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Biogenic carbon fluxes from global agricultural production and consumption

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Key Points:

- Global crop NPP in 2011 was 5.25 Pg C with 2.05 Pg C harvested
- Livestock intake in 2011 was 2.42 Pg C with 52% foraged from noncropland
- Global cropland budget accounts for approximately 80% of harvested carbon

Supporting Information:

- Figure S1
- Figure S2
- Texts S1–S3, Tables S5, S8, and S10–S13, and Figures S1 and S2
- Table S1
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- Table S4
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- Table S9

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Biogenic carbon fluxes from global agricultural production and consumption

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Abstract Quantification of biogenic carbon fluxes from agricultural lands is needed to generate comprehensive bottom-up estimates of net carbon exchange for global and regional carbon monitoring. We estimated global agricultural carbon fluxes associated with annual crop net primary production (NPP), harvested biomass, and consumption of biomass by humans and livestock. These estimates were combined for a single estimate of net carbon exchange and spatially distributed to 0.05° resolution using Moderate Resolution Imaging Spectroradiometer satellite land cover data. Global crop NPP in 2011 was estimated at 5.25 ± 0.46 Pg C yr⁻¹, of which 2.05 ± 0.05 Pg C yr⁻¹ was harvested and 0.54 Pg C yr⁻¹ was collected from crop residues for livestock fodder. Total livestock feed intake in 2011 was 2.42 ± 0.21 Pg C yr⁻¹, of which 2.31 ± 0.21 Pg C yr⁻¹ was emitted as CO₂, 0.07 ± 0.01 Pg C yr⁻¹ was emitted as CH₄, and 0.04 Pg C yr⁻¹ was contained within milk and egg production. Livestock grazed an estimated 1.27 Pg C yr⁻¹ in 2011, which constituted 52.4% of total feed intake. Global human food intake was 0.57 ± 0.03 Pg C yr⁻¹ in 2011, the majority of which was respired as CO₂. Completed global cropland carbon budgets accounted for the ultimate use of approximately 80% of harvested biomass. The spatial distribution of these fluxes may be used for global carbon monitoring, estimation of regional uncertainty, and for use as input to Earth system models.

1. Introduction

A need exists for a globally consistent estimate of carbon uptake by crops and subsequent emissions to the atmosphere via decomposition; and consumption of crop commodities. A globally consistent estimate can be used to compare with, and constrain, atmospheric estimates of carbon fluxes. A similar data set for the U.S. [West et al., 2011] was used for comparison of bottom-up and top-down estimates under the North American Carbon Program [Miles et al., 2012; Schuh et al., 2013]. A globally consistent estimate can also serve to quantify supply and demand of crop commodities in integrated assessment models, thereby enabling analyses of land sustainability, food security, land cover change, and carbon flux contributions to global emissions scenarios [Wise et al., 2009; Thomson et al., 2011, 2014]. Global estimates can therefore contribute to Integrated Assessment and Earth System models [van Asselen and Verburg, 2013; Jones et al., 2013], to models estimating regional and global carbon flux [Potter, 2010; van der Werf et al., 2010; West et al., 2010; Zhao et al., 2013; Liu et al., 2014], and to regional and global carbon budgets [Le Quéré et al., 2013; King et al., 2014].

Consistency among carbon sink and source data is needed in both the spatial distribution of carbon uptake and release and in the methods of carbon accounting used across data sets, such that all data can be combined for estimates of net carbon exchange (NCE) with the atmosphere. Currently, data related to crop net primary production, livestock populations, and human populations are collected independently by countries, and emissions calculated from these data are subsequently reported to the United Nations Framework Convention on Climate Change using methods established by the Intergovernmental Panel on Climate Change (IPCC) [2006]. Developing one global product, as opposed to individual estimates per country, will promote consistent global results. Some global data sets have been generated for cropland NPP [Mueller et al., 2012], livestock populations [Wint and Robinson, 2007], and human populations [Socioeconomic Data and Applications Center (SEDAC), 2005]. However, these data sets do not share consistent methods of carbon accounting or spatial distribution, thereby hindering integration of these data to estimate global cropland NCE at regional or spatially gridded scales.

A global agricultural carbon sink and source estimate with regional resolution should include all components of carbon uptake on agricultural lands (e.g., plants and soils) and all activities that result in the release of crop

biogenic carbon to the atmosphere (e.g., decomposition, loss through processing, and consumption by heterotrophs). Previous estimates of inventory-based cropland NPP were conducted by *Prince et al.* [2001] and *Hicke et al.* [2004]. In some cases, satellite remote sensing data have been used to spatially distribute carbon stocks and fluxes across the landscape, based on respective plant functional types or land cover classes [West et al., 2010, 2014]. Estimation of the removal of carbon through harvesting is needed to quantify regional carbon fluxes to the atmosphere [Ciais et al., 2007; West et al., 2011; Peters et al., 2012]. Most harvested crop biomass is assumed to be consumed by humans and livestock within a short period following harvest (i.e., less than 1 year). Consumption of crop commodities by humans in the U.S. has been quantified using inventory data on human sustenance and human metabolic data on digestion and respiration [West et al., 2009]. Global human-appropriated NPP has also been estimated by *Imhoff and Bounoua* [2006]. Spatially distributed estimates of human populations include those by *Jones and O'Neill* [2013] and *SEDAC* [2005]. The spatial distribution of livestock populations has been estimated by *Kruska et al.* [2003], *Bouwman et al.* [2005], and *Wint and Robinson* [2007]. Greenhouse gas emissions associated with livestock distributions have been estimated by *Pelletier and Tyedmers* [2010], *West et al.* [2011], and *Herrero et al.* [2013].

The objectives of this study were to (i) generate global gridded estimates of annual carbon uptake and release from croplands that represent cropland NCE, (ii) compile primary data in a manner that would enable estimation of standard deviations from the mean, and (iii) balance the resulting global estimates of cropland carbon uptake and release to the extent possible by accounting for all known uses of harvested material. To achieve a balanced budget, carbon that is harvested from croplands should be accounted for as it is consumed and respired or stored long term around the world. A balanced gridded cropland carbon flux product requires consistency across inventory data sets, downscaling and spatial distribution among all of the data, and consistency in carbon accounting across all data sets. This paper documents the data sets and methods used to estimate global cropland NCE and presents results on biogenic carbon sources and sinks from global croplands.

2. Methods

Estimation of carbon uptake and release from global agricultural production and consumption requires compilation and analysis of inventory data. Inventory data refer to global, national, or subnational data that are collected through ground measurements, surveys, statistical estimation, or a combination thereof. The inventory data and application of these data to estimate carbon uptake and release are described below. For presentation of results, nations were grouped by geopolitical regions (Table S1 in the supporting information).

2.1. Estimating Global Crop Carbon Uptake

Estimation of peak biomass production and annual net carbon uptake by croplands has been conducted previously [Prince et al., 2001; Hicke and Lobell, 2004; Kyle et al., 2011; West et al., 2011]. The method used here differs from previous analyses in that crop-specific carbon contents ranging from 0.41 to 0.63 were used for the harvested portion of the plant (e.g., grain, fruit, or other plant part) versus the residue and below-ground biomass, and crop biomass associated with harvest losses was included in estimates of crop NPP. The basis of these calculations was annual harvested biomass (Y) of 92 crops for years 1961–2011, which was compiled from Food and Agriculture Organization of the United Nations Statistics Division (FAOSTAT) [Food and Agriculture Organization (FAO), 2013] for all reporting nations. Coconut, oil palm, date palm, banana, plantain, sugar cane, and cassava were included in the compilation, but crops produced by broad-leaved trees were excluded. For 10 large nations, state- or province-level crop production data were compiled for available years between 2000 and 2011 [U.S. Department of Agriculture (USDA), 2011, 2013; Statistics Canada, 2013] to estimate the proportion of country-level crop production at the subcountry level.

A literature review was conducted to revise existing crop-specific dry matter fractional content (DM_y), harvest index (HI), and root:shoot ratio (RS) for all included crops (Table S2). A range of reported values of DM_y , HI, and RS for 10 major crops was recorded (Table S3) and used to estimate standard deviation around final estimates. The average carbon content of residue and roots has previously been assigned values of 0.40 or 0.42 [Johnson et al., 2006, 2014; Wilhelm et al., 2007] or has been incorporated into a whole-plant average value of 0.45 [Hicke and Lobell, 2004; Bolinder et al., 2007; West et al., 2011]. In this effort, a value of 0.44 was used to represent the carbon content of residue and roots (CC_{cell}) of all crops, based on reported carbon contents in roots and residue of rice, soy, wheat, maize, and sorghum, at maturity [McKendry, 2002;

Abiven *et al.*, 2005; Jensen *et al.*, 2005; Amos and Walters, 2006; Roy *et al.*, 2012]. This value is similar to the molecular mass balance carbon content of cellulose. In contrast to residue and roots, harvested plant portions were assigned crop-specific carbon contents (CC_y) derived from reported nutritional composition (Text S1).

