nature portfolio

https://doi.org/10.1038/s43016-021-00358-x

Supplementary information

Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods

In the format provided by the authors and unedited

Supplementary Materials

Global Greenhouse Gas Emissions from Animal-based Foods are Twice Those of Plant-Based Foods

Xiaoming Xu[1], Prateek Sharma[1], Shijie Shu[1], Tzu-Shun Lin[1], Philippe Ciais[2], Francesco N. Tubiello[3], Pete Smith[4], Nelson Campbell [5], Atul K. Jain[1,*]

[1] University of Illinois, Urbana, IL 61801, USA

[2] Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ, UMR8212, Gif-sur-Yvette, France

[3] Statistics Division, FAO, Rome, 00153, Italy

[4] Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, Aberdeen, UK

[5] PlantPure Communities, Inc., Mebane, NC 27302

* Corresponding author

Contents

Supplementary Methods

1. Method of Calculating Agricultural Biomass

1.1. Crop Biomass

In this study, the agricultural land includes cropland and grazing land, in line with FAO land use definitions. The uncertainty in the estimated spatial distribution of pastureland is large[1]. Therefore, we combine managed pastureland and rangeland, and other unmanaged land used for grazing (e.g., grassland, savannah, shrubland, and tundra) into grazing land category following the grazing land definition of Klein Goldewijk, et al.[2]. The same aligns with FAO's land use definition of "Permanent meadows and pastures"[3]. We divide the aboveground biomass of cropland into grain and residue parts. We define grain as a general term that refers to the yield parts of all crops (i.e., the commodity being of use to humans), such as the grains of cereal crops, beans of pulse crops, and stalk of sugarcane. The crop commodity here refers to basic agricultural products that are either in their original form or have undergone only primary processing [4]. Residue includes the non-grain aboveground biomass component of crop plants, such as straw, stover, and leaves; the separation of grain and residue is only for cropland, not for grazing land. The grain biomass is calculated based on FAO crop production data and ISAM simulation circa 2010. We use the production data of the 16 ISAM simulated crops, which contribute to about 60% of total crop production and 66% of total crop harvested area, together with other 155 crops from updated M3-crop data and ISAM model results for generic C3 and C4 crops to study the crop biomass and GHG emissions, which we describe in the following sections.

1.2. ISAM Based Results for 16 Crops

The process-based dynamic crop and vegetation model (ISAM) [5,6] (see description in Suppl. Methods 3.1) was used to simulate the crop growth and yield of 16 crops (maize, millet, sorghum, sugarcane, soybean, barley, cassava, groundnut, potatoes, pulses, rapeseed, rice, rye, sugar beet, sunflower, and wheat). In this study, we multiply the ISAM simulated crop yield data (also averaged from 2007 to 2013) with their corresponding harvested area maps (using the same method as described in Suppl. Methods 1.3) to get their individual ~2010 production map at 0.5^{o} x 0.5^{o} spatial resolution. We use the crop residue biomass of the 16 crops directly from ISAM simulations.

We have evaluated the 16 major crop productions simulated by ISAM with the production data from FAOSTAT. Suppl. Fig. 7 and Suppl. Table 14 show that the ISAM results and the FAOSTAT crop production data are reasonably compared well, with several exceptions at global and regional scales. For example, the differences are notably significant in cases of millet at a global scale and in SSA, maize in SA, NA and SSA, sorghum in SSA and SSEA, cassava in SSEA, sugar beet in EU, wheat in CIS and CM, rapeseed in CM, and groundnut in SSA. These differences can be attributed to the differences in estimating methods of crop production. Our results are estimated based on a processes-based model, in which the climate and other forcing data sets and agricultural management may introduce uncertainties. Meanwhile, FAOSTAT data is individual country's reported values with possibilities of over- or under-reporting due to lack of rigorous surveys in some countries[7].

1.3. M3 Data-based Results for 155 Crops

The calculations for the additional 155 crops are done using spatially explicit M3-crop production data for circa 2000 [7] and FAOSTAT reported crop production data [8], which is available at country scale and yearly time steps. We use the average values from 2007 to 2013 to fill/remove possible gaps/outliers in a particular year or country to represent the circa 2010 condition. The following methods are used to derive the crop production and harvested area data at 0.5° x 0.5° spatial resolution circa 2010.

1. We use the spatial distributions of crop production for each 155 crops in ~2000 (average of available data from 1997 to 2003) from M3-crops data [7] as spatial references, which is available at 5 x 5 arc minutes spatial resolution. First, we upscale this data to 0.5° x 0.5°. Following the global pattern of land-use change [1,9,10], we assume the spatial extent of all 155 crops under this spatial resolution in ~2010 are the same as in ~2000. Note that M3 data at country scale is approximately the same as FAOSTAT [1].

2. Next, we calculate the country scale production for 155 crops in ~2000 (that is the average for the period 1997-2003) and ~2010 (that is the average for 2007-2013) from the FAOSTAT dataset [2,9]. We calculate the rates of production changes at the country scale between ~2000 and ~2010 as follows:

$$AR_{c,n} = \frac{Production\sim 2010_{c,n}}{Production\sim 2000_{c,n}} \quad \text{(Eq. S1)}$$

where, $AR_{c,n}$ is the ratio of production of crop c in country n from ~2010 to ~2000; $Production\sim 2010_{c,n}$ and $Production\sim 2000_{c,n}$ are the production of crop *c* in country *n* circa the years 2000 and 2010 calculated from FAOSTAT dataset.

3. We multiply $AR_{c,n}$ (Eq. S1) with ~2000 country-specific M3-crop production calculated in step 1 to estimate the crop- and country-specific production for ~2010.

These steps (steps 1-3) are also applied to calculate the spatial distribution of harvested areas for all 155 crops.

To calculate the biomass using ISAM in ~2010, we divide the gridded production of 155 crops calculated in step 3 into C3 and C4 harvested biomass carbon. We harvest the same biomass amount from ISAM estimated C3 and C4 crops in ~2010. In this way, the crop production is consistent with data in FAOSTAT. The rest of ISAM estimated aboveground crop biomass for C3 and C4 are considered as the residue biomass. We multiply the residue biomass with crop- and region-specific residue recovery rates [11] (Suppl. Table 13) to estimate the recovered crop residue.

The crop grain biomass, recovered crop residue biomass of all crops (both 16 ISAM-based and 155 M3 Data-based crops), together with grazed biomass for food, feed, and other socioeconomic uses (such as crop residues used as biofuels) are assumed to be released to the atmosphere within one year (E_{h_CO2}). E_{h_CO2} is a gross term of E_{f_CO2} (see *Eq. 1* for their relationship). The estimated results for E_{h_CO2} and E_{f_CO2} are shown in Suppl. Tables 15 and 16.

1.4. Method of Quantifying Livestock Biomass Feed

We first calculate feed demand for 16 major livestock types (Suppl. Table 4) in each country by multiplying the animal-specific feed demands per-head [11] with live animal heads [8]. We use the animal distribution maps from Gridded Livestock of the World v3.0 [12] to calculate the gridded feed demand. The feed demand in a grid is first satisfied with feed from the same grid. If the feed supply in the grid is not enough, we use the feed from other grids in the same country to satisfy the demand. During all these processes, we make sure the carbon and nitrogen are consistent at a country scale. A few animals lack spatial distributions, including turkey, geese, camel, mule, and camelid. We calculate their feed demands and supplies at a country scale while ensuring the carbon and nitrogen balance. We have used a relatively simple, but well-cited method [11] to quantify the feed demand of different livestock. Although this method does not consider the feed choices of different livestock animals and systems, it fits well with our framework that focuses on the different feed demands for ruminant and monogastric animals.

We consider five types of livestock feeds: crop grain feed, forage crop feed, crop residue feed, grazing feed, scavenging, and other feed. We assume scavenging and other feed is produced by livestock and recycled as livestock feed supply (e.g., kitchen-wasted meat used for feed). We consider the feed supplies based on the following priority order from high to low to reconcile the feed supply and demand balance at the country scale: crop grain feed, forage crop feed, crop residue feed, grazing feed, scavenging, and others in each country. For example, if a country's feed demand can be fully met by crop grain feed, then the feed only consists of crop grain; otherwise, the insufficient amount of feed demand (total feed demand minus crop feed supply) will be supplied by forage crop feed, then crop residue feed, and grazing feed, until the demand is fully met. If the sum of the first four feed sources is still less than the feed demand in a country, then the residue of the feed demand is assumed as scavenging and other feed.

This priority order is not a way of allocating feed to animals, rather, it is our method to reconcile feed supply amount from different sources at a country scale. This order is prescribed primarily based on data availability. In our calculation, crop grain feed and forage feed amounts are collected from FAOSTAT datasets and considered credible. The crop residue feed, grazing feed, scavenging, and other feed data sources at the country scale are relatively less reliable. Therefore, we allocate crop grain feed and forage feed first, and then estimate the amounts of crop residue feed, grazing feed and scavenging, and other feed accordingly. However, the reconciled values for crop grain feed and forage feed will be different and inconsistent with FAOSTAT if we change the priority order.

The amounts of five types of feed are quantified by the following method. Crop grain feed refers to the feed, which is made from the grain part of the crop. The amount of crop grain feed is the biomass that is utilized as feed. We assume all forage crop biomass is used as feed, all harvested biomass of forage crops is used as forage crop feed, either within the producing countries or exported to other countries. If the forage crop biomass supply is exceeding the demand in the country, we assume these exceeding amounts are exported to the countries with the greatest demand for feed after subtracting the feed crop supply. The amount of recovered crop residue is calculated based on the ISAM simulated crop residue (as discussed in Suppl. Methods 1.2 and 1.3) and recovery rate developed by Krausmann, et al. [11] (Suppl. Table 13). This recovered crop residue is used as potential crop residue feed. We use ISAM simulated aboveground biomass of several plant functional types (PFTs) (that can produce grazing feed, such as C3 and C4 pastureland, C3 and C4 grassland) as a potential grazing feed supply. Grazing feed is not traded internationally. The rest of the feed demand is allocated to scavenging and others to ensure the biomass balance. The flowchart diagram of the feed biomass estimation is shown in Suppl. Fig. 6.

In this study, we first quantified the feed categories at a country scale outside of the ISAM model. Then, we downscale the country scale feed biomass to 0.5 deg grid (L/L) level to ensure the carbon and nitrogen balance within the ISAM model using different strategies for different categories of feeds. We discuss them separately as outlined below:

Crop grain feed and forage feed carbon and nitrogen are part of crop production, which is harvested from corresponding PFTs at a gridded level. Note that the productions of 16 specific crops (Suppl. Methods 1.2) are directly harvested from their PFTs. The productions of other 155 crops and forages (Suppl. Methods 1.3) are estimated using gridded M3-crop and harvested from C3 and C4 generic crop biomass in ISAM. Then crop- and country-specific feed fractions from crop commodity balance [13] are used to quantify the gridded crop feed and forage feed amount. We assume that forage crops are only used for feed.

Crop residue feed is part of recovered crop residue. The gridded residue feed is harvested based on the gridded crop residues simulated by ISAM (Suppl. Methods 1.2 and 1.3). Note that we use the residues of C3 and C4 generic crops in ISAM as the residue of the 155 crops (Suppl. Methods 1.3).

We downscale the grazing feed biomass from country scale to grid-level using the ISAM simulated aboveground biomass of grazing land and harvested these downscaled grazing feed in each grid of ISAM model. For the grids with more biomass than demand, we harvest 20%, 50%, and 30% of the gridded feed demand at the end of the first, second, and third phenology stages in the grazing land grids to make sure that there is some biomass left on grazing land across the whole growing season. For the grids with less biomass than demand, we do not harvest them during the growing season.

At the end of the growing season, we first compare the harvested biomass (during the growing season) with the grazing feed demand in each country. For the countries whose grazing feed demands are not fully satisfied, we combine all remaining aboveground biomass at the end of the growing season in all grids within the country, which include the remaining biomass in the harvested grids and total biomass in unharvested grids, to satisfy the rest of the grazing feed demand. The biomass harvested at the end of the growing season is allocated to each grid based on their biomass amount. If the remaining biomass at the end of the growing season is still less than the rest of the grazing feed demand, we harvest all biomass on grazing land.

We separate the 16 livestock animals into monogastric and ruminant animals (Suppl. Table 4), and separate the forages into grass forages and other forages (Suppl. Table 1). Then we prioritize the crop grain feed, other forages, and scavenging to monogastric animals, and all types of feeds to ruminant animals at the country scale. In some countries, crop grain feed, other forages, and scavenging are insufficient to meet the feed demand of monogastric animals. In this case, we allocate grazing feed and crop residue feed to make up for the insufficient feed demand for monogastric animals. Our monogastric animals also include horses and mules that can also use grazing feed and crop residue feed. Our estimated feed amounts for ruminant and monogastric animals are shown in Suppl. Table 17.

2. Method of Calculating GHG Emissions

2.1. Mining, Manufacturing and Transporting of Fertilizers and Pesticides

We calculate the emissions from mining and manufacturing and transporting N, P, K fertilizers, and pesticides by the following equation:

$$E_{mmt} = \sum(EF_{mm,i} + EF_{ts,i}) \times M_i \quad \text{(Eq. S2)}$$

where E_{mmt} is the GHG emissions from mining, manufacturing and transporting of fertilizers and pesticides; $EF_{mm,i}$ is the emission factor for mining and manufacturing of *i*th agricultural material

(N, P, K fertilizers and pesticides) ($kgCO_2$ eq/kg); $EF_{ts,i}$ is the emission factor for transporting of *i*th agricultural material ($kgCO_2$ eq/kg); M_i is the application amount of *i*th agricultural material (kg). Here we use the combined mining and manufacturing emission factors ($EF_{mm,i}$) from existing LCA studies of fertilizers and pesticides, which are at regional and global scales.

In Eq. S2, M_i of N, P, K fertilizers for crops at the spatial scale in circa 2010 are described in Suppl. Methods 4). We only consider N fertilizer for grazing land, the gridded M_i of N fertilizer for grazing land is derived from Xu, et al. [14]. M_i of pesticides at the country scale are from FAOSTAT [8]. Pesticides are not considered for grazing land.

$EF_{mm,i}$ of N, P, K fertilizers are from Kool, et al. [15], which provides the emission factors of mining and manufacturing EF_i at a regional scale. $EF_{mm,i}$ of pesticides, is 28 kg CO_2 eq/kg active ingredient [16,17], which is regarded as a weighted average emission factor of the combination of all active ingredients of different pesticides.

We choose the emission factors from Kool, et al. [15], mainly because they provided consistent estimates of emission factors for N, P and K fertilizers at a continental scale. Kool, et al. [15] have made several assumptions regarding the shares of natural gas, coal and oil in producing fertilizers in some regions such as China and India. The share of clean energy may change with time and affect the emission factors of fertilizers. Nevertheless, because our calculating year is 2010, which is close to their reporting year (roughly around 2005), we assume that the clean energy share has not significantly changed the emission factors.

The values of $EF_{ts,i}$ are calculated as follows. First, we calculate weighted average GHG emissions per tonne-km of each commodity ($kgCO_2$ eq/tonne-km), based on the emission factors (unit: $kgCO_2$ eq / tonne-km) of different transport modes (road, rail, short sea, deep-sea, air freight and pipeline) from Kinnon [18] (Suppl. Table 10) and tonne -kms (unit: tonne -km) of different transport mode for various commodities from Ecoinvent dataset [19]. Then we multiply this weighted average GHG emissions per tonne -km with weighted average shipping distances (unit: km, calculated from Ecoinvent dataset[19]) to get the $EF_{ts,i}$ (unit: $kgCO_2$ eq/kg, see Suppl. Table 11). Note that we use global average values for $EF_{mm,i}$ of pesticides, and $EF_{ts,i}$ of fertilizers and pesticides due to lack of spatial data at the global scale.

2.2. Livestock

Enteric fermentation. Ruminant animals, such as cattle, buffalo, sheep, and goats, produce CH_4 through digestive processes. We use the country- and animal-specific CH_4 emission factors for enteric fermentation emissions from the FAOSTAT dataset [20-22], which is based on the IPCC Tier 1 method [23] (relies on default emission factors for different livestock animals).

Manure management. The decomposition of manure carbon under anaerobic conditions produces CH_4, while nitrification and denitrification of nitrogen contained in the manure generate N_2O. We account for CH_4 and N_2O emissions from manure management in total GHG emissions from livestock products. We use country- and animal-specific emission factors of CH_4 and N_2O from manure management from the FAOSTAT dataset [24].

We use CH_4 emissions from enteric fermentation and CH_4, N_2O emissions from manure management from the FAOSTAT dataset, which do not include E_{farm} and E_{luc}. The E_{farm} and E_{luc} emissions are calculated using ISAM. Therefore, there is no double counting issue in our calculation of the GHG emissions from animal-based food. It is to note that the FAOSTAT dataset uses IPCC Tier 1 method to quantify the E_{live}, in which the amount of CH_4 and N_2O emissions from enteric fermentation and manure management did not depend on the livestock feed categories.

We have used the livestock emissions from FAOSTAT[20], which is calculated using IPCC tier 1 method[23], whereas livestock feed demand is based on Krausmann, et al. [11], which we use to calculate E_{farm}, $E_{luc,}$ and E_{bfg} for animal-based food. Since these two methods are based on different sources, this may introduce some biases in total animal-based emissions. However, we compared our estimated livestock feed demand with other studies, and our estimated values are well within the range of other estimates (Suppl. Table 7).

2.3. Soil Emissions and Livestock Respiration

Our soil emissions include two components, first is the soil emissions from disturbance caused by land-use change, which is a component of E_{luc}, as discussed in the "Land Use Change Emission" section. The second one is soil emission from tillage, which is part of E_{farm}. In the ISAM model, we assume that all fresh carbon input accumulated in the crop growing season in the top 20 cm soils will be lost during the tillage process. Part of the lost carbon is emitted into the atmosphere, and part of it is transported into the deeper layer of soil. In contrast, under no-till conditions, part of the sequestered carbon calculated based on ISAM can still be released back to the atmosphere depending upon the climatic conditions, such as temperature and precipitation [25]. Note that we do not consider no-till practice in this study.

