon[36]	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Other farmed non-freshwater fish	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Crustaceans – capture	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Crustaceans – farmed[2]	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
By-products														
Fish oil[37]	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
Fish meal	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Shrimp meal[2]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Materials products and by-products														
Cotton lint[38]	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90
Cotton linters	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

[1] Based on [367] and global average price of milled rice 2010-20 from [368] and [174].

[2] [367]

[3] [368]. Global average 2010–2020

[4] [369]. US average 2010–2020.
[5] Based on [367], [370–372], [373], and various market data online.
[6] Based on [374]. Rough average export price in the US, UK.
[7] [369]. Refers to middlings. US average 2010–2020.
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[15] 304
[16] 378
[17] [369]. Refers to yellow corn meal. US average 2010–2020.
[18] [369]. 21% protein. US average 2010–2020.
[19] [369]. 60% protein. US average 2010-2020
[20] 305
[21] 379
[22] 309
[23] Weighted for cattle and buffalo milk. EUR: [380]; NAM/USA: [50]; SAS/India: [381]; All others: FAOSTAT [5].
[24] Liveweight price estimate by assuming the equivalent carcass price as for bulls and steers
[25] Liveweight price estimate by assuming the equivalent carcass price as for heifers
[26] Assumed to be 10% lower than price of bulls and steers
[27] [368] reports global average of 4.2 during 2010-20 for *all* beef. Price for bulls and steers adjusted to obtain this value as average for all beef carcass.
[28] Assumed to be 5% lower than price of bulls and steers
[29] OCE: Based on [382]. Others were estimated based on the allocation fraction reported in [221], Table B23.
[30] Weighted average for sheep and goat milk. EUR: EUROSTAT [217]. SAS/India: [383–385]. All others: FAOSTAT [5].
[31] Assumed to be a third of the price of lamb and kid carcass
[32] [368] reports global average of 2.7 during 2010-20 for *all* sheep meat. Price for lamb and kid carcass adjusted to obtain this value as average for all sheep and goat carcass.
[33] [386] April 2021 and April 2016. Approximate average of past decade.
[34] Based on cattle hide price data at [387].
[35] Based on [388].
[36] Based on [141] and [389].
[37] Based on [390].
[38] Based on [391]. Global average since 2010.

A9. Exogenous and endogenous input data: Emission factors

Table S50 Nitrous oxide emission from agricultural soils. Numbers in percent N_2O-N emitted per total N in nitrogen inputs (amounts remaining after ammonia losses). For sources, see table footnotes. For details on methodology, see section 1.4.1.

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Fertilizer[1]															
Annual crops ex. irrigated rice															
Fertilizer only		0.52	1.46	1.40	0.55	1.23	0.54	1.17	1.52	0.99	1.14	1.65	1.30	0.94	1.52
Average incl. effect from combined manure and fertilizer application	1.3	0.53	1.57	1.47	0.56	1.28	0.55	1.18	1.60	1.01	1.24	1.76	1.40	0.96	1.59
Perennial crops															
Fertilizer only		0.51	0.90	0.88	0.52	0.81	0.52	0.78	0.92	0.70	0.77	0.98	0.84	0.68	0.92
Average incl. effect from combined manure and fertilizer application	0.88	0.52	0.91	1.04	0.52	0.88	0.64	0.78	0.92	0.75	0.82	0.98	0.86	0.73	0.98
Manure - applied[2]															
Solid manure types		0.30	0.35	0.35	0.30	0.34	0.30	0.34	0.35	0.32	0.33	0.36	0.34	0.33	0.35
Liquid – surface applied		0.93	1.07	1.07	0.93	1.04	0.93	1.04	1.07	1.00	1.02	1.11	1.05	1.02	1.07
Liquid – sub-surface applied		1.39	1.61	1.61	1.39	1.55	1.39	1.55	1.61	1.50	1.53	1.67	1.58	1.53	1.61
Average all manure incl. effect from combined manure & fertilizer application	1.3	0.60	1.59	1.73	0.62	1.21	1.20	0.92	0.86	0.56	0.49	1.01	1.62	0.60	1.26
Manure - excreted[3]															
Cattle/buffalo	0.46	0.21	0.52	0.50	0.22	0.44	0.21	0.42	0.54	0.36	0.41	0.58	0.47	0.35	0.54
Sheep/goats	0.28	0.21	0.30	0.30	0.22	0.30	0.21	0.30	0.30	0.30	0.30		0.30	0.30	
Plant mass left in field[4]															
Above-ground residues – vegetables	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Above-ground residues – starchy roots, sugar crops, forage crops	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Above-ground residues – other crops	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Above-ground residues – perm. grassland	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Root mass – annual crops	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Root mass turnover, perm. grassland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rice paddies (all inputs) [5]	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40

[1] Based on [28].
[2] Based on [53] [392], [54].
[3] Based on [39].
[4] Based on [53], [56], and [55].
[5] Based on [39].

Table S51 Carbon dioxide and nitrous oxide emissions from drained organic soils. Numbers in Mg CO_2 equivalents per ha physical drained land area per year. Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes. For details on methodology, see section 1.4.2.

Parameter[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cereals															
Wheat	34.2	34.5	35.4	34.3	34.5	31.4	34.5	34.2	44.7	53.4	53.4	53.5	35.6	53.4	34.5
Maize	37.5	34.5	37.3	34.5	34.5	34.9	34.5	35.0	53.4	52.7	53.5	53.5	34.7	52.6	34.5
Rice – irrigated/high input	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7
Rice – low input	50.1		47.6		34.5				53.4	52.1	52.4	53.5		53.0	
Barley	33.0	35.1	35.9	33.4	34.5	29.7	34.5	33.4	36.8	53.5	53.5	27.9	36.1	53.5	34.5
Sorghum	46.2		41.7	34.5	34.5	52.2	34.5		53.5	53.5	51.2	53.5	34.6	53.5	34.5
Millet	45.7		39.9					35.0		53.5	53.1		34.6	50.7	
Oats	32.6	34.5	35.9	34.1	34.5	30.3	34.5	33.6	36.0		53.5	34.5	35.5		34.5
Rye	33.9		35.9	34.1	34.5	30.3		33.6					35.5		
Other	34.2	34.5	35.9	34.1	34.5	30.3		33.6	36.0		53.5		35.5		
Oil and protein field crops															
Soybean	35.3	44.5	35.0	34.6	34.6	34.5		35.1	53.4	53.4	53.4	53.4	34.6	53.3	34.6
Rapeseed	33.5	41.7	35.0	34.4	34.6	29.0	34.6	34.2	39.1	52.8	53.4		34.8	52.8	34.6
Peanut	45.5		47.1		34.6	34.7			53.4	53.4	53.4	53.4	34.6	53.3	34.6
Sunflower	36.7	34.7	37.6	34.6	34.6	32.6		34.7	53.1	53.2	53.4	53.4	35.8	53.2	34.6
Sesame	51.1		49.1							53.3	53.4		34.7	53.1	
Common bean	49.2	34.6	50.7	34.6	34.6	35.1			53.3	53.2	53.4	53.4	35.2	53.2	34.6
Faba bean	43.6		50.7	34.6	34.6				53.3		53.4		35.2		
Cowpea	53.3										53.2				
Chickpea	47.3														
Peas	33.4		35.9	34.3	34.6	29.1		33.4	44.3	53.4	53.1		34.7	53.3	34.6
Pigeon pea	53.0									52.4	53.4			53.3	
Lentil	49.4	34.6	34.8		34.6	28.0					53.4		34.7	53.1	34.6
Other	51.0	40.2	53.4	34.5	34.6	30.3		32.2		53.4	53.4		39.4	53.4	
Oil tree crops and tree nuts															
Oil palm[2]	78.2		78.2			78.2			78.0		78.2	78.2	78.2		
Coconut palm	52.6		53.5	53.5		53.5			53.4	34.5	53.5	53.5	53.5	34.5	53.5
Olive	34.5			34.5	34.5				34.5		34.5				
Cashewnut	53.5		53.5						53.5	53.5	53.5	53.5		53.5	
Almond	34.5			34.5	34.5	34.5			34.5						34.5
Other tree nuts	34.5	34.5	34.5	34.5	34.5	34.5			53.5		34.5	34.5	34.5		34.5
Starchy root crops															
Cassava	53.4		53.4			53.4			53.4	53.4	53.4	53.4	52.6	53.4	
White potato	37.7	35.1	34.8	34.4	34.6	33.0	34.6	33.3	42.3	53.2	53.4	53.4	34.7	53.2	34.6
Sweet potato	51.6		49.8	34.6		34.7			53.4	53.1	53.4	53.4	34.6	53.0	34.6
Yams	53.4		49.8						53.4		53.4				
Sugar crops															
Sugar cane	40.0		53.1		34.6	35.0	53.4		53.4	53.3	53.4	53.4	42.6	53.1	34.6

Parameter[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Sugar beet	34.5	34.6	34.7	34.5	34.6	34.1		35.1	34.7		40.2		34.8		34.6
Vegetables															
Tomato	41.8	38.7	40.9	34.5	34.6	35.3		33.6	52.9	34.6	53.4	53.4	34.8	53.0	34.6
Okra	51.4								52.9	34.6	53.4			53.0	
Peas (green)	39.1		40.9	34.5	34.6					34.6			34.8	53.0	
Cabbage	39.1	38.7	40.9	34.5	34.6	35.3		33.6	52.9	34.6	53.4	53.4	34.8	53.0	34.6
Cucumber	41.0	38.7	40.9	34.5	34.6	35.3		33.6					34.8		34.6
Cauliflower & broccoli	37.4		40.9	34.5		35.3				34.6			34.8	53.0	34.6
Onion	41.2	38.7	40.9	34.5	34.6	35.3		33.6	52.9	34.6	53.4	53.4	34.8	53.0	34.6
Carrot	38.1	38.7	40.9	34.5	34.6	35.3		33.6	52.9		53.4	53.4	34.8	53.0	34.6
Other above-ground veg.	40.7	38.7	40.9	34.5	34.6	35.3	34.6	33.6	52.9	34.6	53.4	53.4	34.8	53.0	34.6
Other below ground veg.	40.9		40.9	34.5											
Fruits															
Grape	35.1	34.6	35.5	34.6	34.6	34.6	34.6	32.6	38.2	53.4	53.4	53.4	35.5	53.4	34.6
Mango	52.7		50.4			39.9			53.4	53.2	53.4	53.4	34.7	53.1	
Plantain	53.4		53.4						53.4	53.4	53.4				
Banana	53.2		53.1		34.6	53.4	53.4		53.4	53.2	53.4	53.4	34.7	53.2	
Apple	39.8	41.9	46.8	34.4	34.6	34.9	34.6	33.3	41.2	51.8	53.1	53.4	36.2	51.2	34.6
Orange	42.8		39.9	40.2	34.6	39.1			53.4	53.2	53.4	53.4	34.7	53.1	35.3
Other - Temperate	42.8	41.9	46.8	34.4	34.6	34.9	34.6	33.3	42.7	51.8	53.1	53.4	36.2	51.2	34.6
Other - Tropical	52.0		50.4		34.6	39.9			53.4	53.2	53.4	53.4	34.7	53.1	
Stimulants															
Cocoa	53.4		53.4						53.4		53.4	53.4			
Coffee	53.0		52.8			53.4			53.4	53.4	53.4	53.4	53.4	53.4	53.4
Tea	52.4		46.5		27.9					53.2	53.4		38.3	53.2	
Forage															
Grass/legumes[3]	26.0	27.8	29.9	25.8	25.9	25.5	25.9	25.8	32.5	37.1	37.3	37.3	26.3	37.1	38.2
Whole cereals	35.5		37.3	34.6	34.6	35.0	34.6		53.4			53.4	34.7		34.6
Fiber crops															
Seed cotton	38.3	34.6	44.7	34.6	53.4	34.6	53.4		53.4	53.4	53.4	53.4	44.4	53.4	34.6
Perm. & semi-perm. pasture[4]															
Originally forest	23.8	19.7	26.4	19.6	19.6	24.8	20.1	20.2	36.6	35.8	37.3	37.3	24.5	36.6	19.8
Originally tropical or sub-tropical grass- or woodland	24.8		20.7	19.6	21.0	26.7	34.1	19.8	35.9	34.1	36.4	36.1	19.6		26.7
Originally temperate or montane grassland	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.8	19.6	19.7	19.6		19.6	19.7	19.6
Originally xeric grassland	37.3	19.6	37.3		37.3	37.3	37.3	37.5	37.3	37.3	37.3		37.3	37.3	37.3

[1] Extent and distribution of organic soils from [29]. Emission factors based on Tables 2.1 and 2.5 in [57], except where indicated. Boreal biome CO_2 emission factor based on [59].
[2] Tropical biome emission factor based on [58], who calculated an average of 78 tons CO_2 (incl. N_2O) from several sources (see Table 8).
[3] Based on [57].

