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Global Greenhouse Gas Emissions from Plant- and Animal-Based Food

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Abstract

The food sector related to agriculture and land use is a major nexus of greenhouse gas (GHG) emissions. Previous studies estimated regional and global emissions, or provided spatial details but for sub-sectors using different methodologies. This study takes the next step forward by providing spatially explicit production- and consumption-based GHG emissions worldwide from plant- and animal-based human food in circa 2010 with a model-data integration approach that ensures full consistency between sub-sectors. Global GHG emissions from the production of food is 17,150 ± 1,760 Tg CO_2 eq/yr, to which the production of animal-based, including livestock feed, contributes 58%, the production of plant-based foods contributes 29%, and the remaining 13% of emissions are caused by other utilizations. Emissions from farmland management activities (38%) and land-use change (30%) are major contributors to total emissions. Rice (12%) and beef (27%) are the largest contributing plant- and animal-based commodities. South and Southeast Asia and South America are the largest emitting regions of production-based emissions.

Introduction

Over the last century, global population has quadrupled. Demographic growth and associated economic growth have increased global food demand and caused dietary changes, such as eating more animal-based products. The United Nations projects that food production from plants and animals will need to increase 70% by 2050, compared to the year 2009, to meet increasing food demand [1]. This will drive expansion of food sub-sectors, including crop cultivation and livestock production as well as product transportation and processing, materials (fertilizer and pesticides), and irrigation [2]. Increased food production may accelerate land-use changes for agriculture, resulting in greater greenhouse gas (GHG) emissions, reduced sequestration of carbon, and further climate change. Developing climate mitigation strategies will rely on the estimates of all major GHG emissions (e.g., CO_2, CH_4, and N_2O) from the production and consumption of total and individual plant- and animal-based food covering all food-related subsectors, such as land-use change and farmland activities at local, regional and global scales, which is also the overall objective of this study. Such comprehensive and quantitative estimates require a framework that dynamically represents the environmental, management and human drivers of major GHGs while satisfying the carbon and nitrogen mass-conservation among plant and livestock production and consumption systems.

Previous efforts have been made to assess GHG emissions from agriculture, forestry, and other land use (AFOLU) [3,4] , a critical sub-set of food systems emissions [5-7]. The recent IPCC Special Report on Climate Change and Land (SRCCL) [6] and subsequent work [7] quantified emissions within and "beyond the farm gate", the latter referring to emissions caused by food systems that are not covered by AFOLU sectors, such as from fertilizer manufacturing, product processing and transportation (Figure 1), to be in the range of 10,800-19,100 Tg CO_2 eq/yr for the decade 2008-2017. These estimates combined results from diverse studies on farm gate agriculture and associated land use [4] with global estimates of emissions along the supply chain up to retail and consumption, each study using a different methodology. The annual assessment of the global carbon budget provides CO_2-only emissions from land use change [8], whereas the FAO gives CO_2 emissions from forest land use changes and peatland degradation [9], but those studies do not cover emissions from changes in agricultural management intensity [8]. Besides, CH_4 and N_2O emissions from agricultural activities are provided globally by different datasets [10,11], usually based on estimation approaches defined by the IPCC Guidelines [12]. The IPCC AR5 WG3 [3] and FAOSTAT [4] quantified regional GHG emissions from sub-sectors of agriculture and land use. There are also studies focusing on spatially explicit GHG emissions for selected crops [13], emissions of the life-cycle of agricultural production [5], such as the FAO GLEAM model to estimate global livestock emissions [14], and accounting for carbon opportunity costs of agricultural land [15].

This study quantifies CO_2, CH_4, and N_2O emissions from the production and consumption of all plant- and animal-based foods on a grid using a consistent unified model-data integration framework. Our approach builds upon and extends the data and methods published in the literature by implementing them into the Integrated Science Assessment Model (ISAM) [16]. Our approach brings several advances, for three main reasons. First, we have a dynamic representation of environmental drivers, such as climate, CO_2, and of direct human drivers (land use change, LUC) using a consistent set of mass-conservative equations and parameters for biophysical and biogeochemical processes to estimate the plant carbon and nitrogen dynamics. In comparison, inventory-based methods, such as from the IPCC[12], usually consider environmental factors as static functions[12]. Second, we estimate CO_2 emissions and sinks from changes in agricultural land management intensity from a set of diverse and spatially variable practices such as plowing the soil, planting crops, fertilization, irrigation, harvesting grains, and recovering crop residues. In comparison, most global vegetation models have a very simple or no representation of those practices and bookkeeping models used for land use emissions ignore changes in management intensity[3]. Third, we separate emissions from feed production in cropland and grazing land so that they can be attributed to livestock production, based on the commodity balance between production and consumption, which allows us to rigorously attribute the total food-related GHG emissions to plant- and animal-based human food. In comparison, there has been much debate and confusion about different "livestock emissions" estimates, mainly because they are defined differently among studies. For example, some studies only consider enteric fermentation and manure management emissions as "livestock emissions"[17], and others include land-use change emissions [2], or feed production [14].

In addition, we include LUC emissions from the expansion of agricultural land (crop plus grazing land) and from "beyond farm gate" emissions under the life cycle assessment (LCA) framework of Poore and Nemecek [5] to include emissions from fertilizers, pesticides, and pre-plate products processing and transportation. Although LUC and "beyond farm gate" emissions were addressed in other studies [3-7], we provide here more details for individual plant- and animal-based food items at a finer spatial scale.

In summary, GHG emissions are estimated for 171 crops and 16 animal products at a 0.5° x 0.5° spatial resolution over the entire globe around the year 2010 (mean of 2007-2013). We choose this period 2007-2013 mainly because this is the period with the most recent complete set of data required to carry out our analysis. For example, the commodity balances for crop and livestock, as well as the forage feed data. Our estimates are aggregated into more than 200 countries, and nine regions (Fig. S1), created by grouping countries into macro-geographical coherent zones[18]. We combine CO_2, CH_4, N_2O emissions by their 100-years global warming potentials[3] caused by or associated with different sub-sectors of plant- (crop and grazing land) and animal-based food production and consumption within countries, where consumption-based emissions are calculated by combining emissions from transportation, stock variation, import and export with the estimates of production-based emissions.

Results

Agricultural Land and Biomass

The estimated agricultural biomass production for 171 crops in Table S1 and grazing land (see Text S1 for definitions) for human food and animal feed, land-use change areas associated with this production, and other non-food utilization such as fiber, rubber, and cotton, but not energy crops, are linked consistently to the ISAM simulation module for GHG emissions.

We estimated global total above-ground biomass production from cropland and grazing land to be 8,964 Tg C/yr (Table S2 and S3), including 9% for plant-based human food, 27% for animal feed, and 20% for non-food products. The rest of the biomass production includes 2% of burned agricultural residue and 42% of residues left as litter and stover (excluding used residues such as feed, Table S2). Our historical LUC area based on ISAM [19] and the LUH2 datasets[20] gives a net agricultural land area increase of 0.11 million hectare/yr during 2007-2013, including 2.12 million hectares/yr of other land converted to agricultural land, and 2.01 million hectares/yr of agricultural land converted to other lands (Table S2). More results are reported in Text S2 and Fig. S2.

The estimated livestock feed demand is 2,450 Tg C/yr. This demand is supplied as follows: 23% from crop grain, 12% from forage crops, 21% from crop residue, 42% from pasture feed (feed produced by grazing land), and 2% from scavenging and other feed (Text S2, Table S5). The average conversion efficiency from feed to livestock products is 5.17% based on biomass, 8.31% based on calories, and 8.49% based on protein of livestock products (Text S2, Table S6 and Fig. S3). Livestock products are split among 16 domesticated animal categories (Table S4). One important point to note here is the importance of crop residues being re-used for feeding livestock, an important loop between crop and livestock production systems often ignored in other models.

Production-Based GHG Emissions for Plant- and Animal-Based Food

From the production-based perspective, global total food-related GHG emissions, including farmland, livestock and LUC, amounts to 17,150 ± 1,760 Tg CO_2 eq/yr (median ± standard deviation of 10,000 Monte Carlo simulations, see Text S7 and Table S12), consisting of 61% CO_2, 28% CH_4, and 11% N_2O emissions (CH_4 and N_2O amounts in CO_2 eq/yr) (Fig. 1).

Farmland (E_{farm}), LUC(E_{luc}), livestock (E_{live}) and "beyond farm gate" emissions account for 38%, 30%, 21%, and 11% of total production-based emissions from food systems, respectively (Table 1). E_{farm} includes CO_2, CH_4 and N_2O emissions from farmland activities (see Methods).

South and Southeast Asia (SSEA, 23%) and South America (SA, 20%) are the top contributing regions for total food-production related emissions. The least contributing region includes Oceania and other East Asia (OC) and Mid East and North Africa (MENA), both contributing ~4% of total emissions.

GHG Emissions from Plant-Based Food Production

Production-based GHG emissions from plant-based food amount to 5,064 ± 1,489 Tg CO_2 eq/yr, which is 29% (19% CO_2, 6% CH_4, and 4% N_2O) of total GHG emissions. Within all sub-sectors of plant-based emissions (Fig. 1 and Table 1), E_{farm} is the greatest, contributing ~12% of the total (Fig. 2d). E_{farm} of plant-based food is composed of CH_4 (6%), N_2O (4%) and CO_2 (2%) emissions. E_{farm} CH_4 emissions are generated from rice cultivation, which is the most GHG-intensive grain among all plant-based foods (Fig. 3a and Fig. S4). E_{farm} N_2O and CO_2 are major contributors to wheat and maize emissions. Wheat has the largest harvest area among all 171 crops, and is the second most GHG-intensive plant-based commodity (5%, Fig. 3a), which is largely because of its E_{farm} (2%).

E_{luc} of plant-based food (Fig. 2f) caused by cropland expansion contributes 12% of total food emissions. It consists of 5% soil disturbance emissions and 7% biomass loss emissions. E_{luc} of rice and wheat are the highest among all plant-based food, contributing 3% and 1% of total food emissions. Although wheat is mainly cultivated in temperate regions where E_{luc} is less intensive, the large harvest area still makes its E_{luc} the second largest.

SSEA and China-Mongolia (CM) are the top GHG contributing regions for plant-based food production, and contribute 11% and 6%, respectively, of total food-related GHG emissions (Fig. S5). In these two regions, China, India, and Indonesia are the countries with the most GHG emissions from production of plant-based food (Fig. 2b), contributing 7%, 4%, and 2%, respectively, of total food-related GHG emissions. These regions and countries account for the largest share of the world's population, demanding more food and land, which drive land-use change and cause CO_2 emissions. In addition, SSEA and CM produce more than 90% of the rice in the world[21], and therefore are responsible for the majority of CH_4 emissions from rice cultivation (Fig. S4).

GHG Emissions from Animal-based Food Production

Production-based GHG emissions from animal-based food is 9,884 ± 887 Tg CO_2 eq/yr, which is 58% (32% CO_2, 20% CH_4 and 6% N_2O) of the total GHG emissions. E_{farm} of animal-based food (Fig. 2e), which includes E_{farm} from cropland (9%) and grazing land (13%) that produce feed, accounts for 22% of total emissions. E_{farm} of cropland is transferred to animal-based food emissions through accounting for the crop production used as feed. Top feed producing crops include maize, wheat and soybean. E_{farm} of grazing land (13%) is the generated from pasture feed production. E_{live} (21%) is another predominant term of animal-based food emissions (Fig. 2h), including 18% CH_4 emissions from enteric fermentation of ruminant animals and 3% from manure management. E_{farm} and E_{live} are the largest major components of emissions from beef and cow milk production. These two commodities contribute the most (27% and 10%) to the total animal-based food GHG emissions (Fig. 3b).

E_{luc} of animal-based food (12%) includes 5% from soil disturbance and 7% from biomass loss (Fig. 2g). E_{luc} and E_{farm} are the major sources of GHG emissions of meat products from monogastric animals, such as pork and chicken meat, mainly because we account for the GHG emissions from production and trade of crop feed for these animals.

The most prominent emitting regions for animal food production are SA (13% of total food-related emissions), SSEA (9%), and CM (8%) (Fig. S5a). China (8%) in CM, Brazil (6%) in

SA, USA (5%) in North America (NA), and India (4%) in SSEA are the countries with leading GHG emissions from production of animal-based foods (Fig. 2c). Beef and cow milk are the commodities that contribute most to the largest emitting regions and countries. E_{farm} and E_{live} are the most dominant components of GHG emissions of animal-based food production in these regions and countries (Fig. 2g, h). These regions and countries have the largest herd size of cattle supporting meat and dairy production, demanding more crop and pasture feed and causing more farmland CO_2 emissions. E_{luc} associated with animal food production in Brazil is the highest among all countries, mainly because of deforestation caused by pasture land expansion [22].

Consumption-Based GHG Emissions

Consumption-based emissions are calculated by combining transportation, stock variation, and international trade, based on the FAOSTAT commodity trade dataset [23,24], with our estimates of production-based emissions for each commodity and sub-sector (see Methods).

For the 2010 base year, roughly 12% and 14% of global total GHG emissions were transferred among regions due to the import and export of food, here plant- and animal-based food combined. Imports transferred 3% of plant-food and 9% of animal-based food from producers to consumers. If attributing emissions to importing consumers, we can say that imports transferred 5% of plant products emissions and 9% of animal products emissions. It is to note that GHG emissions are not exactly balanced between import and export [24], in part due to the emissions attributed to stock-variation (-42 Tg CO_2 eq/yr), and transportation emissions (202

Tg CO_2 eq/yr), as well as slight inconsistencies in the FAOSTAT import and export amounts of plant- and animal-based food.

SSEA has caused the greatest GHG emissions from plant-based-food exports (Fig. S6). Tropical regions such as SSEA and SA, are experiencing an expansion of agricultural land for production of plant-based commodities such as coffee, tea, bananas, citrus fruits, palm oil, rubber, sugarcane, and pasture feed for animal-based food production, which is greatly driven by international trade [25]. The expanded agricultural land is predominantly converted from natural vegetation such as forest, which causes significant land-use change and E_{luc} [25]. These regions thus cause more GHG emissions from exports, particularly related to E_{luc}.

EU has caused the most GHG emissions from both animal-based-food imports and exports, mainly because of the large amount of the internal trades between EU countries [24]. SA, NA and OC also cause large amounts of GHG emissions, predominantly due to their leading positions in exporting animal-based food such as beef [24].

Discussion and Conclusions

Overall, our estimated emissions from food systems account for 35% of global total anthropogenic GHG emissions. At the same time, our study does not account for food-related emissions through specific human/climate disturbances, such as savannah burning, peat drainage and peat fire [3,13,17,26]. By adding all emissions from total savannah burning and drained peat [17,26] (not only related to food systems), our total food-related emissions will be ~37% of total GHG emissions, compared to the IPCC SRCCL estimated percentage range of 21- 37% [6], and 26% according to Poore and Nemecek [5]. Without "beyond farm gate" emissions, our estimated GHG emissions are 31% of global total anthropogenic GHG emissions [3], comparing to 24% from AFOLU in IPCC AR5 [3]. While our overall estimated emissions match well with the higher range value of IPCC SRCCL [6], the strength of our study is that we estimate emissions from sub-sectors for the human food systems using a consistent data-modeling framework, which ensures the carbon and nitrogen balance among biomass flow by considering detailed biophysical and biogeochemical processes.