We use a carbon balance approach in the following equation to estimate the livestock respiration emission E_{res}.

$$E_{res} = E_{feed\_c} - E_{manure\_C} - E_{ef\_C} - E_{prod\_C} \qquad \text{(Eq. S3)}$$

where, E_{feed_C} and E_{manure_C} are biomass carbon emissions in CO_2 from livestock feed and manure (see Suppl. Methods 1.4 for details); E_{ef_C} is the emission due to carbon embedded in CH_4 through enteric fermentation converted to CO_2; and E_{prod_C} is the carbon emissions stored in livestock products such as milk and eggs.

It is noted that E_{feed_C} is part of E_{h_CO2} in *Eq. 1* of the main text (emissions due to harvest of biomass). In addition to E_{feed_C}, E_{h_CO2} also includes the emissions due to the harvested biomass used as food (E_{food_C}) and other utilizations (E_{other_C}).

$$E_{h\_CO2} = E_{food\_C} + E_{feed\_C} + E_{other\_C} \qquad \text{(Eq. S4)}$$

All above terms in Eqs. S3 and S4 are all gross terms of E_{h_CO2}, which itself is a gross term of the net emission E_{f_CO2} (farmland CO_2 emission). The regional results of these terms are shown in Suppl. Tables 15 and 16.

2.4. Product Processing

In this study, we use the "cradle-to-dinning-table" life-cycle assessment (LCA) method to quantify the CO_2, $CH_{4,}$ and N_2O emissions from different subsectors of plant- and animal-based food production/consumption. We use the 100-year global warming potentials (GWP) of CH_4 (34) and N_2O (298) to combine all GHG emissions to CO_2 equivalent (CO_2 eq) [26].

We consider the GHG emissions from the processing of both plant- and animal-based commodities. For the plant-based commodities, we consider processed products that are used as both plant-based human food and livestock feed. Note that these processing procedures are only the first stages of pre-plate food transformation. These products are listed in Suppl. Table 9. As for animal-based commodities, we consider the pre-plate processing emissions for all 16 commodities as listed in Suppl. Table 4.

For the crops with multiple processed products (Suppl. Table 9), we partition the total GHG emissions of the crop to its products based on their caloric values (this method is called the "energy-based allocation method" [27]). The caloric values and GHG shares of different outputs can be found in Suppl. Table 9. In the abovementioned example of wheat, we partition all GHG emissions of wheat to wheat flour and wheat bran.

For animal-based commodities, we assume only meat, dairy, and eggs are responsible for all GHG emissions to simplify the calculation. Other animal-based products, such as hide/skin, offal, and wool, are assumed not to carry GHG emissions. For example, the sheep produce meat, as well as offal, skin/hide, and wools. We assume that sheep meat is accounting for all GHG emissions from the whole sheep productions.

3. ISAM Model Description

3.1. Crop Module

ISAM calculates crop productivity, carbon, nitrogen, energy, and water fluxes at the spatial resolution of 0.5^{o} (L/L) and at multiple temporal resolutions ranging from a half-hour to yearly time scales. Thus, ISAM is able to capture the diurnal and seasonal patterns of crop productivity, water, and energy fluxes for individual crops at the site, national, regional, and global scales [28]. Some of the important features, unique to ISAM and critical for crop productivity calculations, include [5,6]: (i) crop-specific phenology and dynamic carbon allocation schemes, accounting for the sensitivity of different crops to extreme cold, hot dry, and wet environmental conditions (e.g., frost, drought, waterlogging, etc.) and nutrient stresses while allocating the assimilated carbon to leaf, root, stem, and grain pools; (ii) dynamic vegetation structure, which better captures seasonal variability in LAI, canopy height, and root depth; (iii) dynamic root distribution processes at depth, to better simulate root-mediated soil water uptake and transpiration. These features are unique to ISAM and generally not included in other models simulating crop production. In our model simulation, we consider irrigation on crop production by applying enough irrigation to ensure that there is no water stress for the crops.

3.2. N_2O Emission Module

ISAM model contains detailed calculation of organic and mineral N cycle in the terrestrial ecosystem [29]. The major N processes in ISAM include biological fixation, leaching, mineralization and immobilization, plant uptake, nitrification and denitrification [29]. Our study focuses on the "cradle-to-dining table" GHG emissions. Therefore, we do not consider the post-plate N processes such as household and sewage waste and recycling. N_2O emission is produced as a byproduct of nitrification and denitrification. Production of N_2O is determined by multiplying the nitrification and denitrification fluxes with the fraction of N_2O loss from nitrification and denitrification. Both fractions are calculated based on the fraction of anoxic soil depending on soil O_2 concentration, which is non-linearly correlated with the chemical pathways forming N_2O. Under anoxic soil condition, N_2O is produced through denitrification, while under oxic soil condition more N_2O is produced from nitrification. In addition to the processes described above, another important loss term of soil mineral N is NH_4^+ volatilization to the atmosphere after applying the mineral N fertilizer and manure. We have used global gridded manure N application for cropland[30] and grazing land[31] datasets as inputs for ISAM simulations. These datasets account for manure N excretion by livestock and are consistent with FAOSTAT manure N application data at the country scale. The N deposition data used as an input in this study is taken from Lamarque, et al. [32]. In ISAM the NH_4^+ volatilization flux is determined based on the soil anoxic condition and temperature, which increase under a higher temperature and a less soil anoxic condition.

Calibration and validation of the base reaction rates of major mineral N processes are performed to match the ISAM estimation of soil N_2O emission to multiple site observations. We compiled 28 site level annual soil N_2O flux measurements from published literature as observations [33]. We performed ISAM model spin-up for each site first to reach the steady state of soil organic carbon, organic nitrogen and mineral nitrogen under pre-industrial CO_2 and N deposition levels. After reaching the steady-state, ISAM is forced with the historical climate reanalysis, CO_2 and N deposition time series[32] to calculate the N_2O. We adjust the parameters to match observed annual soil N_2O emission (Suppl. Fig. 8).

3.3. Rice Production and CH_4 Emission Module

Rice production module in ISAM includes the key dynamical processes such as crop phenological development, structural growth, biomass accumulation, and allocation. The phenology of rice is determined by rice-specific heat unit index and growing degree days, which is the same method used for maize, soybean, and wheat [5,34]. Assimilated carbon is allocated to different rice tissues based on rice growth-stage dependent allocation scheme developed and calibrated with the site-level leaf area index, canopy height, and biomass data. Modeled rice yields are calibrated using three flux measurements compiled from eddy covariance rice crop sites and validated with the other four field sites.

The simulated rice yield is weighted under irrigated and rainfed conditions by irrigated and rainfed harvested areas over the grid cell. The ratio of irrigated to the total fraction of rice harvested is obtained from Portmann, et al. [35]. To determine the flooded grid cell, we separate naturally inundated areas from rice agriculture using fractional inundation data [36] and a map of fractional rice harvested area [7]. We first identify the grid cell where rice is harvested and then check the inundation status. If it is inundated, that grid cell is viewed as flooded conditions, and soil water content would reach saturation. Otherwise, the soil moisture status is calculated by climate, soil properties and surface hydrological processes in the model. The surface water height is assumed to be 0.04m over the flooded period. The gridded rice yield is aggregated to production in each country. To validate rice production, we compared 16 major rice production countries. The model can reproduce the rice production around the year 2000 with FAO data (Suppl. Fig. 9).

A coupled rice-methane component of ISAM, which accounts for water, energy, and carbon exchange processes, is used to study CH_4 emissions from the rice fields [37]. The model explicitly accounts for heat storage and transfer at the surface water layer, rice-specific growth processes, and methane dynamics for rice [38]. In addition, the model simulates flooded irrigation for rice (as described above) that regulates surface energy and water cycles and therefore impacts the modeled rice methane emissions. The simulated rice methane emissions are weighted under flooded irrigation and rainfed conditions by irrigated and rainfed rice harvested areas over the grid cell. The performance of the model is evaluated using in-situ flux measurements compiled from eddy covariance rice crop sites. The modified model reproduces the observed leaf area index, canopy height, surface water, soil temperatures, momentum, energy, water and carbon fluxes, rice yield, and CH4 fluxes during the growing (flooded) and fallow seasons. We also evaluated modeled rice methane emissions at country-level, regional and global scales with published datasets (see Shu, et al. [37] for model evaluation).

4. Method of Producing Spatial Maps of Synthetic and Mineral NPK Fertilizers in 2010

The following method is used to determine the crop-specific synthetic fertilizers at a grid level in circa 2010. The EarthStat nutrient application dataset [39,40] provides crop-specific total N, P, K application amounts at 5 x 5 arc minutes spatial resolution for the year ~2000. The N application amount of this dataset includes synthetic N, manure N, and atmosphere deposition N. We update the EarthStat N, P, K fertilizer data from circa 2000 to circa 2010 using the following method.

We first aggregate N (combined synthetic, manure and deposition N), P, K fertilizer amounts from 5 x 5 arc minutes to 0.5 degree x 0.5 degree. We assume the same fertilizer use efficiencies (fertilizer amount/crop production) of all crops in each grid in ~2000 and ~2010, based on the finding that the nitrogen fertilizer use efficiency of world cropping system has not changed significantly between ~2000 and ~2010 [41]. We use the following equation to calculate the crop-specific fertilizer spatial maps at ~2010.

$$Fert\_2010_{c,g} = \frac{Fert\_2000_{c,g}}{Prod\_2000_{c,g}} \times Prod\_2010_{c,g} \qquad \text{(Eq. S5)}$$

where $Fert\_2010_{c,g}$ and $Fert\_2000_{c,g}$ mean the fertilizer (N or P or K) amounts at grid cell g for crop c in ~2010 and ~2000; $Prod\_2010_{c,g}$ and $Prod\_2000_{c,g}$ refer to the production amount at grid cell g for crop c in ~2010 and ~2000.

We did not extrapolate circa 2000 EarthStat nutrient application data to circa 2010 using the FAOSTAT fertilizer data, which is only available at a country scale. This is because FAOSTAT does not report fertilizer amounts for individual crops and does not separate the manure application to cropland and grazing land. Therefore, we extrapolate ~2000 EarthStat data to ~2010 by assuming the same nutrient use efficiencies in each grid in ~2000 and ~2010. Note that the fertilizer use efficiencies used in our calculations are different for different crops. They also vary spatially (Suppl. Methods 4).

We have evaluated our estimated nitrogen application amount with FAOSTAT at a country scale. For this evaluation, we combine our generated 2010 nitrogen application on cropland and manure applied to grazing land [31], and compare it with the combined nitrogen application and manure applied to soil data from FAOSTAT at national scale (Suppl. Fig. 10). The result shows that our generated 2010 total nitrogen application data are consistent with FAOSTAT at a country scale (Suppl. Fig. 10).

The nitrogen input in EarthStat nutrient application dataset [39,40] has included total fertilizer amount, i.e., the sum of synthetic nitrogen fertilizer, manure, and atmospheric deposition. We use EarthStat data to project the total N amount in circa 2010, and only retain the synthetic N fertilizer. We use an estimated fraction of synthetic N fertilizer amount to total N application amount in cropland at the regional scale [42] to calculate the synthetic nitrogen fertilizer amount at the spatial scale for different crops. There are 34 crops whose NPK fertilizer spatial maps are not available in the data [39,40] (Suppl. Table 1). We ignore the GHG emissions from mining, manufacturing, and transporting NPK fertilizers of these 34 crops. This assumption is not significantly affecting the estimated total food-related GHG emissions, because the contribution of combined biomass of these 34 crops is less than 0.5% of the sum of 171 crop biomass.

We generated a time-series N fertilizer data for specific crops in ISAM by referencing the temporal N fertilizer trend from LUH2 following the method developed by Lin, et al. [28]. P and K maps are not used in the ISAM simulations; they are used in the calculation of the mining, manufacturing, and transporting emissions.

5. Uncertainty Analysis

We estimate the uncertainty range of the GHG emissions for plant- and animal-based food through a Monte Carlo approach. In this study, we consider the uncertainties caused by a few major contributors of the GHG emissions for plant- and animal-based foods, i.e., E_{luc}, E_{farm} and E_{live} (Suppl. Table 12). We first collect the mean/median, uncertainty ranges and probability distribution functions (PDF) of a few key variables of these sources from previous studies. We assume our estimated E_{luc}, E_{farm} and E_{live} have the same uncertainty ranges as corresponding studies (Suppl. Table 12). Then we randomly sample these key variables within their uncertainty ranges (Suppl. Table 12) and calculate the overall GHG emissions for plant- and animal-based food. We repeat the random sampling and calculation for 10,000 times and report the sample median and standard deviation of GHG emissions for plant- and animal-based food. Specially, because the land-use change emission in Meiyappan, et al. [43] includes both E_{luc} and E_{farm} CO_2 emission in this study, here we apply the same uncertainty range to both E_{luc} and E_{farm} CO_2 emission.

Supplementary Discussion

1. Global Agricultural Land and Biomass

Among all nine macro-geographical regions, South America (SA) and Sub-Saharan Africa (SSA) produced the largest amount of total agricultural biomass (including both harvested and unused biomass), accounting for 18% and 15% of the global total (Suppl. Table 3). Global average biomass, including harvested and unused biomass, productivity (biomass per unit area per year) of cropland is 378 g C/m^2·yr, which is more than three times higher than grazing land (117 g C/m^2·yr). This is grazing land includes rangelands that are unmanaged with lower productivity. SA (547 g C/m^2·yr) and North America (NA, 515 g C/m^2·yr) have the greatest agricultural biomass productivity for cropland, while Mid East and North Africa (MENA) has the lowest (171 g C/m^2·yr). South and Southeast Asia (SSEA) has the highest biomass density (160 g C/m^2·yr) on grazing land, while Oceania and other East Asia (OC) have the lowest (89 g C/m^2·yr).

Among all countries, China (11%) and the USA (11%) produce the most agricultural biomass, followed by Brazil (9%) and Russia (7%). USA has produced the most crop biomass, while China has produced the most grazing biomass (Suppl. Fig. 2).

We estimated a total of 2,450 Tg C/yr of livestock (Suppl. Table 5) biomass feed demand, which is fulfilled with 23% crop grain (including 24% grain production and -1% stock variation, which means changes in commodity stocks, such as leftovers from the present year but consumed in the future years – see Method section), 12% with forage crop, 21% with crop residue, 42% with grazing feed. A fraction of 2% of animal feed is supplied with scavenging and other feed produced by livestock and recycled as livestock feed supply (e.g., kitchen-wasted meat used for feed).

The estimated global total agricultural land area used to produce this total biomass is consistent with global FAO land use statistics, from which our numbers are derived, and precisely: 4,674 million hectares (about 31% of the total land area, excluding areas covered by snow and ice). Of this, 30% is cropland, and 70% is grazing land (pastureland, rangeland, grassland and grazing savanna, tundra, and shrubland). Depending upon the utilization amount, we estimated how much cropland and grazing land are required to produce utilization amount. We estimated agricultural land area used to produce animal-based food (including the area for growing feed) is more than five times the land used to produce plant-based food (Suppl. Table 2). Less than half of the cropland is used to produce plant-based foods supplied to humans.

We estimate that the area of agricultural land in 2007-2013 has increased by 0.11 million hectares/yr (Mha/yr), including 2.12 million hectares/yr of other land converted to agricultural land and 2.01 Mha/yr of agricultural land converted to other lands (Suppl. Table 2). Cropland has increased by 0.43 Mha/yr, while grazing land has increased by 0.16 Mha/yr. Our estimated land-use change area is different from FAOSTAT, which reports the cropland has increased 5.70 Mha/yr during 2007-2013, while permanent meadows and pastures area (corresponding to our grazing land area) has decreased by 12.26 Mha/yr. Such differences, which are nonetheless not significant statistically, may originate from data sources. Our estimated area is based on global gridded land use and land-use change (LULUC) datasets [1,44], while FAOSTAT is based on FAO questionnaires for individual countries. These land-use change (LUC) activities have caused 7,645 Tg C/yr of biomass loss in circa 2010, with 84% of this due to cropland-related land-use change and 16% due to grazing land. Note that this biomass loss is not converted to emissions at one-year time, it is divided into different pools and emitted with time (see Method). Total GHG emissions due to LUC are reported in Suppl. Disucssion.

Poore and Nemecek [45] estimated that 704 Mha and 538 Mha of cropland have been used for plant- and animal-based food, while 1,534 Mha of grazing land has been used for animal-based food. They have estimated ~18% more cropland for plant-based food, as well as ~56% more cropland and ~59% less grazing land used for animal-based food than our results. The differences may be caused by the different estimating methods and data sources. We have combined a global land-use dataset [1] and the commodity balance equation to calculate the cropland area used for plant-based food and animal-based food. We assume all grazing land is used for animal-based food production. By contrast, Poore and Nemecek [45] have used individual data points reporting land use per unit kg of plant- and animal-based food from published literature and extrapolate them to the global scale using the commodity balance. The limited data points in some regions may cause underestimation of grazing land area in their study. In addition, they also economically allocated cropland to crop grains and crop by-products (such as straw or palm kernel expeller) used as feed or bedding in animal production. Our study does not allocate cropland to crop by-products, but assumes all cropland is used for producing crop grains. Therefore, these crop by-products represent ~150 Mha of cropland in Poore and Nemecek [45] but zero in our results. It should be noted that Poore and Nemecek [45] also calculated aquaculture pond area, which is not included in our study; while, our estimates of cropland used for animal-based food compared well with Foley, et al. [46] (345 Mha vs. 350 Mha).

2. Global Agricultural GHG Emissions Due to LUC

Agricultural LUC activities have caused 5,096 ± 301 Tg CO_2 eq /yr emissions (Fig. 1 and Table 1), including 90% from cropland-related LUC activities and 10% from grazing land-related LUC activities. Agriculture land is expanded mainly at the cost of forest land. We have estimated 57% of the E_{luc} is from cleared biomass; 50% of this amount was associated with cropland expansion and 7% with grazing land (Suppl. Table 15). Soil emissions due to LUC disturbance for cropland and grazing land are estimated as 40% and 3% of E_{luc}.

3. Livestock Feed Conversion Efficiency

We calculate feed conversion efficiencies based on biomass, calorie, and protein at a country scale. We collect the dry matter fraction, the carbon content of dry matter from Wolf, et al. [47] and Feedipedia [48], calorie and protein fraction from different data sources, including FAO [49] (livestock products and crop grain feed), Feedipedia [48] (forage crops and crop residues), Eshel, et al. [50] (grazing feed), and Fung, et al. [51] (scavenging and other feed) (Suppl. Table 6). It is noted that the calorie value of scavenging feed in this study is estimated for food waste in developed countries. Scavenging and other feed may also include roadside grazing and poorly digestible residues[51]. When calculating the livestock products, we only estimate the biomass, calorie and protein in meat, milk and egg, and ignore other products such as skin/hide, wool, offal, and slaughter fats. We assume the main purpose of rising livestock animals is to produce meat, milk and egg, and therefore consider other products as the byproducts of meat, milk and egg.