An amount of agricultural harvest losses (e.g., damaged or spilled harvest biomass) occurs between the harvest operation and removal from the farm gate. Gustavsson *et al.* [2011, 2013] provide regional, crop group-specific estimates of food crop agricultural harvest losses expressed as a percentage of harvest. These range from 2% for cereals in cool-climate industrialized regions to 20% for fruits, vegetables, and tubers in warmer regions. We applied a conservative estimate of 2.5% harvest losses, representing losses during mowing [Buckmaster, 1990], to all hay, haylage, silage, and other fodder crops. While larger total losses (e.g., 12%) are reported over all stages of hay or silage production [Buckmaster, 1990; Russelle, 2013], the processes and equipment used vary greatly, and some of these stages are likely to occur after harvests are reported. The percentage agricultural harvest loss quantities were divided by 100 to obtain crop-specific harvest loss proportions (HL) which were applied to respective crops.

Annual crop-specific harvested biomass Y was multiplied by the appropriate crop-specific DM_y to obtain the harvested dry weight (Y_{dw}) (equation (1)). Y_{dw} was then converted to units of carbon (Y_c) by multiplying by the crop-specific CC_y (equation (2)).

$$Y_{dw} = Y \times DM_y \quad (1)$$

$$Y_c = Y_{dw} \times CC_y \quad (2)$$

Total harvestable biomass (H_{dw}) is the sum of harvested yield Y_{dw} and biomass contained in harvest losses (equation (3)). H_{dw} was converted to units of carbon (H_c) by multiplying by the crop-specific CC_y (equation (4)).

$$H_{dw} = Y_{dw} + (Y_{dw} \times HL) \quad (3)$$

$$H_c = H_{dw} \times CC_y \quad (4)$$

Aboveground biomass in units of dry weight (AGB_{dw}) was estimated from H_{dw} using crop-specific HI (equation (5)).

$$AGB_{dw} = H_{dw} / HI \quad (5)$$

Crop residue carbon (RES_c), contained in biomass remaining on the field following harvest, includes carbon from nonharvestable aboveground plant biomass (e.g., stems and leaves) and from harvest losses. Because nonharvestable and harvestable plant material may have different carbon contents, the carbon contained in each fraction is calculated separately using the respective carbon content. Total nonharvestable aboveground plant dry weight is represented by the difference between AGB_{dw} and H_{dw} , and its carbon content is represented by CC_{cell} (equation (6)). Carbon in harvest losses is represented by the difference between H_c and Y_c , which were calculated above using crop-specific CC_y .

$$RES_c = ((AGB_{dw} - H_{dw}) \times CC_{cell}) + (H_c - Y_c) \quad (6)$$

Aboveground biomass carbon (AGB_c) is the sum of RES_c and Y_c (equation (7)). Belowground carbon (BGB_c) is estimated by multiplying AGB_{dw} by the crop-specific RS and by CC_{cell} (equation (8)). Crop NPP carbon (NPP_c) is the sum of total aboveground and belowground crop carbon (equation (9)). Total Y_c and NPP_c for all included crops were summed at the national, regional, and global levels

$$AGB_c = RES_c + Y_c \quad (7)$$

$$BGB_c = AGB_{dw} \times RS_y \times CC_{cell} \quad (8)$$

$$NPP_c = AGB_c + BGB_c \quad (9)$$

Standard deviation of Y_c and NPP_c for each crop was calculated at the global level by developing a probability density function (pdf) for each model parameter (i.e., HI, RS, DM_y , CC_{cell} , and CC_y) and then conducting a Monte Carlo analysis on the complete mathematical model used to calculate Y_c and NPP_c . A range of values for each parameter was compiled through a literature review. The minimum, mode, and maximum values from the collected data (Table S3) were used to develop normal or skewed normal pdfs, depending on the

data distribution. Parameter variability was assumed to be independent. Crop production quantities in each geopolitical region and year were multiplied by relative standard deviations calculated for each crop at the global level. The resulting standard deviations for each crop grown in each nation and year were mathematically combined to national totals by summing in quadrature across crops [Taylor, 1997]. Regional and global total standard deviations across nations were calculated as the straight sums of national total crop standard deviations.

2.2. Estimating Livestock Intake and Emissions

Livestock carbon emissions were estimated based on annual livestock feed consumption, enteric fermentation, production of milk or eggs, and manure management. Annual livestock populations of meat and milk-producing cattle, meat and milk-producing buffaloes, meat and egg-laying chickens, swine, sheep, turkeys, ducks, geese and guinea fowl, goats, horses, mules, asses, camels, and other camelids (i.e., llamas and alpacas) were compiled for years 1961–2011 from FAOSTAT [FAO, 2013]. Annual producing populations of egg-laying chickens and milk-producing cattle and buffalo were subtracted from conspecific total populations to estimate populations raised for meat production. For 10 large nations, subnational livestock population data reported by each nation were compiled for available years between 2000 and 2011 [USDA, 2013; FAO, 2014b], and the proportions of national populations present in each state or province were used to improve the spatial distribution of inventory data.

Accounting of livestock carbon fluxes was conducted similar to methods used by IPCC [2006], EPA [2010], and West *et al.* [2011]. Coefficients for per-animal dry weight feed intake (F_{dw}), dry weight manure production (M_{dw}), manure carbon content (CC_M), milk and egg production carbon (ME_c), and manure management and enteric fermentation methane (CH_4) emissions are from *Intergovernmental Panel on Climate Change (IPCC)* [1996] or were estimated from existing literature (Text S2). Reported livestock dry matter intakes were assumed to have the carbon content of crop residue (CC_{cell}). F_{dw} was multiplied by CC_{cell} to obtain feed intake in units of carbon (F_c) (equation (10)), and M_{dw} was multiplied by CC_M to obtain manure production in units of carbon (M_c) (equation (11)).

$$F_c = F_{dw} \times CC_{cell} \quad (10)$$

$$M_c = M_{dw} \times CC_M \quad (11)$$

The difference between total livestock feed intake carbon and total carbon produced and emitted (i.e., manure, enteric fermentation CH_4 , and milk and eggs) approximates the amount of carbon expired in the form of carbon dioxide (CO_2) over a given year, excluding carbon stored in livestock biomass. Although herd sizes do change over time, carbon stored in livestock biomass is assumed constant in this effort. Therefore, total livestock respiration of CO_2 (E_{CO_2}) is estimated by subtracting M_c , carbon produced in milk and eggs (ME_c), and carbon emitted in enteric fermentation CH_4 (EF_{CH_4}) from F_c (equation (12)).

$$E_{CO_2} = F_c - M_c - ME_c - EF_{CH_4} \quad (12)$$

Management of livestock manure releases CH_4 , the production of which is given in livestock-specific coefficients (MM_{CH_4}). The difference between total M_c and MM_{CH_4} provides an estimate of CO_2 released by livestock manure management (MM_{CO_2}) (equation (13)), which is assumed to be emitted in the same year of manure production.

$$MM_{CO_2} = M_c - MM_{CH_4} \quad (13)$$

Total livestock CO_2 emissions (L_{CO_2}) are the sum of respiration and manure management CO_2 sources (equation (14)). Total livestock CH_4 emissions (L_{CH_4}) are the sum of enteric fermentation and manure management CH_4 sources (equation (15)).

$$L_{CO_2} = E_{CO_2} + MM_{CO_2} \quad (14)$$

$$L_{CH_4} = EF_{CH_4} + MM_{CH_4} \quad (15)$$

Total amounts of carbon in feed intake, manure production, CH_4 emissions, and CO_2 emissions (F_c , M_c , L_{CH_4} , and L_{CO_2}) for each livestock type were summed at the national, regional, and global levels as indicated in the results below. Standard deviations of mean F_c , M_c , L_{CH_4} , and L_{CO_2} were calculated for each of the 314 unique combinations of livestock species in different regions and temperature regimes. A range of values for each

Table 1. Global Crop NPP and Harvested Biomass for 25 Crops That Constitute 95% of Total NPP in 2011