[4] Based on grassland factors in [57]. N_2O emission factor for temperate biome grasslands set to that of nutrient-poor grasslands in IPCC 2014. CO_2 emission factor for temperate biome grassland set to average of deep and shallow, drained nutrient-rich grasslands in [57]. CO_2 emission factor for boreal biome grassland set to temperate factor scaled using the relationship 5.7/6.1.

Table S52 Methane emissions from enteric fermentation. Numbers in percentage energy in methane per gross energy in feed intake and kg methane per animal per year. For sources, see table footnotes. For details on methodology, see 1.5.2.

Parameter[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Dairy cattle/buffalo															
Entire herd - % of feed	6.5%	6.3%	5.9%	5.8%	6.1%	5.6%	6.0%	5.9%	6.3%	6.8%	7.3%	6.3%	6.4%	6.8%	5.4%
Cows															
% of feed	6.6%	6.6%	5.9%	5.7%	6.3%	5.4%	6.0%	5.9%	6.4%	6.8%	8.1%	6.4%	6.0%	6.7%	5.2%
per animal	86	86	92	117	97	119	104	100	105	72	78	100	93	72	123
Replacement heifers															
% of feed	6.2%	6.2%	6.0%	6.0%	6.0%	6.0%	5.9%	5.9%	6.0%	6.4%	6.7%	6.0%	6.1%	6.2%	6.0%
per animal	36	35	44	46	42	46	34	43	46	28	28	100	43	29	47
Other growing animals															
% of feed	6.6%	5.8%	6.2%	6.0%	5.9%	6.0%	5.9%	5.8%	6.3%	6.8%	6.7%	6.2%	6.0%	7.3%	5.9%
per animal	35	58	34	41	54	43	44	50	60	26	37	70	48	16	47
Beef cattle/buffalo															
Entire herd - % of feed	6.6%	6.3%	6.7%	6.6%	6.3%	6.6%	6.4%	6.5%	6.7%	7.0%	6.9%	6.7%	6.5%	7.3%	6.5%
Cows															
% of feed	7.0%	6.5%	6.9%	6.9%	6.5%	6.9%	6.6%	7.0%	7.0%	7.4%	7.5%	6.9%	6.8%	7.6%	6.9%
per animal	94	111	97	97	111	104	112	96	89	71	67	94	100	67	106
Growing animals															
% of feed	6.3%	5.8%	6.0%	6.0%	5.8%	6.1%	5.8%	5.8%	6.4%	6.6%	6.5%	6.5%	5.9%	6.9%	5.9%
per animal	44	48	35	38	46	43	45	56	49	25	35	57	42	18	44
Sheep/goats															
Entire herd - % of feed	5.8%	5.6%	5.8%	5.9%	5.5%	5.5%	5.5%	5.7%	5.7%	5.3%	6.4%	5.7%	5.8%	5.3%	5.2%
Adult animals															
% of feed	6.4%	6.4%	6.3%	6.5%	6.2%	6.7%	6.2%	6.4%	6.4%	6.0%	6.8%	6.3%	6.3%	6.0%	6.5%
per animal	10.4	10.9	12.7	9.9	11.7	9.9	15.4	10.5	10.9	7.6	8.9	11.2	12.8	8.0	10.4
Growing animals															
% of feed	4.8%	4.7%	4.7%	4.6%	4.5%	4.4%	4.4%	4.4%	4.9%	3.8%	5.6%	4.9%	4.7%	4.0%	4.2%
per animal	4.3	4.9	6.8	3.5	4.9	3.7	5.5	4.0	4.0	2.6	4.2	4.5	6.6	2.7	4.4

[1] Emission factors for cattle/buffalo based on prediction equations in [32] and for sheep/goats on equations in [33].

Table S53 Methane and nitrous oxide emissions from manure management in livestock systems. Methane conversion factors refer to methane produced as share of maximum potential methane production of all inputs (including bedding materials and feeding waste) to the stall (housing or other type of confinement) and storage. Nitrous oxide emission factors refer to N_2O-N produced per total nitrogen in all inputs to stall and storage. Numbers shown only for systems in use in each region. For sources, see table footnotes. For details on methodology, see 1.5.3.

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Methane conversion factor – CONFINEMENT															
Slurry/semi-solids below confinements															
Dairy cattle and pigs[4]			48%	35%		40%				71%	71%		45%	72%	42%
Laying hens[1]		1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%			1.5%	1.5%		1.5%
Dry lot[2]		1.0%	2.0%		1.5%	1.5%	1.5%		2.0%	2.0%	2.0%	2.0%	1.5%	2.0%	1.5%
Deep bedding															
Ruminants and pigs[2]				26%			50%								
Poultry[1]		2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
Other systems															
Cattle – liquid systems[3]		2.2%		2.2%		2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%
Ruminants – solid, daily spread		0.2%		0.2%			0.2%	0.2%	0.2%	0.2%	0.2%		0.2%	0.2%	
Pigs – liquid systems[3]			6.1%	6.1%		6.1%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%
Pigs – solid			0.6%	0.6%		0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%
Laying hens[1]		1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%
Methane conversion factor – STORAGE															
Slurry with outdoor storage[4]			39%	20%		26%		19%	57%	72%	71%	64%	32%	73%	28%
Anaerobic lagoon[4]		81%	85%		85%	85%	85%		85%	85%		85%	85%	85%	85%
Separate solid/liquid storage															
Solids[2]		2.5%	4.5%	3.0%	4.0%	3.0%	4.0%	2.0%	4.5%	5.0%	5.0%	4.5%	3.6%	5.0%	3.0%
Liquids[4]		24%	39%	20%	37%	26%	40%	19%	57%	72%	71%	64%	32%	73%	28%
Semi-solids w. frequent removal (laying hens)[1]		2.4%		2.7%	4.2%	2.9%			4.6%	5.0%		4.8%		5.0%	2.9%
Dry lot		0.5%	1.5%		1.0%	1.0%	1.0%		1.5%	1.5%	1.5%	1.5%	1.0%	1.5%	1.0%
Deep bedding															
Cattle, sheep, and pigs				2.0%			2.0%								
Poultry[1]		0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
Average methane conv. factor of system															
Milk (dairy cows and replacement heifers)		3.0%	7.1%	14%	4.6%	40%	81%	4.7%	4,7%	5,3%	7,2%	4.8%	6,0%	5,3%	41%
Beef		2.5%	4.7%	10%		6.1%	4.2%	5.7%	5,1%		6,6%	4,3%	4.4%		5.8%
Dairy bulls/steers		2.9%	5.8%	11%	4.3%	6,5%	4.2%	6.0%	8,0%	5,1%	7,0%	6.4%	5.1%	5,1%	8.1%

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Dairy sheep/goats		2.2%	8.8%	6.4%	3.4%					5,3%	6.8%		7,2%	5,3%	
Meat sheep/goats		2.2%	5,8%	6,2%	3.4%		6.5%		8.4%	5,3%	7,0%		4,7%	5,3%	
Pork			23%	23%		43%	52%	20%	44%	35%	12%	53%	22%	34%	45%
Egg		14%	3.7%	4.6%	16%	3.1%	3.2%	2.4%	4.7%	5.5%	4,4%	4.8%	3.2%	5.5%	3.1%
Chicken meat		3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
Annual methane emissions per head (kg)															
Dairy cows	17	0.94	1.2	63	4.2	180	66	17	2.8	3.2	5.0	1.3	1.0	3.3	180
Dairy replacement heifers	4.5	0.27	0.67	8.2	1.5	27	29	3.2	0.52	0.58	2.8	0.43	0.65	0.91	25
Beef cows	2.9	0.38	0.43	14		6.4	0.20	8.7	1.3		4.1	0.51	0.36		8.2
Beef bulls/steers and heifers	2.2	0.63	0.73	8.0		6.7	1.7	7.5	0.55		2.6	0.52	1.2		3.1
Dairy bulls/steers	1.9	1.2	1.7	11	2.9	7.0	3.5	9.4	1.7	0.52	2.6	1.4	2.1	0.29	8.7
Dairy ewes/does	0.34	0.015	0.31	1.2	0.21		0.051		0.19	0.55	0.16		0.27	0.64	
Meat ewes/does	0.20	0.015	0.05	0.77	0.09					0.45	0.16		0.039	0.60	
Lambs/kids	0.20	0.10	0.17	0.42	0.23		0.28		0.24	0.29	0.11		0.11	0.49	
Sows	25		23	26		34	59	33	33	16	4.9	40	21	12	36
Pig weaners and hogs	8.6		7.1	10		15	25	10	8.6	4.0	1.4	12	6.8	2.7	15
Laying hens	0.078	0.33	0.053	0.087	0.31	0.067	0.089	0.071	0.087	0.11	0.034	0.090	0.056	0.11	0.066
Chicken broilers	0.064	0.039	0.057	0.096	0.045	0.080	0.11	0.12	0.058	0.072	0.037	0.079	0.056	0.074	0.078
Nitrous oxide em. factor – CONFINEMENT															
Slurry/semi-solids below confinements[5]		0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%
Dry lot[5]		2.0%	2.0%		2.0%	2.0%	2.0%		2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Deep bedding															
Ruminants and pigs[5]				1.0%											
Poultry[1]		1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
All other systems[6]		0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%
Nitrous oxide emission factor – STORAGE															
Slurry with outdoor storage[5]			0.25%	0.25%		0.25%		0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%
Anaerobic lagoon[5]		0.0%	0.0%		0.0%	0.0%	0.0%		0.0%	0.0%		0.0%	0.0%	0.0%	0.0%
Separate solid/liquid storage[5]															
Solid		1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Liquid		0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%
Semi-solids w. frequent removal (laying hens)[1]		1.0%		1.0%	1.0%	1.0%			1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Dry lot[7]		1.0%	1.0%		1.0%	1.0%	1.0%		1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Deep bedding[7]				1.0%			1.0%								

[1] Layer chicken emission factors based on [128], [393], [394], [395], [396], [397], and [398]. Broiler chicken emission factors based on [399], [400], [401], [402], and [403].
[2] Based on [39] Table 10.17
[3] Based on [82].
[4] Methane emissions from liquid storage (including indoors) were estimated using the model included in [39], Annex 10A.3; also described in [404]. The model was slightly revised to better match the lower than predicted emission levels that have been observed at temperatures around 15°C [34,78,79], see section 1.5.3 for details.
[5] Based on [39], Table 10.21.
[6] Based on [405].
[7] Based on [128].