Globally, we have estimated the conversion efficiency from feed to livestock products is 5.17% based on biomass, 6.22% based on calorie, and 8.49% based on protein. The spatial distributions are shown in Suppl. Fig. 3.

4. Comparisons with Other Global Estimates on Livestock Feed

Livestock feed biomass amount and its compositions in different countries and regions are the basis of estimating GHG emissions from animal-based food. This study has accounted for the different feed categories associated with ruminant and monogastric animals (Suppl. Table 17). Our estimated biomass feed demand (2,450 Tg C/yr, Suppl. Table 2) is consistent with previous studies (range from ~2,000 to 3,000 Tg C/yr, see Suppl. Table 7). Our estimated percentage of grazing feed to total feed amount is the highest among feed types (42%), following by crop grain (23%), residue feed (21%), and forage (12%). Such order is similar as other studies, in which the percentage of above feed types ranged from 46% to 57%, 13% to 28%, 12% to 20%, and 7% to 12%.

5. Comparisons with Other Global Estimates on GHG Emissions

This study establishes a "cradle-to-dining table" life-cycle assessment framework, which includes the results of a land surface model, ISAM, and other GHG emissions entering in the final consumption of food (such as emissions from fertilizer manufacturing). Our model-data integration approach ensures the conservation of biomass and GHG emissions, as well as external forcing such as land-use change. Here we present a comparison of our results with other published studies on global GHG emissions from agriculture, forestry and other land use (AFOLU) emissions.

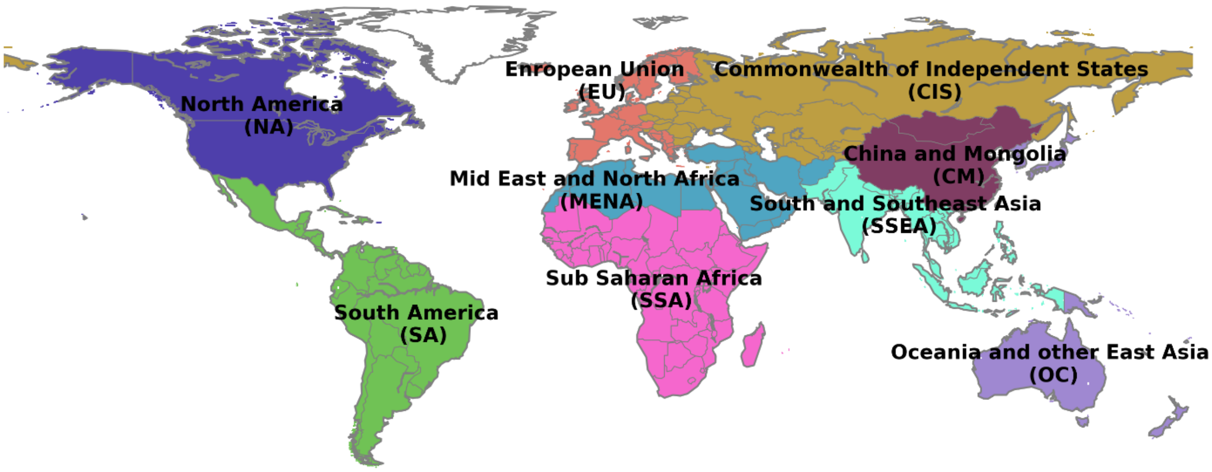
Our estimate E_{bfg} is about half of IPCC SRCCL value (Suppl. Table 8) [52]. One possible reason for this is that we do not consider the post-plate emissions (such as emissions from household refrigerating and cooking).

The cropland and grazing land related E_{luc} is estimated as 5,096 ± 301 Tg CO_2 eq/yr, which is consistent with the SRCCL value (4,900 ± 2,500 Tg CO_2 eq/yr) [52], and the global carbon budget 2019 estimates (5,500 ± 2,500 Tg CO_2 eq/yr) [53]. It should be noticed that global carbon budget has included all land cover changes rather than only cropland and grazing land related, in particular, both SRCCL and global carbon budget include 1,000-2,000 Tg CO_2 eq from peatland degradation and fires. Meanwhile, IPCC AR5 WG3 has reported the Forestry and Other Land Use emissions are ~4,000 Tg CO_2 eq/yr without peatland degradation and fires. Our estimated GHG emissions for animal-based food is ~25% higher than the GLEAM model results for livestock emissions in 2010 [54]. The E_{f_CO2} emissions mainly cause this difference. Our estimate of feed related E_{f_CO2} is 2,571 ± 151 Tg CO_2 eq/yr, while GLEAM assumes this emission to be zero. In addition, our estimated E_{luc} are also higher than for GLEAM, mainly because our estimates are based on a processed-based model, while GLEAM uses the IPCC Tier 2 method. Therefore, our estimates are higher than previously published results, but all these estimates are with large uncertainties.

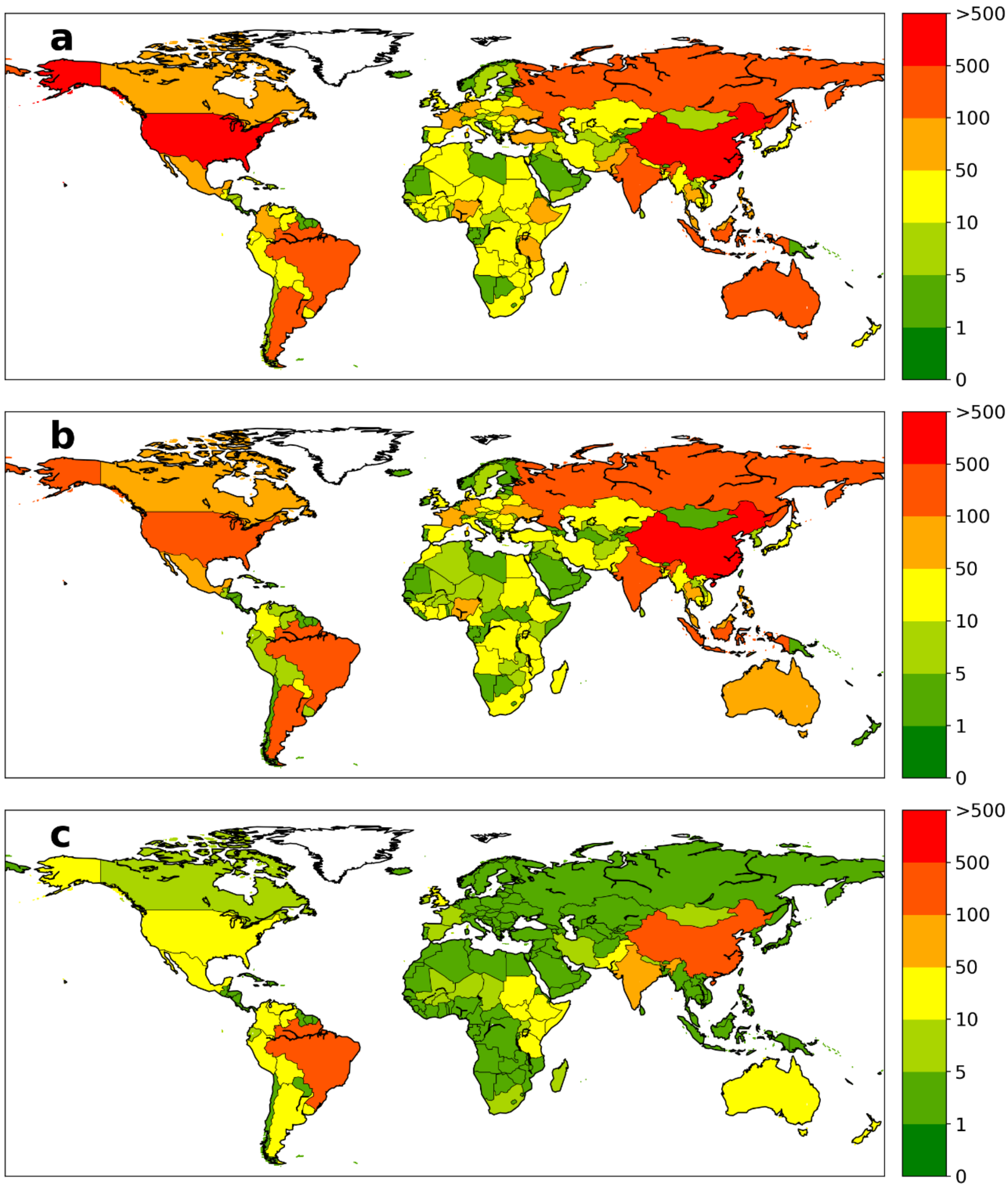
We use the livestock emissions from FAOSTAT[55], which is based on the IPCC Tier 1 method [23]. We use the FAOSTAT dataset mainly because it provides a complete estimate at a country scale covering more than 200 countries for the period 1961 to 2018. This dataset uses default emission factors of IPCC Tier 1 methods for enteric fermentation and manure management in each country. In comparison, Poore and Nemecek [45] have compiled data points from published literature to estimate global average values and variations for different plant and animal products.

This study used detail bilateral trade matrices from FAOSTAT to calculate the consumption-based GHG emissions and GHG transfer between different regions due to trade. Our results represent the consumption-based GHG emissions only due to GHG transfers between the countries in circa 2010 (average from 2007 to 2013). Therefore, it may not be suitable for estimating the time-series consumption-based GHG emissions, because the trade partners of a country may change over time, and the GHG emission transfers between regions will also change. To estimate the time-series consumption-based GHG emissions, the pool representation of trade, which considers all exporting and importing commodities from a global pool, might be more relevant.

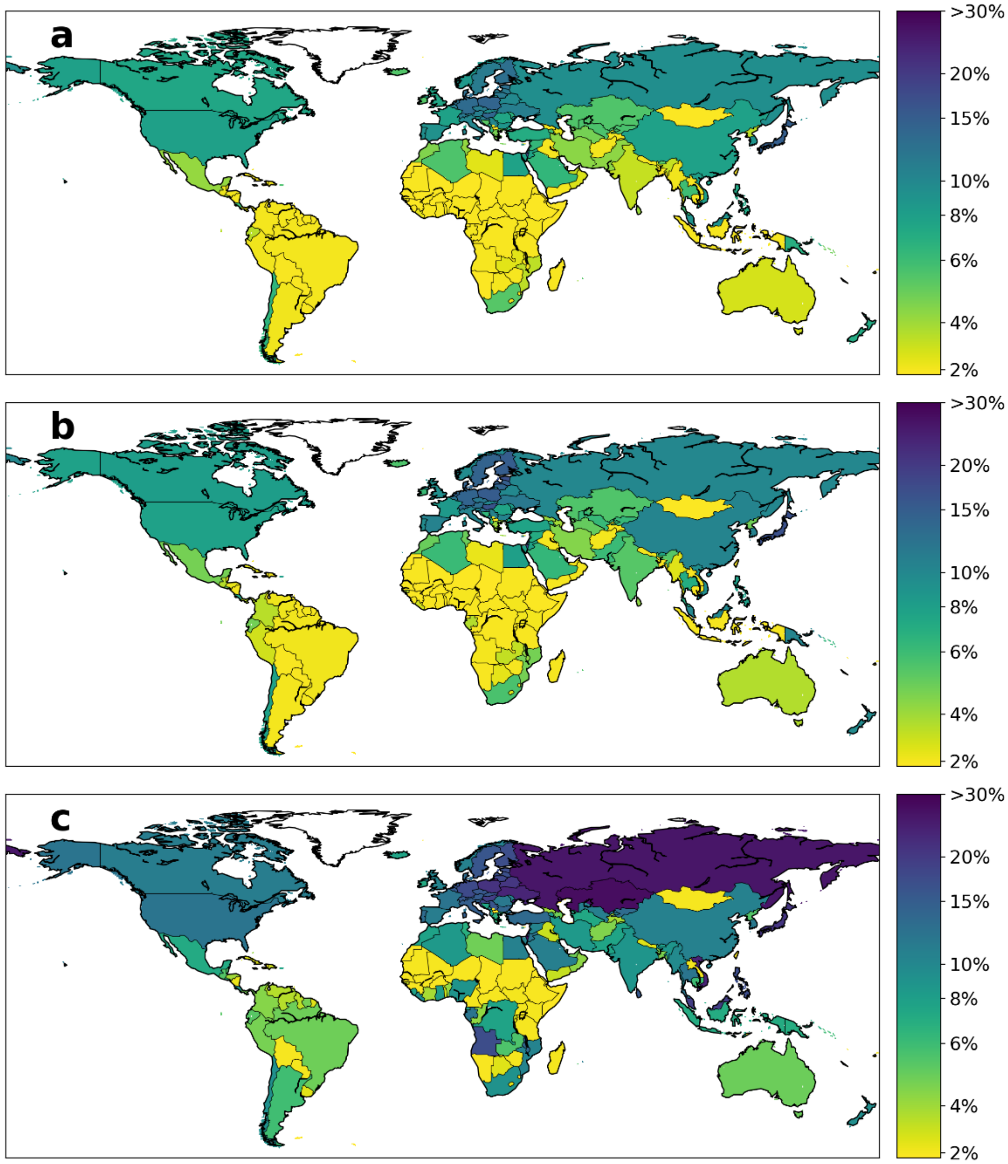
Supplementary Figures



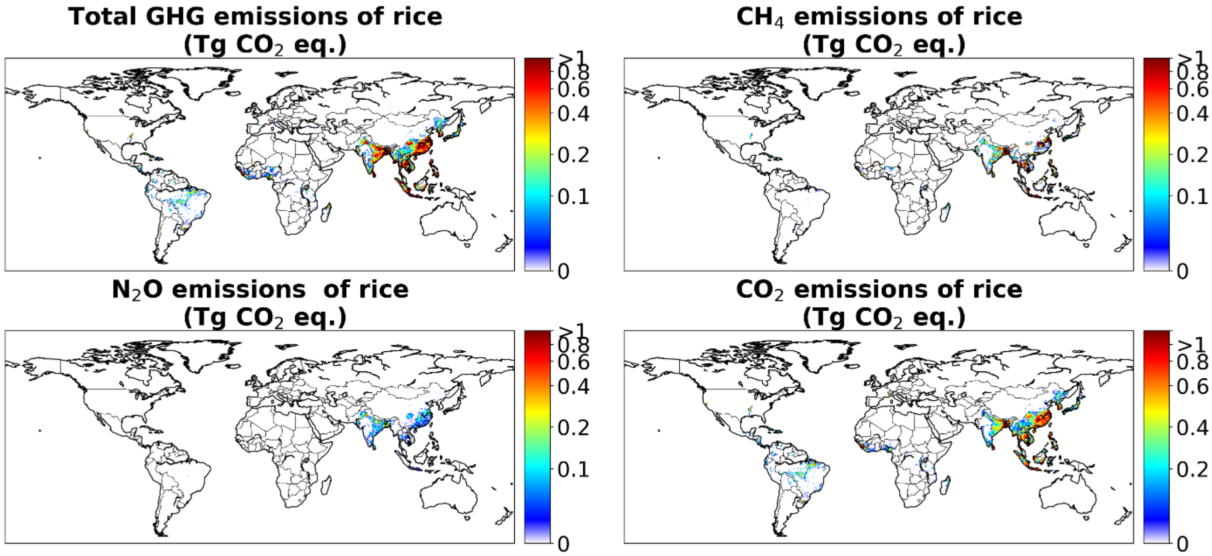
Suppl. Fig. 1. Nine macro-geographical regions in this study.



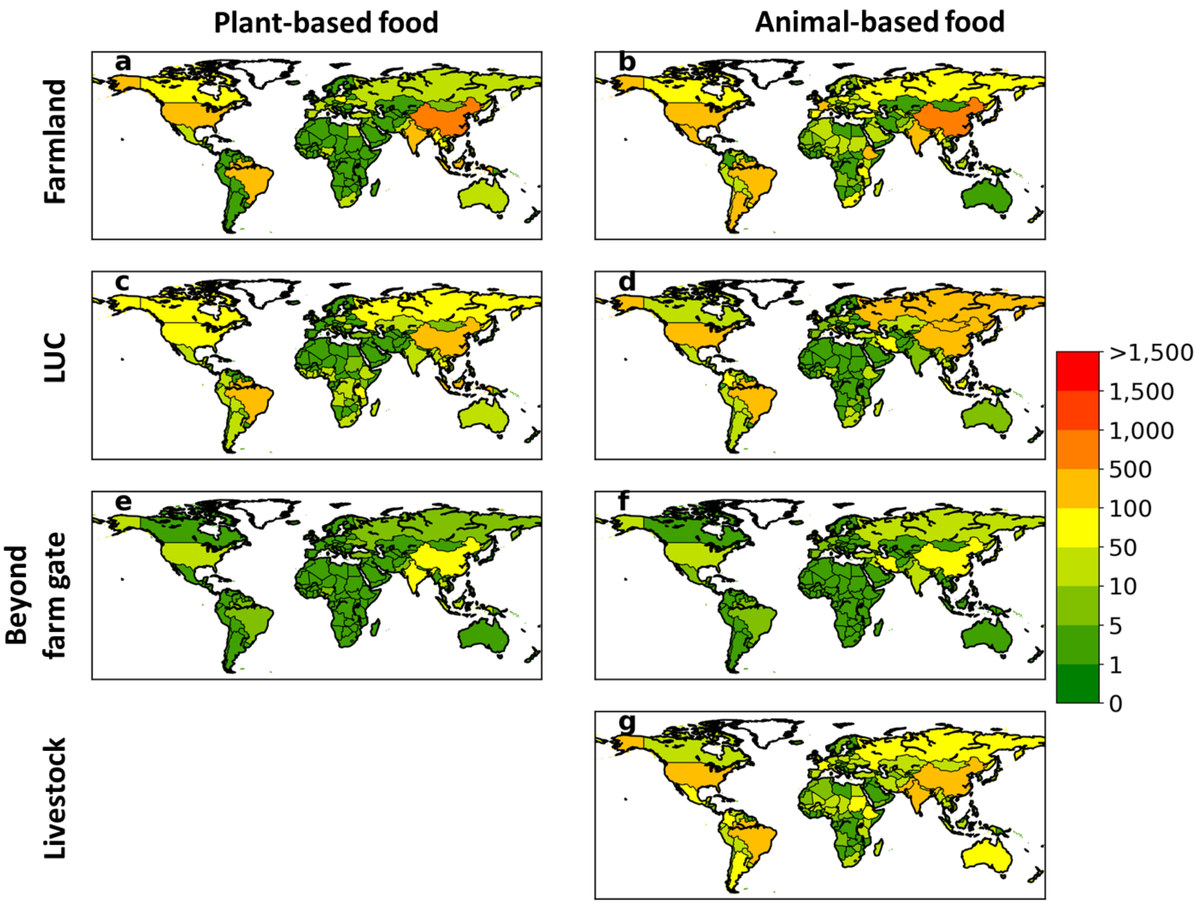
Suppl. Fig. 2. Country-specific estimated total biomass production. a) Cropland and grazing land, b) cropland, and c) grazing land (unit: Tg C/yr) for year 2010.