Crop	NPP	Harvested Biomass	Harvested Biomass
	(Tg C yr ⁻¹ ± 1 SD)		(% of NPP)
Rice	896.2 ± 186.2	302.5 ± 9.7	33.8
Wheat	868.3 ± 129.9	280.7 ± 10.4	32.3
Maize	786.2 ± 146.3	350.2 ± 17.6	44.5
Soybeans	333.6 ± 45.9	119.9 ± 3.2	35.9
Sugar cane	310 ± 28.5	191.9 ± 14.5	61.9
Cassava	258.7 ± 44.8	99 ± 4.2	38.3
Oil palm	209.6 ± 20.3	93.7 ± 6.7	44.7
Grasses for hay and silage	203 ± 18.1	67.9 ± 3	33.4
Barley	128.2 ± 18.8	52.9 ± 2	41.3
Rapeseed	118.8 ± 11.1	35.6 ± 0.8	30.0
Cotton	107.3 ± 13.8	38.2 ± 1.1	35.6
Alfalfa for hay and silage	105.6 ± 9.4	52.3 ± 2.3	49.5
Maize for silage	89.9 ± 8	70.6 ± 3.1	78.5
Potatoes	81.4 ± 12.4	30.6 ± 1.8	37.6
Sunflower seed	78 ± 7	22.8 ± 0.6	29.2
Sugar beet	77.7 ± 15.8	16.8 ± 1.3	21.6
Sorghum	63.9 ± 9.2	23.2 ± 0.7	36.3
Peanuts	53.1 ± 4.7	21.8 ± 0.6	41.1
Bananas	50.1 ± 4.8	11.4 ± 0.5	22.8
Other legumes for hay and silage	47.9 ± 4.3	21.1 ± 0.9	44.1
Millet	31.5 ± 4.4	11.3 ± 0.4	35.9
Oats	24.4 ± 5.4	9.1 ± 0.3	37.3
Sweet potatoes	23.7 ± 4.4	8.6 ± 0.5	36.3
Plantains	23 ± 1.9	5.4 ± 0.1	23.5
Dry beans	22.2 ± 2.3	8.9 ± 0.3	40.1

model parameter (i.e., F_{dw} , CC_{cell} , M_{dw} , CC_{mv} , ME_C , EF_{CH_4} , and MM_{CH_4}) was compiled through a literature review. The mode and minimum and maximum likely values for each model parameter (Text S2) were estimated and then used to develop normal or skewed normal pdfs for each model parameter. Variability in model parameters was assumed to be independent. Monte Carlo analysis was conducted on the complete mathematical model used to calculate F_C , M_C , L_{CH_4} , and L_{CO_2} in each combination of livestock species, region, and temperature regime. The relative standard deviation calculated for the appropriate region and temperature regime was applied to each livestock type in each nation and year, and the resulting standard deviations were mathematically combined to national totals by summing in quadrature across livestock types [Taylor, 1997]. Regional and global standard deviations across nations were calculated as the straight sums of national total livestock standard deviations.

2.3. Estimating Livestock Consumption of Fodder and Forage

For purposes of tracking the use of all harvested crop carbon and estimating amounts of livestock forage, total livestock feed was disaggregated into fodder (i.e., biomass harvested by humans from croplands) and forage (i.e., biomass grazed or scavenged by livestock from noncropland sources). Fodder was further subdivided into (i) market feed items derived from primary harvests (e.g., grains, brans, and crop byproduct feeds), (ii) hay and fodder crops (e.g., harvested quantities of alfalfa, clovers, grasses, corn, and sorghum silage), and (iii) crop residue feed, consisting of crop residue collected from the field for livestock feed. Annual national quantities of all market feed items available, including imports, are reported by FAOSTAT [FAO, 2014a]. These quantities were converted into units of carbon (Text S1), using fractional dry weight and carbon contents (Table S4). Crop residue feed quantities were estimated by applying crop-specific regional percentages of residues collected for feed [Krausmann et al., 2008] to the crop- and country-specific estimates of annual residue production. Total annual fodder intake per nation (FD_C) is the sum of market feeds, hay and fodder crop production, and crop residues collected for feed. At the national level, annual fodder intake was subtracted from total livestock feed to estimate the livestock forage intake (FG_C), including grazing and scavenging (equation (16)).

$$FG_C = F_C - FD_C \quad (16)$$

Figure 1. (a) Global crop net primary production (NPP), harvested biomass, and harvested area and (b) the percentage contribution of major crops to total crop NPP. Maize includes grain crops but not silage crops. Other cereals include barley, millet, oats, rye, and grain sorghum. Sugar crops include sugar beet and sugar cane. Other oil crops include coconut, cottonseed, linseed, mustard seed, peanut, oil palm, rape/canola, safflower, sesame, and sunflower.

ing processing, distribution, and consumption [Gustavsson *et al.*, 2011, 2013] were applied to FAOSTAT food supply data, which resulted in a single food loss multiplier (FL) applicable to each food supply item in each nation. A revised estimate of food supply was developed after correcting for food loss. Following comparison of revised food supply and independent food consumption data sets [Rose *et al.*, 2002; Hells *et al.*, 2003; Bowman *et al.*, 2013; European Food Safety Authority, 2014], an additional correction (AR) was then applied across all food commodity items to better reflect reported food intake (Text S3). The AR was 0.3 in relatively wealthy regions (i.e., Europe, North America, Oceania, and industrialized Asia) and was 0.1 in all other regions (i.e., sub-Saharan Africa, North Africa, West and central Asia, South and Southeast Asia, and Latin America). The total amount of carbon in food supply chain losses and waste (FL_c) was estimated by multiplying FS_c by FL and AR (equation (18)). Total food intake carbon (FI_c) per nation was estimated as the difference between FS_c and FL_c (equation (19)).

$$FL_c = FS_c \times FL \times AR \quad (18)$$

$$FI_c = FS_c - FL_c \quad (19)$$

Release of carbon from humans occurs through respiration and excreta, but unlike livestock emissions, CO₂ is the primary greenhouse gas emitted from both pathways. Therefore, carbon intake and total emissions of

2.4. Estimating Human Carbon Intake and Emissions

Carbon consumed and expired by humans was quantified using data on total food supply, food waste, and food intake. Food consumption surveys are available for a number of individual countries [Rose *et al.*, 2002; Hells *et al.*, 2003; Bowman *et al.*, 2013; European Food Safety Authority, 2014], but global coverage is not available in a single report. Food supply, as opposed to food consumption, for all reporting nations is provided by FAOSTAT. There are large gaps between per capita food supply and food survey reports of per capita food intake. Therefore, FAOSTAT food supply data were modified to approximate reported food consumption (Text S3). National per capita human food supply (FS) quantities by item, excluding fish, seafood, and orchard crop products, were compiled for years 1961 to 2011 from FAOSTAT [FAO, 2014a]. Nations with reported human populations but missing food supply data were assigned per capita food supplies of a neighboring nation with similar climate and development status.

Food supply quantities were converted to units carbon (FS_c) by multiplying by item-specific fractional dry matter (DM_{fs}) and carbon content (CC_{fs}) (Table S9) (equation (17)).

$$FS_c = FS \times DM_{fs} \times CC_{fs} \quad (17)$$

Food supply chain losses were estimated to account for their contribution to the ultimate fate of carbon removed from the land. Percentage losses of food commodities dur-