As the basis of calculating feed emissions, we estimated the total feed demand and its compositions. Our feed amount calculation method (Text S1) is unique and detailed compared to other published studies, including IPCC AR5 WG3 [3] (Text S2 and Table S7), because it ensures that the amounts of different types of feed are consistent with crop and grazing land productions, which are cross-validated with published datasets [21,27]. Our method also ensures the balance between different types of feed supply and total demand not only on the global scale but also in each individual country. Overall, our estimated feed demand (2,450 Tg C/yr) is 20% lower than IPCC AR5 estimates[3], yet is within the range of previous studies (range from ~2,000 to 3,000 Tg C/yr, see Table S7).

Our farmland CO_2 emission is the net carbon flux of cropland and grazing land, which includes both carbon fixation by plant photosynthesis and carbon loss such as soil emissions and livestock respiration. We estimated the soil emissions (including soil disturbance and tillage emissions) and livestock respiration emissions at 2,420 Tg CO_2 eq/yr and 4,840 Tg CO_2 eq/yr, accounting for 14% and 28%, respectively, of our estimated total food-related emissions.

Our study considers several emissions, which other studies have not. It estimates "beyond farm gate" emissions in detail from several sub-sectors, such as mining, manufacturing, and transporting agricultural materials, food processing, and transportation, while IPCC SRCCL[6] reported only the overall emission estimated value. In addition, we include farmland CO_2 emissions (3,082 ± 182 Tg CO_2 eq/yr) through a detailed representation of agricultural land management intensity and practices. This emission is assumed to be neutral and associated with annual cycles of carbon fixation and oxidation through photosynthesis in other studies [3].

Our estimated "beyond farm gate" emission (1,962 Tg CO_2 eq/yr) was calculated from different sub-sectors at the global scale (Text S2 and Table S8), which is about half of the IPCC SRCCL[6] value. Our estimated food processing and transportation emission of 1,296 Tg CO_2 eq/yr is close to Poore and Nemecek [5] estimate of 1,400 Tg CO_2 eq/yr. Our total E_{farm} (6,490 ± 1,814 Tg CO_2 eq/yr) is 2~4 times higher than FAOSTAT [4], Poore and Nemecek [5] and EDGAR [28] (Table S8), mainly because we included the farmland CO_2 emissions. Our estimated E_{live} (3,602 ± 822 Tg CO_2 eq/yr) emission is similar to FAOSTAT, but our combined E_{farm} and E_{live} emission is ~60% higher than the IPCC SRCCL[6], also because of our farmland CO_2 emissions. Our estimated E_{luc} (5,096 ± 301 Tg CO_2 eq/yr) is similar as IPCC AR5 [3] and SRCCL [6] values, and higher than FAOSTAT [4] and Poore and Nemecek [5]. Our simulated farmland CH_4 emission is similar to EDGAR [28] and higher than Carlson et al. [13], Poore and Nemecek [5] and FAOSTAT [4], but the estimated uncertainty range is large. Our estimates for N_2O from cropland and grazing land are consistent with FAOSTAT [4], and slightly higher than EDGAR v4.3.2[28]. Our food-related emissions for most of the countries are either higher or about the same compared to FAOSTAT Our total emissions are ~56% more than FAOSTAT total emissions in circa 2010 (Table S8), mainly because we account for "beyond farm gate" and farmland CO_2 emissions. Extended discussion on the comparison with other studies are added in Text S2.5.

Looking into the future, our results show that the agricultural land required to produce animal-based food in 2010 is already five times more than to produce plant-based food (Table S2). Currently, 56% of the livestock feed demand is fulfilled by cropland, because biomass productivity of cropland is much higher than grazing land. With the population and GDP growth in the future as projected under all shared socioeconomic pathways (SSP) scenarios [29], and assuming historical dietary trends, the demand for protein-dense animal-based foods will increase more. In contrast, calorie-dense starchy staple foods will decrease (known as Bennett's law [30]), particularly in the group of developing countries such as SA, SSEA, and Sub-Saharan Africa (SSA), where the conversion efficiencies of biomass, calorie and protein are also relatively low (Fig. S3). Ruminant products in recent years are increasing at a decelerated rate, while monogastric products are increasing at a higher rate [21]. Along with expected growth in population and income, animal-based food production and consumption, including ruminant and monogastric products, are projected to increase under different SSP scenarios [31]. Without technological change and other mitigation measures, the increasing demand for animal-based food could greatly increase the GHG emissions and demand for agriculture land [31]. Expansion of agricultural land for animal feed crops mostly occurred in tropical regions (SA, SSEA and Sub-Saharan Africa (SSA)) at the expense of native forests [32]. In addition, growth in urban population and international demand for agricultural products also drive deforestation in these regions [33]. We can infer that there might be more deforestation in the tropical regions if no mitigation measures have been implemented in the future. These mitigation measures include options from production and consumption perspectives, such as improvements in technologies and management, increase in livestock productivity from the production end, as well as the moderation of demand for livestock products due to dietary changes for plant-based food and reduction of food loss and waste from the consumption end [2,31].

In this study, we estimate GHG emissions from the food sector, but do not consider the opportunity costs of lost carbon sequestration capacity of agricultural land that would otherwise revert to the forest if allowed to return to its natural state. In follow up studies, we will consider these costs, as well as management strategies for enhancing carbon sequestration on marginal lands, to estimate net carbon flux based upon alternative dietary and land use scenarios, and will combine these estimates with results from this study to provide a comprehensive science-based framework for policymakers and others to assess and discuss strategies for mitigating climate change that harness the natural regenerative capacity of our planet.

Methods

Overview of the Methodology

To quantify the total food-related GHG emissions, we first estimate the total crop and grazing biomass, which includes livestock feed, and then partition the total biomass to plant- and animal-based food (livestock feed) and other utilizations.

Based on the estimated biomass, we calculate and partition the production-based GHG emissions from plant and livestock to plant- and animal-based food and other utilizations. After that, we calculate GHG emissions from the consumption-based perspective taking into account international trade (import and export) and stock variation. We estimate the production- and consumption-based emissions separately to explicitly account for the GHG emissions caused by trade. This is especially important for the regions and countries, which import and/or export large amounts of plant- and animal-based food.

From the production-based perspective, the GHG emissions from plant- and animal-based food include the following sub-sectors (Fig. 1): 1) mining, manufacturing and transportation of nitrogen, phosphorus, potassium (N, P, K) fertilizers and pesticides, which are applied to agricultural land to produce crop and grazing biomass; 2) emissions from land-use change for agricultural land expansion (E_{luc}); 3) farmland emissions (E_{farm}) from farming activities such as plowing soil, planting and fertilizing crops, harvesting crop grains and recovering crop residues for feedstock, and from fuel and electricity consumption by machines used in farming; 4) livestock emissions (E_{live}) including CH_4 emissions from enteric fermentation of ruminant animals and CH_4 and N_2O emissions from manure management; 5) product processing emissions due to fuel and electricity consumption for production of crop (such as emissions from drying, peeling, milling processes) and livestock commodities (such as emissions from slaughtering, splitting meats, energy used in milking machinery and stables etc.)

From the consumption-based perspective, the consumption amounts are supplied by production, import, export, and stock variation of plant and livestock, and are consumed as plant- and animal-based human food and other utilizations. We estimate the net GHG emission transfers among different countries via international trade, i.e., export and import, and emissions from the stock variation of plant and livestock products based on agricultural biomass. We also consider GHG emissions due to domestic and international transportation in consumption-based emissions.

Agricultural Biomass

Crop Biomass

We estimate dry matter biomass carbon of 171 crops by multiplying the crop production in circa 2010 with crop-specific dry matter content and carbon content per dry matter (Table S1) [34-36] (Text S1). We first produce the spatially explicit production data of all crops in circa 2010 (Text S1). In addition, we calculate the amount of crop biomass for different utilizations based on the commodity balance reported by FAOSTAT [23] as described in detail in the "Allocation of Emission from Plant-based Commodities to Different Utilizations" section. We also estimate the crop residue biomass for all 171 crops (Text S1).

Biomass Feed Demand and Supply for Livestock

We first calculate the feed demand for 16 major livestock animals in each country by multiplying the animal-specific feed demands per-head [37] with live animal heads [21] (Table S4). Then we quantify the biomass supply amounts from five sources to meet the feed demand in each country – namely, crop grain feed, forage crop feed, crop residue feed, pasture feed, and scavenging and other feed as described in Text S1. To ensure that the supply (including import and export) and demand of feed are equal in each country, we develop a schematic algorithm to reconcile the feed demand and supply amount at the country level (Text S1 and Fig. S7).

Production-based GHG Emissions for Plant- and Animal-based Food

Emissions from Mining, Manufacturing and Transportation of Fertilizers and Pesticides

Agricultural materials are applied to agricultural land to produce plant biomass. We consider N, P, K fertilizers, and pesticides application emissions from the mining of raw ores and fossil fuels to manufacturing and transportation to the farmland. We multiply the application amounts and emission factors of N, P, K fertilizers, and pesticides to estimate the emissions from mining, manufacturing and transportation of fertilizers and pesticides (Text S3).

Land Use Change Emission

Land-use change (LUC) activities clear existing ecosystems, their biomass and disturb the soil, generating GHG emissions. This cleared biomass is either directly lost, for instance through fire, or used to make different products. We assign the carbon and nitrogen stored in these products into four pools: agriculture and agriculture products in a 1-year product pool, paper and paper products in a 10-year product pool, lumber products in a 100-year product pool, and long-lived products in a 1,000-year product pool. In one particular year, we assume the emission caused by product pools is the sum of the 1-year pool, 1/10 of the 10-year pool, 1/100 of the 100-year pool, and 1/1,000 of the 1,000-year pool. The waste biomass is either burned or left on the ground as litter. For the emissions caused by soil disturbance, we assume a certain amount, depending upon the region and soil type, of the topsoil soil organic carbon is lost in the first year when land-use change occurs [38]. We use the historical LUC areas from Hurtt, et al.

[20], and process it to drive the ISAM model using the methodology developed by Meiyappan and Jain [19]. In order to represent the circa 2010, we calculate the average E_{luc} emissions from 2007 to 2013, which is consistent with the time frame of other emission calculations in this study.

Farmland Emission

Farmland emissions include all emissions due to farming activities, such as plowing soil, planting and fertilizing crops, harvesting crop grains, and recovering crop residues. Fuel and energy use emissions are also part of E_{farm}.

Fuel and energy use emission. Fuel and energy use emissions include GHGs emitted from fuels and electricity consumption by farm machinery, including for irrigation. We use the energy use emissions (excluding fuel oil and energy for fisheries, and transportation emissions) from FAOSTAT [17], and distribute these emissions to individual crops based on their harvest area. This distribution method assumes the same GHG emissions on each unit of harvested area in the individual country. Given the small contributions of fuel and energy use emission (~1% of our total food-related emissions), this relatively simple estimation method to calculate the fuel and energy use emissions in each country does not add much uncertainty to the total GHG emissions. The FAOSTAT dataset is computed following the Tier 1 method of IPCC 2006 Guidelines for National Greenhouse Gas Inventories [12], which calculates the emissions by multiplying fuel burning and electricity generation amounts with their emission factors [12].

CH_4 and N_2O emissions. We assume all farmland CH_4 emissions are generated from rice paddies (since the rest is treated elsewhere—under livestock). We use the ISAM CH_4 module

[39] to simulate the wetland and non-wetland soil CH_4 emissions, and explicitly separate the CH_4 emission from rice paddies (Text S4.3 for brief model description). We use the N_2O module [40] of the ISAM to simulate the N_2O emissions from cropland and grazing land (Text S4.2). The gridded fertilizer and manure input data for ISAM are described in the Data Sources section.

CO_2 emissions. We estimate farmland CO_2 emissions using the ISAM model jointly with FAO crop production data. The farmland CO_2 emissions, E_{f_CO2}, is the difference between all emissions from and all carbon sequestration in agricultural land. Here, the positive values mean emissions, while negative values indicate carbon sequestration. E_{f_CO2} is calculated using Eq. 1.

$$E_{f\_CO2} = R_a + R_h + E_{t\_CO2} + E_{h\_CO2} + E_{w\_CO2} - GPP \qquad \text{(Eq. 1)}$$

where, GPP, R_a and R_h are gross primary productivity, autotrophic, and heterotrophic respiration; E_{t_CO2} is carbon loss due to soil tillage; E_{h_CO2} is carbon loss due to harvest of biomass, including grain biomass and recovery biomass (for feed and other use); E_{w_CO2} is carbon loss due to burning of waste biomass.

ISAM simulates E_{f_CO2} in a dynamic way for 16 major crops. For the 155 remaining crops (accounting for ~40% of total crop production), we refer to E_{f_CO2} of C3 generic crop results of ISAM simulations using weighted average parameters of the 155 crops (such as harvest index, root: shoot ratio). The crop grain biomass, as well as the recovered biomass for livestock feed and other socioeconomic uses (such as crop residues used as biofuels) (calculated using regional-specific recovery rates [37]) are assumed to be released to the atmosphere within one year (E_{h_CO2}). After harvesting and recovery, we assume a certain fraction (vary in different regions) of the rest residue biomass is burned on the ground [41,42] (E_{w_CO2}). Remaining residue biomass after harvesting, recovering, and burning goes into the soil in the form of litterfall. Detailed processes are described in Jain, et al. [18] and Meiyappan, et al. [38].

Livestock Emissions

Livestock emissions include CH_4 and N_2O emissions from enteric fermentation and manure management, which we use the country- and animal-specific CH_4 emission factors from the FAOSTAT dataset [4,9,17] (see details in S3.2).

Processing Emissions

We include emissions from fuels and electricity consumption caused by the processing of crops needed before using, such as heat drying, peeling, and grain milling (see Table S9 for processed crops). For example, wheat grain is usually processed to wheat flour and wheat bran using mills, which consume fuels or electricity and generate additional GHG emissions. We adopt the processing emission factors (Table S9) from the Feedprint NL database (Version 2019.00, Wageningen University & Research, 2019) to estimate the crop processing emissions. For the crops that are processed into multiple products (Table S9), we allocate the GHG emissions of these crops to different products (Text S5).

Similarly, fuel and electricity are consumed during the processing of livestock products, such as slaughtering and splitting meats, which generates additional GHG emissions. We adapt the energy consumption amount of meat, dairy and egg productions and region-specific emission factors from GLEAM v2.0 [43].

Consumption-Based GHG Emissions for Plant- and Animal-Based Foods

Consumption-based GHG emissions include emissions from transportation of the commodities, and GHG is transferred among the importing and exporting countries. We first calculate the transportation emissions. Then we quantify the GHG emissions from the total consumption of plant biomass in each country, including production, import, export, and stock variation, and then partition these emissions to plant- and animal-based food (livestock feed) and other utilizations, based on the commodity balance [23]. Imported food has different GHG intensity based on our results depending on the source region. We use detailed trade matrices from FAOSTAT reporting the imported and exported amounts of different commodities among individual countries to calculate the GHG emissions transferred by trade (see section "Emissions from Consumption of Plant Biomass" for detailed procedures).

The consumption-based GHG emissions from plant biomass used for animal-based food are then considered as part of GHG emissions for livestock products. Finally, we estimate the consumption-based emissions of livestock products, and then partition the emissions to animal-based food and other utilizations. Our approach ensures that all GHG emissions of livestock commodities (including beyond farm gate emissions, E_{luc}, E_{farm} and E_{live}) that are produced in one country would be imported or exported to the trading partner country along with the trade of these commodities.