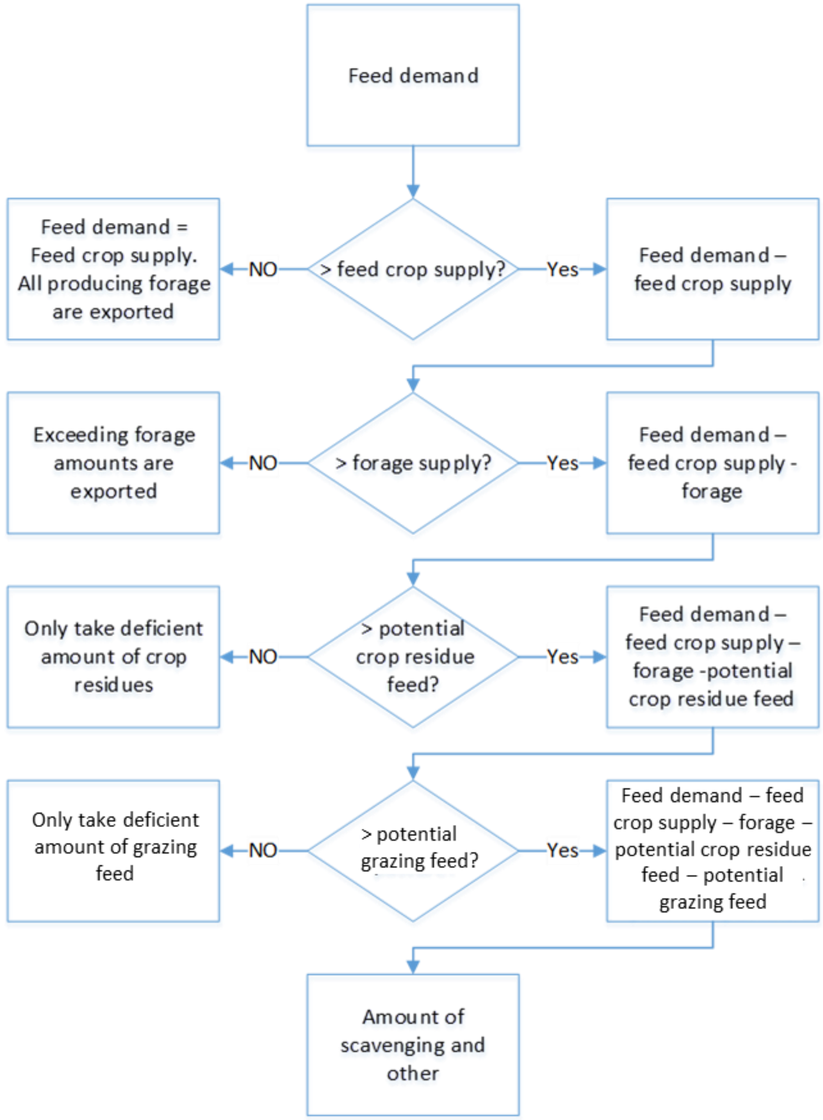
Suppl. Fig. 3. Conversion efficiency from feed to livestock products. a) Based on biomass, b) calorie, and c) protein.



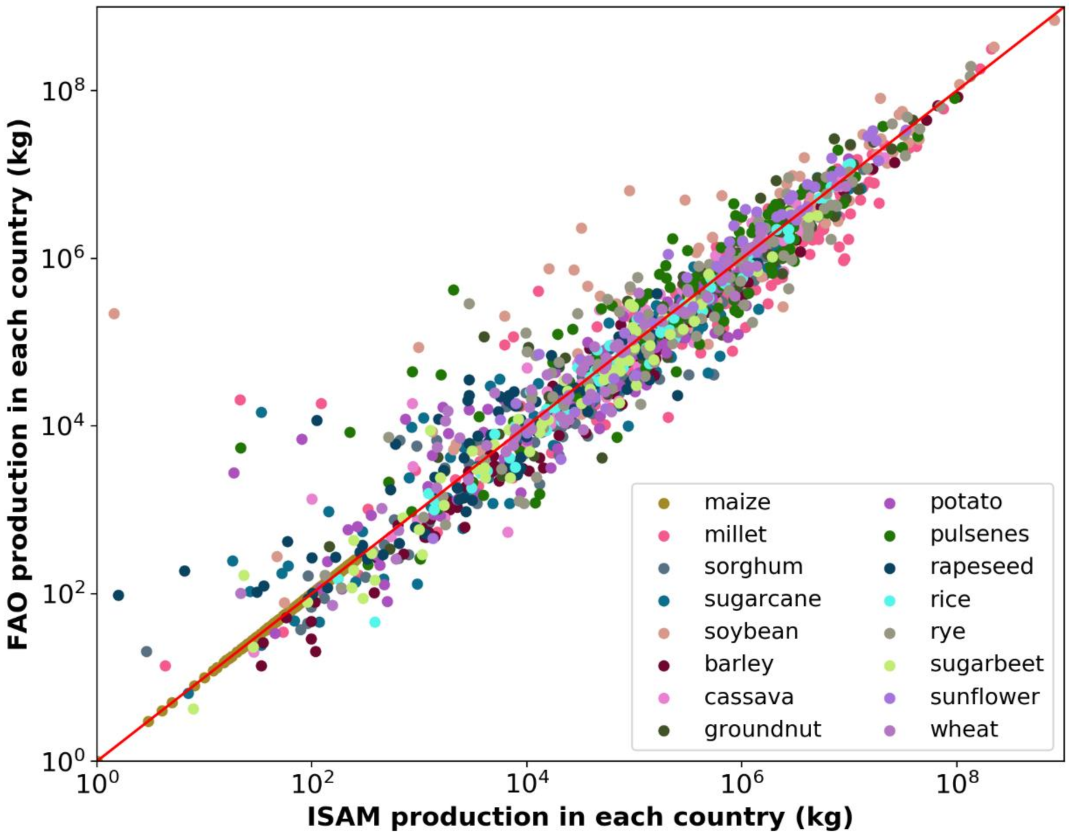
Suppl. Fig. 4. Production-based GHG, CH_4, N_2O and CO_2 emissions for rice production.



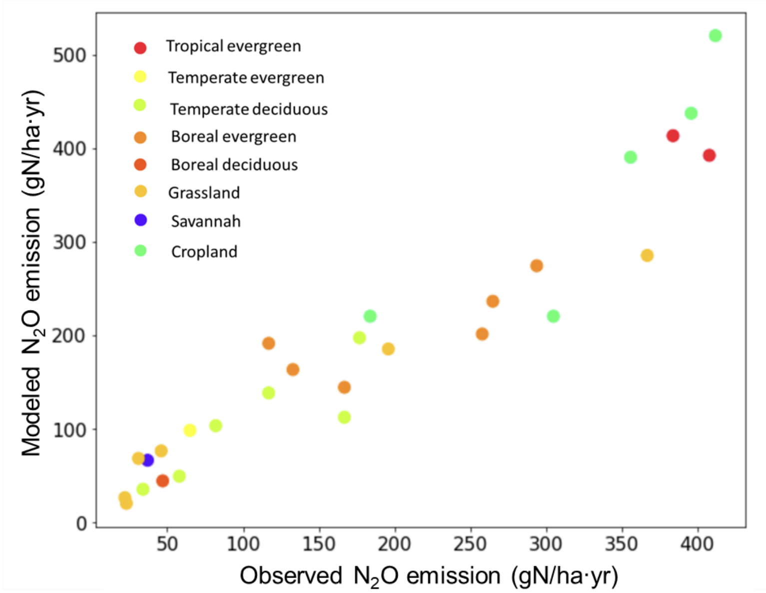
Suppl. Fig. 5. GHG emissions from production of plant- and animal-based food. (a) Farmland emissions of plant-based food, (b) farmland emissions of animal-based food, (c) LUC emissions of plant-based food, (d) LUC emissions of animal-based food, (e) beyond farm gate emissions of plant-based food, (f) beyond farm gate emissions of animal-based food, and (g) livestock emissions of animal-based food in different countries (unit: Tg CO_2 eq/yr).



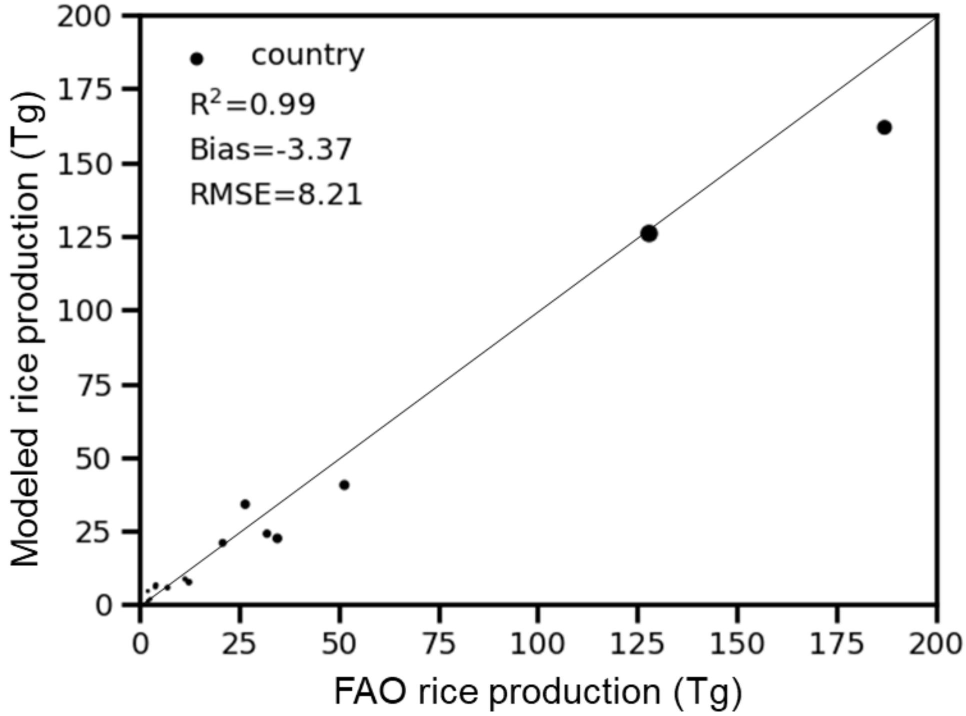
Suppl. Fig. 6. Flowchart diagram of the livestock feed biomass balance at the country scale.



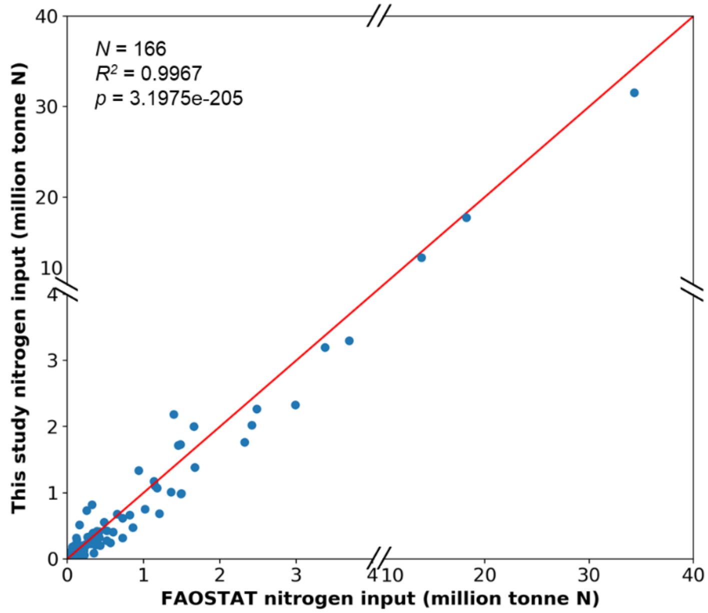
Suppl. Fig. 7. Correlation between ISAM and FAOSTAT data for the crop production of 16 major crops at country scale.



Suppl. Fig. 8. The comparison between biome-specific observed and the ISAM modeled N_2O emission for model calibration and validation.



Suppl. Fig. 9. Comparison of simulated and FAO rice production of 16 major countries averaged over the period 1996-2005. The size of the dots is the harvested area of rice. Countries include China, Japan, Nepal, Pakistan, India, Sri Lanka, Bangladesh, Bhutan, Cambodia, Indonesia, Myanmar, Philippines, Thailand, Vietnam, Laos, and Malaysia.



Suppl. Fig. 10. Comparing the nitrogen application amount between our study and the FAOSTAT at the country scale in circa 2010. The amount is sum of nitrogen fertilizers applied to cropland and manure applied to both cropland and grazing land.

Supplementary Tables

Suppl. Table 1. Crop and forage list and parameters used in this study.

Crop name	Crop name FAO	FAO Code	Category	Corresponding Commodity Item	Harvest Index	Root:Shoot ratio	Water Content	Carbon content	References
abaca*	Manila Fibre (Abaca)	809	Fiber	Abaca	0.40	0.17	0.08	0.44	Refer to Seed cotton
agave*	Agave Fibres Nes	800	Fiber	Hard Fibres, Other	0.40	0.17	0.08	0.44	Refer to Seed cotton
alfalfa ‡	alfalfa	641	Forage	-	0.95	0.87	0.65	0.44	Wolf, et al. [47]
almond	Almonds, with shell	221	Treenuts	Nuts and products	0.42	0.15	0.20	0.62	Kyle, et al. [56]
aniseetc*	Anise, badian, fennel, corian.	711	OtherCrops	Spices, Other	1.00	0.15	0.10	0.41	Kyle, et al. [56]
apple	Apples	515	Fruit	Apples and products	0.85	0.15	0.80	0.41	Kyle, et al. [56]
apricot	Apricots	526	Fruit	Fruits, Other	0.68	0.15	0.80	0.41	Kyle, et al. [56]
areca*	Arecanuts	226	OtherCrops	Nuts and products	1.00	0.15	0.10	0.41	Refer to Spices, nes
artichoke	Artichokes	366	Vegetables&Melons	Vegetables, Other	0.77	0.15	0.70	0.41	Wolf, et al. [47]
asparagus	Asparagus	367	Vegetables&Melons	Vegetables, Other	0.49	0.15	0.70	0.41	Wolf, et al. [47]
avocado	Avocados	572	Fruit	Fruits, Other	0.71	0.15	0.80	0.41	Kyle, et al. [56]
bambara*	Bambara beans	203	Pulses	Pulses, Other and products	0.40	0.07	0.09	0.46	Wolf, et al. [47]
banana	Bananas	486	Fruit	Bananas	0.40	0.42	0.74	0.41	Wolf, et al. [47]
barley†	Barley	44	Cereals	Barley and products	0.46	0.11	0.13	0.46	Wolf, et al. [47]
bean	Beans, dry	176	Pulses	Beans	0.46	0.08	0.16	0.46	Wolf, et al. [47]
beetfor ‡	beetfor	647	Forage	-	0.95	0.43	0.85	0.41	Wolf, et al. [47]
berrynes	Berries Nes	558	Fruit	Fruits, Other	1.00	0.15	0.80	0.41	Refer to Raspberries
blueberry	Blueberries	552	Fruit	Fruits, Other	0.79	0.15	0.85	0.41	Wolf, et al. [47]
brazil*	Brazil nuts, with shell	216	Treenuts	Nuts and products	0.42	0.15	0.20	0.62	Refer to Almonds, with shell
broadbean	Broad beans, horse beans, dry	181	Pulses	Pulses, Other and products	0.46	0.08	0.16	0.46	Wolf, et al. [47]
buckwheat	Buckwheat	89	Cereals	Cereals, Other	0.43	0.10	0.13	0.46	Wolf, et al. [47]
cabbage	Cabbages and other brassicas	358	Vegetables&Melons	Vegetables, Other	0.80	0.15	0.92	0.41	Wolf, et al. [47]
cabbagefor‡	Cabbagefor	644	Forage	-	0.95	0.15	0.92	0.41	Wolf, et al. [47]
canaryseed	Canary seed	101	Cereals	Cereals, Other	0.40	0.15	0.05	0.41	Refer to Cereals, nes
carob	Carobs	461	Fruit	Vegetables, Other	1.00	0.15	0.70	0.41	Refer to Fruit Fresh Nes
carrot	Carrots and turnips	426	Vegetables&Melons	Vegetables, Other	0.53	0.15	0.87	0.41	Wolf, et al. [47]
carrotfor*,‡	Carrotfor	648	Forage	-	0.95	0.15	0.87	0.41	Wolf, et al. [47]
cashew*	Cashew nuts, with shell	217	Treenuts	Nuts and products	0.40	0.15	0.20	0.62	Kyle, et al. [56]
cashewapple	Cashewapple	591	Fruit	Fruits, Other	1.00	0.15	0.70	0.41	Refer to Fruit Fresh Nes