Table 2. Regional and Global Crop NPP and Harvested Biomass

	2005	2006	2007	2008	2009	2010	2011
<i>NPP^a</i>							
Africa	405.6 ± 32.7	424.9 ± 34.1	408.1 ± 32.7	437.0 ± 35.0	440.7 ± 35.9	462.0 ± 38.2	481.0 ± 40.6
Central America and Caribbean	85.6 ± 7.3	90.7 ± 7.9	94.0 ± 8.3	97.0 ± 8.7	92.9 ± 7.9	97.2 ± 8.6	93.2 ± 7.7
Eastern Europe and West and central Asia	469.8 ± 37.1	460.7 ± 35.8	437.0 ± 34.6	523.9 ± 41.5	510.2 ± 41.1	442.9 ± 34.0	562.6 ± 44.3
North America	799.8 ± 67.8	772.4 ± 65.0	823.7 ± 73.2	836.2 ± 71.5	849.0 ± 75.0	773.1 ± 67.4	733.0 ± 65.2
Oceania	69.9 ± 5.2	43.8 ± 2.5	49.5 ± 3.1	62.8 ± 4.5	62.8 ± 4.5	62.4 ± 4.6	71.7 ± 5.5
South, Southeast, and East Asia	1810.9 ± 192.1	1865.4 ± 197.7	1959.9 ± 204.8	2030.4 ± 212.0	2031.8 ± 213.2	2093.8 ± 218.6	2183.6 ± 226.5
South America	465.0 ± 29.5	480.4 ± 30.6	532.8 ± 34.4	556.9 ± 35.8	513.5 ± 31.9	592.0 ± 38.3	612.1 ± 39.3
Western Europe	477.7 ± 28.4	457.2 ± 27.0	470.8 ± 26.9	509.1 ± 30.7	506.2 ± 29.4	487.2 ± 29.1	509.0 ± 29.9
Global total	4584.2 ± 398.1	4595.6 ± 398.6	4775.9 ± 415.9	5053.2 ± 437.6	5007.1 ± 437	5010.6 ± 436.9	5246.1 ± 456.9
<i>Harvested Biomass^a</i>							
Africa	154.1 ± 3.4	160.8 ± 3.6	154.7 ± 3.4	165.7 ± 3.6	167.0 ± 3.7	175.0 ± 3.9	181.6 ± 4.1
Central America and Caribbean	38.8 ± 1.4	41.0 ± 1.5	42.5 ± 1.5	44.0 ± 1.6	41.9 ± 1.5	43.8 ± 1.6	41.9 ± 1.5
Eastern Europe and West and central Asia	173.0 ± 3.5	168.6 ± 3.4	160.3 ± 3.2	192.5 ± 3.9	187.3 ± 3.8	162.4 ± 3.2	206.3 ± 4.2
North America	322.4 ± 8.3	310.8 ± 8.0	335.0 ± 9.1	337.5 ± 8.8	343.5 ± 9.2	310.4 ± 8.2	296.2 ± 7.9
Oceania	26.9 ± 0.6	17.9 ± 0.4	19.9 ± 0.5	24.3 ± 0.5	24.1 ± 0.5	23.9 ± 0.5	26.7 ± 0.6
South, Southeast, and East Asia	683.2 ± 16.7	706.4 ± 17.7	746.1 ± 18.6	774.8 ± 19.6	770.6 ± 19.3	794.9 ± 19.9	831.6 ± 21
South America	196.4 ± 5.3	204.6 ± 5.7	227.9 ± 6.5	241.8 ± 7.2	226.1 ± 7.2	256.6 ± 7.8	264.7 ± 7.9
Western Europe	184.6 ± 3.2	177.5 ± 3.1	183.8 ± 3.2	198.7 ± 3.5	197.2 ± 3.4	189.5 ± 3.4	199.7 ± 3.6
Global total	1779.5 ± 42.2	1787.5 ± 42.9	1870.3 ± 45.6	1979.3 ± 48.3	1957.8 ± 48.3	1956.4 ± 48.1	2048.7 ± 50.6

^aUnits are Tg C yr⁻¹ ± 1 standard deviation.

CO₂ are approximately equal [West *et al.*, 2009]. Respiration (H_{CO_2}) was estimated by multiplying intake carbon by the average ratio of respiration to intake carbon calculated from values reported by West *et al.* [2009], which was 0.88 (equation (20)).

$$H_{CO_2} = F_{Ic} \times 0.88 \quad (20)$$

Total amounts of carbon in human food intake and respiration (F_{Ic} and H_{CO_2}) were summed at the national, regional, and global levels. Standard deviations were calculated for F_{Ic} and H_{CO_2} . pdfs for food intake of 16 food commodity groups were developed from the mode and pooled standard deviation [Taylor, 1997] for each food group reported in 19 European countries by the Comprehensive European Food Consumption Database [European Food Safety Authority, 2014], assuming a truncated normal distribution for each. pdfs for DM_{fs} and CC_{fs} were developed from a range of values within each food group (Table S9). A Monte Carlo analysis was conducted for the full mathematical model for each food item at the global level, and the relative standard deviation was applied to each food item in each nation. The resulting standard deviations for F_{Ic} of each food item in each nation and year were combined by summing in quadrature [Taylor, 1997].

2.5. Spatial Distribution of Carbon Fluxes

To estimate carbon uptake and emissions at a subnational scale, crop carbon data were downscaled and spatially distributed to 0.05° resolution using the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type 5, version 5.1 MCD12Q1 data product, following methods documented by West *et al.* [2014]. Native 500 m MODIS data was initially gridded to 0.05° resolution, commensurate with the MODIS MCD12C1 product for climate modeling. Inventory data at the country level were refined with state- and province-level inventory data when available to generate subcountry distributions of cropland production at the state or province level. Inventory data within each unique geopolitical region (e.g., nation or state/province) and the standard deviations thereof were downscaled to respective grid cells representing similar land classes within each geopolitical area.

Downscaling included the reconciling of land class areas between satellite-based land cover and inventory data. Cropland area in MODIS was compared to the sum of inventory harvested area per geopolitical region (Figure S1 and Text S1). The MODIS cropland areas were then adjusted to equal the summed inventory harvested areas for respective geopolitical regions [West *et al.*, 2014]. Cropland area in MODIS was expanded or contracted as necessary, using a global kernel density representing the combined density of cropland and distance of each grid cell to the nearest cropland region [West *et al.*, 2014]. Following

Figure 2. Regional (a) harvested biomass and (b) harvested biomass per unit area.

the reconciling of cropland area, cropland NPP and harvest carbon totals per geopolitical region were distributed to cropland grid cells within each region. Double or triple cropping is inherent in the spatial distribution methodology, and occurs when there is not enough cropland, grassland, or shrubland area in the MODIS land cover data to meet the harvested land area requirements from the inventory data. In these cases, higher amounts of cropland biomass are spatially distributed to grid cells, thereby maintaining total regional biomass reported in the inventory data.

Livestock carbon fluxes were spatially distributed using livestock populations, estimated area requirements per species for housed and free-ranging animals, regional estimates of the proportion of animals that are free ranging [IPCC, 1996], and a hierarchy of land classes used for livestock distribution over available land areas. The land class hierarchy specifies that livestock be distributed to grassland, shrubland, and cropland in that order. If insufficient grassland and shrubland area was indicated from satellite land cover data, the livestock area requirement was reduced to the lower housed-animal area requirement prior to distribution on cropland areas.

Spatial distribution of human carbon fluxes was based on the 0.04° resolution Gridded Human Population of the World data set [SEDAC, 2005]. These data were initially reprocessed to 0.05° resolution for consistency with the land cover data. Food intake and respiration were distributed using the relative population densities.

2.6. Estimating Net Carbon Exchange

The estimate of cropland NCE follows methods developed by West *et al.* [2010, 2011] and Hayes *et al.* [2012] for North America. Carbon fixed by crops in the field is harvested, transported, consumed, and emitted back to the atmosphere. Gridded estimates of NCE are equal to the sum of carbon uptake and release that was previously distributed to each grid cell (equation (21)). If we consider the release of carbon in situ to occur within the same year the crop was planted, the sum of NPP uptake and carbon released through decomposition in situ is equal to the harvested and removed biomass (equation (22)). Gridded estimates of standard deviation per grid cell were developed from a quadrature summation of the standard deviations of crop, livestock, and human carbon fluxes within each grid cell.

$$\text{NCE} = -\text{NPP}_c + \text{BGB}_c + \text{RES}_c + \text{FD}_c + \text{Fl}_c \quad (21)$$

$$\text{NCE} = -Y_c + \text{FD}_c + \text{Fl}_c \quad (22)$$

2.7. Developing a Global Agricultural Carbon Budget

Balancing of the global cropland carbon budget is intended to provide a measure of accuracy on the combined estimates of harvested crop biomass, consumption, carbon uptake, and emissions. Balancing

Figure 3. Net primary production (NPP) for global croplands in year 2009 at 0.05° resolution.

Table 3. Comparison of Our Results With Reports From Studies Using Comparable Methods^a

Source	Quantity	Year	Reported Value	Our Value
<i>Bouwman et al. [2005]^b</i>	Global livestock feed intake	1970	1467	1705
		1995	2040	2218
	Global forage percent of livestock intake ^c	1970	62.9%	64.1%
		1990	59.2%	54.5%
<i>Ciais et al. [2007]</i>	Global crop harvest (including 19 crops; excluding hay crops)	not specified	1285	1373
FAO [2013]	Global livestock enteric fermentation CH ₄	1961	49.1	44.7
		2011	74.0	64.8
	Global livestock manure management CH ₄	1961	5.9	4.6
		2011	8.2	6.8
<i>Herrero et al. [2013]^b</i>	Global livestock enteric fermentation CH ₄	2000	57.1	60.8
	Global livestock manure management CH ₄		8.93	6.19
	Global livestock feed intake		2068	2223
	Percent of livestock feed intake from grasses ^c		48.0%	55.4%
<i>Hicke and Lobell [2004]^d</i>	Crop NPP in eight Midwestern U.S. states	2001	310	327
	Harvested area in eight Midwestern U.S. states		550,000 km ²	600,036 km ³
<i>Hicke et al. [2004]</i>	Total U.S. NPP (17 crops)	1972	370	370
		2001	530	640
	Total U.S. harvested area (17 crops)	1972	1,100,000 km ²	1,154,445 km ²
		2001	1,100,000 km ²	1,162,398 km ²
<i>Imhoff and Bounoua [2006]</i>	Global NPP required for human food and fiber, including livestock forage	1995	4460 (3150–6270)	5023
<i>Krausmann et al. [2008]^b</i>	Global crop harvest	2000	1544	1590
	Global crop residues		1949	1720
	Global livestock intake		3095	2223
	Global livestock of market feeds		396	379
	Global hay and crop residue feeds		1012	612
	Global foraged biomass		1687	1231
	Global forage percent of livestock intake		54.5%	55.4%
	Global crop NPP	2000	3890	4087
<i>Monfreda et al. [2008]</i>	U.S. crop NPP (17 crops)	2000	572.4	643.2
<i>West et al. [2011]</i>		2008	618.6	734.1
	U.S. crop harvest (17 crops)	2000	246.9	266.6
		2008	265.6	302.1
	U.S. livestock and pet feeds	2000	154.4	160.9
		2008	147.2	166.8
	U.S. human food intake	2000	20.1	24.5
		2008	21.7	25.3

^aUnits are Tg C yr⁻¹ unless otherwise specified. Our analysis included 92 crop types.