Table S54 Methane production potential (B_o) of manure, feeding waste and bedding materials. Numbers in liter CH_4 g^{-1} volatile solids. For sources, see table footnotes. For details on methodology, see section 1.5.3.

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cattle and buffalo[1]														
Dairy cows	0.13	0.18	0.24	0.17	0.24	0.22	0.21	0.16	0.13	0.10	0.15	0.16	0.13	0.24
Other	0.17	0.15	0.18	0.17	0.18	0.18	0.18	0.14	0.10	0.12	0.14	0.17	0.10	0.18
Sheep and goats[2]	0.15	0.19	0.19	0.16	0.19	0.19		0.13	0.13	0.13		0.19	0.13	
Pigs[3]		0.41	0.45		0.45	0.45	0.45	0.36	0.27	0.27	0.37	0.42	0.27	0.45
Poultry[4]														
Layers	0.38	0.34	0.39	0.35	0.39	0.39	0.39	0.39	0.39	0.24	0.39	0.36	0.39	0.39
Broilers	0.25	0.30	0.36	0.27	0.36	0.36	0.36	0.32	0.35	0.24	0.36	0.30	0.35	0.36
Feeding waste[5]														
Concentrates	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Forages	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Bedding materials (cereal straw)[6]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

1 39,125,127
2 39
3 39,125,127
4 39
5 406,407
6 408

Table S55 Ammonia emission factors for fertilizer and manure application and excretion. Numbers in percent NH_3-N emitted per amount nitrogen in inputs (inorganic N or total N). Incorporation of fertilizer is assumed to reduce emissions by 90%. For sources, see table footnotes.

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Fertilizer (broadcast EFs except ammonia)[1]															
Ammonia, anhydrous (incorporated)		3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Ammonium nitrate		3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Ammonium sulfate		9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Urea		13.0	16.0	13.0	17.5	17.5	16.0	13.0	14.2	30.7	17.5	14.2	16.0	30.7	17.5
Urea ammonium nitrate		8.0	9.5	8.0	10.3	10.3	9.5	8.0	8.6	16.9	10.3	8.6	9.5	16.9	10.3
Average all incl. effect of incorporation	12.0	8.6	12.5	3.5	13.6	7.3	10.9	8.3	7.2	22.5	10.8	7.9	12.5	22.5	7.3
Manure – applied on arable land[2]															
Liquid manure (slurry, urine, etc.)															
Milk (dairy cows & replacements)															
Per inorganic N		30	58	25	33	30	38	30	31	59	30	31	58	59	30
Per total N		26	43	16	28	20	21	26	26	50	21	27	43	50	20
Beef cattle															
Per inorganic N		30	58	28		30	32	30	31		30	31	58		30
Per total N		25	48	19		25	17	24	25		25	25	48		25
Dairy bulls/steers															
Per inorganic N		30	58	25	32	30	33	30	31	59	30	31	58	59	30
Per total N		25	48	17	27	25	18	24	26	48	25	26	49	49	25
Pork															
Per inorganic N			51	16		28	41	35	31	51	31	31	51	51	28
Per total N			41	12		21	33	26	23	40	23	23	41	39	21
Egg															
Per inorganic N		41	51	16	49	28	41	35	31	51	31	31	51	51	28
Per total N		24	33	9.5	29	16	26	19	27	36	22	23	30	35	16
Solid manure															
Milk (dairy cows & replacements)															
Per inorganic N		71	70	58	69	63	59	71	53	71	71	45	70	71	63
Per total N		12	18	19	16	19	28	10	14	19	17	13	18	20	11
Beef cattle															
Per inorganic N		71	70	66		67	67	71	55		71	45	70		67
Per total N		8.8	14	19		8.6	13	7.3	12		11	10	12		10
Dairy bulls/steers															
Per inorganic N		71	70	57	70	59	66	71	55	71	71	45	70	71	57
Per total N		10	10	21	11	7.8	11	7.5	10	14	11	8.9	10	14	7.2
Sheep/goats															
Per inorganic N		71	71	71	71		71	71	71	71	71		71	71	
Per total N		9.2	15	15	13		12	7.3	15	14	14		14	16	
Pork															

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Per inorganic N			49	32		40	43	43	36	49	43	36	49	49	40
Per total N			13	19		23	28	6.4	7.7	8.9	13	8.1	18	11	23
Egg															
Per inorganic N		43		32	49	40				49	43		49	49	40
Per total N		26		18	29	23				28	12		25	29	23
Chicken meat															
Per inorganic N		35	40	26	40	32	35	35	29	40	35	29	40	40	32
Per total N		22	25	17	25	21	22	22	18	25	21	18	25	24	21
Average all applied manure (per total N)														0	
All livestock	*21*	*14*	*32*	*17*	*21*	*18*	*18*	*20*	*17*	*20*	*19*	*17*	*32*	*21*	*18*
Milk (dairy cows & replacements)	18	14	32	18	18	19	19	19	15	20	19	13	33	20	18
Beef cattle	16	11	28	19		16	13	17	13		14	11	32		16
Dairy bulls/steers	16	13	33	19	14	16	11	18	16	15	14	12	35	15	16
Lamb	17	10	25	20	13		16	17	17	18	14		24	18	
Pork	27		38	13		21	32	26	22	33	16	22	38	32	21
Egg	27	24	33	16	29	18	26	19	22	29	12	22	30	29	18
Chicken meat	21	22	25	17	25	21	22	22	18	24	21	18	25	24	20
Manure – excreted on pasture[3]															
Feces (per total N)		1.6	2.2	1.8	2.1	1.8	2.2	1.5	2.4	2.6	2.6	2.5	2.0	2.7	1.8
Urine (per total N)		11.9	16.6	13.1	15.6	13.1	15.9	11.1	17.8	19.6	19.6	18.7	14.6	19.7	13.7
Average															
Per inorganic N	17.8	12.5	17.3	13.9	16.4	13.8	16.8	11.8	18.7	20.0	20.4	19.5	15.3	20.4	14.4
Per total N	9.4	6.7	9.1	7.8	9.0	7.5	9.2	6.7	9.7	10.2	10.4	10.1	8.2	10.2	7.8

[1] Based on [39] and [409].
[2] Based on [410], [411], [392], and [412].
[3] Based on [413].

Table S56 Ammonia emissions from manure management in livestock systems. Numbers in percent NH_3-N emitted per inorganic N in nitrogen inputs, unless otherwise stated. For sources, see table footnotes.

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
CONFINEMENT[1]															
Slurry/semi-solids below confinements															
Dairy cattle/buffalo						50									50
Pigs			50	50		50	50	50	50	50	50	50	50	50	50
Laying hens		20	20	20	20	20	20	20	20	20	20	20	20	20	20
Dry lot		90	90		90	90	90		90	90	90	90	90	90	90
Deep bedding															
Ruminants				15											15
Pigs				30			30								
Laying hens		30		30	30	30					30				30
Broilers		20	20	20	20	20	20	20	20	20	20	20	20	20	20
All other systems															
Cattle – liquid systems			20	20		20	20								20
Ruminants – solid/liquid, daily spread		10	10	10	10	10	10	10	10	10	10	10	10	10	10
Pigs		25	25	25	25	25	25	25	25	25	25	25	25	25	25
Laying hens		10	10	10	10	10	10	10	10	10	10	10	10	10	10
STORAGE[2]															
Slurry w. outdoor storage															
Cattle			12,6	10,0		10,0		8,5					11,1		10,0
Pigs			18,9	15,0		15,0		12,8	20,4	22,5	22,5	21,3	16,7	22,5	15,0
Anaerobic lagoon		46	63		60	50	61		68	75		71	56	75	50
Separate solid/liquid storage															
Solid		13,6	18,9	15,0	17,9	15,0	18,3	12,8	20,4	22,5	22,5	21,3	16,7	22,5	15,0
Liquid		18,2	25,2	20,0	23,8	20,0	24,4	17,0	27,2	30,0	30,0	28,4	22,2	30,0	20,0
Semi-solids w. frequent removal (laying hens)		13,6		15,0	17,9	15,0			20,4	22,5		21,3		22,5	15,0
Dry lot		13,6	18,9		17,9	15,0	18,3		20,4	22,5	22,5	21,3	16,7	22,5	15,0
Deep bedding															
Ruminants				15,0											
Pigs				28,0			34,2								
Laying hens		13,6		15,0	17,9	15,0					22,5				15,0
Broilers		13,6	18,9	15,0	17,9	15,0	18,3	12,8	20,4	22,5	22,5	21,3	16,7	22,5	15,0

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
AVERAGE – average for stalls and storage for all manure systems (per <u>total</u> N inputs)															
Milk (dairy cows and replacement heifers)	29	40	27	19	45	30	46	22	53	26	39	50	26	26	32
Beef	34	39	28	21		32	53	21	41		40	45	31		37
Dairy bulls/steers	35	42	39	20	46	34	58	22	26	25	42	40	39	25	34
Sheep/goats	39	49	17	24	54	24	41		32	48	40		14	48	
Pork	45		51	35		39	57	31	43	59	69	41	49	58	39
Egg	23	21	20	24	24	20	20	18	21	36	72	21	19	36	20
Chicken meat	25	22	26	23	25	23	25	22	27	28	27	27	24	28	23
Average all livestock	*32*	*40*	*34*	*23*	*34*	*30*	*46*	*23*	*36*	*28*	*41*	*36*	*34*	*28*	*32*

[1] Based on [410], [414], [415], [416]. For poultry manure emission factors, see footnotes at Table 34.
[2] Based on [410], [124], [411], [417], [418], [419], [420], [412], [421]. For poultry manure emission factors, see footnotes at Table 34.

Table S57 Nitrous oxide and methane emissions and foregone plant and soil carbon stocks in aquaculture. Pond-related data are not applicable to salmonoid and other non-freshwater fish production. Data is not shown for regions and crops with a production of less than 0.05 Tg dry matter per year. For sources, see table footnotes.

Parameter[1]	**CAS**	**EAS**	**EUR**	**MEA**	**NAM**	**OCE**	**RUS**	**SAM**	**SAS**	**SSA**	**Brazil**	**China**	**India**	**USA**
Carps														
Foregone carbon stocks of ponds (Mg C/ha)		261		19					246	32		215	212	
N_2O from feed (N_2O-N per N in external feed)[2]		1.6%		1.6%					1.6%	1.6%		1.6%	1.6%	
CH_4 from ponds (kg CH_4/ha/year)		220		180					200	200		220	250	
Tilapias														
Foregone carbon stocks of ponds (Mg C/ha)		261						260	246	32	201	215		
N_2O from feed (N_2O-N per N in external feed)[2]		1.6%						1.6%	1.6%	1.6%	1.6%	1.6%		
CH_4 from ponds (kg CH_4/ha/year)		460						420	420	460	420	500		
Catfish and other freshwater fish														
Foregone carbon stocks of ponds (Mg C/ha)		261						260	246	32		215	212	
N_2O from feed (N_2O-N per N in external feed)[2]		1.6%						1.6%	1.6%	1.6%		1.6%	1.6%	
CH_4 from ponds (kg CH_4/ha/year)		400						400	420	400		450	490	
Salmonids														
N_2O from feed (N_2O-N per N in external feed)[2]			1.6%	1.6%	1.6%			1.6%						
Other non-freshwater fish														
N_2O from feed (N_2O-N per N in external feed)[2]		1.6%							1.6%	1.6%		1.6%	1.6%	
Crustaceans														
Foregone carbon stocks of ponds (Mg C/ha)		261			133			260	246			215	212	
N_2O from feed (N_2O-N per N in external feed)[2]		1.6%			1.6%			1.6%	1.6%			1.6%	1.6%	
CH_4 from ponds (kg CH_4/ha/year)		800			800			880	880			880	880	

[1] Foregone native carbon stocks calculated from [25] and [37], see section 1.9. Nitrous oxide emission factor based on [89]. Methane emissions based on [35] and [87].
[2] The emission factor is applied to the amount of feed nitrogen input to the water mass that is not retained in animal mass, that is, to feed nitrogen excreted in feces and feed nitrogen not ingested.