Crop name	Crop name FAO	FAO Code	Category	Corresponding Commodity Item	Harvest Index	Root:Shoot ratio	Water Content	Carbon content	References
cassava†	Cassava	125	Roots&Tubers	Cassava and products	0.50	0.15	0.12	0.44	Wolf, et al. [47]
castor	Castor oil seed	265	Oilcrops	Oilcrops, Other	0.30	0.15	0.00	0.62	Refer to Rapeseed
cauliflower	Cauliflowers and broccoli	393	Vegetables&Melons	Vegetables, Other	0.80	0.15	0.92	0.41	Wolf, et al. [47]
cerealnes	Cereals, nes	108	Cereals	Cereals, Other	0.40	0.15	0.05	0.46	Refer to Cereals, nes
cherry	Cherries	531	Fruit	Fruits, Other	0.85	0.15	0.80	0.41	Kyle, et al. [56]
chestnut	Chestnuts	220	Treenuts	Nuts and products	0.40	0.15	0.20	0.62	Kyle, et al. [56]
chickpea	Chick peas	191	Pulses	Pulses, Other and products	0.46	0.08	0.13	0.46	Wolf, et al. [47]
chicory*	Chicory roots	459	OtherCrops	Vegetables, Other	1.00	0.15	0.75	0.41	Refer to Spices, nes
chilleetc*	Chillies and peppers, green	401	Vegetables&Melons	Vegetables, Other	0.60	0.15	0.91	0.41	Wolf, et al. [47]
cinnamon*	Cinnamon (canella)	693	OtherCrops	Spices, Other	1.00	0.15	0.10	0.41	Kyle, et al. [56]
citrusnes	Citrus fruit, nes	512	Fruit	Citrus, Other	0.93	0.15	0.80	0.41	Kyle, et al. [56]
clove*	Cloves	698	OtherCrops	Cloves	1.00	0.15	0.10	0.41	Kyle, et al. [56]
clover ‡	Clover	640	Forage	-	0.95	1.10	0.65	0.44	Wolf, et al. [47]
cocoa	Cocoa beans	661	OtherCrops	Cocoa Beans and products	1.00	0.15	0.11	0.41	Kyle, et al. [56]
coconut	Coconuts	249	Oilcrops	Coconuts - Incl Copra	0.66	0.15	0.80	0.63	Wolf, et al. [47]
coffee	Coffee, green	656	OtherCrops	Coffee and products	1.00	0.15	0.11	0.41	Kyle, et al. [56]
cotton	Seed cotton	328	Fiber	-	0.40	0.17	0.08	0.54	Wolf, et al. [47]
cowpea	Cow peas, dry	195	Pulses	Pulses, Other and products	0.45	0.08	0.16	0.46	Wolf, et al. [47]
cranberry	Cranberries	554	Fruit	Fruits, Other	1.00	0.15	0.90	0.41	Wolf, et al. [47]
cucumberetc	Cucumbers and gherkins	397	Vegetables&Melons	Vegetables, Other	0.80	0.15	0.96	0.41	Wolf, et al. [47]
currant	Currants	550	Fruit	Fruits, Other	1.00	0.15	0.80	0.41	Kyle, et al. [56]
date	Dates	577	Fruit	Dates	0.80	0.15	0.23	0.41	Wolf, et al. [47]
eggplant	Eggplants (aubergines)	399	Vegetables&Melons	Vegetables, Other	0.59	0.15	0.80	0.41	Wolf, et al. [47]
fibrenes*	Fibre Crops Nes	821	Fiber	Hard Fibres, Other	0.40	0.17	0.08	0.44	Refer to Cottonseed
fig	Figs	569	Fruit	Fruits, Other	0.62	0.15	0.70	0.41	Kyle, et al. [56]
flax	Flax fibre and tow	773	Fiber	Soft-Fibres, Other	0.40	0.17	0.08	0.44	Refer to Cottonseed
fonio*	Fonio	94	Cereals	Cereals, Other	0.25	0.11	0.11	0.46	Wolf, et al. [47]
fornes#	Fornes	651	Forage	-	0.95	0.18	0.65	0.44	Wolf, et al. [47]
fruitnes	Fruit Fresh Nes	619	Fruit	Fruits, Other	1.00	0.15	0.70	0.41	Kyle, et al. [56]
garlic	Garlic	406	Vegetables&Melons	Vegetables, Other	1.00	0.15	0.64	0.41	Wolf, et al. [47]
ginger*	Ginger	720	OtherCrops	Spices, Other	1.00	0.15	0.70	0.41	Wolf, et al. [47]
gooseberry	Gooseberries	549	Fruit	Fruits, Other	1.00	0.15	0.80	0.41	Refer to Raspberries
grape	Grapes	560	Fruit	Grapes and products (excl wine)	0.79	0.15	0.81	0.41	Wolf, et al. [47]

Crop name	Crop name FAO	FAO Code	Category	Corresponding Commodity Item	Harvest Index	Root:Shoot ratio	Water Content	Carbon content	References
grapefruitetc	Grapefruit (inc. pomelos)	507	Fruit	Grapefruit and products	0.93	0.15	0.80	0.44	Kyle, et al. [56]
grassnes#	grassnes	639	Forage	-	0.95	1.81	0.65	0.44	Wolf, et al. [47]
greenbean	Beans, green	414	Vegetables&Melons	Vegetables, Other	0.46	0.08	0.79	0.41	Wolf, et al. [47]
greenbroadbean	Leguminous vegetables, nes	420	Vegetables&Melons	Vegetables, Other	0.46	0.08	0.70	0.41	Refer to Broad beans, horse beans, dry
greencorn	Maize, green	446	Vegetables&Melons	Vegetables, Other	0.53	0.18	0.80	0.44	Wolf, et al. [47]
greenonion	Onions (inc. shallots), green	402	Vegetables&Melons	Vegetables, Other	0.56	0.15	0.90	0.41	Wolf, et al. [47]
greenpea	Peas, green	417	Vegetables&Melons	Vegetables, Other	0.30	0.08	0.79	0.41	Wolf, et al. [47]
groundnut†	Groundnuts, with shell	242	Oilcrops	Groundnuts (in Shell Eq)	0.40	0.07	0.09	0.60	Wolf, et al. [47]
hazelnut	Hazelnuts, with shell	225	Treenuts	Nuts and products	0.40	0.15	0.20	0.62	Kyle, et al. [56]
hemp	Hemp Tow Waste	777	Fiber	Soft-Fibres, Other	0.40	0.17	0.08	0.62	Refer to Cottonseed
hempseed	Hempseed	336	Oilcrops	Oilcrops, Other	0.18	0.15	0.09	0.62	Wolf, et al. [47]
hop	Hops	677	OtherCrops	-	1.00	0.15	0.10	0.41	Refer to Spices, nes
jute	Jute	780	Fiber	Jute	0.30	0.10	0.08	0.44	Wolf, et al. [47]
jutelikefiber	Other Bastfibres	782	Fiber	Jute-Like Fibres	0.40	0.17	0.08	0.44	Refer to Cottonseed
kapokfiber*	Kapok Fibre	778	Fiber	Soft-Fibres, Other	0.40	0.17	0.08	0.44	Refer to Cottonseed
kapokseed*	Kapokseed in Shell	311	Fiber	Oilcrops, Other	0.40	0.17	0.08	0.44	Refer to Cottonseed
karite*	Karite Nuts (Sheanuts)	263	Oilcrops	Oilcrops, Other	0.26	0.15	0.15	0.62	Refer to Linseed
kiwi	Kiwi fruit	592	Fruit	Fruits, Other	0.72	0.15	0.80	0.41	Kyle, et al. [56]
kolanut*	Kolanuts	224	OtherCrops	Nuts and products	1.00	0.15	0.10	0.41	Refer to Spices, nes
legumenes‡	legumenes	643	Forage	-	0.95	1.10	0.65	0.44	Wolf, et al. [47]
lemonlime	Lemons and limes	497	Fruit	Lemons, Limes and products	0.95	0.15	0.80	0.41	Kyle, et al. [56]
lentil	Lentils	201	Pulses	Pulses, Other and products	0.61	0.15	0.16	0.46	Wolf, et al. [47]
lettuce	Lettuce and chicory	372	Vegetables&Melons	Vegetables, Other	0.94	0.15	0.96	0.41	Wolf, et al. [47]
linseed	Linseed	333	Oilcrops	Oilcrops, Other	0.26	0.15	0.08	0.62	Wolf, et al. [47]
lupin	Lupins	210	Pulses	Pulses, Other and products	0.61	0.15	0.20	0.46	Refer to Lentils
maize†	Maize	56	Cereals	Maize and products	0.53	0.18	0.14	0.46	Wolf, et al. [47]
maizefor‡	maizefor	636	Forage	-	0.95	0.18	0.65	0.44	Wolf, et al. [47]
mango	Mangoes, mangosteens, guavas	571	Fruit	Fruits, Other	0.45	0.15	0.80	0.41	Kyle, et al. [56]
mate*	MatŽ	671	OtherCrops	Tea (including mate)	1.00	0.15	0.10	0.41	Refer to Tea
melonetc	Other melons (inc.cantaloupes)	568	Vegetables&Melons	Vegetables, Other	0.91	0.15	0.90	0.41	Wolf, et al. [47]

Crop name	Crop name FAO	FAO Code	Category	Corresponding Commodity Item	Harvest Index	Root:Shoot ratio	Water Content	Carbon content	References
melonseed*	Melonseed	299	Oilcrops	Oilcrops, Other	0.30	0.15	0.00	0.62	Refer to Rapeseed
millet†	Millet	79	Cereals	Millet and products	0.45	0.25	0.11	0.46	Wolf, et al. [47]
mixedgrain	Mixed grain	103	Cereals	Cereals, Other	0.40	0.15	0.05	0.46	Refer to Cereals, nes
mushroom	Mushrooms and truffles	449	Vegetables&Melons	Vegetables, Other	1.00	0.15		0.41	Kyle, et al. [56]
mustard	Mustard seed	292	Oilcrops	Rape and Mustardseed	0.30	0.15	0.90	0.62	Wolf, et al. [47]
nutmeg*	Nutmeg, mace and cardamoms	702	OtherCrops	Spices, Other	1.00	0.15	0.08	0.41	Kyle, et al. [56]
nutnes	Nuts, nes	234	Treenuts	Nuts and products	0.40	0.15	0.10	0.62	Kyle, et al. [56]
oats	Oats	75	Cereals	Oats	0.52	0.40	0.20	0.46	Wolf, et al. [47]
oilpalm	Oil palm fruit	254	Oilcrops	Palm kernels	0.46	0.15	0.13	0.62	Wolf, et al. [47]
oilseedfor‡	oilseedfor	642	Forage	-	0.95	1.10	0.35	0.44	Wolf, et al. [47]
oilseednes	Oilseeds, Nes	339	Oilcrops	Oilcrops, Other	0.30	0.15	0.65	0.62	Refer to Rapeseed
okra	Okra	430	Vegetables&Melons	Vegetables, Other	0.60	0.15	0.00	0.41	Wolf, et al. [47]
olive	Olives	260	Oilcrops	Olives (including preserved)	0.69	0.15	0.91	0.62	Kyle, et al. [56]
onion	Onions, dry	403	Vegetables&Melons	Onions	0.56	0.15	0.70	0.41	Wolf, et al. [47]
orange	Oranges	490	Fruit	Oranges, Mandarines	0.91	0.15	0.90	0.41	Kyle, et al. [56]
papaya	Papayas	600	Fruit	Fruits, Other	0.99	0.15	0.80	0.41	Kyle, et al. [56]
pea	Peas, dry	187	Pulses	Peas	0.30	0.08	0.80	0.46	Wolf, et al. [47]
peachetc	Peaches and nectarines	534	Fruit	Fruits, Other	0.86	0.15	0.13	0.41	Kyle, et al. [56]
pear	Pears	521	Fruit	Fruits, Other	0.88	0.15	0.80	0.41	Kyle, et al. [56]
pepper	Pepper (Piper spp.)	687	OtherCrops	Pepper	1.00	0.15	0.80	0.41	Kyle, et al. [56]
peppermint*	Peppermint	748	OtherCrops	-	1.00	0.15	0.91	0.41	Refer to Spices, nes
persimmon	Persimmons	587	Fruit	Fruits, Other	1.00	0.15	0.10	0.41	Refer to Fruit Fresh Nes
pigeonpea	Pigeon peas	197	Pulses	Pulses, Other and products	0.30	0.08	0.70	0.46	Wolf, et al. [47]
pimento*	Chillies and peppers, dry	689	OtherCrops	Pimento	0.60	0.15	0.13	0.41	Wolf, et al. [47]
pineapple	Pineapples	574	Fruit	Pineapples and products	0.26	0.15	0.10	0.41	Wolf, et al. [47]
pistachio	Pistachios	223	Treenuts	Nuts and products	0.40	0.15	0.80	0.62	Kyle, et al. [56]
plantain	Plantains	489	Fruit	Plantains	0.40	0.42	0.20	0.41	Wolf, et al. [47]
plum	Plums and sloes	536	Fruit	Fruits, Other	0.80	0.15	0.65	0.41	Kyle, et al. [56]
poppy	Poppy seed	296	Oilcrops	Oilcrops, Other	0.27	0.06	0.80	0.62	Refer to Sunflower seed
potato†	Potatoes	116	Roots&Tubers	Potatoes and products	0.50	0.07	0.07	0.41	Wolf, et al. [47]
pulsenes†	Pulses, nes	211	Pulses	Pulses, Other and products	0.35	0.15	0.80	0.46	Kyle, et al. [56]

Crop name	Crop name FAO	FAO Code	Category	Corresponding Commodity Item	Harvest Index	Root:Shoot ratio	Water Content	Carbon content	References
pumpkinetc	Pumpkins, squash and gourds	394	Vegetables&Melons	Vegetables, Other	0.88	0.15	0.70	0.41	Wolf, et al. [47]
pyrethrum*	Pyrethrum,Dried	754	OtherCrops	-	1.00	0.15	0.70	0.41	Refer to Spices, nes
quince	Quinces	523	Fruit	Fruits, Other	1.00	0.15	0.10	0.41	Refer to Fruit Fresh Nes
quinoa*	Quinoa	92	Cereals	Cereals, Other	0.28	0.12	0.70	0.46	Wolf, et al. [47]
ramie*	Ramie	788	Fiber	Soft-Fibres, Other	0.40	0.17	0.13	0.44	Refer to Cottonseed
rapeseed†	Rapeseed	270	Oilcrops	Rape and Mustardseed	0.30	0.15	0.08	0.62	Wolf, et al. [47]
rasberry	Raspberries	547	Fruit	Fruits, Other	1.00	0.15	0.07	0.41	Wolf, et al. [47]
rice†	Rice, paddy	27	Cereals	Rice (Paddy Equivalent)	0.42	0.22	0.87	0.46	Wolf, et al. [47]
rootnes	Roots and Tubers, nes	149	Roots&Tubers	Roots, Other	0.94	0.15	0.09	0.41	Kyle, et al. [56]
rubber	Natural rubber	836	OtherCrops	Rubber	1.00	0.15	0.80	0.41	Refer to Tea
rye†	Rye	71	Cereals	Rye and products	0.50	0.14	0.60	0.46	Wolf, et al. [47]
ryefor#	ryefor	638	Forage	-	0.95	1.50	0.10	0.44	Wolf, et al. [47]
safflower	Safflower seed	280	Oilcrops	Oilcrops, Other	0.20	0.10	0.65	0.62	Wolf, et al. [47]
sesame	Sesame seed	289	Oilcrops	Sesame seed	0.27	0.15	0.08	0.62	Wolf, et al. [47]
sisal	Sisal	789	Fiber	Sisal	0.04	0.04	0.05	0.44	Wolf, et al. [47]
sorghum†	Sorghum	83	Cereals	Sorghum and products	0.44	0.18	0.08	0.46	Wolf, et al. [47]
sorghumfor, #	sorghumfor	637	Forage	-	0.95	0.18	0.14	0.44	Wolf, et al. [47]
sourcherry	Sour cherries	530	Fruit	Fruits, Other	0.85	0.15	0.65	0.41	Refer to Cherries
soybean†	Soybeans	236	Oilcrops	Soyabeans	0.42	0.19	0.80	0.52	Wolf, et al. [47]
spicenes*	Spices, nes	723	OtherCrops	Spices, Other	1.00	0.15	0.12	0.41	Kyle, et al. [56]
spinach	Spinach	373	Vegetables&Melons	Vegetables, Other	0.95	0.15	0.10	0.41	Wolf, et al. [47]
stonefruitnes	Stone fruit, nes	541	Fruit	Fruits, Other	1.00	0.15	0.92	0.41	Refer to Fruit Fresh Nes
strawberry	Strawberries	544	Fruit	Fruits, Other	0.45	0.15	0.70	0.41	Wolf, et al. [47]
stringbean	String beans	423	Vegetables&Melons	Vegetables, Other	0.46	0.08	0.92	0.41	Wolf, et al. [47]
sugarbeet†	Sugar beet	157	SugarCrops	Sugar beet	0.40	0.43	0.79	0.41	Wolf, et al. [47]
sugarcane†	Sugar cane	156	SugarCrops	Sugar cane	0.75	0.18	0.85	0.41	Wolf, et al. [47]
sugarnes*	Sugar crops, nes	161	SugarCrops	Sweeteners, Other	0.70	0.18	0.74	0.41	Refer to Sugar cane
sunflower†	Sunflower seed	267	Oilcrops	Sunflower seed	0.27	0.06	0.30	0.62	Wolf, et al. [47]
swedefor*,‡	swedefor	649	Forage	-	0.95	0.15	0.09	0.41	Wolf, et al. [47]
sweetpotato	Sweet potatoes	122	Roots&Tubers	Sweet potatoes	0.53	0.15	0.87	0.41	Wolf, et al. [47]
tangetc	Tangerines, mandarins, clem.	495	Fruit	Oranges, Mandarines	0.91	0.15	0.80	0.41	Kyle, et al. [56]
taro	Taro (cocoyam)	136	Roots&Tubers	Roots, Other	0.53	0.15	0.80	0.41	Wolf, et al. [47]
tea	Tea	667	OtherCrops	Tea (including mate)	1.00	0.15	0.80	0.41	Kyle, et al. [56]
tobacco	Tobacco, unmanufactured	826	OtherCrops	Tobacco	0.60	0.80	0.10	0.44	Wolf, et al. [47]

Crop name	Crop name FAO	FAO Code	Category	Corresponding Commodity Item	Harvest Index	Root:Shoot ratio	Water Content	Carbon content	References
tomato	Tomatoes	388	Vegetables&Melons	Tomatoes and products	0.33	0.14	0.20	0.41	Wolf, et al. [47]
triticale	Triticale	97	Cereals	Cereals, Other	0.50	0.14	0.95	0.46	Wolf, et al. [47]
tropicalnes	Fruit, tropical fresh nes	603	Fruit	Fruits, Other	1.00	0.15	0.10	0.41	Refer to Fruit Fresh Nes
tung*	Tung Nuts	275	Oilcrops	Oilcrops, Other	0.19	0.15	0.70	0.62	Refer to Oil palm fruit
turnipfor‡	turnipfor	646	Forage	-	0.95	0.15	0.70	0.41	Wolf, et al. [47]
vanilla*	Vanilla	692	OtherCrops	Spices, Other	1.00	0.15	0.87	0.41	Kyle, et al. [56]
vegetablenes	Vegetables fresh nes	463	Vegetables&Melons	Vegetables, Other	1.00	0.15	0.10	0.41	Kyle, et al. [56]
vegfor‡	vegfor	655	Forage	-	0.95	0.15	0.80	0.41	Wolf, et al. [47]
vetch*	Vetches	205	Pulses	Pulses, Other and products	0.95	1.10	0.87	0.44	Wolf, et al. [47]
walnut	Walnuts, with shell	222	Treenuts	Nuts and products	0.40	0.15	0.65	0.62	Kyle, et al. [56]
watermelon	Watermelons	567	Vegetables&Melons	Vegetables, Other	0.91	0.15	0.20	0.41	Wolf, et al. [47]
wheat†	Wheat	15	Cereals	Wheat and products	0.39	0.20	0.92	0.46	Wolf, et al. [47]
yam	Yams	137	Roots&Tubers	Yams	0.53	0.15	0.13	0.41	Wolf, et al. [47]
yautia*	Yautia (cocoyam)	135	Roots&Tubers	Roots, Other	0.53	0.15	0.80	0.41	Wolf, et al. [47]

* indicates the crops whose spatial N, P, K fertilizer maps are not available
† denotes the 16 specific crops (PFTs) in ISAM model
# represents grass forage
‡ indicates other forage

Suppl. Table 2. Land area and biomass productivity of crop and grazing land for plant- and animal-based food and other utilizations. Land areas are in million hectare (Mha) and biomass productivity is in Tg C/yr.