^bReported biomass dry matter was converted to units carbon by multiplying by 0.44.

^cReported livestock forage includes grazing and harvested grass crops; in contrast, our percent pasturage does not include harvested fodder/hay crops.

^dIncluding 17 crops grown in South Dakota, Nebraska, Kansas, Missouri, Iowa, Minnesota, Wisconsin, and Illinois.

Figure 4. Global populations of (a) mammalian livestock and (b) poultry. Note the different y axis scales. Equids include horses, mules, and asses. Camelids include camels, llamas, and alpacas. Other poultry include turkeys, geese, guinea fowl, and ducks.

the carbon budget differs from estimates of NCE in that an effort is made to account for all harvested carbon, regardless of its contribution to NCE. For 2005 and 2009, carbon contained in crop harvest, residues collected for livestock fodder, crop-based foods (i.e., excluding meat, dairy products, eggs, and animal fats), fiber (e.g., cotton lint and sisal), tobacco, harvested biomass used for biofuels, and biomass contributing to food reserves were compiled from independent data sources.

National or regional production volumes of bioethanol [U.S. Department of Energy, 2014] were used to estimate harvested biomass processed for bioenergy products, using conversion factors for corn ethanol [Perrin et al., 2009], sugarcane ethanol [Meyer et al., 2012], and respective carbon coefficients (Table S2). All bioethanol produced in Brazil was assumed to be made from sugarcane, and all bioethanol produced in other countries was assumed to be made from corn [Organisation for Economic Cooperation and Development/International Energy Agency, 2007]. For bioethanol produced from corn, 32% of the harvest used for production was assumed to be recovered in the form of dried distillers grains with solubles (DDGS) [USDA, 2014]. The carbon contained in DDGS was estimated based on a fractional dry matter content of 0.89 and carbon content of 0.49 [Kim et al., 2008] (Text S1).

Production volumes of biodiesel fuel in major producing nations and regions

[Lamers, 2011] were used to estimate total harvested biomass for bioenergy, using conversion factors for soybean oil [Gray, 2007] and respective carbon coefficients (Tables S2 and S4). All biodiesel was calculated based on production from soybean oil, and 78% of the harvest used for production was assumed to be recovered as soybean meal [North Carolina Soybean Producers Association, 2014]. Because DDGS and soybean meal are used as livestock feed, total harvest carbon used for biofuel produced from corn and soybeans was calculated as the amount of crop harvest carbon processed minus the amount recovered in these byproducts.

Annual changes in food reserves of grains, oils, oilseeds, oilseed meals, and sugar were compiled [FAO, 2013] and converted to units of carbon using respective coefficients (Table S9). Subtraction of all end uses of crop biomass from harvested and imported amounts provides the unaccounted quantity, an indication of error in the total budget. Changes in soil carbon were not included in this analysis, so any change in soil carbon caused in part by changes in crop biomass is included in the budget error. A study by West et al. [2011] indicates that soil C change in the U.S. was about 3% of the remaining annual above-ground and belowground residue, but this percentage will change by region and land management.

Table 4. Global Livestock Feed Intake and Emissions in 2011

Species/Type	Population (Millions)	Feed Intake ^a	Manure Production ^a	CH ₄ Emissions ^{a,b}	CO ₂ Emissions ^{a,b}
Buffalo, dairy	58.9	56.7 ± 9.6	28.7 ± 5.7	2.6 ± 0.3	50.5 ± 9.5
Buffalo, meat	136.3	132.6 ± 22.2	61.7 ± 13.2	6.0 ± 0.6	126.5 ± 22.2
Camels	20.2	17.6 ± 1.4	6.4 ± 1.0	0.7 ± 0.1	16.8 ± 1.4
Cattle, dairy	253.5	323.0 ± 54.3	147.9 ± 29.6	12.2 ± 1.3	287.2 ± 52.9
Cattle, meat	1146.4	1001.6 ± 168.4	435.1 ± 88.4	36.7 ± 4.0	964.3 ± 168.4
Chickens, laying	6563.2	74.2 ± 5.1	27.9 ± 4.7	0.2 ± 0.03	64.7 ± 4.5
Chickens, meat	13376.1	186.1 ± 9.5	69.3 ± 9.0	0.5 ± 0.1	185.1 ± 9.5
Ducks	1363.2	22.5 ± 1.3	8.4 ± 1.1	0.05 ± 0.01	22.5 ± 1.3
Geese and guinea fowls	370.2	9.7 ± 0.6	3.6 ± 0.5	0.01 ± 0.001	9.7 ± 0.6
Goats	875.5	106.9 ± 8.5	38.7 ± 6	3.4 ± 0.4	103.4 ± 8.5
Horses	58.9	56.4 ± 4.5	17.8 ± 2.4	0.9 ± 0.1	55.5 ± 4.5
Llamas and alpacas ^c	7.9	4.3	1.6	-	-
Mules and asses	52.3	27.3 ± 2.2	8.3 ± 1.1	0.4 ± 0.04	26.9 ± 2.2
Pigs	963.0	236.7 ± 23.9	67.9 ± 7.9	2.9 ± 0.3	233.8 ± 23.9
Sheep	1043.7	138.7 ± 11	50.4 ± 5.4	4.8 ± 0.5	133.6 ± 10.9
Turkeys	463.0	29.8 ± 1.9	11.0 ± 1.5	0.02 ± 0.003	29.8 ± 1.9

^aUnits are Tg C yr⁻¹ ± 1 standard deviation.

^bEmissions include those from manure management and enteric fermentation.

^cUncertainty and emissions were not estimated for llamas and alpacas.

Harvest used as seed was also not included in the accounting and contributes to between 1% and 3% of total harvest [FAO, 2013].

3. Results and Discussion

3.1. Cropland NPP and Harvest

Twenty-eight of the most productive crops accounted for 95% of global crop NPP in 2011 (Table 1). Wheat and rice were the most dominant global crops over the period from 1961 to 2011, each accounting for more than 15% of global crop NPP. In contrast, the relative contributions of other crops trend upward or downward over these years (Figure 1b). In recent decades, the percentages of total crop NPP contributed by maize grain, soybean, and other oil crops have increased, while the percentages contributed by other cereals (i.e., barley, millet, oats, rye, and grain sorghum) and potatoes have decreased. Global crop NPP in 2011 was 5.25 ± 0.46 Pg C yr⁻¹, of which 2.05 ± 0.051 Pg C yr⁻¹ was harvested (Table 2). Global annual harvested area

increased by 27% over the period of analysis, from 9.92 million km² in 1961 to 12.57 million km² in 2011. Global annual harvested biomass increased by 207% over this time period (Figure 1a). Global mean harvested biomass per area increased from 67 Mg C km⁻² in 1961 to 163 Mg C km⁻² in 2011.

Harvested biomass (Figure 2a) and yield (Figure 2b) vary over time and among regions of the world. In eastern Europe and West and central Asia, harvested biomass and harvested area both declined after the dissolution of the USSR in 1991. The region's yield also dropped (Figure 2b), reflecting the known occurrences of both farm abandonment and reduction in farm inputs [Osborne and Trueblood, 2002]. Regional harvested biomass and yield in North and South

Figure 5. Estimated carbon fluxes associated with global livestock. Enteric fermentation and manure management are abbreviated as E.F. and M.M., respectively.