A10. Exogenous input data: Carbon stocks per hectare, plant and soil carbon decay rates

Table S58 Plant carbon stocks of potential native vegetation on current agricultural land and aquaculture ponds. Numbers in Mg C per ha physical land area. Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes.

Parameter[1]	**World**	**CAS**	**EAS**	**EUR**	**MEA**	**NAM**	**OCE**	**RUS**	**SAM**	**SAS**	**SSA**	**Brazil**	**China**	**India**	**USA**
Aquaculture ponds	140		152		11	76			129	149	27	99	121	124	
All cropland	87	11	132	91	46	50	38	52	109	102	90	125	99	105	49
Cereals	82	11	122	90	46	44	35	50	101	106	76	123	95	110	39
Wheat	59	11	90	91	47	25	35	45	72	82	50	111	90	106	23
Maize	88	16	100	82	52	56	42	54	111	114	95	127	80	116	45
Rice – irrigated/high input	137	15	152	84	77	106	33	55	107	132	85	87	128	128	104
Rice – low input	142		167		71				145	156	113	143		155	
Barley	57	10	91	90	43	30	34	59	60	81	70	145	78	85	23
Sorghum	58		77	91	22	30	39	50	108	69	55	87	73	70	10
Millet	54		76							63	49		58	64	
Oats	70	10	80	102	62	42	60	52	87		84	127	61		50
Rye	87		80	102	62	42		52					61		
Other	87	10	80	102	62	42		52	87	119	84	127	61	139	50
Oil and protein field crops	82	11	117	86	51	47	39	47	105	91	70	124	97	90	53
Soybean	86	11	90	103	50	57		53	105	102	79	125	86	102	55
Rapeseed	78	13	120	100	43	25	38	70	132	101		156	120	97	7.6
Peanut	83		125		43	111			101	67	71		112	67	112
Sunflower	51	10	54	64	56	11		41	61	61	58	132	27	77	10
Sesame	72		148		22					108	45		117		
Common bean	99	10	144	88	58	43			122	84	94	110	67	84	29
Faba bean	105		144	88	58	43	63	54	122	84	94		67		29
Cowpea	64		172								62				
Chickpea	100		163												
Peas	59	13	96	94	48	20	35	49	98	57	87		85	47	11
Pigeon pea	92		149								77				
Lentil	72	8.2	96		51						80		94	142	7.1
Other	86	11	103	75	31	24		39		81	109		74	79	20
Oil tree crops and tree nuts	143	9.7	199	70	45	65	30		152	131	137	150	41	124	61
Oil palm	197		210			172			170		153	101	145		
Coconut palm	181		209			128			180	139	151	198	146	130	
Olive	59			70	49		30		86						
Cashewnut	124								113	114	126			114	
Almond	60	9.1	23	70	51	61			91						56
Other tree nuts	38	9.1	23	70	25	50			136		77	228	23	114	76
Starchy root crops	121	14	125	97	49	54	59	73	131	145	126	144	109	143	47
Cassava	135		164			176			147	126	129	147	163	118	

Parameter[1]	**World**	**CAS**	**EAS**	**EUR**	**MEA**	**NAM**	**OCE**	**RUS**	**SAM**	**SAS**	**SSA**	**Brazil**	**China**	**India**	**USA**
White potato	96	14	92	98	49	43	59	73	96	146	85	138	90	144	36
Sweet potato	123		139	50		120			124	154	108	108	132	147	122
Yams	133		175						161		133	138			
Sugar crops	119	11	162	110	42	104	87	69	136	91	69	134	144	105	68
Sugar cane	126	9.2	170		26	127	87		136	91	76	134	163	105	102
Sugar beet	77	11	37	110	46	40		69	86		15		22		40
Vegetables															
Above-ground	116	13	127	91	44	70	39	44	120	130	107	136	119	130	62
Below-ground	99	13	129	91	38	55	49	42	121	89	74	130	119	89	51
Fruits	100	16	111	87	51	83	62	57	119	105	110	133	92	113	72
Grape	72	13	83	85	55	60	53	56	63	73	39	137	80	87	62
Mango	120		144		37	83			144	114	116	138	121	121	
Plantain	145		200						160	177	137				
Banana	130		175		34	124	77		138	128	108	132	159	129	
Apple	81	17	92	90	52	87	75	54	81	86	72	117	81	94	80
Orange	109		148	71	38	114	95		136	104	71	140	146	116	94
Other - Temperate	81	15	92	91	52	70	68	60	81	86	72	117	81	94	67
Other - Tropical	132		144		37	110	101		144	114	116	138	121	121	
Stimulants	135		125						141	136	138	112	136	135	
Cocoa	136		212						150		121	121			
Coffee	132		62			138			138	74	189	110	183	121	
Tea	140		137		81				170	165	128	143	134	144	
Forage	71	11	117	87	44	61	48	62	78	106	33	118	106	106	63
Grass/legumes	71	11	117	87	44	61	48	62	78	106	33		106	106	63
Whole cereals	77		117	87		61	48		78			118	106		63
Fiber crops															
Seed cotton	65	12	40	82	37	61	27		85		86		35	81	62
Perm. & semi-perm. pasture	48	9.2	38	95	13	33	32	44	98	73	63	126	33	91	32
Originally forest	119	25	115	107	65	88	97	73	146	135	148	145	103	132	89
Orig. trop./sub-trop. grass-/woodland	60	0	59	71	24	58	34	63	92	108	61	101	56	48	58
Orig. temp. & montane grassl.	20	12	17	12	21	18	28	24	33	24	61	0	17	22	19
Originally xeric grassland	10	6.9	3.5	0	2.9	16	17	8.7	52	23	16	0	3.5	43	16

[1] Potential plant carbon stock per hectare based on [37]. Crop and pasture distribution from [220] (permanent and semi-permanent pastures), [43] (grapes and forage crops), and [23] (all other crops).

Table S59 Soil C stocks under potential native vegetation on current agricultural land and aquaculture ponds. Numbers in Mg C per ha physical land area. Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes.

Parameter[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Aquaculture ponds	101		109		7,0	66			121	100	6,7	107	92	94	
All cropland	97	60	116	97	37	113	47	112	121	74	101	127	109	85	114
Cereals	93	65	108	99	37	117	41	111	120	73	94	123	120	92	118
Wheat	80	67	86	98	37	114	41	111	110	49	74	120	86	63	112
Maize	112	35	117	96	45	119	61	89	125	84	109	125	110	86	123
Rice – irrigated/high input	97	25	106	87	48	90	28	143	112	88	86	112	167	131	89
Rice – low input	109	10	108	67	50	149	50	0	121	108	111	114	3	150	0
Barley	82	67	121	98	35	141	44	108	113	54	94	119	120	55	121
Sorghum	85		107	94	5	82	26	115	123	70	86	132	106	72	80
Millet	64		105							40	73		103	40	97
Oats	112	72	111	108	49	152	44	124	102		109	117	112		138
Rye	112		111	108	49	152		124					112		
Other	108	72	111	108	49	152		124	102	109	109	117	112	120	138
Oil and protein field crops	102	63	115	93	42	130	40	101	116	70	93	123	114	71	124
Soybean	117	75	136	92	47	124		146	116	89	101	124	136	89	124
Rapeseed	104	78	102	105	25	167	40	107	121	47		129	102	45	159
Peanut	92		104		42	96			112	67	94		97	67	97
Sunflower	86	73	92	82	53	119		85	113	64	87	124	89	80	119
Sesame	83		103		25					65	83		92		
Common bean	90	49	112	100	41	81			124	59	123	116	110	60	119
Faba bean	101		112	100	41	81	28	115	124	59	123		110		119
Cowpea	77		101								76				
Chickpea	88		105												
Peas	108	41	110	94	39	139	46	104	110	87	110		108	95	133
Pigeon pea	94		106								125				
Lentil	101	30	107		40						120		107	95	130
Other	95	72	157	72	42	133		88		81	106		127	79	122
Oil tree crops and tree nuts	125	80	167	75	41	51	36	45	139	109	125	153	139	102	38
Oil palm	160		173			135			153		112	146	123		
Coconut palm	146		160	170		124	0	0	142	121	146	132	97	113	0
Olive	57			74	41		39	0	81						
Cashewnut	125								123	87	137			86	
Almond	56	81	145	74	41	44			103						39
Other tree nuts	82	81	145	74	41	44			130	0	99	248	145	86	39
Starchy root crops	113	60	111	103	35	101	78	125	130	86	117	125	101	85	91
Cassava	122		123			140			131	124	121	126	88	120	
White potato	100	60	108	103	35	100	80	125	126	83	112	120	105	81	94
Sweet potato	113		104	74		95			132	113	120	121	96	112	95

Parameter[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Yams	108		151						138		108	123			
Sugar crops	107	36	107	105	37	121	113	95	141	55	88	141	92	64	113
Sugar cane	110	4	108		11	127	113		141	55	100	141	92	64	126
Sugar beet	90	37	100	105	44	104		95	91	74	0		93		103
Vegetables															
Above-ground	97	30	104	95	32	76	91	107	117	89	103	122	99	91	80
Below-ground	95	30	104	95	32	76	91	107	117	89	103	122	99	91	80
Fruits	93	31	102	89	38	65	65	85	114	87	113	129	93	97	52
Grape	72	25	94	87	45	32	49	104	58	67	42	110	89	81	32
Mango	93		105		26	50			133	86	100	130	95	96	
Plantain	136		103		0				154	175	135				
Banana	127		129		19	134	143		138	106	132	126	92	110	
Apple	83	33	99	91	38	79	77	64	73	89	77	115	93	98	75
Orange	88		110	80	26	85	82		133	54	82	138	106	81	71
Other - Temperate	82	33	99	91	38	62	82	105	73	89	77	115	93	98	55
Other - Tropical	101		105		26	80	116		133	86	100	130	95	96	
Stimulants	135		144		65	137			151	128	123	141	80	114	
Cocoa	134		188						156		118	161	0		
Coffee	146		162			136			149	109	137	135	93	108	
Tea	115		106		88				113	137	147	132	98	119	
Forage	90	60	106	101	36	86	71	125	102	82	30	121	98	82	104
Grass/legumes	89	60		101	36	86		125		82	30			82	104
Whole cereals	95		106	101		86	71		102			121	98		104
Fiber crops															
Seed cotton	64	13	34	65	19	69	20		129	57	106	124	30	68	71
Perm. & semi-perm. pasture	74	50	116	101	11	71	60	151	108	80	75	124	115	100	75
Originally forest	119	135	116	111	42	102	108	196	129	107	126	121	110	104	99
Orig. trop./sub-trop. grass-/woodland	79	0	147	75	21	55	58	173	117	75	78	126	147	42	56
Orig. temp. & montane grassl.	104	96	142	72	27	92	23	123	66	107	76	0	142	160	88
Originally xeric grassland	16	16	31	0	2	24	8	51	93	18	20	0	31	47	26

[1] Potential soil carbon per hectare based on LPJ model results ([101], [38]). Crop and pasture distribution from [220] (permanent and semi-permanent pastures), [43] (grapes and forage crops), and [23] (all other crops).