	Plant-based food		**Animal-based food**		**Other utilizations**		**Sum**	
	Land	Biomass	Land	Biomass	Land	Biomass	Land	Biomass
Crop	595	1,364	345	1,657	453	2,239	1,393	5,260
Forage feed			*80*	*289*			*80*	*289*
Crop grain	*595*	*855*	*265*	*578*	*453*	*448*	*1,313*	*1,881*
Crop residue				*523*		*1,318*		*1,841*
Burned		*67*		*35*		*62*		*164*
Litter		*442*		*232*		*411*		*1,085*
Grazing land†			3,281	3,711			3,281	3,711
Grazing feed			*1,345*	*1,028*			*1,345*	*1,028*
Litter			*1,936*	*2,683*			*1,936*	*2,683*
Scavenging and other feeds				48				48
Stock variation[δ] and trade		-23		-16		-16		-55
Sum	595	1,341	3,626	5,400	453	2,223	4,674	8,964
Used		*832*	*1,690*	*2,450*		*1,750*	*2,738*	*5,032*
Burned and litter		*509*	*1,936*	*2,950*		*473*	*1,936*	*3,932*

δ The stock variation includes the FAO commodity reported stock variation and the discrepancies of the biomass of 16 major crops between ISAM simulations and FAO reported values.

† The grazing land includes all pastureland/grassland, grazing savanna, tundra, and shrubland.

Suppl. Table 3. Area and biomass of cropland, grazing land and total population of nine regions in circa 2010

Region	Cropland			Grazing land			Population (million people)
	Area (million ha)	Biomass (Tg C/yr)	Biomass density (gC/m^2)	Area (million ha)	Biomass (Tg C/yr)	Biomass density (gC/m^2)	
NA	145	746	515	360	421	117	347
SA	159	867	547	597	788	132	588
EU	90	431	480	127	188	148	432
MENA	68	158	234	73	87	119	487
SSA	208	673	323	733	678	93	827
CIS	149	628	421	545	628	115	384
CM	173	534	309	326	491	151	1,379
SSEA	365	1,055	289	94	151	160	2,205
OC	36	168	466	314	278	89	264
Global	1,392	5,260	378	3,170	3,710	117	6,912

Suppl. Table 4. List of livestock and animal products

	Livestock	Products	Type
1	Cattle, meat	Beef	Ruminant
2	Cattle, dairy	Cow milk	Ruminant
3	Buffalo, meat	Buffalo meat	Ruminant
4	Buffalo, dairy	Buffalo milk	Ruminant
5	Sheep	Sheep meat	Ruminant
6	Goat	Goat meat	Ruminant
7	Swine	Pork	Monogastric
8	Layer chicken	Hen egg	Monogastric
9	Meat chicken	Chicken meat	Monogastric
10	Duck	Duck meat	Monogastric
11	Turkey	Turkey meat	Monogastric
12	Geese	Geese meat	Monogastric
13	Horse	Horse meat	Monogastric
14	Camel	Camel meat	Ruminant
15	Mule	Mule meat	Monogastric
16	Camelid	Camelid meat	Ruminant

Suppl. Table 5. Livestock feed demand, composition and manure carbon amount at country scale. Values are expressed in Gigagram C/yr.

Country	Total feed demand	Crop grain feed	Forage crop feed	Crop residue feed	Grazing feed	Scavenging and other feed	Manure carbon amount
Afghanistan	7055	380	0	2468	3564	643	3204
Albania	1389	208	787	14	380	0	569
Algeria	6340	2304	659	793	2583	1	2361
American Samoa	4	0	0	1	0	4	1
Angola	3853	2419	0	1433	0	0	1694
Antigua and Barbuda	19	0	0	0	0	19	8
Argentina	65277	4694	20542	18906	21135	0	26929
Armenia	1041	165	387	85	404	0	446
Australia	49683	4815	1848	786	42234	0	21430
Austria	4335	1677	1002	180	1476	0	1624
Azerbaijan	5095	664	117	447	3865	1	2144
Bahamas	57	2	0	1	54	0	19
Bahrain	21	0	0	0	0	21	8
Bangladesh	24309	2957	26	21326	0	0	10949
Barbados	82	28	0	5	0	49	29
Belarus	6906	3420	3167	201	117	2	2956
Belgium	6260	3042	2651	111	456	1	2204
Belize	140	29	0	34	70	7	56
Benin	1836	614	0	791	432	0	799
Bermuda	3	0	0	0	0	3	1
Bhutan	285	0	0	63	222	0	141
Bolivia (Plurinational State of)	15557	587	76	1086	13806	2	6077
Bosnia and Herzegovina	1226	358	245	22	601	0	499
Botswana	1807	24	0	9	1774	0	799
Brazil	272502	29900	41288	43090	158109	115	111514
British Virgin Islands	6	0	0	0	0	6	2
Brunei Darussalam	203	6	0	1	132	63	67
Bulgaria	1547	712	294	216	324	0	629
Burkina Faso	8508	202	0	925	7380	0	3629
Burundi	727	0	0	224	503	0	303
Cambodia	4474	492	0	3982	0	0	1990
Cameroon	5165	722	0	1411	3033	0	2204
Canada	23704	10632	1376	1588	7140	2967	8337
Cape Verde	64	11	0	3	0	50	27
Cayman Islands	3	0	0	0	0	3	1
Central African Republic	3344	38	0	202	3104	1	1470
Chad	7715	152	0	702	6861	0	3234
Chile	8080	1708	870	760	4741	0	3148
China	356380	116104	9067	57303	172772	1134	127492
Colombia	33909	2684	0	2362	28864	0	14099
Comoros	56	0	0	16	0	40	23
Congo	294	17	0	185	92	0	127
Cook Islands	12	0	0	0	0	11	3
Costa Rica	2102	394	0	305	1400	3	867
Côte d'Ivoire	1982	323	0	1007	652	0	804
Croatia	997	997	0	0	0	0	425
Cuba	5999	1210	0	512	4242	35	2429
Cyprus	371	208	36	12	98	17	121
Czech Republic	2995	1700	1294	0	0	0	1114
Democratic People's Republic of Korea	2148	508	0	503	1117	20	722
Democratic Republic of the Congo	1461	0	0	1461	0	0	583
Denmark	7100	3976	3125	0	0	0	2199
Djibouti	362	12	0	0	121	229	150
Dominica	22	2	0	1	0	19	9
Dominican Republic	6780	722	0	354	4783	921	2543
Ecuador	9308	767	0	1024	7446	70	3654

Country	Total feed demand	Crop grain feed	Forage crop feed	Crop residue feed	Grazing feed	Scavenging and other feed	Manure carbon amount
Egypt	10569	6857	3712	0	0	0	4602
El Salvador	1733	407	0	261	1064	0	714
Equatorial Guinea	14	0	0	14	0	0	5
Eritrea	2167	0	0	62	1839	267	919
Estonia	515	234	7	26	248	0	196
Ethiopia	42530	589	1	3694	38153	95	18578
Falkland Islands (Malvinas)	128	0	0	0	128	0	46
Faroe Islands	14	0	0	0	0	14	5
Fiji	558	22	0	4	531	0	239
Finland	2024	1098	100	132	592	103	766
France	38713	13186	15419	2847	7261	0	14931
French Guiana	22	0	0	6	16	0	9
French Polynesia	28	5	0	0	0	23	10
Gabon	124	61	0	55	7	0	49
Gambia	366	25	0	72	269	0	157
Georgia	1888	176	7	57	1649	0	813
Germany	31855	15143	16712	0	0	0	11660
Ghana	2660	1666	0	995	0	0	1048
Greece	3856	1889	1615	174	177	1	1416
Greenland	4	0	0	0	0	4	1
Grenada	12	6	0	1	0	5	5
Guadeloupe	94	0	0	12	0	82	38
Guam	6	0	0	2	0	4	2
Guatemala	4631	541	0	866	3220	3	1939
Guinea	3831	304	0	956	2572	0	1693
Guinea-Bissau	600	19	0	71	511	0	262
Guyana	561	196	0	184	182	0	198
Haiti	2607	108	0	248	2251	0	1032
Honduras	3969	361	0	474	3041	93	1607
Hungary	2414	2414	0	0	0	0	974
Iceland	282	31	0	0	109	141	105
India	256559	21814	18137	145935	67209	3464	123008
Indonesia	39210	8876	0	30334	0	0	14734
Iran (Islamic Republic of)	24561	6126	4480	8019	5937	0	9049
Iraq	3419	943	255	692	1525	4	1399
Ireland	10902	1520	29	80	5968	3305	4431
Israel	1279	1271	0	8	0	0	457
Italy	17474	9119	8355	0	0	0	6516
Jamaica	519	138	0	41	339	0	194
Japan	11166	10058	1107	0	0	0	3959
Jordan	805	598	32	17	157	1	284
Kazakhstan	10250	1925	107	8218	0	0	4204
Kenya	20473	340	0	913	19219	1	8596
Kiribati	12	1	0	3	0	7	4
Kuwait	608	192	3	4	17	393	207
Kyrgyzstan	2393	543	27	700	1101	21	973
Lao People's Democratic Republic	3397	443	0	1766	1188	0	1506
Latvia	691	285	42	51	313	0	296
Lebanon	919	320	7	42	428	123	313
Lesotho	736	12	0	18	705	0	304
Liberia	216	23	0	147	46	0	81
Libya	1737	0	120	58	1134	425	629
Liechtenstein	12	0	0	0	0	12	5
Lithuania	1434	645	217	108	465	0	614
Luxembourg	310	59	232	7	12	0	126
Madagascar	7454	421	0	1388	5644	0	3327
Malawi	1583	1313	0	270	0	0	659
Malaysia	4254	2214	0	2040	0	0	1518
Mali	10629	423	0	1228	8978	0	4386
Malta	66	46	0	1	0	20	23
Martinique	34	0	0	4	0	30	13

Country	Total feed demand	Crop grain feed	Forage crop feed	Crop residue feed	Grazing feed	Scavenging and other feed	Manure carbon amount
Mauritania	4115	44	0	54	3954	62	1589
Mauritius	200	65	0	61	74	0	67
Mexico	57469	11901	7499	6605	31464	0	22099
Micronesia (Federated States of)	25	0	0	4	0	22	12
Mongolia	9079	69	3	43	8898	65	3405
Montenegro	196	33	11	0	152	0	84
Montserrat	14	0	0	0	0	14	6
Morocco	7920	1953	431	1382	4150	4	2969
Mozambique	2385	689	0	1307	389	0	951
Myanmar	20580	7786	716	12078	0	0	9065
Namibia	2240	28	0	21	2191	0	965
Nauru	0	0	0	0	0	0	0
Nepal	10246	773	15	3638	5796	23	4878
Netherlands	12064	6027	1681	68	2027	2261	4279
Netherlands Antilles	7	0	0	0	0	7	3
New Caledonia	138	9	0	0	129	0	59
New Zealand	19469	991	543	19	17739	177	8356
Nicaragua	5137	144	0	360	4619	13	2147
Niger	10712	557	0	1147	8019	990	4460
Nigeria	25469	13179	0	12290	0	0	10401
Niue	1	0	0	0	0	1	0
Norway	2221	691	51	38	777	665	847
Occupied Palestinian Territory	278	0	3	11	249	15	101
Oman	673	112	45	4	186	325	263
Pakistan	66662	3822	3	18271	20633	23933	30986
Panama	2273	269	0	130	1863	12	928
Papua New Guinea	402	0	0	30	372	0	184
Paraguay	13719	1128	5510	2778	4302	0	5741
Peru	14591	1765	946	1516	10358	6	5603
Philippines	11552	4326	208	7018	0	0	4439
Poland	12768	9023	3745	0	0	0	5384
Portugal	3717	1812	1905	0	0	0	1367
Puerto Rico	695	0	0	0	695	0	271
Qatar	210	0	0	0	9	200	73
Republic of Korea	8458	5691	15	685	2041	25	2880
Republic of Moldova	979	528	16	63	371	0	375
Réunion	286	0	0	28	258	0	95
Romania	7608	3784	3092	394	338	1	3078
Russian Federation	42127	16826	3963	21338	0	0	17475
Rwanda	1317	18	0	309	989	0	562
Saint Helena, Ascension and Tristan da Cunha	1	0	0	0	0	1	0
Saint Kitts and Nevis	10	0	0	0	0	9	4
Saint Lucia	26	1	0	0	0	24	10
Saint Pierre and Miquelon	1	0	0	0	0	1	0
Saint Vincent and the Grenadines	13	7	0	1	0	5	5
Samoa	75	2	0	0	0	73	34
Sao Tome and Principe	9	1	0	3	0	5	4
Saudi Arabia	4238	4111	127	0	0	0	1492
Senegal	4427	230	0	495	3702	0	1780
Serbia	2381	2062	319	0	0	0	1021
Seychelles	5	0	0	0	0	5	2
Sierra Leone	1030	311	0	622	96	0	384
Singapore	33	0	0	0	0	33	12
Slovakia	1197	684	513	0	0	0	445
Slovenia	851	236	217	11	387	0	330
Solomon Islands	28	3	0	4	21	0	13
Somalia	12104	0	0	71	12034	0	4688
South Africa	15942	3053	810	2505	9575	0	6519
South Sudan	12238	0	0	309	11928	0	5249
Spain	22435	12945	3542	806	5141	1	7460

Country	Total feed demand	Crop grain feed	Forage crop feed	Crop residue feed	Grazing feed	Scavenging and other feed	Manure carbon amount
Sri Lanka	1283	298	0	985	0	0	616
Sudan	33422	548	0	1469	31285	119	13978
Suriname	167	32	0	52	81	2	61
Sweden	2960	1526	0	196	1224	14	1145
Switzerland	3282	689	352	41	977	1224	1298
Syrian Arab Republic	3476	0	139	822	2477	39	1331
Tajikistan	2613	541	153	540	1334	45	1120
Thailand	12456	7170	74	5211	0	0	4958
Timor-Leste	387	11	0	76	300	0	167
Togo	1045	88	0	325	632	0	398
Tokelau	0	0	0	0	0	0	0
Tonga	41	0	0	8	0	33	17
Trinidad and Tobago	629	61	0	16	137	416	212
Tunisia	3257	1093	0	355	1738	72	1180
Turkey	20355	6615	2494	6298	4943	6	8368
Turkmenistan	4606	690	91	639	2224	962	1864
Tuvalu	2	0	0	0	0	2	1
Uganda	10107	459	0	1218	8430	0	4432
Ukraine	12014	8824	1885	1305	0	0	4996
United Arab Emirates	1044	624	276	0	43	100	375
United Kingdom	23729	7252	1086	979	14059	352	9174
United Republic of Tanzania	16705	941	0	2615	13149	0	7402
United States of America	204402	77982	86122	7184	32723	391	72272
United States Virgin Islands	12	0	0	0	0	12	5
Uruguay	14733	524	0	1145	13064	0	6118
Uzbekistan	11376	2173	380	3292	4879	651	4907
Vanuatu	235	3	0	1	122	110	108
Venezuela (Bolivarian Republic of)	21237	1824	0	915	18457	41	8783
Viet Nam	15583	5932	28	9622	0	0	6687
Wallis and Futuna Islands	5	0	0	0	0	5	2
Western Sahara	120	0	0	0	0	120	43
Yemen	4370	283	496	157	3255	178	1660
Zambia	2742	161	0	586	1995	0	1185
Zimbabwe	4555	198	0	282	4075	0	2002

Suppl. Table 6. Dry matter fraction, carbon fraction of dry matter, calorie and protein fraction of different commodities