Transportation Emissions

Plant- and animal-based products are transported domestically and internationally through different transport modes, which generate GHG emissions. We calculate the transportation emissions based on the emission factors of different transport modes and transporting ton-km of plant- and animal-based commodities (Table S10 and S11) [44,45].

Emissions from the Consumption of Plant Biomass

The consumption of crop biomass is calculated using the following relationship [23]:

$$Consumption_{c,n} = Production_{c,n} + Stock\ variation_{c,n} + Import_{c,n} - Export_{c,n} \quad \text{(Eq. 2)}$$

where $Consumption_{c,n}$ is the biomass consumption of crop c in country n (kg); $Production_{c,n}$ is the biomass production of crop c in country n (kg); $Import_{c,n}$ and $Export_{c,n}$ are imported and exported biomass of crop c in country n (kg); $Stock\ variation_{c,n}$ refers to changes in stocks at all levels between the production and the retail levels (kg). All these values are calculated from the FAOSTAT dataset [24] and averaged from 2007 to 2013.

We estimate the imported and exported amounts of forage crop biomass in Text S1. We assume there are no import, export, and stock variation for pasture feed due to lack of information. Therefore, the production-based and consumption-based GHG emissions are the same for pasture.

Note that we have attributed the imbalance amount of the biomass of 16 major crops between ISAM simulations and FAO reported values to $Stock\ variation_{c,n}$ in Eq. 2 to ensure mass balance.

Then, we adapted the following equation from Cassidy, et al. [46] to estimate the GHG emissions for $Consumption_{c,n}$ by accounting for GHG emissions from stock variation and international trade (bilateral trade, see detailed discussion in Text S2.5).

$$GHG_{c,n} = \left(Production_{c,n} + Stock\ variation_{c,n} - Export_{c,n}\right) \times EI_{c,n} + \sum_{i=1}^{m} Import_{c,i} \times EI_{c,i} \qquad \text{(Eq. 3)}$$

where, m is the number of importing countries for crop c in country i; $GHG_{c,n}$ is GHG emissions (kg CO_2 eq) from domestic supply of crop c in country n (kg CO_2 eq); $EI_{c,n}$ is the weighted average GHG emission intensity of per kg crop c in country n (kg CO_2 eq/kg); $EI_{c,i}$ is the weighted average GHG emission intensity of per kg crop c in importing country i (kg CO_2 eq/kg). We assume $Stock\ variation_{c,n}$ has the same $EI_{c,n}$ as $Production_{c,n}$.

In Eq. 3, emission intensities $EI_{c,n}$ and $EI_{c,i}$ are calculated by the country- and crop-specific GHG emissions (before considering trade) divided by that specific crop's production. Our approach of estimating the consumption-based GHG emissions cannot rule out the effect of through-trade. We assume that all products imported from a country are produced in that country. The through-trade may have a large effect on consumption-based GHG emissions in some countries, like the Netherlands. To minimize the effect of through-trade, we reported our consumption-based GHG emissions at the regional scale.

Allocation of Emission from Plant-Based Commodities to Different Utilizations

We calculate the GHG emissions from different utilizations based on the commodity balance of the FAOSTAT dataset [23]. This procedure does not generate additional GHG emissions; it only estimates the GHG emissions for different utilizations. The biomass balance is as follows:

$$Consumption_{c,n} = Food_{c,n} + Feed_{c,n} + Others_{c,n} \qquad \text{(Eq. 4)}$$

where $Food_{c,n}$ and $Feed_{c,n}$ refer to biomass used as plant-based food and livestock feed for crop c in country n; $Others_{c,n}$ is the combined biomass for all non-food and non-feed utilizations.

The $Food_{c,n}$, $Feed_{c,n}$ and $Others_{c,n}$ values are collected from the FAOSTAT commodity balance sheet [23]. We have combined biomass for processing, losses, seed production, and other usages as '$Others_{c,n}$'. Note that the processing usages in FAOSTAT are also used for food or feed; for instance, soybeans are processed to soybean oil and cakes. Here, we exclude the food and feed usages in the processing but include them into the biomass for food and feed correspondingly. Therefore, the $Others_{c,n}$ are combined biomass for all non-food and non-feed biomass.

Based on Eq. 4, we calculate GHG emissions from plant-based food ($Food\_GHG_{c,n}$) for crop c in country n by:

$$Food\_GHG_{c,n} = \frac{Food_{c,n}}{Consumption_{c,n}} \times GHG_{c,n} \qquad \text{(Eq. 5)}$$

where, $GHG_{c,n}$ is calculated in Eq. 3. We then use the same method to calculate the GHG emissions from feed and others. It should be noticed that the FAOSTAT commodity balance sheet [23] has combined some crops into a broader commodity item (see column "corresponding commodity item" in Table S1). We follow the same scheme to combine the GHG emissions from crops into different commodity groups (Table S1), and then estimate GHG emissions from plant-based food, livestock feed, and other utilizations.

We attribute all crop GHG emissions, including fuel and energy use emissions, to food, feed and other usage through the commodity balance. The GHG emissions that are generated from crop production but part of it is used as feed. The emissions related to the crop feed are transferred to livestock emissions. The GHG emissions from forage crops and pasture feed productions, including fuel and energy use emissions, are all attributed to livestock emissions.

Allocation of Emissions from Animal-Based Commodities to Different Utilizations

We use the same approach as the consumption-based emissions of plant biomass (Eqs. 3 ~ 6) to account for the consumption-based GHG emissions from livestock products in each country, including production, import, export and stock variation, and the consumption-based GHG emissions from animal-based food and other utilizations. Note that parts of livestock meat, dairy, and egg products are used as feed according to the livestock commodity balance [24]. We consider the animal-based feed GHG emissions as part of the animal-based food emissions.

Data Sources

Spatial Data for N, P, K Fertilizers

For cropland, we have produced the spatial maps of N, P, K fertilizer application amount for different crops at 0.5^{o} x 0.5^{o} for circa 2010 based on EarthStat nutrient application spatial data for N, P, K fertilizer application amount for circa 2000 [47,48], M3-crop [27] and FAOSTAT dataset [21] for crop-specific production data (Text S6). The N fertilizer amount is the combined N amount of synthetic N fertilizer, manure, and atmospheric deposition. We use an estimated fraction of synthetic N fertilizer amount to total N application amount in cropland at the regional scale [49] to calculate the synthetic nitrogen fertilizer amount at the spatial scale for different crops. The amount of pesticides is not available at a spatial scale. Therefore we use the country scale data, which we collected from FAOSTAT [50].

For grazing land, we use the gridded N inputs for circa 2010 from Xu, et al. [51], including synthetic N fertilizer, manure N left on and applied to grazing land.

Spatial data for Manure Nitrogen and Carbon

We consider nitrogen and carbon from manure in this study. Manure is either left on the grazing land or collected in feedlot and then applied to cropland and grazing land. CH_4 and N_2O emissions are emitted during the storage and compositing processes of the collected manure, which we consider as part of the livestock emissions (see Livestock Emissions section).

For cropland, the crop-specific spatial data of manure nitrogen application amount is estimated in our produced N fertilizer application amount based on published datasets [27,47,48,52,53] (Text S6). For grazing land, we use the gridded nitrogen inputs for circa 2010 from Xu, et al. [51], which provide manure nitrogen left and applied to grazing land separately. These crop and grazing land manure nitrogen data are at gridded scale that is required by the ISAM simulations. The abovementioned nitrogen datasets [27,47,48,51,52] are all based on and consistent with FAOSTAT manure nitrogen data at the country scale [53]. Therefore, our usage of FAOSTAT manure management emissions are also consistent with these manure nitrogen input data. Manure contains both organic and mineral nitrogen. Organic nitrogen cannot be directly used by plants. In ISAM model, the organic manure nitrogen is gradually decomposed by soil microbes to mineral nitrogen. Part of it then enters into the soil mineral nitrogen pool together with the inorganic (mineral) manure nitrogen [18].

To obtain the spatial data of the manure carbon, we first estimate the total manure carbon amount by multiplying the animal-specific manure production per-head [37] with live animal heads [21] in different countries (Table S4). Then we calculate the global total manure nitrogen (estimated in the last paragraph) and determine the global average C:N ratio of manure. We multiply this C:N ratio with the spatial maps of manure nitrogen to get the gridded manure carbon map on a global scale. ISAM considers manure carbon in organic form as litterfall, and simulates its impact on farmland CO_2 emissions through dynamic processes.

Uncertainty Analysis

We estimate the uncertainty range of the GHG emissions for plant- and animal-based food through a Monte Carlo approach, which simulates the uncertainties caused by major contributors of the GHG emissions, such as E_{luc}, E_{farm} and E_{live} by referring to their individual uncertainty ranges from previous studies (Text S7 and Table S12). In addition, we acknowledge that the uncertainties of all spatial data we cited from previous studies and produced in this study are largely of unknown magnitude.

Acknowledgements

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Data Availability

The results for CO_2, CH_4 and N_2O from plant- and animal-based food are available at the ISAM website http://climate.atmos.uiuc.edu/Food_Emissions. The results for individual plant- and animal-based commodities are available upon request.

Code Availability

All codes are available upon request.

Author Contributions

X.X. and A.K.J. designed the framework of this study, collected data, and analyzed the results. X.X., P.S., S.S. and T.S.L. performed the model simulations. P.C., F.N.T., P.S., and N.C. contributed to the interpretation and implication of the results. X.X. wrote the paper with inputs from all coauthors.

Competing Interests

The authors declare no competing interests.

References

1 FAO. How to feed the world in 2050 (FAO, Rome). http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf. [Accessed 12/12/2019]. (2019).

2 Herrero, M. *et al.* Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc Natl Acad Sci U S A* **110**, 20888-20893, doi:10.1073/pnas.1308149110 (2013).

3 IPCC. *Climate Change 2014,Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2014).

4 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).

5 Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987-992, doi:10.1126/science.aaq0216 (2018).

6 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).

7 Rosenzweig, C. *et al.* Climate change responses benefit from a global food system approach. *Nature Food* **1**, 94-97, doi:10.1038/s43016-020-0031-z (2020).

8 Friedlingstein, P. *et al.* Global carbon budget 2019. *Earth Syst Sci Data* **11**, 1783-1838 (2019).

9 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).

10 Syakila, A. & Kroeze, C. The global nitrous oxide budget revisited. *Greenhouse Gas Measurement and Management* **1**, 17-26 (2011).

11 Saunois, M. *et al.* The Global Methane Budget 2000–2017. *Earth Syst. Sci. Data* **12**, 1561-1623, doi:10.5194/essd-12-1561-2020 (2020).

12 IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. (Institutefor Global Environmental Strategies, 2006).

13 Carlson, K. M. *et al.* Greenhouse gas emissions intensity of global croplands. *Nat Clim Change* **7**, 63-+, doi:10.1038/Nclimate3158 (2017).

14 Gerber, P. J. *et al. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities*. (Food and Agriculture Organization of the United Nations (FAO), 2013).

15 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).

16 Jain, A. K. & Yang, X. Modeling the effects of two different land cover change data sets on the carbon stocks of plants and soils in concert with CO_2 and climate change. *Global Biogeochem Cy* **19**, n/a-n/a, doi:10.1029/2004gb002349 (2005).

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

18 Jain, A. K., Meiyappan, P., Song, Y. & House, J. I. CO2 emissions from land-use change affected more by nitrogen cycle, than by the choice of land-cover data. *Global Change Biology* **19**, 2893-2906, doi:10.1111/gcb.12207 (2013).

19 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).

20 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).

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

22 Zalles, V. *et al.* Near doubling of Brazil's intensive row crop area since 2000. *Proceedings of the National Academy of Sciences* **116**, 428-435, doi:10.1073/pnas.1810301115 (2019).

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

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

25 Pendrill, F. *et al.* Agricultural and forestry trade drives large share of tropical deforestation emissions. *Global Environmental Change* **56**, 1-10, doi:https://doi.org/10.1016/j.gloenvcha.2019.03.002 (2019).

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

27 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).

28 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).

29 Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **42**, 153-168, doi:https://doi.org/10.1016/j.gloenvcha.2016.05.009 (2017).

30 Gouel, C. & Guimbard, H. Nutrition transition and the structure of global food demand. *Am J Agr Econ* **101**, 383-403 (2019).

31 Springmann, M. *et al.* Options for keeping the food system within environmental limits. *Nature* **562**, 519-525, doi:10.1038/s41586-018-0594-0 (2018).

32 Ripple, W. J. *et al.* Ruminants, climate change and climate policy. *Nat Clim Change* **4**, 2-5, doi:10.1038/nclimate2081 (2014).

33 DeFries, R. S., Rudel, T., Uriarte, M. & Hansen, M. Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nat Geosci* **3**, 178-181, doi:10.1038/ngeo756 (2010).

34 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).

35 Wolf, J. *et al.* Biogenic carbon fluxes from global agricultural production and consumption. *Global Biogeochem Cy* **29**, 1617-1639, doi:10.1002/2015gb005119 (2015).

36 Heuzé, V., Tran, G., Bastianelli, D., Archimede, H. & Sauvant, D. Feedipedia: an open access international encyclopedia on feed resources for farm animals. (2013).

37 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).

38 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).

39 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:10.1029/2019gb006251 (2020).

40 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).

41 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).

42 Wang, R. *et al.* High-resolution mapping of combustion processes and implications for CO_2 emissions. *Atmos Chem Phys* **13**, 5189-5203, doi:10.5194/acp-13-5189-2013 (2013).

43 FAO. Global Livestock Environmental Assessment Model Version 2.0 Description. *Accessed at* http://www.fao.org/fileadmin/user_upload/gleam/docs/GLEAM_2.0_Model_description.pdf. *[12/22/2019]* (2018).

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

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

46 Cassidy, E. S., West, P. C., Gerber, J. S. & Foley, J. A. Redefining agricultural yields: from tonnes to people nourished per hectare. *Environ Res Lett* **8**, doi:10.1088/1748-9326/8/3/034015 (2013).

47 Mueller, N. D. *et al.* Closing yield gaps through nutrient and water management. *Nature* **490**, 254-257, doi:10.1038/nature11420 (2012).

48 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).

49 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).

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

51 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).

52 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).

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

Figure Legends

Fig. 1. GHG emissions from different sub-sectors of plant- and animal-based food production/consumption (Unit: Tg CO_2 eq). The contributions of individual GHGs provided are the % of the total emissions. Solid arrows indicate production-based emissions, while dashed arrows show consumption-based emissions. This figure represents mean values, which may slightly differ from the median values of Monte Carlo simulations in the text.

Fig. 2. Production-based GHG emissions from (a) total food systems (b) plant-based food, (c) animal-based food, (d) farmland emissions of plant-based food, (e) farmland emissions of animal-based food, (f) LUC emissions of plant-based food, (g) LUC emissions of animal-based

food, and (h) livestock emissions of animal-based food in different countries (unit: Tg CO_2 eq/yr).

Fig. 3. Production-based GHG emissions of a) top ten plant-based and b) animal-based food items.