Table 5. Regional and Global Livestock Intake and Output Carbon

	2005	2006	2007	2008	2009	2010	2011
<i>Feed Intake^a</i>							
Africa	282.4 ± 23.6	288.0 ± 24.0	297.7 ± 24.8	307.0 ± 25.1	310.8 ± 25.1	317.6 ± 25.6	281.5 ± 22.9
Central America and Caribbean	88.3 ± 8.8	89.3 ± 8.9	90.7 ± 9.0	91.8 ± 9.1	93.1 ± 9.3	94.1 ± 9.4	94.6 ± 9.5
Eastern Europe and West and central Asia	167.1 ± 14.5	167.8 ± 14.4	170.0 ± 14.4	169.0 ± 14.4	167.9 ± 14.3	167.4 ± 14.2	168.6 ± 14.1
North America	226.8 ± 21.5	229.2 ± 21.7	229.3 ± 21.6	230.5 ± 21.6	226.1 ± 21.2	225.2 ± 21.0	223.9 ± 20.7
Oceania	75.5 ± 7.2	74.5 ± 7.3	72.9 ± 7.2	70.2 ± 7.1	69.8 ± 7.2	67.3 ± 7.0	70.4 ± 7.3
South, Southeast, and East Asia	833.3 ± 55.7	848.0 ± 56.7	846.2 ± 56.6	865.1 ± 57.7	887.7 ± 58.9	902.8 ± 59.7	910.4 ± 60.1
South America	459.9 ± 59.7	462.2 ± 60.0	459.3 ± 59.3	464.6 ± 59.7	468.5 ± 59.7	469.9 ± 59.6	475.1 ± 60.3
Western Europe	207.2 ± 16.3	205.8 ± 16.3	205.6 ± 16.2	204.3 ± 16.2	203.1 ± 16.1	201.6 ± 16.0	199.4 ± 15.7
Global total	2340.5 ± 206.8	2364.8 ± 208.5	2371.7 ± 208.5	2402.5 ± 210.4	2427.2 ± 211.1	2445.8 ± 211.8	2423.9 ± 210.1
<i>Manure Production^a</i>							
Africa	118.0 ± 13.5	120.4 ± 13.7	124.4 ± 14.1	128.4 ± 14.3	129.9 ± 14.3	132.7 ± 14.6	117.5 ± 13.0
Central America and Caribbean	34.8 ± 4.4	35.1 ± 4.5	35.7 ± 4.5	36.2 ± 4.6	36.7 ± 4.7	37.1 ± 4.8	37.3 ± 4.8
Eastern Europe and West and central Asia	69.2 ± 7.6	69.5 ± 7.5	70.3 ± 7.5	69.9 ± 7.5	69.4 ± 7.5	69.2 ± 7.4	69.7 ± 7.4
North America	82.3 ± 10.2	83.1 ± 10.3	83.2 ± 10.3	83.4 ± 10.3	81.9 ± 10.1	81.5 ± 10.0	80.9 ± 9.9
Oceania	32.1 ± 3.8	31.7 ± 3.9	31.2 ± 3.8	30.1 ± 3.8	30.1 ± 3.8	29.0 ± 3.7	30.4 ± 3.9
South, Southeast, and East Asia	346.4 ± 31.5	352.8 ± 32.1	353.3 ± 32.1	360.8 ± 32.7	369.6 ± 33.4	376.1 ± 33.9	379.7 ± 34.2
South America	188.5 ± 29.5	189.4 ± 29.7	188.0 ± 29.3	190.1 ± 29.5	191.8 ± 29.6	192.3 ± 29.5	194.5 ± 29.8
Western Europe	77.8 ± 8.1	77.1 ± 8.0	77.0 ± 8.0	76.6 ± 8.0	76.1 ± 8.0	75.5 ± 7.9	74.6 ± 7.8
Global total	949.1 ± 108.5	959.3 ± 109.4	963.1 ± 109.6	975.5 ± 110.6	985.5 ± 111.1	993.5 ± 111.5	984.6 ± 110.6
<i>CO₂ Emissions^{a,b}</i>							
Africa	270.3 ± 23.7	275.7 ± 24.0	285.0 ± 24.8	293.9 ± 25.2	297.6 ± 25.2	304.1 ± 25.7	269.7 ± 23.0
Central America and Caribbean	84.6 ± 8.8	85.5 ± 8.8	86.8 ± 8.9	87.8 ± 9.1	89.1 ± 9.3	90.1 ± 9.4	90.6 ± 9.4
Eastern Europe and West and central Asia	156.0 ± 14.1	156.7 ± 14.0	159.0 ± 14.1	158.1 ± 14.1	157.0 ± 13.9	156.6 ± 13.8	157.8 ± 13.8
North America	216.1 ± 21.1	218.4 ± 21.3	218.6 ± 21.2	219.8 ± 21.2	215.5 ± 20.8	214.6 ± 20.7	213.3 ± 20.3
Oceania	71.8 ± 7.2	70.8 ± 7.2	69.4 ± 7.2	66.7 ± 7.0	66.3 ± 7.2	63.9 ± 6.9	66.8 ± 7.3
South, Southeast, and East Asia	797.3 ± 55.6	811.2 ± 56.6	808.5 ± 56.5	826.7 ± 57.6	848.7 ± 58.8	863.0 ± 59.7	870.2 ± 60.1
South America	439.2 ± 59.3	441.5 ± 59.5	438.7 ± 58.9	443.8 ± 59.3	447.4 ± 59.3	448.7 ± 59.1	453.7 ± 59.8
Western Europe	195.5 ± 16.0	194.2 ± 15.9	194.0 ± 15.9	192.8 ± 15.9	191.7 ± 15.7	190.3 ± 15.6	188.2 ± 15.4
Global total	2230.7 ± 205.4	2254.0 ± 207.1	2260.0 ± 207.1	2289.6 ± 209.0	2313.3 ± 209.8	2331.2 ± 210.5	2310.3 ± 208.7
<i>CH₄ Emissions^{a,b}</i>							
Africa	9.7 ± 0.7	9.9 ± 0.7	10.2 ± 0.7	10.5 ± 0.7	10.6 ± 0.7	10.8 ± 0.7	9.4 ± 0.6
Central America and Caribbean	2.4 ± 0.2	2.4 ± 0.2	2.4 ± 0.2	2.4 ± 0.2	2.5 ± 0.2	2.5 ± 0.2	2.5 ± 0.2
Eastern Europe and West and central Asia	5.1 ± 0.3	5.1 ± 0.3	5.1 ± 0.3	5.1 ± 0.3	5.1 ± 0.3	5.0 ± 0.3	5.1 ± 0.3
North America	5.8 ± 0.5	5.8 ± 0.5	5.8 ± 0.5	5.8 ± 0.5	5.7 ± 0.5	5.7 ± 0.4	5.6 ± 0.4
Oceania	2.9 ± 0.2	2.8 ± 0.2	2.8 ± 0.2	2.7 ± 0.2	2.7 ± 0.2	2.6 ± 0.2	2.7 ± 0.2
South, Southeast, and East Asia	24.2 ± 1.4	24.6 ± 1.4	24.8 ± 1.4	25.2 ± 1.4	25.6 ± 1.4	26.0 ± 1.5	26.3 ± 1.5
South America	14.4 ± 1.3	14.4 ± 1.4	14.2 ± 1.3	14.3 ± 1.3	14.4 ± 1.3	14.4 ± 1.3	14.6 ± 1.4
Western Europe	5.7 ± 0.3	5.7 ± 0.3	5.6 ± 0.3	5.6 ± 0.3	5.6 ± 0.3	5.5 ± 0.3	5.4 ± 0.3
Global total	70.0 ± 4.9	70.6 ± 4.9	71.0 ± 5.0	71.7 ± 5.0	72.1 ± 5.0	72.5 ± 5.0	71.6 ± 5.0

^aUnits are Tg C yr⁻¹ ± 1 standard deviation.

^bEmissions include those from manure management and enteric fermentation.

America increased sharply between 1984 and 1985. This was due primarily to large increases in reported hay and fodder crop harvests for some nations in those regions. Global total hay and fodder increased gradually from 39 Tg C yr⁻¹ in 1961 to 79 Tg C yr⁻¹ in 1984 but then increased sharply to 162 Tg C in 1985.

Our estimates of crop NPP carbon (Figure 3) [Wolf *et al.*, 2015], harvested carbon, and cropland area, consisting of 92 crops, ranged from 0% to 21% greater than the estimates from studies that included a lesser number of crops [Ciais *et al.*, 2007; Hicke *et al.*, 2004; Monfreda *et al.* 2008; West *et al.*, 2011] (Table 3). In addition to the greater number of crops represented in this analysis, root:shoot ratios, harvest indices, and carbon contents were revised to improve flux estimates and estimates of statistical uncertainty. This analysis used separate carbon contents for harvested material versus residue and belowground biomass. Using separate carbon contents for primary plant components, as opposed to a value of 0.45 for all plant components, decreased global crop NPP carbon by 0.3%, increased global harvest carbon by 2.6%, and decreased global crop residue carbon by 2.0%. Individual crops were impacted differently with, for example, an increase in rice and soybean harvested carbon of 2.0% and 13.0%, respectively.