Item	Dry matter fraction	Carbon fraction of dry matter	Calorie (kcal/kg)	Protein fraction
Beef	0.46	0.60	1500	0.19
Cow milk	0.12	0.51	610	0.03
Buffalo meat	0.46	0.60	770	0.11
Buffalo milk	0.12	0.51	970	0.04
Sheep meat	0.46	0.60	1190	0.13
Goat meat	0.46	0.60	1230	0.14
Pork	0.55	0.60	3260	0.12
Hen egg	0.24	0.60	1390	0.11
Chicken meat	0.29	0.60	1220	0.12
Duck meat	0.29	0.60	2910	0.08
Turkey meat	0.29	0.60	1260	0.16
Geese meat	0.29	0.60	3010	0.13
Horse meat	0.46	0.60	850	1.12
Camel meat	0.46	0.60	1740	0.13
Mule meat	0.46	0.60	940	0.15
Camelid meat	0.46	0.60	1430	0.15
Maize and products	0.86	0.46	3560	0.10
Soybean Cake	0.88	0.55	2610	0.46
Brans	0.86	0.46	2445	0.13
Wheat and products	0.87	0.46	3340	0.12
Barley and products	0.87	0.46	3320	0.12
Cassava and products	0.88	0.44	1090	0.01
Rice (Paddy Equivalent)	0.91	0.46	2800	0.06
Vegetables, Other	0.16	0.41	380	0.01
Potatoes and products	0.20	0.41	670	0.02
Sweet potatoes	0.20	0.41	920	0.01
Rape and Mustard Cake	0.89	0.55	4231	0.33
Sugar cane	0.26	0.41	300	0.00
Sorghum and products	0.86	0.46	3430	0.10
Cereals, Other	0.92	0.46	3400	0.08
Oats	0.87	0.46	3850	0.13
Molasses	0.75	0.45	2320	0.00
Sunflowerseed Cake	0.89	0.55	4127	0.29
Soyabeans	0.88	0.52	3350	0.38
Cottonseed Cake	0.91	0.55	4345	0.12
Sugar beet	0.15	0.41	700	0.01
Oilseed Cakes, Other	0.88	0.55	3870	0.15
Cottonseed	0.90	0.62	2530	0.17
Groundnut Cake	0.90	0.54	3630	0.42
Yams	0.20	0.41	1010	0.01
Pulses, Other and products	0.77	0.46	3400	0.22
Rye and products	0.90	0.46	3190	0.12
Palm kernel Cake	0.91	0.55	4381	0.15
Rape and Mustard seed	0.93	0.62	4815	0.22
Millet and products	0.89	0.46	3400	0.10
Peas	0.87	0.46	3460	0.23
Beans	0.84	0.46	3410	0.22
Sunflower seed	0.91	0.62	3080	0.12
Oil crops, Other	0.92	0.61	3870	0.15
Copra Cake	0.92	0.55	4396	0.20
Tomatoes and products	0.05	0.41	170	0.01
Bananas	0.26	0.41	600	0.01

Sesameseed Cake	0.93	0.55	3760	0.41
Plantains	0.35	0.41	750	0.01
Roots, Other	0.20	0.41	910	0.02
Rape and Mustard Oil	1.00	0.77	8840	0.00
Apples and products	0.20	0.41	480	0.00
Sugar non-centrifugal	0.97	0.42	3510	0.01
Dates	0.77	0.41	1560	0.02
Onions	0.10	0.41	240	0.02
Fruits, Other	0.23	0.41	450	0.01
Sugar, Refined Equiv	0.99	0.42	3870	0.00
Coconuts - Incl Copra	0.20	0.63	1840	0.02
Sweeteners, Other	0.70	0.41	3100	0.00
Soyabean Oil	1.00	0.77	8840	0.00
Oranges, Mandarines	0.20	0.41	340	0.01
Cocoa Beans and products	1.00	0.41	4140	0.04
Sesame seed	0.95	0.62	5730	0.18
Groundnuts (Shelled Eq)	0.91	0.60	4140	0.19
Oilcrops Oil, Other	1.00	0.77	8840	0.00
Olive Oil	1.00	0.77	8840	0.00
Palm kernels	0.30	0.62	5140	0.07
Olives (including preserved)	0.30	0.62	8840	0.00
Sesameseed Oil	1.00	0.77	8840	0.00
Palm Oil	1.00	0.77	8840	0.00
Cloves	1.00	0.41	3230	0.06
alfalfa	0.35	0.44	1506	0.06
beetfor	0.15	0.41	563	0.02
cabbagefor	0.08	0.41	333	0.02
carrotfor	0.13	0.41	500	0.02
clover	0.35	0.44	1531	0.09
fornes	0.35	0.44	1456	0.07
grassnes	0.35	0.44	1456	0.07
legumenes	0.35	0.44	1581	0.08
maizefor	0.35	0.44	1581	0.03
oilseedfor	0.35	0.44	1456	0.07
ryefor	0.35	0.44	1489	0.05
sorghumfor	0.35	0.44	1514	0.03
swedefor	0.13	0.41	541	0.03
turnipfor	0.13	0.41	541	0.03
vegfor	0.13	0.41	541	0.03
Crop residuefeed	0.91	0.44	3,371	0.04
Grazing feed			2,765 (dry matter)	0.19 (fraction of dry matter)
Scavenging and other feed			4,318 (dry matter)	0.19 (fraction of dry matter)

Suppl. Table 7. Comparison between the livestock feed biomass estimation. Values are expressed in Tg C/yr, and numbers in bracket are percentage of total feed biomass in bracket.

<table>
<tr><th>Biomass</th><th>This study</th><th>IPCC AR5/ Smith, et al. [57]*</th><th>Wolf, et al. [47]</th><th>Wolf, et al. [58]</th><th>Krausmann, et al. [11]*</th><th>Herrero, et al. [59]*</th><th>GLEAM [60]*</th></tr>
<tr><td>Year</td><td>Circa 2010</td><td>2000</td><td>2009</td><td>2011</td><td>2000</td><td>2000</td><td>2010</td></tr>
<tr><td>Crop grain</td><td>562 (23%)</td><td rowspan="3">1382 (45%)</td><td>391 (16%)</td><td>493 (17%)</td><td>396 (13%)</td><td>572 (28%)</td><td>634 (24%)</td></tr>
<tr><td>Forage</td><td>289 (12%)</td><td>237 (10%)</td><td>217 (7%)</td><td rowspan="2">1,012 (33%)</td><td>252 (12%)</td><td>211 (8%)</td></tr>
<tr><td>Crop residue</td><td>523 (21%)</td><td>492 (20%)</td><td>537 (19%)</td><td>246 (12%)</td><td>502 (19%)</td></tr>
<tr><td>Grazing feed</td><td>1,028 (42%)</td><td>1,703 (55%)</td><td>1,308 (54%)</td><td>1,650 (57%)</td><td>1,687 (55%)</td><td>995 (48%)</td><td>1,214 (46%)</td></tr>
<tr><td>Scavenging and others</td><td>48 (2%)</td><td></td><td></td><td></td><td></td><td></td><td>79 (3%)</td></tr>
<tr><td>Sum</td><td>2,450</td><td>3,085</td><td>2,428</td><td>2,897</td><td>3,095</td><td>2,065</td><td>2,640</td></tr>
</table>

* assume 0.44 carbon content of dry matter

Suppl. Table 8. Comparison of GHG emissions from different sub-sectors (unit: Tg CO_2 eq/yr)

GHG emission	Gas	This study (Circa 2010)	IPCC AR5 WG3[26] (2010)	FAOSTAT[55] (2010)	IPCC SRCCL[52] (Mean of 2007-2016)	Carlson et al.[61] (circa 2000)	EDGAR v4.3.2[62] (2010)	Poore and Nemecek [45] (Circa 2010)
Beyond farm gate emissions		**2,123**			**3,900 (2,600 – 5,200)**			**2,420**
Mining, manufacturing, and transporting agricultural materials	CO_2	666			3,900 (2,600 – 5,200)			
Food processing and transportation emission	CO_2	1,457						1,400
Farmland emissions		**6,493 ± 1,896**	**5,400 (5,000 – 5,800)** combined farmland and livestock emissions	**3,908**	**6,200 ± 1,400** combined farmland and livestock emissions	**1,365 ± 2,171**	**2,718**	**3,680**
Fuel and energy use emissions	CO_2	169		848				
Farmland CO_2 emissions	CO_2	3,084 ± 181		697 †				
Rice cultivation	CH_4	1,274 ± 1,812		794		962 ± 2,170	1,258 (total agricultural soil emission)	1,108
Synthetic fertilizers and manure for all crops and grazing land	N_2O	1,969 ± 373		1,569		403 ± 74 (only for cropland)	1,460 (total agricultural soil emission)	
Livestock emissions‡		**3,608 ± 836**		**3,675**			**3,909**	**4,140**
Enteric Fermentation	CH_4	3,160 ± 827 (calculated from FAOSTAT [55])		3,223			3,400	
Manure Management	CH_4	317 ± 49 (calculated from FAOSTAT [55])		321			408	
	N_2O	130 ± 108 (calculated from FAOSTAT [55])		131			101	
LUC emissions		**5,096 ± 301**	**4,900 (4,300–5,500)**	**1,529**	**4,900 ± 2,500**	**630 ± 90 ***		**2,380**
Total		**17,318 ± 1,675**	**11,000 (10,000 – 12,000**	**9,119** #	**14,950 (10,800 – 19,100)**	**1,994 ± 2,172**	**6,627**	**13,700** #

* only GHG emissions due to peatland drainage for cropland

The total values of FAOSTAT [55] and Poore and Nemecek [45] are sums of all subsectors of agriculture and land-use emissions. We have not listed all subsectors of these two studies in this table. We use the 100-year GWP values in IPCC AR5 to recalculates all these values.

† This value is part of land use emission in FAOSTAT.

‡ Livestock emissions exclude emissions from feed production.

Suppl. Table 9. By-product allocation parameters of different crops, and processing emission factors

Commodity name	Products	Mass share of products	Energy (kcal/tonne)	Water content	Emission share	Processing GHG emission factor
Rice	Milled rice	0.67	3600000	0.09	0.87	0.109
	Rice bran	0.08	4409656	0.10	0.13	0.170
Rice bran	Rice bran oil	0.14	8840000	0.00	0.30	0.397
	Cake of rice bran	0.80	3616157	0.11	0.70	0.170
Wheat	Wheat flour	0.79	3640000	0.11	0.80	0.076
	Wheat bran	0.18	3929971	0.13	0.20	0.310
Barley	Pot barley	0.72	3480000	0.10	0.77	0.016
	Barley bran	0.19	3830402	0.13	0.23	0.055
Maize	Flour of maize	0.82	3630000	0.13	0.81	0.045
	Maize bran	0.11	3921965	0.11	0.12	0.382
	Maize germ	0.06	4729732	0.04	0.08	0.321
Maize germ	Maize oil	0.45	8840000	0.00	0.65	0.838
	Maize cake	0.52	4087357	0.12	0.35	0.045
Rye	Flour of rye	0.80	3410000	0.10	0.80	0.082
	Bran of rye	0.17	3891013	0.12	0.20	0.338
Oat	Oats rolled	0.53	3840000	0.08	0.70	0.063
	Oat offals	0.20	4287476	0.09	0.30	0.057
Millet	Flour of millet	0.86	3400000	0.05	0.88	0.109
	Bran of millet	0.10	3929971	0.13	0.12	0.170
Sorghum	Flour of sorghum	0.90	3430000	0.13	0.91	0.048
	Bran of sorghum	0.08	4043977	0.10	0.09	0.459
Coconut (incl. Copra)	Coconut oil	0.61	1840000	0.00	0.41	0.168
	Cake of copra	0.36	4395674	0.09	0.59	0.069
Cotton	Cottonseed	0.63	2530000	0.00	1.00	0.090
	Cotton lint	0.35	0	0.00	0.00	0.162
Cottonseed	Cottonseed oil	0.16	8840000	0.00	0.39	0.285
	Cottonseed cake	0.51	4345124	0.09	0.61	0.182
Groundnut (shelled eq.)	Oil of groundnuts	0.43	8840000	0.00	0.62	0.048
	Cake of groundnuts	0.54	4321224	0.10	0.38	0.019
Oilcrop, other	Oil of oilcrop, other	0.18	8840000	0.00	0.33	0.038
	Cake of oilcrop, other	0.79	4138695	0.12	0.67	0.096
Soybean	Oil of soyabeans	0.18	8840000	0.00	0.33	0.038
	Cake of soyabeans	0.79	4138695	0.12	0.67	0.096
Olive	Oil of olives	0.20	8840000	0.00	0.50	0.014
	Olive residues	0.40	4359847	0.12	0.50	0.009
	Palm kernel	0.19	5140000	0.70	0.77	0.009

Commodity name	Products	Mass share of products	Energy (kcal/tonne)	Water content	Emission share	Processing GHG emission factor
Oil palm fruit	Oil of palm	0.06	4971319	0.00	0.23	0.014
Palm kernel	Oil of palm kernels	0.46	8840000	0.00	0.64	0.207
	Cakes of palm kernels	0.52	4381262	0.09	0.36	0.074
Rape and mustard seed	Oil of repeseed	0.38	8840000	0.00	0.56	0.146
	Cake of rapeseed	0.60	4337524	0.11	0.44	0.055
Sesame	Oil of sesame seed	0.43	8840000	0.00	0.62	0.048
	Cake of sesame seed	0.51	4569025	0.07	0.38	0.019
Sunflower seed	Oil of sunflower seed	0.41	8840000	0.00	0.65	0.097
	Cake of sunflower seed	0.47	4126673	0.11	0.35	0.026
Sugarcane	Raw centirifugal cane sugar	0.11	3730000	0.00	0.46	0.564
	Sugar cane molasses	0.05	2564771	0.27	0.15	0.388
	Non centrifugal sugar	0.09	3830000	0.00	0.39	0.580
Sugarbeet	Raw centirifugal beet sugar	0.14	3730000	0.00	0.82	0.232
	Beet molasses	0.04	2793260	0.25	0.18	0.162

Suppl. Table 10. Emission factors of different transportation mode [18,19]

Transport mode	**Emission factors (kgCO_2 eq /tonne-km)**
Road transport	0.062
Rail	0.022
Short sea	0.016
Deep-sea	0.008
Air freight	0.602
Pipeline	0.005

Suppl. Table 11. Estimated transportation emission factors of different commodities

Commodity	Weighted average distance (km)	Transporting emission factor ($kgCO_2$ eq /kg)
Fertilizers	1,111	0.0192
Pesticides	719	0.0254
Leguminous crops and oilseeds	1,393	0.0225
Cereal grains	1,257	0.018
Vegetables and melons, roots and tubers	1,284	0.0313
Cocoa, and cocoa preparations	564	0.0308
Vegetable and animal oils and fats	697	0.0225
Other food products n.e.c.	946	0.0292
Animal feed	533	0.0116
Other annual crops	699	0.0147
Sugar crops	601	0.0228
Dairy products	292	0.0139
Meat	658	0.0287

Suppl. Table 12. Uncertainty ranges and probability distribution functions of major GHG emission sub-sectors

Variable	Considered uncertainty sources	Mean (normal distribution) or median (lognormal distribution)	95% confidence interval	Unit	probability distribution functions	Reference
Farmland N_2O emission	Variations in emission factors of N_2O from Nitrogen fertilizers	0.0125	-80% ~ +380%	kg N_2O-N / kg N	Lognormal distribution [63]	IPCC [23] and references therein
Farmland CH_4 emission	Variations in Emission rates of CH4 from rice	1.3	–38.5% ~ +69.2%	kg CH_4 ha^{-1} d^{-1}	Lognormal distribution[64]	IPCC [23] and references therein
E_{farm} CO_2 emission + E_{luc}	Differences in the LULUC datasets	1.63	-11% ~ +11%	Pg C yr^{-1}	Normal distribution [65]	Meiyappan, et al. [43]
E_{live} enteric fermentation emissions	CH_4 emission factor	1 ~ 128 (Vary with animals and regions)	-50% ~ +50%	kg CH_4 $head^{-1}$ yr^{-1}	Normal distribution [64]	IPCC [23] and references therein
E_{live} manure management emissions	CH_4 emission factor	0.01 ~ 48 (Vary with different animals and regions)	-30% ~ +30%	kg CH_4 $head^{-1}$ yr^{-1}	Normal distribution [64]	IPCC [23] and references therein
	Direct N_2O emission factor	0.005 ~ 0.0228 (Vary with different animals and regions)	–50% ~ +100%	kg N_2O-N (kg Nitrogen $excreted)^{-1}$	Lognormal distribution [64]	IPCC [23] and references therein

Suppl. Table 13. Residue biomass carbon of different crops and crop residue feed (Tg C/yr) in nine regions

	NA	SA	EU	MENA	SSA	CIS	CM	SSEA	OC	*World*
Maize	57	49	13	2	37	15	36	22	1	*233*
Millet	0	0	0	0	10	1	1	7	0	*20*
Sorghum	3	4	0	0	17	0	1	8	0	*34*
Sugarcane	2	36	0	0	4	0	4	24	1	*71*
Soybean	57	42	1	0	1	1	15	8	1	*126*
Barley	6	1	15	5	1	20	1	0	3	*52*
Cassava	0	18	0	0	68	0	1	14	0	*102*
Groundnut	1	1	0	0	10	0	6	8	0	*27*
Potato	1	1	3	0	1	12	5	1	0	*26*
Pulses	0	0	0	0	0	0	0	0	0	*1*
Rapeseed	9	0	13	0	0	5	10	8	3	*47*
Rice	4	22	1	2	18	0	64	209	13	*334*
Rye	0	0	2	0	0	9	0	0	0	*12*
Sugar beet	1	0	6	1	0	8	1	0	0	*19*
Sunflower	2	9	4	1	1	22	2	3	0	*45*
Wheat	60	19	54	28	4	94	37	40	19	*354*
Other crops	145	220	64	23	204	145	35	113	45	*994*
Sum	349	422	178	64	376	334	220	466	87	2,495
Recovered crop residue	267	293	133	50	271	253	167	340	65	1,840
Crop residue feed *	9 (2.6%)	84 (19.9%)	6 (3.4%)	21 (32.8%)	44 (11.7%)	38 (11.4%)	57 (25.9%)	262 (56.2%)	2 (2.3%)	*523 (21.0%)*

* Numbers in brackets are % of crop residue feed to total crop residue in each region.