Tables

Table 1. Production- and consumption-based GHG emissions from different sub-sectors of plant- and animal-based food (Unit: Tg CO_2 eq, numbers in brackets are % of each emission to total emissions+)

Sub-sectors		**Plant-based food**	**Animal-based food**	**Other utilizations**
Land-use change emissions		2,051 (12%)	2,102 (12%)	941 (6%)
Farmland emissions	Cropland (include Fuel and energy use emissions)	2,057 (12%)	1,467 (9%)	654 (4%)
	Grazing land		2,247 (13%)	69 (0%)
Livestock emissions	Enteric fermentation		3,065 (18%)	95 (0%)
	Manure management		435 (3%)	13 (0%)
Beyond farm gate emissions	Mining, manufacturing and transporting fertilizers and pesticides	269 (2%)	280 (2%)	117 (1%)
	Product processing	693 (4%)	288 (2%)	315 (2%)
	Transportation, trade and stock variation*	-107 (-1%)	39 (0%)	-71 (0%)
Sum (production-based emission)		***5,070***	***9,884***	***2,204***
Sum (consumption-based emission)		***4,963***	***9,923***	***2,133***

+ Total production- and consumption-based emissions are close; the % are the same using either number.

* Only included in consumption-based emission, not in production-based emissions.

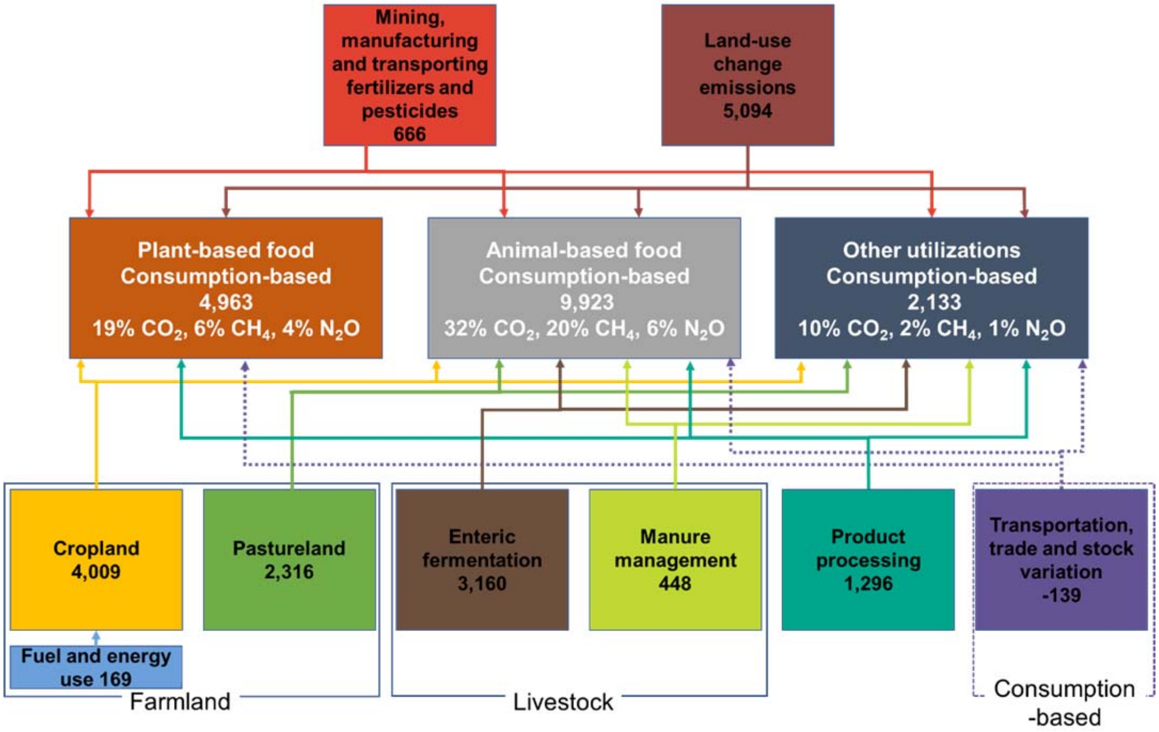
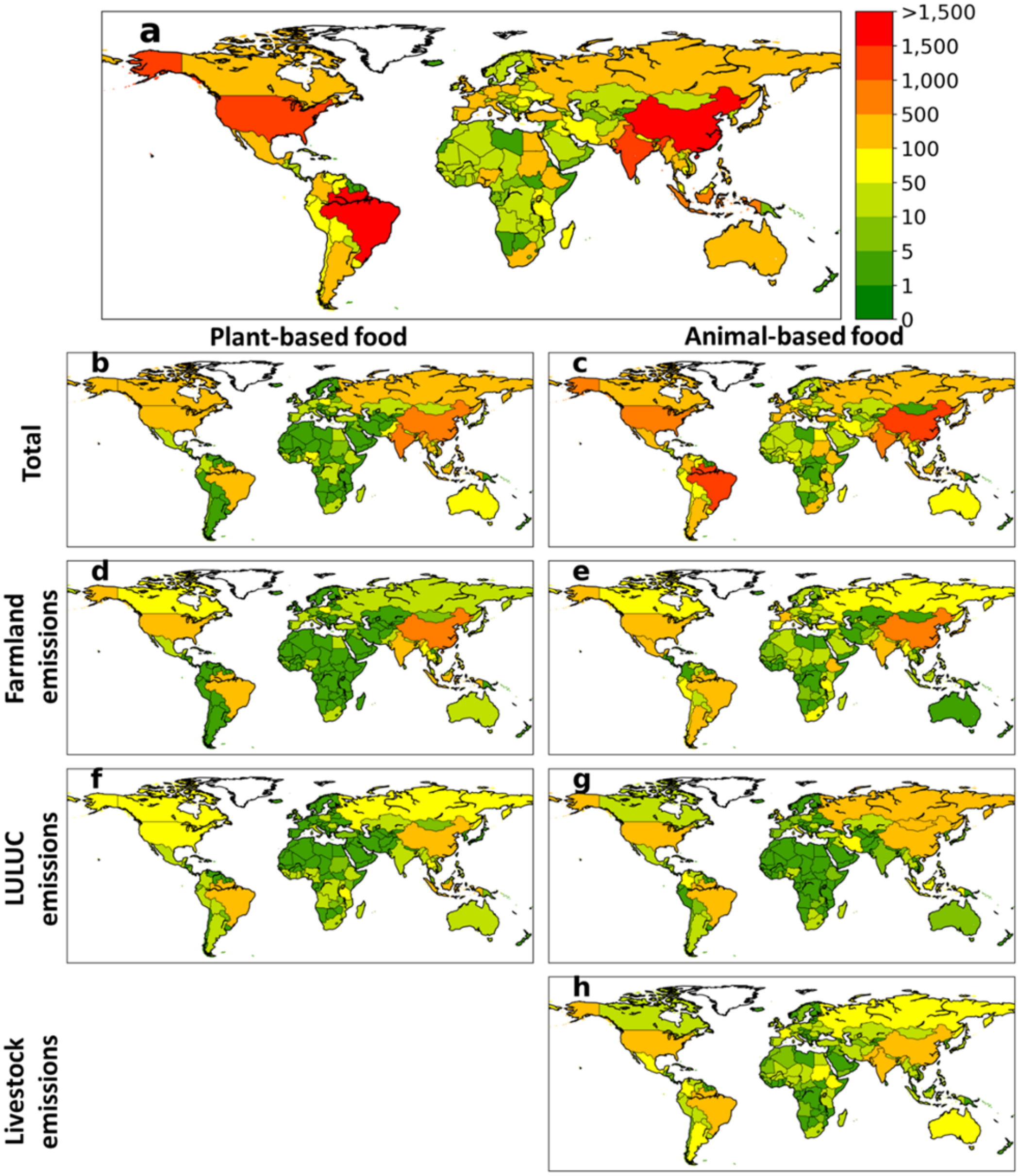

Mining, manufacturing and transporting fertilizers and pesticides 666
Land-use change emissions 5,094
Plant-based food Consumption-based 4,963 19% CO₂, 6% CH₄, 4% N₂O
Animal-based food Consumption-based 9,923 32% CO₂, 20% CH₄, 6% N₂O
Other utilizations Consumption-based 2,133 10% CO₂, 2% CH₄, 1% N₂O
Cropland 4,009
Pastureland 2,316
Enteric fermentation 3,160
Manure management 448
Product processing 1,296
Transportation, trade and stock variation -139
Fuel and energy use 169
Farmland
Livestock
Consumption -based

Fig. 1.



a
>1,500
1,500
1,000
500
100
50
10
5
1
0
Plant-based food
Animal-based food
b
c
Total
d
e
Farmland emissions
f
g
LULUC emissions
h
Livestock emissions

Fig. 2.

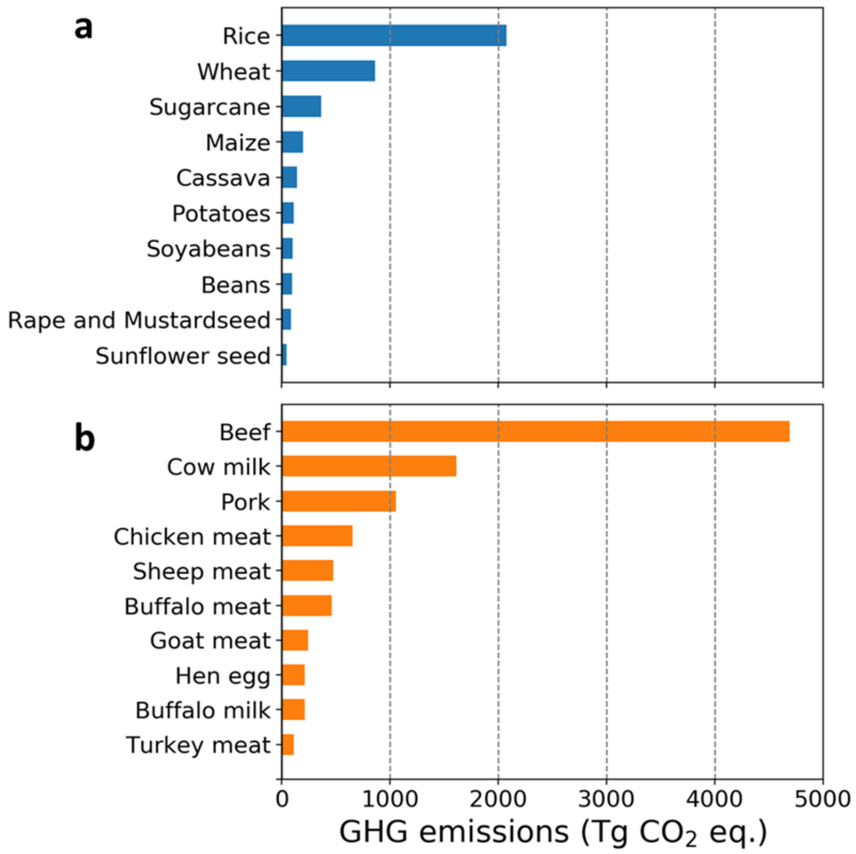

a
Rice
Wheat
Sugarcane
Maize
Cassava
Potatoes
Soyabeans
Beans
Rape and Mustardseed
Sunflower seed
b
Beef
Cow milk
Pork
Chicken meat
Sheep meat
Buffalo meat
Goat meat
Hen egg
Buffalo milk
Turkey meat
0
1000
2000
3000
4000
5000
GHG emissions (Tg CO_2 eq.)

Fig. 3.

Supplementary Materials

Global Greenhouse Gas Emissions from Plant- and Animal-Based Food

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Contents

Supplementary Text

S1. Method of Calculating Agricultural Biomass

S1.1. Crop Biomass

In this study, the agricultural land include both cropland and grazing land, in line with FAO land use definitions. Accordingly, grazing land includes managed pastureland and rangeland and other unmanaged grazing lands such as grassland, savannah, shrubland and tundra. 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. 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 circa 2010. We describe the method of producing crop production data in 2010 in the following sections.

The calculations of 16 major crops' productions are carried out using ISAM. These crops cover about 60% of total crop production and 66% of total crop harvested area. The calculations for an additional 155 crops are done using spatially explicit M3-crop production data for circa 2000 [1] and FAOSTAT reported crop production data [2], 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 produce the crop production and harvested area data at 0.5° x 0.5° spatial resolution circa 2010. The crop residue biomass of 16 major crops is directly calculated using ISAM. The crop residue biomass of the remaining 155 crops is calculated using the production data (produced in S1.3) and crop-specific harvest index (Table S1).

S1.2. ISAM Based Results for 16 Crops

The process-based dynamic crop and vegetation model (ISAM) [3,4] (see description in Text S2.1) 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 Text S1.3) to get their individual ~2010 production map at 0.5° x 0.5° 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 at a national scale. The results show that the ISAM results of the 16 major crops match well with the FAOSTAT crop production data at the national scale (Fig. S8). We use the production data of the 16 ISAM simulated crops, together with other 155 crops from updated M3-crop data to study the crop biomass and GHG emissions.

S1.3. M3 Data-based Results for 155 Crops

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 [1] as spatial references. We aggregate the

M3-crop production data in ~2000 from 5 x 5 arc minutes spatial resolution to 0.5^o x 0.5^o. We assume the spatial extents of all 155 crops under this spatial resolution in ~2010 are the same as ~2000, meaning that all 0.5^o x 0.5^o grids that have no particular crops (production of this crop equals to zero) in ~2000 will have no such crops in ~2010. We make this assumption because there is limited change in the spatial extent of cropland in different land cover products at a global scale during this period [5-7]. We then upscale the M3-crop production for the year 2000 to the country scale using the country mask produced from the Global Administrative Areas [8] v2.8 data.

2. Next, we calculate the crop- and country-specific production for 155 crops in ~2000 (average of available data from 1997 to 2003) and ~2010 (average of available data from 2007 to 2013) from the FAOSTAT dataset [2,9]. We calculate the crop- and country-specific changing rates of crop productions from year ~2000 to ~2010 as follows:

$$AR_{c,n} = \frac{Production2010_{c,n}}{Production2000_{c,n}} \quad \text{(Eq. S1)}$$

where, $AR_{c,n}$ is the changing rate of production of crop c in country n from 2000 to 2010; $Production2010_{c,n}$ and $Production2000_{c,n}$ are the production of crop c in country n in the years 2000 and 2010 calculated from FAOSTAT dataset.

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

4. Finally, we multiply each grid crop production value of M3-crop data for the year 2000 with the corresponding country crop production change value as calculated in step 3 to get the ~2010 spatial distributions of harvested area.

We use the same approach (steps 1-4) to calculate the spatial distribution of harvested areas for all 155 crops.

S1.4. Method of Quantifying Livestock Biomass Feed

We first calculate feed demand for 16 major livestock types (Table S4) in each country by multiplying the animal-specific feed demands per-head [10] with live animal heads [2]. We use the animal distribution maps from Gridded Livestock of the World v3.0 [11] 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. There are a few animals which lack of spatial distributions, including turkey, geese, camel, mule and camelid. We calculate their feed demands and supplies at a country scale while ensure the carbon and nitrogen balance. It is to note that we used a relatively simple, but well cited method [10] 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 total feed demand and does not consider the different digestibility of various feed categories.

We consider five types of livestock feeds; namely, crop grain feed, forage crop feed, crop residue feed, pasturefeed, 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, pasture 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 pasture 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 as credible. The crop residue feed, pasture feed and scavenging and other feed data sources at the country scale are less reliable. Therefore, we allocate crop grain feed and forage feed first, and then estimate the amounts of crop residue feed, pasture 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 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 producting 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 potential crop residue used as feed is calculated based on the method and data developed by Krausmann, et al. [10] (Table S13). We use ISAM simulated aboveground biomass of several plant functional types (PFTs) (that can produce pasture feed, such as C3 and C4 pastureland, C3 and C4 grassland) as potential pasture supply. We do not consider international trade of the pastures due to lack of information. 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 Fig. S7.