Figure 6. (a) Total livestock feed intake by region and (b) regional and global forage contribution to total livestock feed intake.

3.2. Livestock Intake and Emissions

Global livestock populations exhibit different trends over the 51 years of available data (Figure 4). Meat cattle consumed more feed and emitted greater quantities of CO₂ and CH₄ than all other livestock in 2011 (Table 4). Estimated global livestock feed intake in 2011 was 2.42 ± 0.21 Pg C yr⁻¹, of which 2.31 ± 0.21 Pg C yr⁻¹ was released back to the atmosphere as CO₂ through respiration and manure management (Figure 5), and 71.6 ± 0.47 Tg C yr⁻¹ was released as CH₄ through enteric fermentation and manure management (Table 5). From 1961 to 2011, meat cattle numbers increased by 50% (i.e., 381 million additional animals) and dairy cattle numbers increased by 43% (i.e., 76 million additional animals). Populations of other livestock also increased over this time period (Figure 4), including meat chickens by 566%, other poultry by 405%, goats by 151%, pigs by 137%, and buffalo by 121%. In contrast, despite being the most abundant mammalian livestock species in the 1960s, sheep numbers exhibited a small increase of 5% over this time period.

Livestock feed was estimated separately by fodder and forage for purposes of tracking carbon uptake and emissions from croplands versus noncropland areas. Sources of fodder include market feed supplies, hay and fodder crop harvests [FAO, 2014a], and crop residues collected for feed. Crop residues for feed were estimated using regional, crop-specific percentages of residue collection [Krausmann *et al.*, 2008]. Total fodder available in each nation and year was subtracted from the total livestock feed intake (Figure 6a) to estimate the minimum required percent of feed originating from forage (Figure 6b).

Figure 7. Livestock fodder intake in year 2009 at 0.05° resolution.

Fodder intake and estimated standard deviation were distributed to 0.05° resolution (Figure 7) [Wolf *et al.*, 2015]. The percentage of forage contribution to total livestock intake was calculated at regional and global levels over all data years (Figure 6b). In 2009, the most recent year with verified hay and fodder production data, global and regional percent forage intakes were as follows: global weighted average, 53.9%; in Africa, 77.2%; in Central America and the Caribbean, 66.5%; in eastern Europe and central and West Asia, 21.1%; in North America, 22.9%; in Oceania, 88.3%; in South, Southeast, and East Asia, 49.3%; in South America, 76.9%; and in western Europe, 28.9%. Several regions, particularly North and South America, indicate sharp changes in percentage forage intake between 1984 and 1985 (Figure 6b) which are most likely artifacts of FAOSTAT reporting.

Figure 8. Contributions of major food groups to total human food intake. Starchy roots include potatoes, sweet potatoes, and cassava.

Table 6. Human Food Intake and Emissions

	2005	2006	2007	2008	2009	2010	2011
<i>Food Intake^a</i>							
Africa	87.0 ± 6.7	90.0 ± 6.9	92.0 ± 7.0	94.5 ± 7.1	96.9 ± 7.2	100.1 ± 7.4	103.9 ± 7.8
Central America and Caribbean	16.4 ± 1.0	16.8 ± 1.0	17.2 ± 1.0	17.1 ± 1.0	17.3 ± 1.0	17.7 ± 1.0	18.0 ± 1.0
Eastern Europe and West and central Asia	45.9 ± 2.7	46.7 ± 2.8	47.4 ± 2.8	47.6 ± 2.8	48.1 ± 2.8	48.8 ± 2.9	49.6 ± 2.9
North America	28.6 ± 1.5	28.5 ± 1.5	28.5 ± 1.5	28.2 ± 1.5	28.2 ± 1.5	28.4 ± 1.5	28.6 ± 1.5
Oceania	1.9 ± 0.1	2.0 ± 0.1	2.0 ± 0.1	2.1 ± 0.1	2.1 ± 0.1	2.1 ± 0.1	2.2 ± 0.1
South, Southeast, and East Asia	259.6 ± 14.6	265.2 ± 15.0	272.5 ± 15.3	277.8 ± 15.8	281.4 ± 15.9	289.3 ± 16.3	293.3 ± 16.5
South America	35.1 ± 2.0	35.7 ± 2.0	36.4 ± 2.0	37.4 ± 2.1	37.6 ± 2.1	38.4 ± 2.1	39.2 ± 2.1
Western Europe	32.1 ± 1.7	32.2 ± 1.7	32.4 ± 1.7	32.6 ± 1.7	32.7 ± 1.7	32.7 ± 1.7	32.6 ± 1.7
Global total	506.7 ± 30.4	517.0 ± 31.0	528.4 ± 31.5	537.4 ± 32.1	544.3 ± 32.3	557.6 ± 33.0	567.4 ± 33.7
<i>Respiration of CO₂^a</i>							
Africa	76.6 ± 5.9	79.2 ± 6.1	81.0 ± 6.1	83.2 ± 6.3	85.3 ± 6.3	88.1 ± 6.5	91.5 ± 6.9
Central America and Caribbean	14.5 ± 0.9	14.8 ± 0.9	15.1 ± 0.9	15.1 ± 0.9	15.2 ± 0.9	15.6 ± 0.9	15.8 ± 0.9
Eastern Europe and West and central Asia	40.4 ± 2.4	41.1 ± 2.5	41.8 ± 2.5	41.9 ± 2.5	42.4 ± 2.5	43.0 ± 2.5	43.6 ± 2.6
North America	25.2 ± 1.4	25.1 ± 1.3	25.1 ± 1.3	24.9 ± 1.3	24.8 ± 1.3	25.0 ± 1.3	25.2 ± 1.3
Oceania	1.7 ± 0.1	1.7 ± 0.1	1.8 ± 0.1	1.8 ± 0.1	1.8 ± 0.1	1.9 ± 0.1	1.9 ± 0.1
South, Southeast, and East Asia	228.6 ± 12.9	233.4 ± 13.2	239.9 ± 13.6	244.5 ± 14.0	247.7 ± 14.0	254.7 ± 14.4	258.2 ± 14.6
South America	30.9 ± 1.7	31.4 ± 1.8	32.0 ± 1.8	33.0 ± 1.8	33.1 ± 1.8	33.8 ± 1.8	34.5 ± 1.9
Western Europe	28.3 ± 1.5	28.4 ± 1.5	28.6 ± 1.5	28.7 ± 1.5	28.8 ± 1.5	28.8 ± 1.5	28.7 ± 1.5
Global total	446.1 ± 26.8	455.1 ± 27.4	465.1 ± 27.8	473.0 ± 28.4	479.1 ± 28.5	490.9 ± 29.1	499.5 ± 29.8

^aUnits are Tg C yr⁻¹ ± 1 standard deviation.

Our estimates of total livestock feed intake were 4 to 16% greater than previous estimates [Bouwman *et al.*, 2005; Herrero *et al.*, 2008; West *et al.*, 2011], although 28% less than that estimated by Krausmann *et al.* [2008] (Table 3). Compared to our estimates for the year 2000, Krausmann *et al.* [2008] reported 1.4 times greater total livestock intake and grazing intake, and 1.7 times greater livestock intake from hay and fodder crops and crop residues, but a similar quantity of market feed carbon and a similar percent grazing intake. We used per-animal coefficients to calculate required total livestock feed intake, whereas Krausmann *et al.* [2008] used a livestock model and also included carbon contained in livestock bedding. Our estimates of livestock CH₄ emissions from enteric fermentation are 6% greater than Herrero *et al.* [2013] but 8 to 12% less than quantities reported by FAO [FAO, 2013; Tubiello *et al.*, 2013], depending on the year of comparison (Table 3). A recent comparison between estimates using inventory data and atmospheric inversion modeling indicates that the inventory approach for livestock may underestimate emissions [Wecht *et al.*, 2014], thereby necessitating a revision of global methane emissions coefficients.

3.3. Human Consumption and Emissions

Total food intake was estimated as the sum intake of different foods (Table S10). Grain intake comprised 52%–54% of total global food intake carbon from 1961 to 1996 but declined after 1997 to 49% in 2011 (Figure 8). The percentage of total intake contributed by root, legume, and dairy commodities also decreased and was replaced by an increase in intake of fat, meat, and fruits and vegetables (Figure 8). The percentage contribution of fermented and distilled alcoholic beverages to total carbon intake ranged from 2.0% to 2.6% between 1961 and 2011.