Table S60 Plant carbon stocks of current agricultural vegetation. Numbers in Mg C per ha physical land area. Numbers shown only for crops with significant plant carbon stocks (>2 Mg C/ha). Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes.

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Oil tree crops and tree nuts															
Oil palm[1]	25		27			24			25		19	25	24		
Coconut palm[2]	38		38	46	46	40	46	46	46	40	28	50	48	40	40
Olive[3]	11			13	8.0		13		15						
Cashewnut[4]	12								9.6	13	12			13	
Almond[5]	7.4	9.4		4.4	6.8	9.6			12						12
Other tree nuts	7.6	9.0	12	6.2	4.1	8.3			7.9		5.9	4.1	16		8.3
Sugar cane[6]	10		10		10	10	10		10	10	10	10	10	10	10
Fruits															
Grape[7]	10	10	14	8.3	9.1	13	11	9.1	11	14	14	14	14	15	13
Mango[8]	20		20		18	20			22	20	18	26	22	20	
Plantain	3.8		6.6						5.9	3.6	3.2				
Banana	6.1		8.3		6.1	8.1	7.2		6.6	8.9	3.4	3.9	8.5	9.3	
Apple[9]	9.3	5.8	10	9.7	8.1	14	14	6.2	14	6.2	13	15	10	6.2	16
Orange[10]	13		13	15	14	13	14		15	11	14	16	13	11	14
Other - Temperate	6.8	9.3	7.5	6.6	6.0	8.9	9.7	6.6	8.1	5.0	4.5	11	8.3	5.2	12
Other - Tropical	7.6		5.3		8.9	16			17	11	7.1	17	3.1	13	
Stimulants															
Cocoa[11]	13		12						13		13	12			
Coffee[12]	10		11			6.0			11	9.6	8.0	13	10	9.6	
Tea	5.2		4.0		14				8.0	7.6	7.2		3.6	8.4	
Perm. & semi-perm. pasture[13]	8.2	3.5	3.8	5.8	2.8	6.1	9.0	7.2	12	4.2	14	16	3.8	5.0	6.4
Originally forest	6.0	7.4	5.4	5.2	6.9	6.2	6.8	6.2	6.0	5.3	5.5	6.2	5.4	5.4	6.1
Orig. trop./sub-trop. grass-/woodland	16		6.4	8.0	6.4	15	14	12	22	4.4	16	24	5.9	2.4	17
Orig. temp. & montane grassl.	5.2	4.9	3.9	5.6	2.9	7.1	9.6	7.8	4.0	4.3	8.9		3.9	6.2	7.2
Originally xeric grassland	3.7	2.3	1.4		1.3	4.1	3.1	6.2	8.9	2.2	12		1.4	2.7	3.8

[1] Based on [422].
[2] Based on [423], [424], [425], [426], [427], [428], [429], and [430].
[3] Based on [186].
[4] Based on [431], [432], [433], and [434].
[5] Based on [435–437].
[6] Based on [438].
[7] Based on [439], and [440].
[8] Based on [441], [442], [443], [444], and [445].
[9] Based on [446].
[10] Based on [447], [448], [449].
[11] Based on [450], [451], [452], [453], [454], [455], and [456].

[12] Based on [457], [458], [459], [460].
[13] Based on [102].

Table S61 Soil carbon stocks under current agricultural vegetation. Numbers in *percent loss* from native C soil stocks (see Table S59). Negative values indicate gain of soil carbon; gains are prevalent in dry regions with extensive use of irrigation (see Wang et al. 2023). Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per year. For sources, see table footnotes.

Parameter[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cropland - average	20%	15%	28%	19%	-12%	21%	-5.8%	23%	21%	10%	19%	22%	27%	9.1%	21%
Cereals															
Wheat	19%	17%	27%	24%	-5.3%	20%	-10%	23%	21%	15%	11%	24%	27%	17%	20%
Maize	22%	2.8%	27%	25%	-4.1%	22%	26%	23%	22%	10%	18%	23%	27%	8.7%	22%
Rice – irrigated/high input	21%	-7.8%	26%	0.8%	24%	25%	24%	19%	21%	14%	20%	21%	27%	14%	25%
Rice – low input	23%		24%		11%				23%	23%	21%	23%		23%	
Barley	16%	15%	22%	20%	-9.4%	18%	-11%	25%	20%	15%	8.5%	24%	20%	17%	12%
Sorghum	13%				-61%	15%	22%		18%	-32%	19%	21%	26%	-32%	20%
Millet	14%		26%							-11%	20%		26%	-13%	
Oats	22%	16%		25%	-5.8%	22%	-6.0%	24%	17%		13%	23%			
Rye	24%		23%	25%	-5.8%	22%		24%					22%		24%
Other	19%	16%	23%	25%	-5.8%	22%		24%	17%		13%		22%		
Oil and protein field crops															
Soybean	22%	19%	26%	27%	-22%	23%		19%	22%	19%	20%	22%	27%	19%	23%
Rapeseed	22%	19%	27%	29%	-4.3%	20%	-20%	25%	20%	20%			27%	19%	20%
Peanut	15%	6.1%	27%		-25%	20%			22%	-32%	20%	23%	28%	-33%	20%
Sunflower	20%	15%	22%	20%	5.6%	20%		23%	21%	-44%	19%	22%	19%	-44%	20%
Sesame	19%		26%							7.8%	20%		29%		
Common bean	17%	18%	25%	21%	-5.4%	11%			24%	3.6%	20%	24%	25%	3.4%	20%
Faba bean	21%		25%	21%	-5.4%	11%			24%		20%		25%		
Cowpea	20%										20%				
Chickpea	14%														
Peas	18%	8%	25%	15%	-24%	20%	-19%	24%	17%	9.5%	18%		25%	10%	20%
Pigeon pea	1.8%		25%								20%			-2.9%	
Lentil	20%	13%	25%		-14%	20%				24%	4.6%		25%	25%	19%
Other	10%	16%	25%	-29%	-31%	20%		22%		3.8%	20%		25%	1.1%	
Oil tree crops and tree nuts															
Oil palm[2]	19%		20%			20%			18%		18%	20%	20%		
Coconut palm	18%		20%		-80%	20%			19%	11%	19%	20%	21%	9.2%	
Olive	-40%			-40%	-40%				-40%		-40%				
Cashewnut	20%		20%						20%	20%	20%	20%		20.0%	
Almond	-39%	16%		-40%	-40%	-62%			-6.1%						-40%
Other tree nuts	-5.0%	16%	16%	-40%	-40%	-62%			20%		16%	18%	16 %	20.0%	-40%
Starchy root crops															
Cassava	22%		25%			25%			23%	19%	21%	24%	25%	19%	
White potato	22%	12%	24%	27%	-7.5%	18%	14%	25%	19%	23%	21%	23%	23%	22%	14%
Sweet potato	22%		27%	-37%		21%			24%	24%	15%	24%	27%	24%	21%
Yams	21%		27%						24%		21%				

Parameter[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Sugar crops															
Sugar cane	20%		25%		-29%	23%	25%		23%	-3.2%	17%	23%	25%	-4.1%	22%
Sugar beet	25%	3.4%	26%	28%	9.0%	16%		27%	-0.8%		20%		25%		15%
Vegetables															
Above-ground	22%	4.4%	27%	15%	-10%	15%	23%	23%	21%	15%	17%	23%	27%	14%	19%
Below-ground	21%	4.4%	27%	15%	-10%	15%		23%	21%	15%	17%	23%	27%	14%	19%
Fruits															
Grape	0.1%	4.7%	22%	-5.5%	-1.5%	-0.5%	1.5%	20%	7.1%	-14%	-14%	20%	21%	-13%	1.1%
Mango	11%		21%			-4.9%			17%	5.4%	17%	19%	21%	4.4%	
Plantain	18%		18%						18%	19%	18%				
Banana	16%		20%		-38%	20%			18%	8.8%	15%	20%	20%	8.1%	
Apple	14%	3.5%	22%	2.6%	-17%	12%	3.2%	24%	10%	12%	10%	20%	22%	12%	11%
Orange	12%		21%	-20%	-12%	8.7%			17%	0.2%	15%	18%	21%	-1.1%	11%
Other - Temperate	15%	3.5%	22%	2.6%	-17%	14%	10%	19%	10%	12%	10%	20%	22%	12%	13%
Other - Tropical	18%		21%		-15%	14%			17%	5.4%	17%	19%	21%	4.4%	
Stimulants															
Cocoa	19%		20%						19%		19%	20%			
Coffee	17%		20%			20%			18%	-17%	17%	19%	20%	-19%	
Tea	21%		21%		24%					20%	18%		22%	20%	
Forage															
Grass/legumes	16%	10%	21%	18%	-17%	20%	2.8%	18%	14%	4.4%	0.0%	18%	19%	1.7%	17%
Whole cereals	22%		26%	23%	-14%	25%	7.2%		20%			24%	24%		23%
Fiber crops															
Seed cotton	7.3%	-10%	20%	26%	-28%	22%	16%		20%	-7.2%	20%	20%	18%	-8.1%	23%
Permanent & semi-permanent pasture – average	11%	8.3%	9.6%	15%	8.6%	11%	14%	13%	12%	12%	10%	12%	9.3%	12%	12%
Originally forest[3]	16%	17%	17%	18%	18%	17%	18%	16%	15%	15%	15%	15%	17%	15%	18%
Originally tropical/sub-tropical grassland and woodland[4]	9.4%		7.2%		0.1%	5.5%	9.2%	7.5%	9.8%	8.0%	10%	10%	7.5%	7.1%	5.6%
Originally temperate & montane grassland[5]	8.7%	10%	7.8%	10%	10%	10%	9.5%	9.6%	8.8%	7.1%	7.5%		7.8%	7.0%	10%
Originally xeric grassland	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%

[1] Based on [103,461]. For forest to cropland and grassland to cropland, numbers were also based on [462] and [463]. Soil carbon changes from conversion to cropland in dry biomes were based on [104].
[2] Based on [464].
[3] Based on [103].
[4] Based on [103,465,466]
[5] Based on [103,465,466]

Table S62 Plant and soil decay data for calculating carbon opportunity costs. Plant decay rates refer to decay of above-ground plant matter in percent of plant mass decomposed per year; soil C linearization period in years (for details, see section 1.9). Sources: Plant decay rates based on [95]. Soil C linearization period based on soil respiration data in [98]. Decay numbers shown only where biome area exceeds 0.1% of the agricultural area in the region.