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 production of 16 specific crops (Text S1.2) are directly harvested from their PFTs, while the production of other 155 crops and forages (Text S1.3) 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 [12] 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 calculated by gridded crop production data and harvest indices (Table S1). Note that the harvest indices for C3 and C4 generic crops are weighted average values from corresponding crops.

We downscale the pasture feed biomass from country scale to gird level using the ISAM simulated aboveground biomass of grazing land and harvest these downscaled pasture 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 growing season, we first compare the harvested biomass (during the growing season) with the pasture feed demand in each country. For the countries whose pasture 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 pasture 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 pasture feed demand, we harvest all biomass on grazing land and assume the rest of the feed demand as scavenging and other feed.

S2. Extended Results and Discussion

S2.1. 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 (Table S3). 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 productiviy. 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) has the lowest (89 g C/m^2·yr).

Among all countries, China (11%) and USA (11%) produce the most agricultural biomass, followed by the Brazil (9%), and Russia (7%). USA has produced the most crop biomass, while China has produced the most grazing biomass (Fig. S2).

We estimated total 2,450 Tg C/yr of livestock (including 16 domesticated animals in Table S5) 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 present year but consumed in the future years – see method section), 12% with forage crop, 21% with crop residue, 42% with pasture feed. A fraction of 2% of animal feed is supplied with scavenging and other feed, which is 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 grazingland (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 area for growing feed) is more than five times the land used to produce plant-based food (Table S2). 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 hectare/yr, including 2.12 million hectares/yr of other land converted to agricultural land, and 2.01 million hectares/yr of agricultural land converted to other land (Table S2). Cropland has increased by 0.43 million hectares/yr, while grazing land has increased by 0.16 million hectares. Our estimated land use change area isdifferent 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 difference, 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 [7,13], while FAOSTAT is based on FAO questonnaires 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. Not that this biomass loss is not converting 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 Text S2.

Poore and Nemecek [14] 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 [7] 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 [14] 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. In our study, we do not allocate cropland to crop by-products, but assume all cropland is used for producing crop grains. Therefore, these crop by-products represent ~150 Mha of cropland in Poore and Nemecek [14] but zero in our results. It should be noted that Poore and Nemecek [14] 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. [15] (345 Mha vs. 350 Mha).

S2.2. Global Agricultural GHG Emissions Due to LUC

Agricultural LUC activities have caused 5,094 Tg CO_2 eq /yr emissions (Fig. 1), including 90% from cropland-related LUC activities, and 10% from grazing land-related LUC activities. Agriculture land is expanded mostly 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. Soil emissions due to LUC disturbance for cropland and grazing land are estimated as 40% and 3% of E_{luc}.

S2.3. 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, carbon content of dry matter from Wolf, et al. [16] and Feedipedia [17], calorie and protein fraction from different data sources, including FAO [18] (livestock products and crop grain feed), Feedipedia [17] (forage crops and crop residues), Eshel, et al. [19] (pasture feed), and Fung, et al. [20] (scavenging and other feed). 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, 8.31% based on calorie, and 8.49% based on protein. The spatial plots is shown in Fig. S3.

S2.4. Compairsons 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. Our estimated biomass feed demand (2,450 Tg C/yr, Table S2) is consistent with previous studies (range from ~2,000 to 3,000 Tg C/yr, see Table S7). Our estimated percentage of pasture 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%.

This study has not considered the different feed categories associated with different livestock animals and systems due to lack of detailed data, such as the different feed preferences for specific animals, and the distinguish between mixed feeding and pasture feeding systems [21]. Therefore, our estimated feed composition at the country scale cannot be used to study substitutions among different feed categories or livestock systems. In addition, we did not consider the digestibility of different feed categories for animals. This also limits the use of our results to estimate feed substitution studies.

S2.5. Compairsons 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 “beyond farm gate” emission is about half of IPCC SRCCL value (Table S8) [22]. One possible reason for this is that we do not consider the post-plate emissions (such as emissions from household refreigning 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) [22], and the global carbon budget 2019 estimates (5,500 ± 2,500 Tg CO_2 eq/yr) [23]. 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 eqfrom 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 ~22% higher than the GLEAM model results for livestock emissions in 2010 [24]. This difference is mainly caused by the CO_2 emissions from farmland activities (E_{farm} CO_2 in our study). Our estimated E_{farm} CO_2 of animal-based food is 2,823 ± 167 Tg CO_2 eq/yr, while GLEAM assumes this emission to be zero. In addition, the E_{luc} estimates are also different in two studies, mainly because we calculated using the processed-based model, while GLEAM uses the IPCC Tier 1 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[25], which is based on the IPCC Tier 1 method [26]. 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 [14] have complied 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.

S3. Extended Method

S3.1. Emissions from 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 [27-29], 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 is described in Text S6). We only consider N fertilizer for grazing land, the gridded M_i of N fertilizer for grazing land is derived from Xu, et al. [30]. M_i of pesticides at the country scale are from FAOSTAT [2]. Pesticides are not considered for grazing land.

$EF_{mm,i}$ of N, P, K fertilizers are from Kool, et al. [29], 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 [27,28], 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. [29], mainly because they provided consistent estimates of emission factors for N, P and K fertilizers at a continental scale. Kool, et al. [29] 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 ton-km of each commodity (kgCO_2 eq /ton-km), based on the emission factors (unit: kgCO_2 eq /ton-km) of different transport modes (road, rail, short sea, deep-sea, air freight and pipeline) from Kinnon [31] (Table S10) and ton-kms (unit: ton-km) of different transport mode for various commodities from Ecoinvent dataset [32]. Then we multiply this weighted average GHG emissions per ton-km with weighted average shipping distances (unit: km, calculated from Ecoinvent dataset[32]) to get the $EF_{ts,i}$ (unit: kgCO_2 eq/kg, see Table S11). 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.

S3.2. Livestock Emissions

Enteric fermentation. Ruminant animals, such as cattle, buffalo, sheep, and goat, 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 [33-35], which is based on the IPCC Tier 1 method [26] (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 [36].

We use CH_4 emissions from enteric fermentation and CH_4, N_2O emissions from manure management from FAOSTAT dataset, which do not include Efarm and Eluc. The Efarm and Eluc 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.

S3.3. 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}. We assume that all carbon accumulated in the crop growing season in the top 20 cm soils is released to the atmosphere through tillage after the harvest. Therefore, the tillage emission is calculated by differencing the soil organic carbon contents at the end and beginning of the crop growing season.

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

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

where, C_{feed} and C_{manure} are the biomass carbon in livestock feed and manure (see Text S1.4 for details); C_{ef} is the carbon as part of CH_4 emissions through enteric fermentation; and C_{prod} is the carbon stored in livestock products such as milk and eggs.

S4. ISAM Model Description

S4.1. ISAM Model Crop Module

ISAM calculates crop productivity, carbon, nitrogen, energy, and water fluxes at the spatial resolution of 0.5° (L/L) and at multiple temporal resolutions ranging from 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 [37]. Some of the important features, unique to ISAM and critical for crop productivity calculations, include [3,4]: (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.

S4.2. N_2O Emission Module

ISAM model contains detailed calculation of organic and mineral N cycle in the terrestrial ecosystem [38]. The major N processes in ISAM include biological fixation, leaching, mineralization and immobilization, plant uptake, nitrification and denitrification [38]. The household and sewage waste and recycling processes as described in Bodirsky, et al. [39] are not directly accounted for in our modeling framework, but they are lumped together with other processes, such as N application and leaching, as well as product pools for organic N. 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. 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 is 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 literatures as observations [40]. For each site, we performed ISAM model spin-up first to reach the steady state of soil organic carbon, organic nitrogen and mineral nitrogen under pre-industrial CO_2 and N deposition level. After reaching the steady-state, ISAM is forced with the historical climate reanalysis, CO_2 and N deposition time series to calculate the N_2O. We adjust the parameters to match observed annual soil N_2O emission (Fig. S9).

S4.3. 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 [3,41]. 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. Model 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. [42]. To determine the grid cell where is flooded, we separate naturally inundated areas from rice agriculture using a fractional inundation data [43] and a map of fractional rice harvested area [1]. 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 (Fig. S10).

A coupled rice-methane component of ISAM, which accounts for the processes of water, energy, and carbon exchange, is used to study CH_4 emissions from the rice fields [44]. The model explicitly accounts for heat storage and transfer at the surface water layer, rice-specific growth processes, and methane dynamics for rice [45]. 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 emission 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, and soil temperatures, momentum, energy, water and carbon fluxes, rice yield, CH_4 fluxes during both 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. [44] for model evaluation).

S5. Method of calculating GHG Emissions from 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) [46].

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 Table S9. As for animal-based commodities, we consider the pre-plate processing emissions for all 16 commodities as listed in Table S4.

For the crops with multiple processed products (Table S9), 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" [47]). The caloric values and GHG shares of different outputs can be found in Table S9. 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 in order to simplify the calculation. Other animal-based products, such as hide/skin, offal, and wool, are assumed to not carry GHG emissions. For example, the sheep produces 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.

S6. Method of Producing Spatial Maps of NPK Fertilizers in 2010

The EarthStat nutrient application dataset [48,49] provides crop-specific total N, P, K application amounts at 5 x 5 arc minutes spatial resolution for 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 [50]. We use the following equation to calculate the crop-specific fertilizer spatial maps at ~2010.

$$Fert\_2010_{c,g} = \frac{Fert\_2000_{c,g}}{Prod\_2000_{c,g}} \times Prod\_2010_{c,g} \qquad \text{(Eq. S4)}$$

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 rescale f each country's fertilizer amount to the FAOSTAT. This is because rescaling at a country scale may cause unrealistically high (or low) NPK fertilizer application rates in some countries, which could cause overestimation (or underestimation) of the ‘beyond farm gate’ emission and E_{farm}. Therefore, we only rescaled the data at a global scale to avoid over or under estimation.

The nitrogen input in EarthStat nutrient application dataset [48,49] has included total fertilizer amount, i.e., the sum of synthetic nitrogen fertilizer, manure, and atmospheric deposition. We use an estimated fraction of synthetic N fertilizer amount to total N application amount in cropland at the regional scale [51] 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 [48,49] (Table S1). 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. [37]. P and K maps are not used in the ISAM simulations; they are used in the calculation of the mining, manufacturing, and transporting emissions.

S7. 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} (Table S12). 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 (Table S12). Then we randomly sample these key variables within their uncertainty ranges (Table S12) 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. [52] 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 Figures

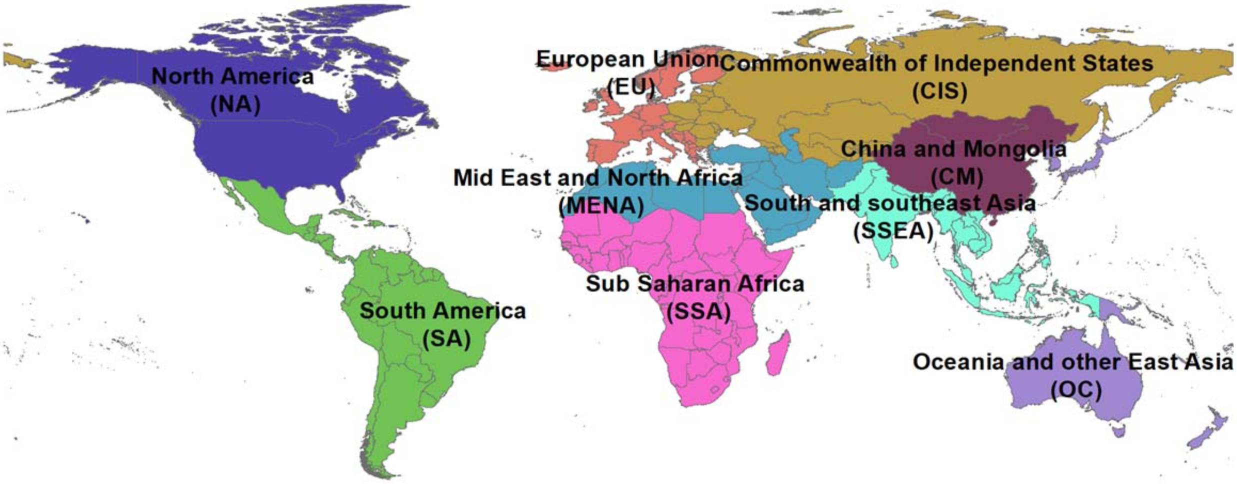

Fig. S1. Nine macro-geographical regions in this study.

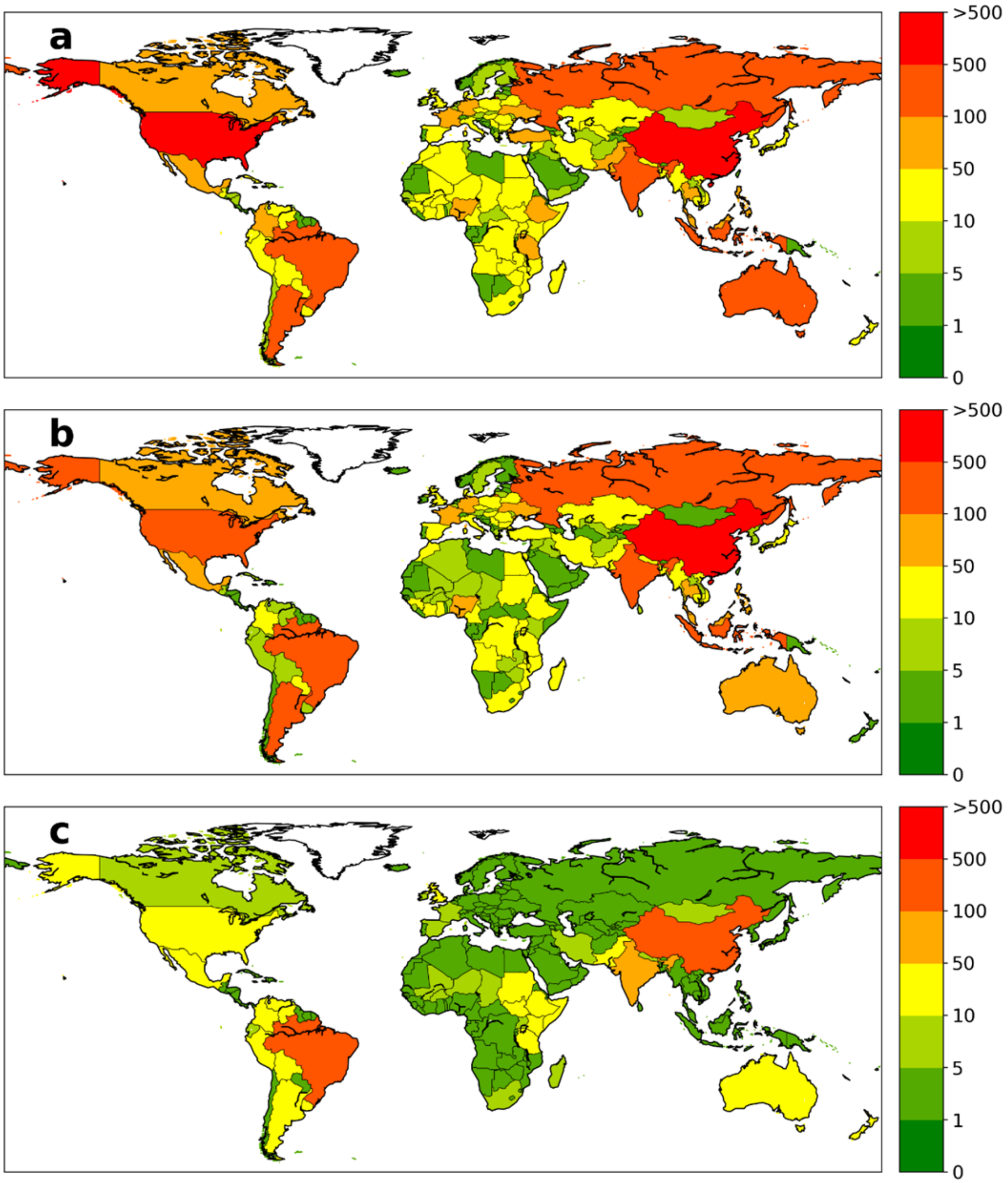

Fig. S2. Country-specific estimated total biomass production of a) cropland and grazing land, b) cropland, and c) grazing land (unit: Tg C/yr) for year 2010.