Suppl. Table 14. Comparison of ISAM simulation and FAOSTAT productions for major crops (unit: million tonnes)

	NA		**SA**		**EU**		**MENA**		**SSA**		**CIS**		**CM**		**SSEA**		**OC**		**World**	
	FAO	ISAM	FAO	ISAM	FAO	ISAM	FAO	ISAM	FAO	ISAM	FAO	ISAM	FAO	ISAM	FAO	ISAM	FAO	ISAM	FAO	ISAM
Maize	329	217	121	172	47	40	14	8	55	161	48	61	182	163	64	88	2	3	867	917
Millet	0	0	0	0	0	0	0	0	14	23	0	1	1	2	12	14	0	0	29	42
Sorghum	9	5	13	10	0	0	1	0	23	45	0	0	2	1	7	13	2	1	60	79
Sugarcane	26	19	918	983	0	0	21	5	69	70	0	0	118	105	557	388	32	15	1745	1588
Soybean	89	107	122	132	1	1	0	0	1	3	3	7	13	26	13	19	0	1	245	299
Barley	13	11	4	4	48	38	16	19	2	2	40	48	2	1	1	1	8	8	138	136
Cassava	0	0	33	25	0	0	0	0	134	148	0	0	4	2	75	29	0	0	248	206
Groundnut	2	1	1	1	0	0	0	0	11	18	0	0	15	9	10	9	0	0	41	40
Potato	24	16	17	15	46	31	21	8	14	20	82	111	81	95	52	32	6	6	346	337
Pulses	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	0	0	3	4
Rapeseed	14	11	0	0	14	15	0	0	0	0	9	12	13	9	7	7	2	2	61	59
Rice	9	6	26	32	2	2	9	4	19	42	1	1	196	134	416	408	21	21	705	653
Rye	0	0	0	0	4	4	0	0	0	0	8	13	0	0	0	0	0	0	15	19
Sugar beet	29	15	1	0	99	60	30	14	0	0	72	71	9	6	0	0	3	3	246	172
Sunflower	1	1	3	3	3	3	1	0	1	2	19	22	2	1	1	1	0	0	35	37
Wheat	86	107	25	31	108	100	59	72	6	8	133	196	116	69	110	85	22	39	670	710

Suppl. Table 15. GHG emissions in all subsectors by nine regions (unit: Tg CO_2 eq/yr)

	NA	**SA**	**EU**	**MENA**	**SSA**	**CIS**	**CM**	**SSEA**	**OC**	**World**
E_{bfg}										
Mining and manufacturing of	***64***	***49***	***45***	***30***	***31***	***49***	***187***	***194***	***14***	***664***
• NPK fertilizers*	53	30	37	27	30	45	138	189	11	561
• Pesticides	11	19	8	3	1	4	49	5	3	103
Transportation of NPK fertilizers and pesticides	0	0	0	0	0	0	1	1	0	2
Products processing	245	446	164	94	95	50	57	120	26	1,457
E_{luc}										
E_{luc} from cropland	***533***	***1170***	***161***	***40***	***894***	***379***	***230***	***1058***	***141***	***4,606***
• Product pool	93	741	66	2	589	98	82	872	30	2,573
• Soil disturbance #	440	429	95	38	305	281	148	186	111	2,033
E_{luc} from grazing land	***39***	***335***	***3***	***1***	***37***	***23***	***44***	***0***	***6***	***488***
•·Product pool	24	260	1	1	34	11	12	0	5	348
•·Soil disturbance #	15	75	2	0	3	12	32	0	1	140
E_{farm}										
Farmland fuel and energy use emissions	30	9	10	10	29	26	8	44	2	169
E_{f_CO2}‡	***718***	***878***	***422***	***82***	***10***	***409***	***344***	***32***	***187***	***3,082***
• *GPP †*	10,852	29,072	4,271	2,040	30,175	8,282	7,931	9,976	9,051	111,655
• $R_a + R_h$	9,250	26,230	3,268	1,513	27,425	6,815	5,925	6,493	8,546	95,466
• E_{t_CO2}	13	22	20	7	30	45	37	16	14	204
• E_{h_CO2}	2,234	3,581	1,365	587	2,635	1,758	2,265	3,385	660	18,473
• E_{w_CO2}	73	117	40	15	95	73	48	114	18	594
Farmland CH_4 emissions	5	17	1	1	41	0	250	933	28	1,276
Farmland N_2O emissions	159	222	84	113	260	56	394	549	129	1,967
E_{lived}										
Enteric fermentation CH_4	228	832	229	113	454	179	251	743	131	3,160
Manure management CH_4	53	21	62	6	17	28	42	74	14	317
Manure management N_2O	16	10	19	2	6	15	37	21	5	131
Consumption-based emissions										
Transportation of food commodities	16	83	30	13	22	12	4	12	10	202
Import	257	287	1,201	355	82	260	147	217	246	3,052
Export	653	603	828	67	45	259	49	587	283	3,373
Stock variation	-11	6	-14	47	-4	1	-29	-36	3	-38

* N, P, K represent nitrogen, phosphorus, and potassium fertilizers

\# Only refer to the soil disturbance emissions caused by land-use change

† GPP of crop and grazing land

‡ Farmland CO_2 emissions are calculated based on Eq. 1 in the main text.

Suppl. Table 16. Components of emissions due to harvesting biomass and the livestock feed balance (unit: Tg C/yr)

	NA	**SA**	**EU**	**MENA**	**SSA**	**CIS**	**CM**	**SSEA**	**OC**	**World**
E_{food_C}	154	253	183	224	348	161	660	964	103	3,051
E_{other_C}	1,241	1,260	448	-14	1,216	1,109	267	694	216	6,439
E_{feed_C}	840	2,068	733	378	1,071	488	1,338	1,727	341	8,983
•E_{ef_C} *	18	67	19	9	37	14	20	60	11	256
•E_{prod_C}	25	20	32	11	7	24	21	39	10	189
•E_{manure_C}	297	840	271	147	451	202	480	792	139	3,619
•E_{res}	500	1,141	411	211	576	247	817	835	181	4,920
Sum (E_{h_CO2})	2,234	3,581	1,365	587	2,635	1,758	2,265	3,385	660	18,473

* Carbon embedded in the CH_4 emitted through enteric fermentation, here converted to CO_2

Suppl. Table 17. Feed of monogastric and ruminant animals in different regions (unit: Tg C/yr)

Livestock types	**Feed categories**	**NA**	**SA**	**EU**	**MENA**	**SSA**	**CIS**	**CM**	**SSEA**	**OC**	**World**
Monogastric animals	Crop grain	33	57	19	17	14	14	116	42	14	325
	Other forage	57	14	42	8	1	17	0	0	2	140
	Grazing feed	0	29	0	4	8	0	99	0	1	142
	Crop residue	0	0	0	0	1	0	0	16	0	17
	Scavenging	3	2	5	2	1	1	1	8	0	23
	Sum	94	102	66	31	24	32	216	66	17	648
Ruminant animals	Crop grain	55	5	66	17	17	43	0	25	8	236
	Grazing feed	40	310	41	28	206	18	83	95	63	886
	Crop residue	9	84	6	21	43	38	57	246	2	507
	Scavenging	0	0	3	1	1	1	0	20	0	26
	Grass forage	31	19	33	3	0	3	9	19	6	122
	Other forage	0	3	12	7	0	5	0	0	0	27
	Sum	135	462	134	72	268	102	149	405	75	1,803

Supplementary References

1 Meiyappan, P. & Jain, A. K. Three distinct global estimates of historical land-cover change and land-use conversions for over 200 years. *Front Earth Sci-Prc* **6**, 122-139, doi:10.1007/s11707-012-0314-2 (2012).

2 Klein Goldewijk, K., Beusen, A., Doelman, J. & Stehfest, E. Anthropogenic land use estimates for the Holocene – HYDE 3.2. *Earth Syst. Sci. Data* **9**, 927-953, doi:10.5194/essd-9-927-2017 (2017).

3 FAO. FAOSTAT Land Use Domain. *available at: http://fenixservices.fao.org/faostat/static/documents/RL/RL_EN.pdf [Accessed: Apr,2, 2021]* (2020).

4 Crawford, I. *Agricultural and food marketing management*. (Food and Agriculture Organization of the United Nations Rome, 1997).

5 Song, Y., Jain, A. K. & McIsaac, G. F. Implementation of dynamic crop growth processes into a land surface model: evaluation of energy, water and carbon fluxes under corn and soybean rotation. (vol 10, pg 8039-8066, 2013). *Biogeosciences* **10**, 8201-8201, doi:DOI 10.5194/bg-10-8201-2013 (2013).

6 Song, Y. *et al.* The Interplay Between Bioenergy Grass Production and Water Resources in the United States of America. *Environ Sci Technol* **50**, 3010-3019, doi:10.1021/acs.est.5b05239 (2016).

7 Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochem Cy* **22**, doi:10.1029/2007gb002947 (2008).

8 FAO. FAOSTAT Online Database. *Accessed at http://www.fao.org/faostat/en/#data [7/19/2019]*, (2019).

9 Hurtt, G. C. *et al.* Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic Change* **109**, 117-161, doi:10.1007/s10584-011-0153-2 (2011).

10 Goldewijk, K. K., Beusen, A., Doelman, J. & Stehfest, E. Anthropogenic land use estimates for the Holocene - HYDE 3.2. *Earth Syst Sci Data* **9**, 927-953 (2017).

11 Krausmann, F., Erb, K. H., Gingrich, S., Lauk, C. & Haberl, H. Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecol Econ* **65**, 471-487, doi:10.1016/j.ecolecon.2007.07.012 (2008).

12 Gilbert, M. *et al.* Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Sci Data* **5**, 180227, doi:10.1038/sdata.2018.227 (2018).

13 FAO. Food Balance, FAOSTAT Online Database. *Accessed at http://www.fao.org/faostat/en/#data [7/19/2019]*, (2019).

14 Xu, R. T. *et al.* Increased nitrogen enrichment and shifted patterns in the world's grassland: 1860-2016. *Earth Syst Sci Data* **11**, 175-187 (2019).

15 Kool, A., Marinussen, M. & Blonk, H. LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization. *GHG Emissions of N, P and K fertiliser production* (2012).

16 Searchinger, T. D., Wirsenius, S., Beringer, T. & Dumas, P. Assessing the efficiency of changes in land use for mitigating climate change. *Nature* **564**, 249-253, doi:10.1038/s41586-018-0757-z (2018).

17 EPA. Life-Cycle Analysis of Greenhouse Gas Emissions from Renewable Fuels. (2010).

18 Kinnon, A. Guidelines for Measuring and Managing CO2 Emission from Freight Transport Operations. *The European Chemical Industry Council* (2011).

19 Borken-Kleefeld, J. & Weidema, B. Global default data for freight transport per product group. *Manuscript for special ecoinvent* **3** (2013).

20 FAO. Emissions - Agriculture, FAOSTAT Online Database. *Accessed at http://www.fao.org/faostat/en/#data [7/19/2019]*, (2019).

21 Tubiello, F. Greenhouse Gas Emissions Due to Agriculture. In: Ferranti, P., Berry, E.M., Anderson, J.R. (Eds.), *Encyclopedia of Food Security and Sustainability*, vol. 1, pp. 196–205. Elsevier. ISBN: 9780128126875., doi:10.1016/B978-0-08-100596-5.21996-3 (2019).
22 Tubiello, F. N. *et al.* Carbon Emissions and Removals by Forests: New Estimates 1990-2020. *Earth Syst. Sci. Data Discuss.* **2020**, 1-21, doi:10.5194/essd-2020-203 (2020).
23 IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. (Institute for Global Environmental Strategies, 2006).
24 Yevich, R. & Logan, J. A. An assessment of biofuel use and burning of agricultural waste in the developing world. *Global Biogeochem Cy* **17**, doi:10.1029/2002gb001952 (2003).
25 Jain, A. K., West, T. O., Yang, X. & Post, W. M. Assessing the impact of changes in climate and CO2 on potential carbon sequestration in agricultural soils. *Geophys Res Lett* **32**, doi:https://doi.org/10.1029/2005GL023922 (2005).
26 IPCC. *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2014).
27 Xu, X. & Lan, Y. A comparative study on carbon footprints between plant- and animal-based foods in China. *J Clean Prod* **112**, 2581-2592, doi:10.1016/j.jclepro.2015.10.059 (2016).
28 Lin, T. S., Song, Y., Jain, A. K., Lawrence, P. & Kheshgi, H. S. Effects of environmental and management factors on worldwide maize and soybean yields over the 20th and 21st centuries. *Biogeosciences Discuss.* **2020**, 1-25, doi:10.5194/bg-2020-68 (2020).
29 Yang, X. J., Wittig, V., Jain, A. K. & Post, W. Integration of nitrogen cycle dynamics into the Integrated Science Assessment Model for the study of terrestrial ecosystem responses to global change. *Global Biogeochem Cy* **23**, doi:10.1029/2009gb003474 (2009).
30 Zhang, B. *et al.* Global manure nitrogen production and application in cropland during 1860–2014: a 5 arcmin gridded global dataset for Earth system modeling. *Earth Syst Sci Data* **9**, 667-678, doi:10.5194/essd-9-667-2017 (2017).
31 Xu, R. *et al.* Increased nitrogen enrichment and shifted patterns in the world's grassland: 1860–2016. *Earth Syst Sci Data* **11**, 175-187, doi:10.5194/essd-11-175-2019 (2019).
32 Lamarque, J. F. *et al.* Multi-model mean nitrogen and sulfur deposition from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP): evaluation of historical and projected future changes. *Atmos Chem Phys* **13**, 7997-8018, doi:10.5194/acp-13-7997-2013 (2013).
33 Shu, S., Jain, A. & Kheshgi, H. Estimates of global nitrous oxide (N2O) emissions from contemporary and future soils. AGU 2018 Fall Meeting. 10-14 December 2018. Washington, DC, USA. (2018).
34 Gahlot, S. *et al.* Impact of environmental changes and land management practices on wheat production in India. *Earth Syst. Dynam.* **11**, 641-652, doi:10.5194/esd-11-641-2020 (2020).
35 Portmann, F. T., Siebert, S. & Döll, P. MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochem Cy* **24**, doi:https://doi.org/10.1029/2008GB003435 (2010).
36 Schroeder, R. *et al.* Development and evaluation of a multi-year fractional surface water data set derived from active/passive microwave remote sensing data. *Remote Sens-Basel* **7**, 16688-16732 (2015).
37 Shu, S., Jain, A. K. & Kheshgi, H. S. Investigating Wetland and Nonwetland Soil Methane Emissions and Sinks Across the Contiguous United States Using a Land Surface Model. *Global Biogeochem Cy* **34**, e2019GB006251, doi:https://doi.org/10.1029/2019GB006251 (2020).
38 Lin, T.-S. & Jain, A. Studying the Impacts of Environmental Factors and Agricultural Management Practices on Methane Emissions from Rice Fields Using a Land Surface Model. Asia Oceanic Geosciences Society (AOGS) Meeting. Honolulu, Hawaii, June 3-8, 2018. (2018).
39 Mueller, N. D. *et al.* Closing yield gaps through nutrient and water management. *Nature* **490**, 254-257, doi:10.1038/nature11420 (2012).

40 West, P. C. *et al.* Leverage points for improving global food security and the environment. *Science* **345**, 325-328, doi:10.1126/science.1246067 (2014).
41 Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J. & Garnier, J. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environ Res Lett* **9**, doi:10.1088/1748-9326/9/10/105011 (2014).
42 Liu, J. G. *et al.* A high-resolution assessment on global nitrogen flows in cropland. *Proc Natl Acad Sci U S A* **107**, 8035-8040, doi:10.1073/pnas.0913658107 (2010).
43 Meiyappan, P., Jain, A. K. & House, J. I. Increased influence of nitrogen limitation on CO2 emissions from future land use and land use change. *Global Biogeochem Cy* **29**, 1524-1548, doi:10.1002/2015gb005086 (2015).
44 Hurtt, G. C. *et al.* Harmonization of Global Land-Use Change and Management for the Period 850-2100 (LUH2) for CMIP6. *Geosci. Model Dev. Discuss.* **2020**, 1-65, doi:10.5194/gmd-2019-360 (2020).
45 Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987-992, doi:10.1126/science.aaq0216 (2018).
46 Foley, J. A. *et al.* Solutions for a cultivated planet. *Nature* **478**, 337-342, doi:10.1038/nature10452 (2011).
47 Wolf, J. *et al.* Biogenic carbon fluxes from global agricultural production and consumption. *Global Biogeochem Cy* **29**, 1617-1639, doi:10.1002/2015gb005119 (2015).
48 Feedipedia. (2020).
49 FAO. Nutritive Factors. *http://www.fao.org/economic/the-statistics-division-ess/publications-studies/publications/nutritive-factors/en/[Accessed: July 15, 2020]* (2020).
50 Eshel, G., Shepon, A., Makov, T. & Milo, R. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. *Proceedings of the National Academy of Sciences* **111**, 11996-12001, doi:10.1073/pnas.1402183111 (2014).
51 Fung, L., Urriola, P. E., Baker, L. & Shurson, G. C. Estimated energy and nutrient composition of different sources of food waste and their potential for use in sustainable swine feeding programs. *Translational Animal Science* **3**, 359-368, doi:10.1093/tas/txy099 (2018).
52 Mbow, C. *et al.* Food Security. *In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, et al (eds.)]. In press.* (2019).
53 Friedlingstein, P. *et al.* Global carbon budget 2019. *Earth Syst Sci Data* **11**, 1783-1838 (2019).
54 FAO. *Five practical actions towards low-carbon livestock. Rome*. (2019).
55 Tubiello, F. N. *et al.* The FAOSTAT database of greenhouse gas emissions from agriculture. *Environ Res Lett* **8**, doi:10.1088/1748-9326/8/1/015009 (2013).
56 Kyle, G. P. *et al.* GCAM 3.0 agriculture and land use: data sources and methods. (Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2011).
57 Smith, P. *et al.* How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology* **19**, 2285-2302, doi:10.1111/gcb.12160 (2013).
58 Wolf, J., Asrar, G. R. & West, T. O. Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock. *Carbon Balance Manag* **12**, 16, doi:10.1186/s13021-017-0084-y (2017).
59 Herrero, M. *et al.* Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences* **110**, 20888, doi:10.1073/pnas.1308149110 (2013).
60 FAO. Global Livestock Environmental Assessment Model Model Description Version 2.0,. *http://www.fao.org/fileadmin/user_upload/gleam/docs/GLEAM_2.0_Model_description.pdf [Accessed: July 25, 2010]* (2018).

61 Carlson, K. M. *et al.* Greenhouse gas emissions intensity of global croplands. *Nat Clim Change* **7**, 63-+, doi:10.1038/Nclimate3158 (2017).
62 Janssens-Maenhout, G. *et al.* EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012. *Earth Syst. Sci. Data* **11**, 959-1002, doi:10.5194/essd-11-959-2019 (2019).
63 Penman, J. *et al.* Good practice guidance and uncertainty management in national greenhouse gas inventories. (2000).
64 Chen, X. & Corson, M. S. Influence of emission-factor uncertainty and farm-characteristic variability in LCA estimates of environmental impacts of French dairy farms. *J Clean Prod* **81**, 150-157, doi:https://doi.org/10.1016/j.jclepro.2014.06.046 (2014).
65 Kheshgi, H. S., Jain, A. K. & Wuebbles, D. J. Model-based estimation of the global carbon budget and its uncertainty from carbon dioxide and carbon isotope records. *Journal of Geophysical Research: Atmospheres* **104**, 31127-31143 (1999).