Parameter	**CAS**	**EAS**	**EUR**	**MEA**	**NAM**	**OCE**	**RUS**	**SAM**	**SAS**	**SSA**	**Brazil**	**China**	**India**	**USA**
Decay rates for plant matter														
Tropical moist forest		11.2%			12.7%	10.5%		10.1%	14.1%	12.2%	10.6%	7.8%	14.2%	
Tropical dry forest		16.1%			11.8%			13.5%	15.4%	14.1%	14.8%		15.3%	
Tropical coniferous forest					7.5%			11.1%	7.3%				7.3%	
Temperate broadleaf forest		4.7%	3.6%	4.4%	4.3%	5.7%	2.4%	3.5%	4.9%			4.7%	4.7%	4.5%
Temperate coniferous forest		2.4%	2.8%	4.1%	4.0%				6.7%			2.4%	3.1%	4.2%
Boreal forest & taiga			2.3%		1.9%		1.9%							
Tropical/sub-tropical grass- & shrubland				10.0%	10.8%	9.0%		11.3%	12.4%	13.7%	11.6%		11.6%	10.2%
Temperate grass- & shrubland	2.4%	2.4%	3.6%	4.4%	3.8%	6.3%	2.6%	6.6%				2.4%		4.3%
Flooded grassland		2.6%		15.4%			1.8%	10.3%	17.8%	14.7%	14.8%	2.6%	17.8%	
Montane grass- & shrubland	1.5%	2.0%		4.7%		2.7%		2.9%		7.0%		2.0%		
Mediterranean forest & shrub			5.5%	6.5%	6.0%	6.8%		5.1%		6.8%				6.0%
Deserts	4.4%	3.6%		8.7%	6.3%	7.3%	2.9%	10.7%	15.1%	11.1%		3.6%	15.5%	4.5%
Mangroves		16.4%						13.7%	15.4%	15.6%	14.7%		16.1%	
Soil carbon linearization period														
Agricultural land	50	30	40	30	40	30	60	25	20	20	25	35	20	40
Aquaculture ponds	75	75	60	45	60	45	90	38	30	30	38	53	30	60

A11. Endogenous input data: Nitrogen inputs in crop and pasture production

Table S63 Fertilizer nitrogen inputs per ha in open-field crop production. Numbers in kg of N before gas losses per ha physical land area per year. Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per year. Source: Estimates of this study (see 1.3.4).

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cereals															
Wheat	98	29	232	102	47	87	41	62	71	160	71	53	268	219	88
Maize	135	129	150	121	145	176	156	93	144	200	53	163	231	200	191
Rice – irrigated/high input	122	25	141	73	69	105	137	52	102	121	1.4	135	204	142	107
Rice – low input	15	17	13		55	44			42	26	0	41		33	
Barley	38	25	24	67	5.6	70	50	24	76	74	60	65	80	83	91
Sorghum	18		42	66	20	47	81		51	48	4.1	43	92	53	81
Millet	11		59							30	0		80	35	17
Oats	24	21	40	37	16	39	22	4.0	30		4.9	37	39		0
Rye	67		70	75	57	52		35					93		
Other	43	24	41	73	55	57		5.0	51	61	16	50	60	66	59
Oil and protein field crops															
Soybean	22	31	32	84	47	28		47	4.0	62	0	0	37	25	29
Rapeseed	139	67	135	175	130	143	85	71	110	137		69	144	116	129
Peanut	12		22		32	7.6			3.3	41	0		29	0	7.4
Sunflower	106	50	138	177	124	89		75	93	51	13	64	167	22	97
Sesame	7.3		24		33					40	0		98		
Common bean	20	29	38	51	56	28			22	13	8.7	25	45	0	57
Faba bean	3,7		12	0	0	0	0	0	0	6.6	0		0		0
Cowpea	0,3		0								0				
Chickpea	14		13												
Peas	9,2	3.6	0	0	0	23	0	0	0	12	0		0	0	24
Pigeon pea	10		0								0				
Lentil	10	2.6	11		0						0		13	0	6.9
Other	5,4	4.8	0	2.4	0	0		6.9		12	0		3.2	0	0
Oil tree crops and tree nuts															
Oil palm	168		216			161			65		8.7	62	172		
Coconut palm	76		83			105	167		55	105	0	64	172	117	107
Olive	32			54	12		73	63	31						
Cashewnut	22								9.2	61	8.0			65	
Almond	118	153	332	27	45	364			135						369
Other tree nuts	94	122	194	66	20	117			40	132	23	19	214	0	119
Starchy root crops															
Cassava	42		117			66			65	168	26	69	96	193	
White potato	125	105	106	123	145	234	238	80	98	188	51	147	114	212	269
Sweet potato	76		122	57		124			72	141	38	75	141	156	127
Yams	34		100						53		34	49			

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Sugar crops															
Sugar cane	204	16	204		209	201	355		143	350	70	97	241	403	237
Sugar beet	211	119	249	235	219	251		164	201	455	89		256		247
Vegetables															
Tomato	193	191	409	363	352	550	617	185	256	168	4.8	436	563	200	732
Okra	72		226		87				90	276	0	91	300	301	
Peas (green)	44		40	9.3	17	14			0	79	0		63	88	
Cabbage	488	428	785	339	281	530	607	402	281	369	33	284	634	403	
Cucumber	186	164	236	200	187	158		193	73		0	73	501		
Pepper (capsicum)	169		207	407	309	217					5.7		311		
Eggplant	258		511	331	265					173			594	197	
Cauliflower & broccoli	877		829	604	993	723			396	1000		400	1090	1100	
Onion	127	198	145	192	197	380	434	183	165	121	7.4		219	147	557
Carrot	238	289	269	227	175	336	398	170	127		17	128	495		402
Other above-ground veg.	158	238	195	174	163	194	147	171	96	150	0	104	261	177	255
Other below ground veg.	49	134	45	164	156										
Fruits															
Grape	76	101	165	55	32	148	126	80	54	187	38	80	177	227	152
Mango	145		164		150	174			93	181	33	128	215	190	
Plantain	11		77		29				35		0				
Banana	157		293		79	273	265		99	366	13	50	324	431	
Apple	29	12	28	33	41	84	97	16	38	0	15	45	30		106
Orange	126		176	204	77	163	208		104	111	48	122	171	126	209
Other - Temperate	40	85	56	45	18	95	123	59	37	0	3.8	61	75	2.9	145
Other - Tropical	63		30		46	282	231		139	175	19	140	0	242	
Stimulants															
Cocoa	12		25						24		8.3	19	26		
Coffee	38		76			11			41	34	5.2	58	59	38	
Tea	270		214		334				65	550	105	81	196	686	
Forage															
Whole cereals	58			71		63	104		20			62	102		67
Grass/legumes – silage	18	10	19	36	48	7.1		7.2		16	31		46	27	5.1
Grass/legumes – grazed	2.9		9.3	4.7		70		0							0
Fiber crops															
Seed cotton	85	91	257	17	155	111	187		144	49	20	162	281	51	110
Perm. & semi-perm. pasture	0.4	0	0	0.9	0	1.7	1.9	0	0	0	0	3.0	0	0	2.2

Table S64 Manure nitrogen inputs per ha by manure application and excretion at grazing. Numbers in kg of N before gas losses per ha physical land area per year. Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per year. Source: Estimates of this study (see section 1.3.4).

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cereals															
Wheat	9	2	23	27	2	2	5	2	3	2	18	3	16	3	1
Maize	62	29	83	79	204	75	92	66	63	38	19	69	89	34	69
Barley	20	2	17	29	21	7	6	26	2	5	18	3	0	7	1
Sorghum	20	15		77	5	45	45	38	52	1	17	49	56	0	30
Oats	8	0	0	0	0	0	0	23	18		15	0	0		0
Forage															
Whole cereals	58			89		126	79		205			143			123
Grass/legumes – silage	88	40		106	77	80		64		121	64			112	73
Grass/legumes – grazed	119	32	57	138	63	111		89	146	103	53	92	59	91	116
Perm. & semi-perm. pasture	16	6	26	29	10	10	8	7	39	67	9	57	18	82	10

Table S65 Nitrogen inputs per ha from plant mass left in field. Numbers in kg of N before gas losses per ha physical land area per year. Data is not shown for regions and crops with a production of less than 0.1 Tg dry matter per year. Source: Estimates of this study (see section 1.3.4 and 1.4.1)

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Cereals															
Wheat	33	18	69	44	25	37	23	31	29	18	32	25	73	22	37
Maize	88	94	100	97	34	119	110	92	80	27	64	100	132	25	123
Rice – irrigated/high input	65	35	81	56	54	64	70	48	69	48	39	77	98	50	64
Rice – low input	20	19	19	49	38	32	75	23	33	25	14	33	12	27	64
Barley	27	17	26	36	15	34	26	24	30	12	36	28	32	12	36
Sorghum	34		48	62	35	63	72	35	34	9	33	35	61	9	70
Millet	9		35							6	9		42	6	16
Oats	24	14	27	28	16	32	19	18	19		15	21	30		24
Rye	44		43	50	39	37		31					50		
Other	30	18	25	42	31	33		9	27	11	22	28	31	11	33
Oil and protein field crops															
Soybean	89	71	62	83	89	94		59	109	13	55	131	64	46	95
Rapeseed	57	39	60	86	66	69	42	43	61	12		41	61	40	63
Peanut	50		111		112	148			99	11	34		129	46	47
Sunflower	55	30	59	83	61	45		42	51	10	26	38	65	16	47
Sesame	15		21		25					5	16		50		
Common bean	31	48	59	74	76	47			44	5	46	47	62	16	73
Faba bean	69		72	88	43	59	57	55	47	9	77		72		59
Cowpea	68		81								68				
Chickpea	55		65												
Peas	67	56	62	88	45	87	51	77	72	11	52		62	40	87
Pigeon pea	23		66								94				
Lentil	34	41	79		43						66		80	34	60
Other	33	66	56	74	57	46		75		7	37		85	23	41
Oil tree crops and tree nuts															
Oil palm	105		112			101			105		79	103	100		
Coconut palm	113		115	139		121	139	139	139	121	85	152	146	121	121
Olive	30			37	23		37	37	42						
Cashewnut	64								51	72	62			72	
Almond	18	24	28	11	17	30			30						30
Other tree nuts	22	26	35	18	12	24			23	31	17	12	45	2	24
Starchy root crops															
Cassava	28		44			34			31	30	25	37	39	31	
White potato	40	48	45	51	54	68	65	44	36	13	25	56	46	14	73
Sweet potato	48		70	59		74			45	9	31	64	73	9	74
Yams	28		58						36		28	48			
Sugar crops															
Sugar cane	86	29	103		119	112	167		100	34	91	110	112	36	126

Parameter	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Sugar beet	126	92	127	131	128	131		117	120	25	122		125		131
Vegetables															
Tomato	47	40	65	69	65	95	98	40	53	30	19	84	82	32	122
Okra	23		54		29				31	57	10	31	65	57	
Peas (green)	150		150	110	113	108			70	182	163		180	183	
Cabbage	127	130	185	103	86	147	154	127	91	85	58	91	146	85	
Cucumber	32	30	36	36	33	28		36	17.2	9	4	17	64		
Pepper (capsicum)	43		51	103	79	59					16		78		
Eggplant	60		110	88	71					44			141	45	
Cauliflower & broccoli	306		305	273	350	310			194	318		194	376	319	
Onion	25	36	26	36	35	60	62	35	32	22	17		33	23	84
Carrot	75	96	77	77	61	102	110	62	50		42	50	123		118
Other above-ground veg.	48	71	53	55	50	55	41	55	35	41	29	37	64	43	70
Other below ground veg.	17	32	17	38	36										
Fruits															
Grape	33	34	46	27	30	42	35	30	37	46	45	46	47	49	42
Mango	52		53		3	53			58	53	48	69	58	52	
Plantain	27		46		42				42	25	22				
Banana	72		97		72	94	84		77	104	40	45	99	109	
Apple	23	16	28	27	1	37	37	17	37	17	35	41	28	17	43
Orange	30		29	34	31	29	31		34	24	31	36	29	24	32
Other - Temperate	19	26	21	18	16	24	27	18	22	14	12	31	23	14	33
Other - Tropical	19		13		23	41	35		43	29	18	43	8	34	
Stimulants															
Cocoa	29		28						30		29	27	28		
Coffee	22		25			13			25	21	18	30	22	21	
Tea	15		12		42				24	23	21	28	11	25	
Forage															
Whole cereals	49		48	48		51	48		48			48	48		51
Grass/legumes – silage	110	76		135	64	115		90		131	78			125	115
Grass/legumes – grazed	117	73	71	127	65	115		87	98	129	76	85	71	123	116
Fiber crops															
Seed cotton	47	55	114	18	84	61	89		84	29	22	93	118	28	59
Perm. & semi-perm. pasture	40	15	57	67	22	24	17	16	88	116	37	131	37	111	23

A12. Endogenous input data: Feed rations, feed efficiencies and land use efficiencies

Table S66 Feed baskets of cattle/buffalo dairy production (% of DM) and their average metabolizable energy (MJ/ kg DM) and crude protein content (% DM). Source: Estimates of this study (see section 1.3.3).