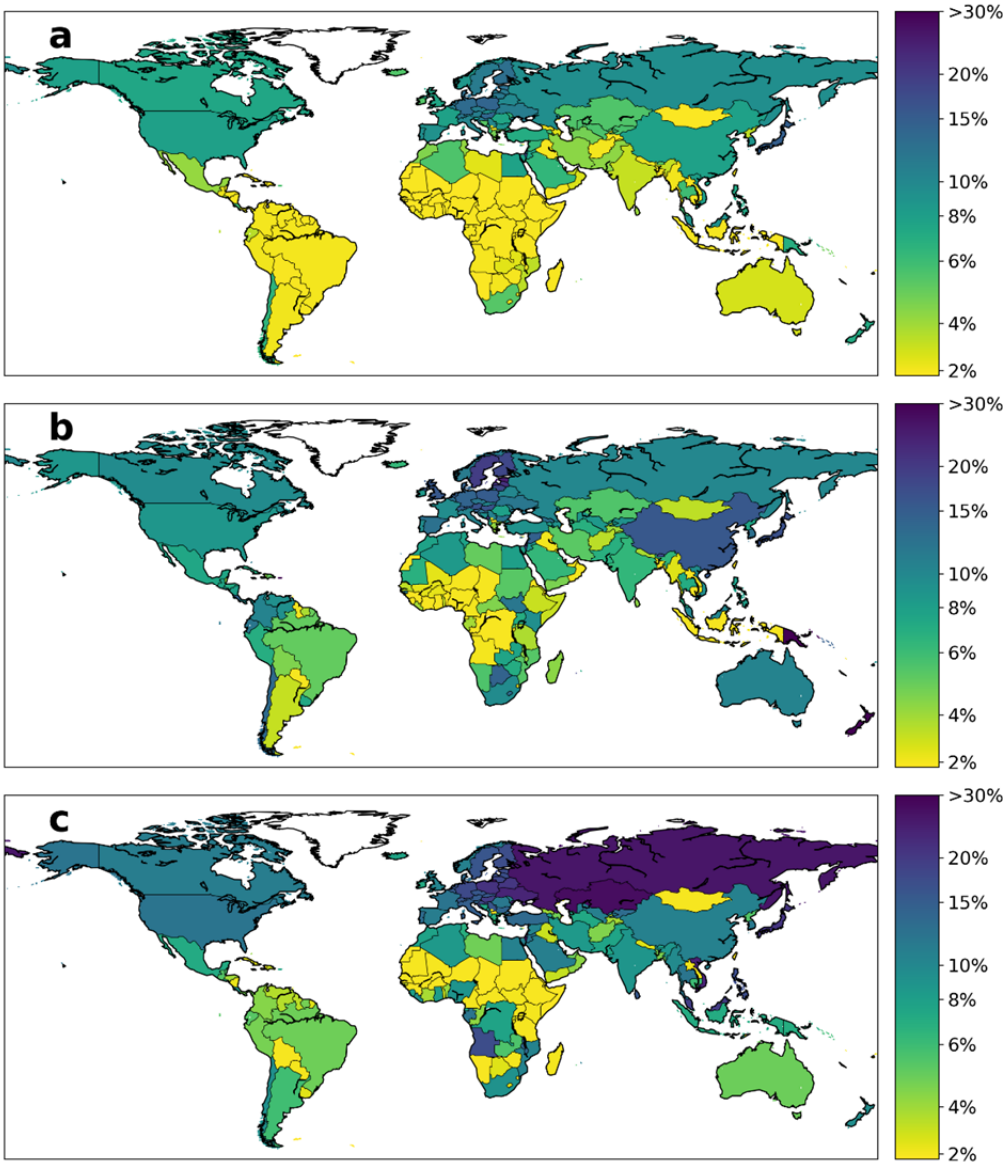

Fig. S3. Conversion efficiency from feed to livestock products from a) biomass, b) calorie, and c) protein.

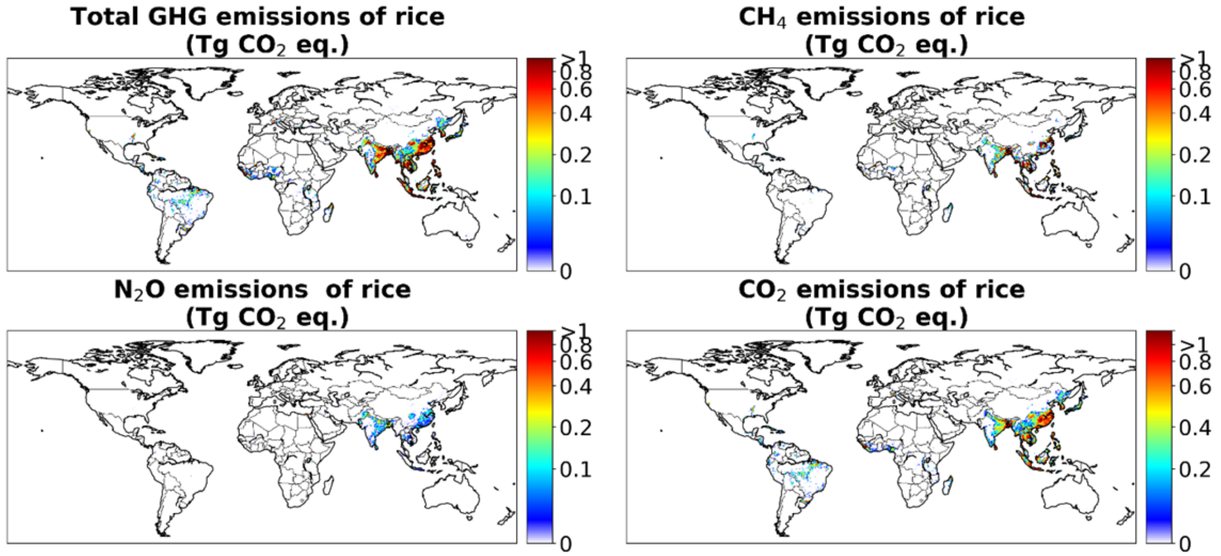

Fig. S4. Production-based GHG, CH_4, N_2O and CO_2 emissions for rice production.

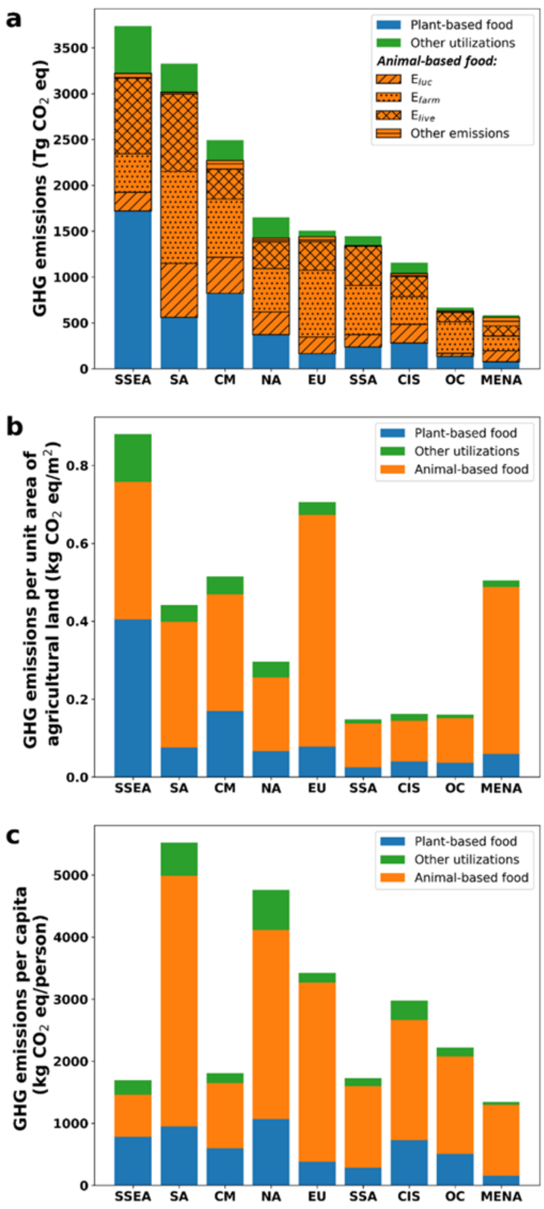

Fig. S5. Production-based GHG emissions from a) plant-based food, animal-based food and others in different regions, b) per unit area of agricultural land, and c) per capita. (NA: North America, SA: South America, EU: European Union, MENA: Mid East and North Africa, SSA: Sub-Saharan Africa, CIS: Commonwealth of Independent States, CM: China and Mongolia, SSEA: South and Southeast Asia, OC: Oceania and other East Asia)

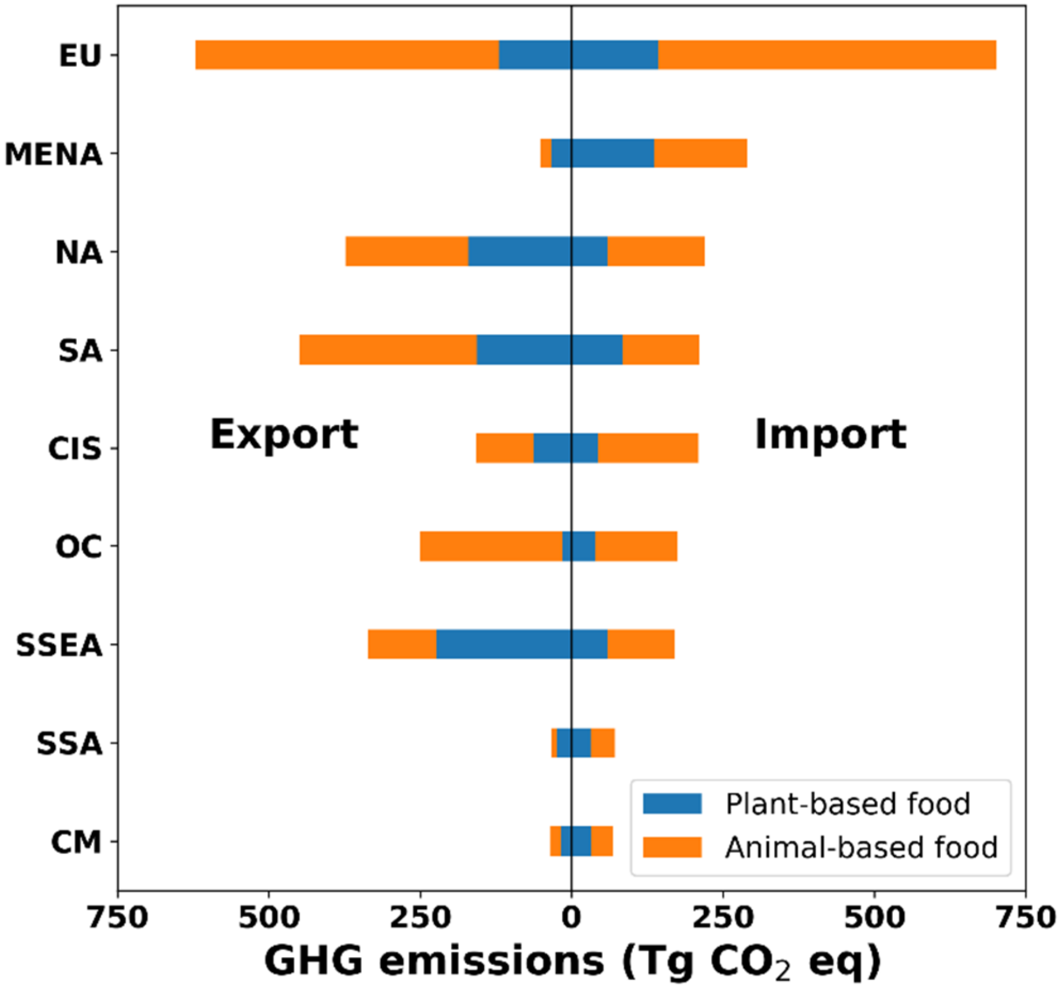

Fig. S6. GHG emissions due to import and export of both plant- and animal-based food in different regions (unit: Tg CO_2 eq/yr).

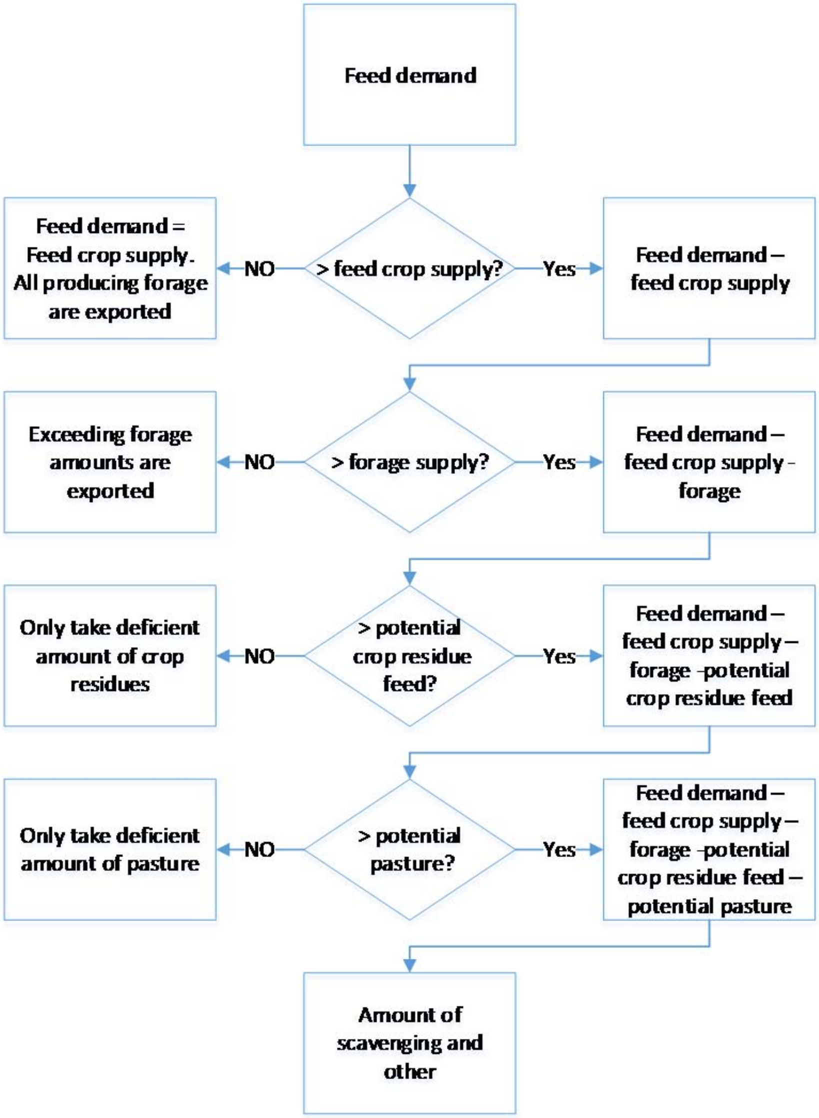

Fig. S7. Flowchart diagram of the livestock feed biomass balance at the country scale

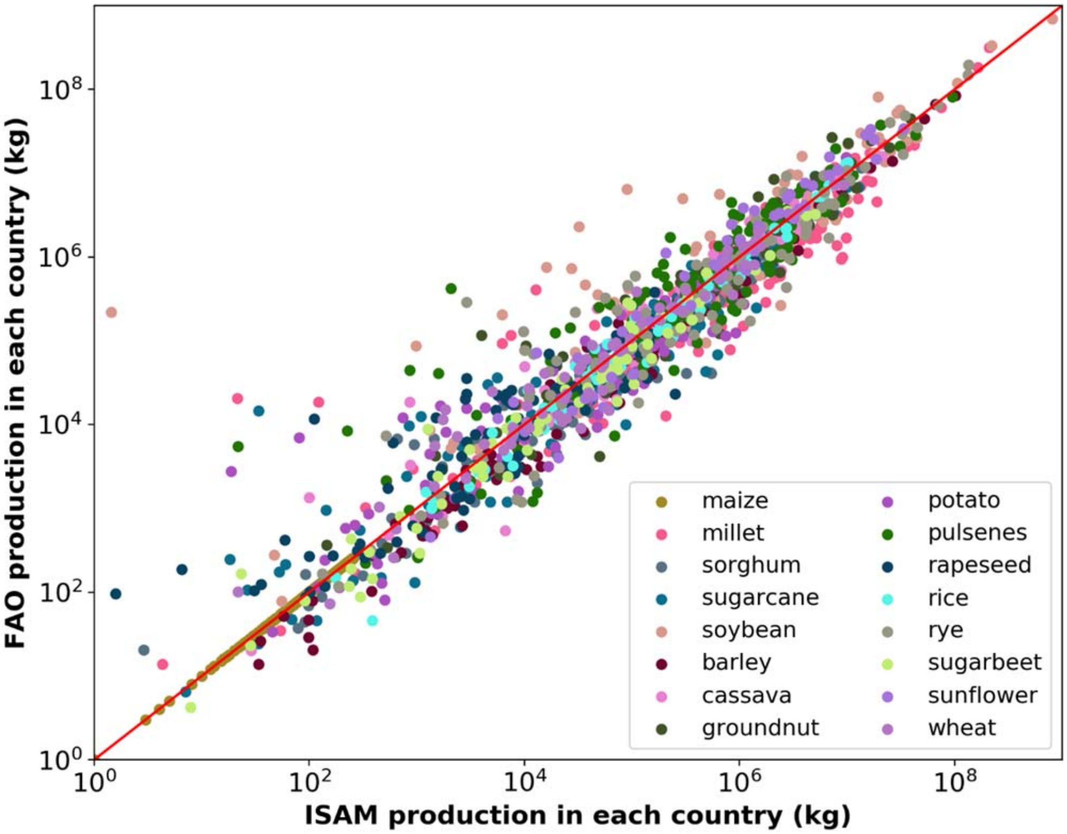

Fig. S8. Correlation between ISAM and FAOSTAT data for the crop production of 16 major crops at country scale.

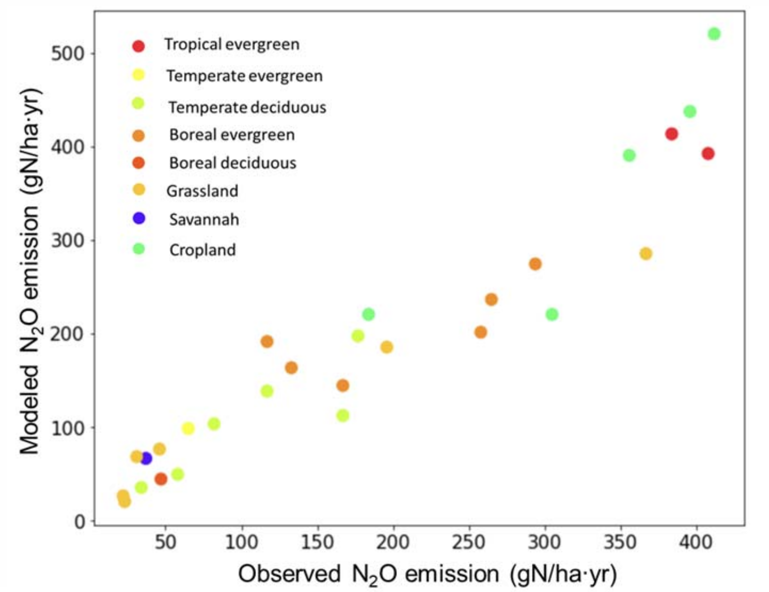

Fig. S9. The comparison between biome-specific observed and the ISAM modeled N_2O emission for model calibration and validation.

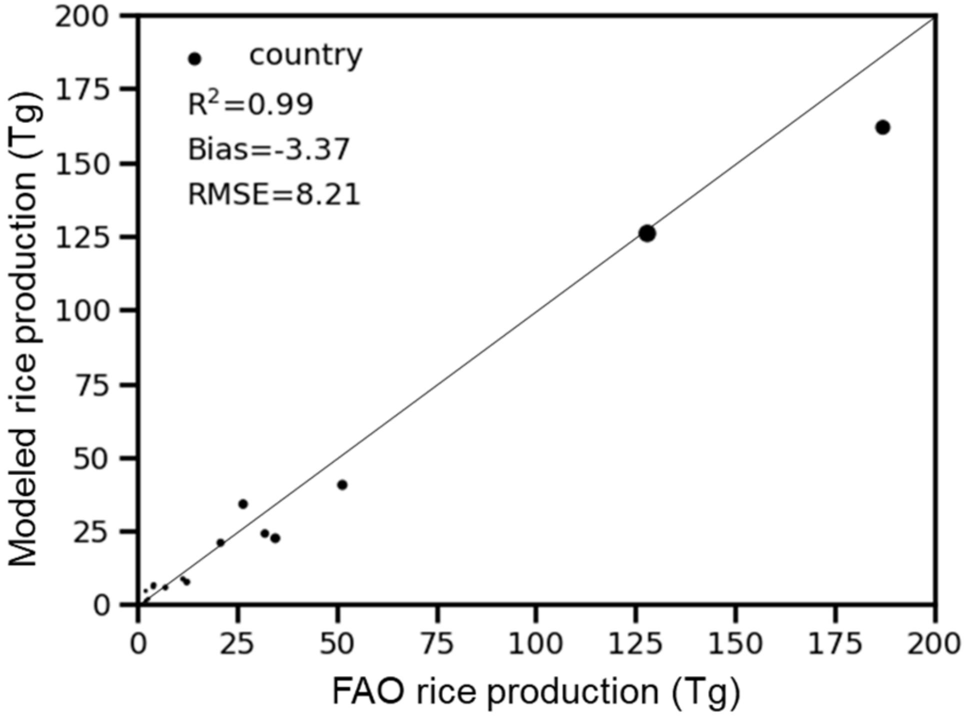

Fig. S10. Comparison of simulated and FAO rice production (Tg) of 16 major countries averaged over the period 1996-2005. The size of the dots is the harvested area of rice. Countries include China, Japan, Nepal, Pakistan, India, Sri Lanka, Bangladesh, Bhutan, Cambodia, Indonesia, Myanmar, Philippines, Thailand, Vietnam, Laos, and Malaysia.

Supplementary Tables

Table S1. 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., 2015
almond	Almonds, with shell	221	Treenuts	Nuts and products	0.42	0.15	0.20	0.62	Kyle et al., 2011
aniseetc*	Anise, badian, fennel, corian.	711	OtherCrops	Spices, Other	1.00	0.15	0.10	0.41	Kyle et al., 2011
apple	Apples	515	Fruit	Apples and products	0.85	0.15	0.80	0.41	Kyle et al., 2011
apricot	Apricots	526	Fruit	Fruits, Other	0.68	0.15	0.80	0.41	Kyle et al., 2011
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., 2015
asparagus	Asparagus	367	Vegetables&Melons	Vegetables, Other	0.49	0.15	0.70	0.41	Wolf et al., 2015
avocado	Avocados	572	Fruit	Fruits, Other	0.71	0.15	0.80	0.41	Kyle et al., 2011
bambara*	Bambara beans	203	Pulses	Pulses, Other and products	0.40	0.07	0.09	0.46	Wolf et al., 2015
banana	Bananas	486	Fruit	Bananas	0.40	0.42	0.74	0.41	Wolf et al., 2015
barley†	Barley	44	Cereals	Barley and products	0.46	0.11	0.13	0.46	Wolf et al., 2015
bean	Beans, dry	176	Pulses	Beans	0.46	0.08	0.16	0.46	Wolf et al., 2015
beetfor	beetfor	647	Forage	-	0.95	0.43	0.85	0.41	Wolf et al., 2015
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., 2015
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., 2015
buckwheat	Buckwheat	89	Cereals	Cereals, Other	0.43	0.10	0.13	0.46	Wolf et al., 2015
cabbage	Cabbages and other brassicas	358	Vegetables&Melons	Vegetables, Other	0.80	0.15	0.92	0.41	Wolf et al., 2015
cabbagefor	cabbagefor	644	Forage	-	0.95	0.15	0.92	0.41	Wolf et al., 2015
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., 2015
carrotfor*	carrotfor	648	Forage	-	0.95	0.15	0.87	0.41	Wolf et al., 2015
cashew*	Cashew nuts, with shell	217	Treenuts	Nuts and products	0.40	0.15	0.20	0.62	Kyle et al., 2011
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., 2015
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., 2015
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., 2011
chestnut	Chestnuts	220	Treenuts	Nuts and products	0.40	0.15	0.20	0.62	Kyle et al., 2011
chickpea	Chick peas	191	Pulses	Pulses, Other and products	0.46	0.08	0.13	0.46	Wolf et al., 2015
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., 2015
cinnamon*	Cinnamon (canella)	693	OtherCrops	Spices, Other	1.00	0.15	0.10	0.41	Kyle et al., 2011
citrusnes	Citrus fruit, nes	512	Fruit	Citrus, Other	0.93	0.15	0.80	0.41	Kyle et al., 2011
clove*	Cloves	698	OtherCrops	Cloves	1.00	0.15	0.10	0.41	Kyle et al., 2011
clover	clover	640	Forage	-	0.95	1.10	0.65	0.44	Wolf et al., 2015
cocoa	Cocoa beans	661	OtherCrops	Cocoa Beans and products	1.00	0.15	0.11	0.41	Kyle et al., 2011
coconut	Coconuts	249	Oilcrops	Coconuts - Incl Copra	0.66	0.15	0.80	0.63	Wolf et al., 2015
coffee	Coffee, green	656	OtherCrops	Coffee and products	1.00	0.15	0.11	0.41	Kyle et al., 2011
cotton	Seed cotton	328	Fiber	-	0.40	0.17	0.08	0.54	Wolf et al., 2015
cowpea	Cow peas, dry	195	Pulses	Pulses, Other and products	0.45	0.08	0.16	0.46	Wolf et al., 2015
cranberry	Cranberries	554	Fruit	Fruits, Other	1.00	0.15	0.90	0.41	Wolf et al., 2015
cucumberetc	Cucumbers and gherkins	397	Vegetables&Melons	Vegetables, Other	0.80	0.15	0.96	0.41	Wolf et al., 2015
currant	Currants	550	Fruit	Fruits, Other	1.00	0.15	0.80	0.41	Kyle et al., 2011
date	Dates	577	Fruit	Dates	0.80	0.15	0.23	0.41	Wolf et al., 2015
eggplant	Eggplants (aubergines)	399	Vegetables&Melons	Vegetables, Other	0.59	0.15	0.80	0.41	Wolf et al., 2015
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., 2011
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., 2015
fornes	fornes	651	Forage	-	0.95	0.18	0.65	0.44	Wolf et al., 2015
fruitnes	Fruit Fresh Nes	619	Fruit	Fruits, Other	1.00	0.15	0.70	0.41	Kyle et al., 2011
garlic	Garlic	406	Vegetables&Melons	Vegetables, Other	1.00	0.15	0.64	0.41	Wolf et al., 2015
ginger*	Ginger	720	OtherCrops	Spices, Other	1.00	0.15	0.70	0.41	Wolf et al., 2015
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., 2015
grapefruitet	Grapefruit (inc.	507	Fruit	Grapefruit and products	0.93	0.15	0.80	0.44	Kyle et al., 2011

Crop name	**Crop name FAO**	**FAO Code**	**Category**	**Corresponding Commodity Item**	**Harvest Index**	**Root:Shoot_ ratio**	**Water Content**	**Carbon content**	**References**
c	pomelos)								
grassnes	grassnes	639	Forage	-	0.95	1.81	0.65	0.44	Wolf et al., 2015
greenbean	Beans, green	414	Vegetables&Melons	Vegetables, Other	0.46	0.08	0.79	0.41	Wolf et al., 2015
greenbroad bean	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., 2015
greenonion	Onions (inc. shallots), green	402	Vegetables&Melons	Vegetables, Other	0.56	0.15	0.90	0.41	Wolf et al., 2015
greenpea	Peas, green	417	Vegetables&Melons	Vegetables, Other	0.30	0.08	0.79	0.41	Wolf et al., 2015
groundnut†	Groundnuts, with shell	242	Oilcrops	Groundnuts (in Shell Eq)	0.40	0.07	0.09	0.60	Wolf et al., 2015
hazelnut	Hazelnuts, with shell	225	Treenuts	Nuts and products	0.40	0.15	0.20	0.62	Kyle et al., 2011
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., 2015
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., 2015
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., 2011
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., 2015
lemonlime	Lemons and limes	497	Fruit	Lemons, Limes and products	0.95	0.15	0.80	0.41	Kyle et al., 2011
lentil	Lentils	201	Pulses	Pulses, Other and products	0.61	0.15	0.16	0.46	Wolf et al., 2015
lettuce	Lettuce and chicory	372	Vegetables&Melons	Vegetables, Other	0.94	0.15	0.96	0.41	Wolf et al., 2015
linseed	Linseed	333	Oilcrops	Oilcrops, Other	0.26	0.15	0.08	0.62	Wolf et al., 2015
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., 2015
maizefor	maizefor	636	Forage	-	0.95	0.18	0.65	0.44	Wolf et al., 2015
mango	Mangoes, mangosteens, guavas	571	Fruit	Fruits, Other	0.45	0.15	0.80	0.41	Kyle et al., 2011
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., 2015
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., 2015