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Dairy cows														
Cereals, starchy roots	2.6	2.1	19,2	17.1	27.5	4.4	4.5	1.9			2.1			29.5
Grass-legume silage/hay or cut-and-carry	9.1	1.1	25,1		22.7	4.4	56.8		9.9			1.1	10.7	17.1
Whole-cereals silage		0.4	31.0	4.0	25.2	8.0		10.3			8.0	0.4		24.1
Oil meals, brewers grains, etc.	2.6	11.9	12,9	6.6	17.1	7.8	7.9	7.0	3.1	2.6	6.2	12.3	4.5	21.8
Brans, molasses etc.	3.2	15.0	2.3	9.0	7.5	2.2	11.0	4.0	15.2	2.0	3.4	10.7	16.9	7.5
Crop residues	1.8	5.3		9.9				16.8	54.6	22.9	8.0	5.3	55.6	
Grazed on cropland			9.6				19.6							
Grazed on permanent grassland	79.9	64.2		53.4		73.1	0.2	6.0	10.7	72.4	72.3	70.2	8.5	
Grazed on non-agric. land									6.6				3.9	
Metabolizable energy content	8.4	10.1	11.5	10.1	12.4	11.1	11.0	9.1	8.3	8.5	8.7	9.8	8.6	12.7
Protein content	11.4	13.6	15.0	12.8	15.2	15.5	16.0	11.3	9.0	9.8	11.5	14.7	9.3	16.4
Dairy replacement heifers														
Cereals	0.2		3.3	0.5	3.4	1.3	0.8	1.2			0.2	0.4		4.2
Grass-legume silage/hay or cut-and-carry	4.6	0.6	27.3	14.7	33.3	29.4	36.7	1.5	1.4			0.6	2.0	29.4
Whole-cereals silage		0.2	1.0	0.6	1.0	2.8		8.0			2.0	0.2		0.2
Oil meals, brewers grains, etc.	0.5	1.6	0.6	0.7	3.7	1.2	1.4	6.9			0.7	1.7	0.3	4.0
Brans, molasses etc.	0.9	4.3	1.3	2.5	2.6	0.7	3.1	4.3	1.6	2.5	0.8	4.1	2.0	2.5
Crop residues	1.8	11.4		5.7				8.8	28.2	20.4	8.0	11.8	40.8	
Grazed on cropland			4.0		56.0									59.7
Grazed on permanent grassland	92.0	81.9	62.5	75.4		64.7	58.1	69.3		77.1	88.3	81.2		
Grazed on non-agric. land									68.5				54.9	
Metabolizable energy content	8.2	8.4	9.6	8.7	10.3	1	9.3	8.8	8.0	7.8	7.7	8.7	7.8	10.3
Protein content	10.2	10.5	13.1	11.8	14.6	14.2	13.6	11.9	8.3	8.6	9.7	10.7	7.6	14.6

Table S67 Feed baskets of beef production (% of DM) and their average metabolizable energy (MJ/ kg DM) and crude protein content (% DM). Source: Estimates of this study (see section 1.3.3).

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Beef cows & replacement heifers														
Cereals, starchy roots	0.1		0.4		0.3	0.2	0.1				0.1	0.1		0.4
Grass-legume silage/hay or cut-and-carry	2.1	0.4	27.2		31.7	1.3	35.5	0.1		0.2		0.3		30.6
Whole-cereals silage		0.1	1.0		0.5			0.7			1.2	0.1		0.1
Oil meals, brewers grains, etc.		0.5	0.3		0.9	0.2	0.5	0.2		0.1	0.1	0.5		1.0
Brans, molasses etc.	0.2	1.4	0.7		0.6	0.2	0.9	0.3		0.6	0.3	1.3		0.6
Crop residues	2.0	18.6	7.3				3.1	12.9		23.5	8.7	18.1		
Grazed on cropland			5.4			1.6								
Grazed on permanent grassland	95.4	79.1	57.7		66.0	96.4	59.8	85.7		75.5	86.9	79.6		67.3
Metabolizable energy content	8.0	8.0	9.0		9.2	8.3	8.9	7.6		7.7	7.5	8.1		9.2
Protein content	10.2	9.4	12.5		12.6	10.7	12.8	8.9		8.7	8.9	9.5		12.6
Beef bulls/steers & heifers														
Cereals, starchy roots	6.0		33.7		43.1	17.7	9.1	0.5			1.3	4.2		50.8
Grass-legume silage/hay or cut-and-carry	20.4	5.9	14.5		9.8	18.9	6	0.9		2.2		5.8		8.6
Whole-cereals silage		1.8	9.2		10.8	27.1		3.9			6.3	1.7		5.5
Oil meals, brewers grains, etc.	2.0	11.0	3.7		19.0	7.9	6.8	3.2		0.9	2.7	11.3		20.8
Brans, molasses etc.	3.3	22.3	6.1		10.3	3.8	20.1	3.4		9.2	2.7	21.0		6.8
Crop residues	2.3	21.6						5.5		14.1	3.7	21.5		
Grazed on cropland			18.2		6.9									7.5
Grazed on permanent grassland	66.0	37.4	14.5			24.6		82.2		70.7	83.3	34.4		
Metabolizable energy content	8.8	9.1	11.1		12.2	10.4	10.1	8.2		8.1	8.2	9.4		12.6
Protein content	12.0	12.1	13.0		16.2	13.6	17.1	10.6		9.4	10.2	13.3		16.3
Dairy bulls/steers & heifers														
Cereals, starchy roots	6.9		34.9	9.5	43.2	18.7	5.2	0.5			1.3	3.6		49.9
Grass-legume silage/hay, (cut-and-carry)	15.6	3.4	13.1	7.7	9.6	17.3	43.8	0.8	5.3	1.9		3.4	5.3	8.6
Whole-cereals silage		1.1	9.4	3.9	10.6	26.4		3.9			6.6	1.1		5.9
Oil meals, brewers grains, etc.	1.9	9.4	1.9	4.6	18.7	7.6	8.8	3.3	1.4	0.8	2.6	9.5	1.5	20.3
Brans, molasses etc.	3.1	18.9	6.3	12.6	10.1	3.5	16.3	3.4	6.1	9.2	2.8	17.8	6.8	6.6
Crop residues	1.7	14.6		8.1				5.0	39.1	12.5	3.6	11.5	39.0	
Grazed on cropland			21.5		7.8									8.6
Grazed on permanent grassland	70.9	52.6	12.9	53.6	5.0	26.5	25.8	83.2		72.3	83.1	53.2		
Grazed on non-agric. land									48.2				47.4	
Metabolizable energy content	9.0	9.0	11.6	9.6	12.6	10.6	9.8	8.3	7.9	8.1	8.3	9.4	7.9	12.9
Protein content	11.9	10.8	12.5	12.1	15.4	12.7	14.8	10.6	7.9	9.2	10.2	11.8	7.7	15.0

Table S68 Feed baskets of sheep and goat production (% of DM) and their average metabolizable energy (MJ/ kg DM) and crude protein content (% DM). Source: Estimates of this study (see section 1.3.3).

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Dairy ewes/does and replacements														
Cereals, starchy roots		0.1	11.9	8.7										
Grass-legume silage/hay or cut-and-carry		1.6	29.8	1.3				1.0	1.1	0.4		1.6	1.0	
Whole-cereals silage														
Oil meals, brewers grains, etc.		7.5	3.1	3.5				0.2	0.2	0.2		0.3	0.2	
Brans, molasses etc.		0.6	0.2	0.5				0.2	0.6	0.1		0.4	0.7	
Crop residues		9.2		10.0				7.4	59.5	12.6		9.4	59.7	
Grazed on cropland														
Grazed on permanent grassland		81.1	55.1	76.1				91.1		86.7		88.2		
Grazed on non-agric. land									38.6				38.4	
Metabolizable energy content		8.3	9.6	8.5				7.5	7.3	7.5		8.0	7.2	
Protein content		12.0	13.7	11.1				9.0	7.0	9.0		9.7	6.6	
Meat ewes/does and replacements														
Cereals, starchy roots		0.1	0.2			0.2						0.1		
Grass-legume silage/hay or cut-and-carry	1.4	1.6	31			1.8		1.0	1.4	0.4		1.6	1.3	
Whole-cereals silage														
Oil meals, brewers grains, etc.		0.3	0.1			0.2		0.2	0.2	0.2		7.6	0.2	
Brans, molasses etc.	0.1	0.6	0.2			0.1		0.2	0.8	0.1		0.4	0.9	
Crop residues	1.1	9.0						7.4	60.2	13.3		9.1	60.5	
Grazed on cropland						0.4								
Grazed on permanent grassland	97.4	88.5	68.8			97.3		91.1		85.9		88.4		
Grazed on non-agric. land									37.4				37.1	
Metabolizable energy content	7.9	8.0	9.0			8.4		7.5	7.2	7.5		8.4	7.2	
Protein content	10.1	9.7	13.2			10.7		9.0	6.9	8.9		12.3	6.6	
Lambs/kids (weaned)														
Cereals, starchy roots		10.0	7.0	12.4		1.1						10.0		
Grass-legume silage/hay or cut-and-carry	25.5		25.0	23.4		13.3		8.5	15.3	3.4			18.8	
Whole-cereals silage														
Oil meals, brewers grains, etc.	1.0	10.0	4.0	7.5		5.0			5.0	5.0		10.0	5.0	
Brans, molasses etc.	2.3	18.0	5.0	11.5		2.5		5.3	17.0	3.0		12.5	20.5	
Crop residues	0.7								31.7				32.9	
Grazed on cropland			6.5			31.2								
Grazed on permanent grassland	70.6	62.0	52.5	45.1		47.0		81.2		88.6		67.5		
Grazed on non-agric. land									31.0				22.9	
Metabolizable energy content	8.4	10.1	9.6	9.4		9.4		8.3	8.5	8.0		9.9	8.7	

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Protein content	12.0	13.9	14.2	14.3		13.6		11.9	10.9	11.0		14.2	10.9	

Table S69 Feed baskets of pork production (% of DM) and their average metabolizable energy (MJ/ kg DM) and crude protein content (% DM). Source: Estimates of this study (see section 1.3.3).

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Sows and replacement gilts														
Cereals, starchy roots		62.6	80.2		74.6	80.8	70.5	82.6	50.6	73.4	83.7	68.4	77.2	78.6
Oil meals, brewers grains, etc.		19.9	17.3		17.4	16.7	18.5	14.8	12.4	11.6	14.2	19.1	12.5	17.7
Brans, molasses etc.		14.4	2.5		8.0	2.5	11.0	2.7	37.0	15.0	2.2	12.5	10.3	3.7
Metabolizable energy content		15.1	14.9		15.3	14.7	14.0	15.2	14.3	14.2	15.2	15.3	15.1	15.5
Protein content		17.0	16.4		16.6	17.8	17.6	14.4	15.1	11.3	13.6	16.9	14.3	16.5
Weaners and hogs														
Cereals, starchy roots		59.8	77.3		71.7	77.9	67.5	79.1	47.9	70.7	80.3	66.0	74.6	75.6
Oil meals, brewers grains, etc.		22.7	20.2		20.3	19.6	21.5	18.3	15.1	14.3	17.5	21.5	15.2	20.6
Brans, molasses etc.		17.5	2.5		8.0	2.5	11.0	2.7	37.0	15.0	2.2	12.5	10.3	3.7
Metabolizable energy content		15.1	14.9		15.3	14.7	14.0	15.2	14.3	14.2	15.2	15.3	15.1	15.5
Protein content		18.1	17.4		17.8	18.9	18.8	15.8	16.0	12.1	15.0	17.9	15.2	17.7

Table S70 Feed baskets of egg and chicken meat production (% of DM) and their average metabolizable energy (MJ/ kg DM) and crude protein content (% DM). Source: Estimates of this study (see section 1.3.3).