Crop name	**Crop name FAO**	**FAO Code**	**Category**	**Corresponding Commodity Item**	**Harvest Index**	**Root:Shoot_ratio**	**Water Content**	**Carbon content**	**References**
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., 2011
mustard	Mustard seed	292	Oilcrops	Rape and Mustardseed	0.30	0.15	0.90	0.62	Wolf et al., 2015
nutmeg*	Nutmeg, mace and cardamoms	702	OtherCrops	Spices, Other	1.00	0.15	0.08	0.41	Kyle et al., 2011
nutnes	Nuts, nes	234	Treenuts	Nuts and products	0.40	0.15	0.10	0.62	Kyle et al., 2011
oats	Oats	75	Cereals	Oats	0.52	0.40	0.20	0.46	Wolf et al., 2015
oilpalm	Oil palm fruit	254	Oilcrops	Palm kernels	0.46	0.15	0.13	0.62	Wolf et al., 2015
oilseedfor	oilseedfor	642	Forage	-	0.95	1.10	0.35	0.44	Wolf et al., 2015
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., 2015
olive	Olives	260	Oilcrops	Olives (including preserved)	0.69	0.15	0.91	0.62	Kyle et al., 2011
onion	Onions, dry	403	Vegetables&Melons	Onions	0.56	0.15	0.70	0.41	Wolf et al., 2015
orange	Oranges	490	Fruit	Oranges, Mandarines	0.91	0.15	0.90	0.41	Kyle et al., 2011
papaya	Papayas	600	Fruit	Fruits, Other	0.99	0.15	0.80	0.41	Kyle et al., 2011
pea	Peas, dry	187	Pulses	Peas	0.30	0.08	0.80	0.46	Wolf et al., 2015
peachetc	Peaches and nectarines	534	Fruit	Fruits, Other	0.86	0.15	0.13	0.41	Kyle et al., 2011
pear	Pears	521	Fruit	Fruits, Other	0.88	0.15	0.80	0.41	Kyle et al., 2011
pepper	Pepper (Piper spp.)	687	OtherCrops	Pepper	1.00	0.15	0.80	0.41	Kyle et al., 2011
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., 2015
pimento*	Chillies and peppers, dry	689	OtherCrops	Pimento	0.60	0.15	0.13	0.41	Wolf et al., 2015
pineapple	Pineapples	574	Fruit	Pineapples and products	0.26	0.15	0.10	0.41	Wolf et al., 2015
pistachio	Pistachios	223	Treenuts	Nuts and products	0.40	0.15	0.80	0.62	Kyle et al., 2011
plantain	Plantains	489	Fruit	Plantains	0.40	0.42	0.20	0.41	Wolf et al., 2015
plum	Plums and sloes	536	Fruit	Fruits, Other	0.80	0.15	0.65	0.41	Kyle et al., 2011
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., 2015
pulsenes†	Pulses, nes	211	Pulses	Pulses, Other and products	0.35	0.15	0.80	0.46	Kyle et al., 2011
pumpkinetc	Pumpkins, squash and gourds	394	Vegetables&Melons	Vegetables, Other	0.88	0.15	0.70	0.41	Wolf et al., 2015
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., 2015

Crop name	**Crop name FAO**	**FAO Code**	**Category**	**Corresponding Commodity Item**	**Harvest Index**	**Root:Shoot_ ratio**	**Water Content**	**Carbon content**	**References**
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., 2015
rasberry	Raspberries	547	Fruit	Fruits, Other	1.00	0.15	0.07	0.41	Wolf et al., 2015
rice†	Rice, paddy	27	Cereals	Rice (Paddy Equivalent)	0.42	0.22	0.87	0.46	Wolf et al., 2015
rootnes	Roots and Tubers, nes	149	Roots&Tubers	Roots, Other	0.94	0.15	0.09	0.41	Kyle et al., 2011
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., 2015
ryefor	ryefor	638	Forage	-	0.95	1.50	0.10	0.44	Wolf et al., 2015
safflower	Safflower seed	280	Oilcrops	Oilcrops, Other	0.20	0.10	0.65	0.62	Wolf et al., 2015
sesame	Sesame seed	289	Oilcrops	Sesame seed	0.27	0.15	0.08	0.62	Wolf et al., 2015
sisal	Sisal	789	Fiber	Sisal	0.04	0.04	0.05	0.44	Wolf et al., 2015
sorghum†	Sorghum	83	Cereals	Sorghum and products	0.44	0.18	0.08	0.46	Wolf et al., 2015
sorghumfor	sorghumfor	637	Forage	-	0.95	0.18	0.14	0.44	Wolf et al., 2015
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., 2015
spicenes*	Spices, nes	723	OtherCrops	Spices, Other	1.00	0.15	0.12	0.41	Kyle et al., 2011
spinach	Spinach	373	Vegetables&Melons	Vegetables, Other	0.95	0.15	0.10	0.41	Wolf et al., 2015
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., 2015
stringbean	String beans	423	Vegetables&Melons	Vegetables, Other	0.46	0.08	0.92	0.41	Wolf et al., 2015
sugarbeet†	Sugar beet	157	SugarCrops	Sugar beet	0.40	0.43	0.79	0.41	Wolf et al., 2015
sugarcane†	Sugar cane	156	SugarCrops	Sugar cane	0.75	0.18	0.85	0.41	Wolf et al., 2015
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., 2015
swedefor*	swedefor	649	Forage	-	0.95	0.15	0.09	0.41	Wolf et al., 2015
sweetpotato	Sweet potatoes	122	Roots&Tubers	Sweet potatoes	0.53	0.15	0.87	0.41	Wolf et al., 2015
tangetc	Tangerines, mandarins, clem.	495	Fruit	Oranges, Mandarines	0.91	0.15	0.80	0.41	Kyle et al., 2011
taro	Taro (cocoyam)	136	Roots&Tubers	Roots, Other	0.53	0.15	0.80	0.41	Wolf et al., 2015
tea	Tea	667	OtherCrops	Tea (including mate)	1.00	0.15	0.80	0.41	Kyle et al., 2011
tobacco	Tobacco, unmanufactured	826	OtherCrops	Tobacco	0.60	0.80	0.10	0.44	Wolf et al., 2015
tomato	Tomatoes	388	Vegetables&Melons	Tomatoes and products	0.33	0.14	0.20	0.41	Wolf et al., 2015
triticale	Triticale	97	Cereals	Cereals, Other	0.50	0.14	0.95	0.46	Wolf et al., 2015
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

Crop name	**Crop name FAO**	**FAO Code**	**Category**	**Corresponding Commodity Item**	**Harvest Index**	**Root:Shoot_ ratio**	**Water Content**	**Carbon content**	**References**
turnipfor	turnipfor	646	Forage	-	0.95	0.15	0.70	0.41	Wolf et al., 2015
vanilla*	Vanilla	692	OtherCrops	Spices, Other	1.00	0.15	0.87	0.41	Kyle et al., 2011
vegetablenes	Vegetables fresh nes	463	Vegetables&Melons	Vegetables, Other	1.00	0.15	0.10	0.41	Kyle et al., 2011
vegfor	vegfor	655	Forage	-	0.95	0.15	0.80	0.41	Wolf et al., 2015
vetch*	Vetches	205	Pulses	Pulses, Other and products	0.95	1.10	0.87	0.44	Wolf et al., 2015
walnut	Walnuts, with shell	222	Treenuts	Nuts and products	0.40	0.15	0.65	0.62	Kyle et al., 2011
watermelon	Watermelons	567	Vegetables&Melons	Vegetables, Other	0.91	0.15	0.20	0.41	Wolf et al., 2015
wheat†	Wheat	15	Cereals	Wheat and products	0.39	0.20	0.92	0.46	Wolf et al., 2015
yam	Yams	137	Roots&Tubers	Yams	0.53	0.15	0.13	0.41	Wolf et al., 2015
yautia*	Yautia (cocoyam)	135	Roots&Tubers	Roots, Other	0.53	0.15	0.80	0.41	Wolf et al., 2015

* indicates the crops whose spatial N, P, K fertilizer maps are not available

† denotes the 16 specific crops (PFTs) in ISAM model

Table S2. Land area (unit: million hectare, Mha) and biomass productivity (unit: Tg C/yr) of crop and grazing land for plant- and animal-based food and other utilizations.

	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
Pasture 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, as well as the discrepancies of the biomass of 16 major crops between ISAM simulations and FAO reported values.

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

Table S3. Area 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	5,259	378	3,170	3710	117	6,912

Table S4. Livestock list and its products

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

Table S5. Livestock feed demand, composition and manure carbon amount at country scale (Unit: Gigagram C)

Country	**Total feed demand**	**Crop grain feed**	**Forage crop feed**	**Crop residue feed**	**Pasture 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

Country	**Total feed demand**	**Crop grain feed**	**Forage crop feed**	**Crop residue feed**	**Pasture feed**	**Scavenging and other feed**	**Manure carbon amount**
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
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

Country	Total feed demand	Crop grain feed	Forage crop feed	Crop residue feed	Pasture feed	Scavenging and other feed	Manure carbon amount
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
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

Country	Total feed demand	Crop grain feed	Forage crop feed	Crop residue feed	Pasture feed	Scavenging and other feed	Manure carbon amount
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
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

Table S6. 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 (Cal/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 residue	0.91	0.44	3371	0.04
Pasture			562 (dry matter)	0.19 (fraction of dry matter)
Scavenging and others			5153 (dry matter)	0.19 (fraction of dry matter)

Table S7. Comparison between the feed biomass estimation (percentage of total feed biomass in bracket) (Unit: Tg C/yr)

Biomass		**This study**	**IPCC AR5/ Smith, et al.** [53]*	**Wolf, et al.** [16]	**Wolf, et al.** [54]	**Krausmann, et al.** [10]*	**Herrero, et al.** [21]*	**GLEAM** [55]*
Year		**Circa 2010**	**2000**	**2009**	**2011**	**2000**	**2000**	**2010**
Livestock feed	Crop grain	562 (23%)	1382 (45%)	391 (16%)	493 (17%)	396 (13%)	572 (28%)	634 (24%)
	Forage	289 (12%)		237 (10%)	217 (7%)	1,012 (33%)	252 (12%)	211 (8%)
	Crop residue	523 (21%)		492 (20%)	537 (19%)		246 (12%)	502 (19%)
	Pasture	1,028 (42%)	1,703 (55%)	1,308 (54%)	1,650 (57%)	1,687 (55%)	995 (48%)	1,214 (46%)
	Scavenging and others	48 (2%)						79 (3%)
	Sum	*2,450*	*3,085*	*2,428*	*2,897*	*3,095*	*2,065*	*2,640*

* assume 0.44 carbon content of dry matter

Table S8. Comparison between the biomass estimation and GHG emissions (unit: Tg CO_2 eq/yr)

GHG emission	**Gas**	**This study (Circa 2010)**	**IPCC AR5 WG3[46] (2010)**	**FAOSTAT[25] (2010)**	**IPCC SRCCL[22] (Mean of 2007-2016)**	**Carlson et al.[56] (circa 2000)**	**EDGAR v4.3.2[57] (2010)**	**Poore and Nemecek [14] (Circa 2010)**
Beyond farm gate emissions		**1,962**			**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	1,296						1,400
Farmland emissions		**6,490 ± 1,814**	**5,400 (5,000 – 5,800)** combined farmland and livestock emissions	**3,432**	**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	3,082 ± 182						
Rice cultivation	CH_4	1,283 ± 1,788		831		962 ± 2,170	1,258 (total agricultural soil emission)	1,108
Synthetic fertilizers and manure for all crops and grazing land	N_2O	1,956 ± 244		1,753		403 ± 74 (only for cropland)	1,460 (total agricultural soil emission)	
Livestock emissions		**3,602 ± 822**		**3,675**			**3,909**	**4,140**
Enteric Fermentation	CH_4	3,156 ± 816 (calculated from FAOSTAT [25])		3,223			3,400	
Manure Management	CH_4	317 ± 48 (calculated from FAOSTAT [25])		321			408	
	N_2O	129 ± 108 (calculated from FAOSTAT [25])		131			101	
LUC emissions		**5,096 ± 301**	**4,900 (4,300–5,500)**	**3,346**	**4,900 ± 2,500**	**630 ± 90 ***		**2,380**
Total		**17,150 ± 1,760**	**11,000 (10,000 – 12,000**	**10,978 ****	**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 [25] and Poore and Nemecek [14] 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.

Table S9. By-product allocation parameters of different crops, and processing emission factors

Commodity name	Products	Mass share of products	Energy (kcal/ton)	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
Oil palm fruit	Palm kernel	0.19	5140000	0.70	0.77	0.009
	Oil of palm	0.06	4971319	0.00	0.23	0.014

Commodity name	**Products**	**Mass share of products**	**Energy (kcal/ton)**	**Water content**	**Emission share**	**Processing GHG emission factor**
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

Table S10. Emission factors of different transportation mode [31,32]

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

Table S11. 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

Table S12. Uncertainty ranges and probability distribution functions of major biomass and GHG emission sources

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 [58]	IPCC [26] 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[59]	IPCC [26] 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 [60]	Meiyappan, et al. [52]
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 [59]	IPCC [26] 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 [59]	IPCC [26] 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 [59]	IPCC [26] and references therein

Table S13. Residue biomass carbon (Tg C/yr) 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*
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.

References for Supplementary

1 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).

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

3 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).

4 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).

5 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).

6 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).

7 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).

8 Global Administrative Areas. GADM Database of Global Administrative Areas, version 2.8. *URL* http://www.gadm.org (2018).

9 FAO. FAOSTAT. Food and Agriculture Organization of the United Nations, Rome, Italy. Available at http://faostat.fao.org/. (2010).

10 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).

11 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).

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

13 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).

14 Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987-992, doi:10.1126/science.aaq0216 (2018).

15 Foley, J. A. *et al.* Solutions for a cultivated planet. *Nature* **478**, 337-342, doi:10.1038/nature10452 (2011).

16 Wolf, J. *et al.* Biogenic carbon fluxes from global agricultural production and consumption. *Global Biogeochem Cy* **29**, 1617-1639, doi:10.1002/2015gb005119 (2015).

17 Feedipedia. (2020).

18 FAO. Nutritive Factors. *http://www.fao.org/economic/the-statistics-division-ess/publications-studies/publications/nutritive-factors/en/[Accessed: July 15, 2020]* (2020).

19 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).

20 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).

21 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).

22 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).

23 Friedlingstein, P. *et al.* Global carbon budget 2019. *Earth Syst Sci Data* **11**, 1783-1838 (2019).

24 FAO. *Five practical actions towards low-carbon livestock. Rome.* (2019).

25 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).

26 IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. (Institutefor Global Environmental Strategies, 2006).

27 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).

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

29 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).

30 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).

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

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

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

34 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).

35 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).

36 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).

37 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).

38 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).

39 Bodirsky, B. L. *et al.* Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nat Commun* **5**, 3858, doi:10.1038/ncomms4858 (2014).

40 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).

41 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).

42 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).

43 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).

44 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).

45 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).

46 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).

47 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).

48 Mueller, N. D. *et al.* Closing yield gaps through nutrient and water management. *Nature* **490**, 254-257, doi:10.1038/nature11420 (2012).

49 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).

50 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).

51 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).

52 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).

53 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).

54 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).

55 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).

56 Carlson, K. M. *et al.* Greenhouse gas emissions intensity of global croplands. *Nat Clim Change* **7**, 63-+, doi:10.1038/Nclimate3158 (2017).

57 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).

58 Penman, J. *et al.* Good practice guidance and uncertainty management in national greenhouse gas inventories. (2000).

59 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).

60 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).