Parameter	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Laying hens														
Cereals	72.5	55.7	70.5	72.0	68.2	71.0	69.2	7	66.2	76.6	71.2	59.6	64.6	68.1
Vegetable oils	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		1.0	1.0	1.0	1.0
Calcium carbonate	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	2.2	9.0	9.0	9.0	9.0
Oil meals, brewers grains, etc.	16.0	17.8	20.5	14.4	22.8	2	21.8	18.4	15.6	6.2	17.7	18.9	16.2	22.9
Brans, molasses etc.	2.5	17.5		5.0				2.7	9.3	15.0	2.2	12.5	10.3	
Metabolizable energy content	12.4	13.0	12.2	12.4	13.1	12.1	11.7	13.2	13.0	14.1	13.2	13.1	12.9	13.2
Protein content	15.7	15.7	16.4	15.0	17.3	17.9	17.6	16.0	14.5	11.8	15.6	16.1	14.6	17.5
Broilers														
Cereals	85.0	49.7	62.0	76.4	61.7	62.5	60.7	66.7	60.7	71.3	62.7	56.1	59.1	61.6
Vegetable oils	2.0	2.0	4.0	2.0	4.0	4.0	4.0	3.0	3.0		4.0	2.0	3.0	4.0
Oil meals, brewers grains, etc.	10.5	30.8	34.0	16.6	34.3	33.5	35.3	27.7	27.1	13.7	31.2	29.4	27.2	34.4
Brans, molasses etc.	2.5	17.5		5.0				2.7	9.3	15.0	2.2	12.5	10.3	
Metabolizable energy content	14.1	14.0	13.5	13.8	14.6	13.6	13.0	14.6	14.2	14.1	14.6	14.2	14.1	14.8
Protein content	14.7	21.6	21.6	16.8	22.5	23.9	23.6	20.5	19.1	14.1	21.5	21.2	19.1	22.9

Table S71 Feed use per produced unit of milk, egg, meat and aquaculture products. Numbers in kg of dry matter intake per kg of product including water and per kg of edible protein. Note that numbers are not allocated over co-products; hence, feed use numbers for milk only have milk in the denominator, although these systems also produce significant amounts of meat. Also, note that feed use in aquaculture includes non-external feed (see 1.6.1). Source: Estimates of this study (see 1.3.3), except for aquaculture (see 1.6.1).

Parameter[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Kg DM per kg fresh weight															
Cattle/buffalo whole milk															
Dairy cows	1.64	2.85	1.46	0.89	1.57	0.71	1.15	1.09	2.09	2.02	6.16	2.23	1.61	1.87	0.65
Dairy replacement heifers	0.41	0.65	0.58	0,32	0.59	0.22	0.29	0.37	0.67	0.31	1.21	0.73	0.60	0.36	0.19
Total	2.05	3.50	2.04	1.21	2.16	0.93	1.44	1.46	2.75	2.33	7.37	2.96	2.21	2.23	0.84
Sheep/goat whole milk	12		24	4.6	18				15	5,9	18		19	5,2	
Egg (whole)	3.2	3.3	3.4	3.0	3.4	2.4	2.7	2.8	2.7	3.3	4.6	2.7	3.2	3.1	2.4
Suckler beef (carcass)															
Beef cows & repl. heifers	33	40	50	24		21	34	27	35		48	32	37		19
Bulls/steers & heifers	18	12	7.9	8.1		8.5	8.0	11	33		52	38	8.6		7.1
Total	52	52	58	32		29	42	38	68		100	70	46		26
Dairy bulls/steers (carcass)	42	18	12	11	12	11	11	10	51	93	76	61	11	121	9.0
Sheep/goat meat (carcass)															
Ewes/does & replacements	42	44	32	34	33		36		56	59	63		29	77	
Lambs	12	20	5.0	8.7	13		9.7		37	13	23		5.0	14	
Total	55	64	37	43	47		46		93	72	86		34	91	
Pork (carcass)															
Sows & repl. gilts	0.83		0.93	0.66		0.70	0.69	0.61	0.87	1.89	1.46	0.84	0.89	1.61	0.60
Weaners & hogs	2.86		2.76	2.76		2.81	2.59	2.89	3.54	4.37	5.19	3.42	2.70	3.30	2.71
Total	3.69		3.69	3.42		3.51	3.28	3.80	4.42	6.26	6.64	4.26	3.59	4.91	3.31
Chicken (carcass)	2.71	4.20	2.84	2.37	3.35	2.37	2.37	2.33	2.81	2.38	4.14	2.50	2.87	2.43	2.30
Carp (whole)	1.57		1.57		1.57					1.57	1.58		1.57	1.57	
Tilapia (whole)	1.48		1.47						1.47	1.48	1.49	1.47	1.47		
Other freshwater fish (whole)	1.67		1.67						1.67	1.68	1.69	1.67	1.67	1.68	
Salmonid (whole)	1.28			1.28	1.28	1.28			1.28						
Other non-freshwater fish (whole)	1.60		1.60	1.59	1.59					1.60	1.62		1.60	1.60	

Parameter[1]	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Crustacean (whole)	1.23		1.23			1.23			1.23	1.24			1.23	1.24	
Kg DM per kg edible protein															
Cattle/buffalo whole milk	59	100	61	38	62	29	39	46	86	60	180	92	69	55	26
Sheep/goat whole milk	270		490	99	370				270	160	430		360	140	
Egg	27	28	28	25	28	20	23	23	23	27	42	23	26	26	20
Suckler beef carcass	340	340	380	210		190	270	250	440		650	460	300		170
Dairy bulls/steers carcass	280	120	78	75	88	73	74	69	340	620	510	410	74	800	60
Sheep/goat carcass	410	460	290	330	350		350		700	550	630		260	690	
Pork carcass	24		24	22		22	21	22	28	40	42	27	23	31	21
Chicken carcass	20	28	20	17	24	17	17	17	20	17	30	18	21	18	17
Carp fillet	21		20.8		20.7					20.8	20.9		20.7	20.8	
Tilapia fillet	20		19.9						19.8	20.0	20.2	19.8	19.8		
Other freshwater fish fillet	26		26.1						26.1	26.2	26.3	26.1	26.1	26.2	
Salmonid fillet	14			14.1	14.1	14.1			14.1						
Other non-freshwater fish fillet	18		17.8	17.7	17.7	17.7				17.8	18.0		17.7		
Crustacean meat	12		11.9						11.9	11.9			11.9	11.9	

[1] Aquaculture feed efficiencies based on [83], [16], and [141].

Table S72 Land use per produced unit of milk, egg, meat and aquaculture products. Numbers in square meters per kg of product including water and per kg of edible protein. All numbers are allocated (see 1.11) and include area use from purchased feed, including by-products and crop residues. Note that for South Asia (SAS) and India, numbers include areas of grazed forest (see 1.9.8). Source: Estimates of this study (see 1.3.3).

	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Square meters per kg fresh weight															
Cattle/buffalo whole milk	7.8	54	9.0	2.4	23	1.4	1.9	6.8	8.0	4.0	43	5.9	14	3.6	1.2
Sheep/goat whole milk	52		40	14	110				35	11	91		54	10	
Egg (whole)	5.8	19	4.9	5.6	11	3.8	15	10	4.6	6.7	13	4.0	4.3	7.0	3.4
Suckler beef (carcass)	310	1040	290	120		270	860	420	240		750	180	350		250
Dairy bulls/steers (carcass)	240	440	72	32	170	19	32	96	200	280	610	160	97	370	17
Sheep/goat meat (carcass) – avg all	310	900	160	89	390		570		210	100	510		220	120	
Pork (carcass)	6.6		5.9	6.5		5.5	18	13	7.8	11	19	6.4	5.4	11	4.8
Chicken (carcass)	6.3	25	5.0	5.2	12	4.3	16	9.7	5.7	6.4	16	4.6	5.0	7.3	3.9
Carp (whole)	1.8		1.66		3.47					1.97	5.05		1.69	2.04	
Tilapia (whole)	4.7		3.52						3.89	4.79	8.63	3.63	3.55		
Other freshwater fish (whole)	3.3		3.01						3.53	3.67	8.81	3.28	3.08	4.00	
Salmonid (whole)	4.0			3.52	5.41	1.92			4.16						
Other non-freshwater fish (whole)	4.2		3.29	2.47	6.83					3.52	12.1		3.52		
Crustacean (whole)	4.1		4.00			3.88			4.30	4.93			4.11	5.24	
Square meters per kg edible protein															
Cattle/buffalo whole milk															
Total	220	1550	270	76	650	42	52	210	250	100	1000	180	450	93	39
Cropland	41	36	19	44	56	42	19	100	15	44	51	12	21	47	38
Sheep/goat whole milk															
Total	1200		820	310	2300				640	290	2100		1000	260	
Cropland	66		44	67	110				27	55	48		37	51	
Egg	53	180	44	51	100	34	140	92	42	62	120	36	39	64	31
Suckler beef (carcass)															
Total	2000	6800	1900	790		1750	5600	2800	1600		4900	1200	2300		1600
Cropland	120	98	50	200		170	80	380	50		260	48	49		150
Dairy bulls/steers (carcass)															
Total	1400	3000	480	210	1100	130	210	640	1300	1900	4100	1100	650	2500	110
Cropland	170	150	53	150	140	130	130	220	55	290	250	59	55	420	110

	World	CAS	EAS	EUR	MEA	NAM	OCE	RUS	SAM	SAS	SSA	Brazil	China	India	USA
Sheep/goat meat (carcass) – avg all															
Total	2400	6800	1200	670	3000		4300		1600	800	3900		1600	1100	
Cropland	91	120	39	120	130		60		75	150	92		34	180	
Pork (carcass)	42		38	42		35	120	80	50	72	120	4	35	70	31
Chicken (carcass)	45	180	36	37	85	31	120	70	41	46	110	33	36	53	28
Carp (fillet)															
Total including ponds	24		21.9		45.9					26.0	66.7		22.4	27.0	
Cropland	10		9.0		11.6					12.7	23.9		8.40	13.7	
Tilapia (fillet)															
Total including ponds	63		47.6						52.6	64.7	117	49.0	47.9		
Cropland	55		40.7						43.5	55.7	103	39.9	41.0		
Other freshwater fish (fillet)															
Total including ponds	52		47.0						55.2	57.3	138	51.3	48.1	62.5	
Cropland	37		33.1						36.0	44.6	84.3	33.5	32.4	49.8	
Salmonid (fillet)	44			38.8	59.5	21.1			45.7						
Other non-freshwater fish (fillet)	47		36.3	27.5	75.9					39.1	135		42.0	43.8	
Crustacean (meat)															
Total including ponds	40		38.5			37.4			41.5	47.5			39.6	50.5	
Cropland	20		19.0			18.1			22.2	28.2			19.9	31.3	

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