Global total food intake in 2011 was estimated to be 0.57 ± 0.03 Pg C yr⁻¹ (Table 6). The difference between food intake and food supply quantities reported by FAOSTAT indicates that an additional 0.26 Pg C yr⁻¹ or 31% of total food supply is lost from the food supply chain. This percentage is similar to recent independent estimates [Gunders, 2012; Institution of Mechanical Engineers, 2013; Qusted *et al.*, 2013]. Regional food supply chain losses in 2011 range from 23% of total food supply in Africa to 44% in western Europe (Tables 6 and S11). Global average per capita food intake carbon has increased over the 51 years of available data, and some regional differences exist (Figure 9b). Lacking comprehensive and consistent food intake survey data, the regional differences estimated here were compared with national food intake survey data where available (Table S12). Regional patterns in per capita food carbon intake (Figure 9b) are not expected to duplicate regional patterns in nutritional or caloric intake. For example, per capita food carbon intake in

Figure 9. (a) Total food intake by region and (b) regional and global per capita food intake carbon.

Figure 10. Human food intake in year 2009 at 0.05° resolution.

Figure 11. Net carbon exchange by region.

Africa was consistently among the largest regional values (Figure 9b), driven in part by a minimal contribution of livestock-based food to total food intake carbon (Table S13). Resulting national food intake and estimated standard deviation were distributed to 0.05° resolution (Figure 10) [Wolf *et al.*, 2015]. To our knowledge, there are no other studies providing global food intake in units of carbon. The values for U.S. food intake estimated in this effort were 16%–22% greater than those reported by West *et al.* [2011] (Table 3), reflecting adjustments made for the apparent underreporting of food consumption in the food intake surveys.

3.4. Net Carbon Exchange

Cropland NCE (Figure 11) was estimated as the sum of carbon uptake by crops, decomposition of in situ crop biomass, and the release of carbon occurring from the consumption of crops by livestock and humans. Exports are implicitly included in the NCE estimates and are represented by the NPP that is harvested but not consumed or released to the atmosphere. Likewise, imports are implicitly included as food and fodder commodities consumed by humans and livestock. Net imports and exports per country are therefore correlated to country-level net flux estimates. While regions such as North and South America act as apparent regional carbon sinks (Table 7) due to production and export of large quantities of crop carbon, there are many regions and urban centers that are sources of biogenic carbon due to consumption and respiration by concentrated populations of livestock or humans (Figure 12) [Wolf *et al.*, 2015]. In contrast to other world regions, NCE in eastern Europe and in West and central Asia was positive until recent years (Figure 11).

Table 7. Regional Net Carbon Exchange (NCE) Quantities ($\text{Tg C yr}^{-1} \pm 1$ Standard Deviation)

	2005	2006	2007	2008	2009	2010	2011
Africa	-2.4 ± 9.5	-2.6 ± 9.9	3.2 ± 9.8	-1.1 ± 10.1	0.9 ± 10.2	-0.1 ± 10.6	-4.0 ± 11.1
Central America and Caribbean	6.0 ± 3.3	6.6 ± 3.5	6.4 ± 3.6	6.6 ± 3.8	6.6 ± 3.6	7.0 ± 3.8	7.4 ± 3.6
Eastern Europe and West and central Asia	9.1 ± 14.1	12.0 ± 13.9	21.4 ± 13.7	-8.7 ± 15.5	-4.1 ± 15	20.2 ± 12.7	-19.1 ± 16.3
North America	-107.0 ± 19.6	-102.2 ± 18.9	-121 ± 19.7	-129 ± 19.1	-141.0 ± 18.8	-137.6 ± 15.8	-131.0 ± 15.0
Oceania	-16.1 ± 1.0	-7.8 ± 0.9	-9.7 ± 0.9	-13.2 ± 1.1	-13.8 ± 1.0	-12.9 ± 1.1	-16.0 ± 1.1
South, Southeast, and East Asia	-16.1 ± 35.5	-27.0 ± 36.4	-35.7 ± 38.3	-54.4 ± 39.3	-39.5 ± 39.4	-29.6 ± 41.2	-38.9 ± 43.1
South America	-63.1 ± 13.9	-66.9 ± 14.6	-80.1 ± 15.9	-85.9 ± 17.0	-80.5 ± 15.7	-96.9 ± 17.4	-99.5 ± 18.0
Western Europe	-12.8 ± 12.5	-7.0 ± 12.2	-8.6 ± 12.9	-20.2 ± 13.5	-22.7 ± 13.2	-18.0 ± 12.9	-25.9 ± 13.6

Figure 12. Net carbon exchange (NCE) of biogenic cropland carbon in year 2009 at 0.05° resolution.

This reflects the significant and variable quantities of feed grains and meat imported by the former Soviet Republics in the years before the dissolution of the USSR and to a lesser extent up to recent years [Osborne and Trueblood, 2002]. Positive NCE in this region is also due to trade characteristics of both the former Soviet Republics and of many arid Middle East nations where fossil fuels and mineral resources are exported and national food supplies are imported [World Trade Organization, 2011].

The downscaling and spatial distribution of NCE disaggregates biogenic crop fluxes such that carbon uptake and release can be identified at a subprovince scale and subsequently at the 0.05° resolution (Figure 12). The geospatial estimate of fluxes would not be possible without the use of satellite-based land cover data and spatial distribution methods. The spatial distribution indicates the drawdown of carbon in global crop-intensive regions (e.g., U.S. Corn Belt region) but also illustrates net releases in some grid cells and regions west of the U.S. Corn Belt. The uptake and release of agricultural carbon, presented in units of $\text{g C m}^{-2} \text{yr}^{-1}$ (Figure S2), are similar in pattern to that of Ciais *et al.* [2007], although the uptake and release are more pronounced in our results. For example, the U.S. Midwest indicates uptake closer to -150 to $-200 \text{ g C m}^{-2} \text{yr}^{-1}$ in dense crop production regions, as opposed to $-100 \text{ g C m}^{-2} \text{yr}^{-1}$ estimated by Ciais *et al.* [2007]. There are also regions of high carbon release from livestock (i.e., $>100 \text{ g C m}^{-2} \text{yr}^{-1}$), including the western U.S. grazing lands just west of the dense cropland areas. While the higher uptake and release estimates per grid cell may be an artifact of spatial resolution and may counter each other when summed to a coarser scale (i.e., $1^\circ \times 1^\circ$), the global and regional totals for NPP and harvested carbon remain higher in this study compared to other studies (Table 3).

3.5. Cropland Carbon Budget

A global cropland budget was completed for years 2005 and 2009 (Table 8). The budget is intended to sum all sources and sinks of harvested carbon to determine whether there are sources of CO_2 emissions or carbon stocks that are not accounted for in our global flux estimates (Figure 13). Some of the most notable changes between 2005 and 2009 include a 423 Tg C yr^{-1} increase in cropland NPP, an increase in contributions to global food reserves (i.e., carbon stock), and approximately twice as much harvested carbon used in biofuel production. Following the inclusion of all known data sets on crop production, processing, and consumption, there remains 19% and 22% of harvested biomass unaccounted for in 2005 and 2009, respectively (Table 8). Unaccounted items of the global cropland carbon budget are either sequestered in carbon stocks with slow turnover times, such as fibrous materials and landfills, or may be released to the atmosphere through currently unquantified processes. Regional percentages of unaccounted biomass range from 6% in North America to 24% in Southeast Asia. The range of the global carbon budget error may be due in part to differences in data collection and reporting across regions. For example, China's food reserves are not reported directly and are, therefore, estimated by FAO [Gale, 2002]. Additionally, over-reporting of crop harvests and livestock numbers in China has been suggested [Gale, 2002] and may occur in other nations as well.

Table 8. Regional and Global Agricultural Carbon Budget^a

Quantity	Africa	Central America and Caribbean	Eastern Europe, West Asia, and Central Asia	North America	Oceania	South, Southeast, and East Asia	South America	Western Europe	Globe
2005									
Crop plant NPP C	405.6	85.6	469.8	799.8	69.9	1810.9	465.0	477.7	4584.2
Crop plant root biomass ^b	67.4	16.9	79.7	193.6	12.7	287.7	87.9	122.2	868.1
Crop plant residue left on field ^c	134.0	18.9	140.5	262.2	28.4	529.8	122.1	153.1	1389.0
Crop plant residue collected for livestock feed ^c	34.4	9.0	66.0	6.7	1.0	271.9	48.2	9.0	446.1
Livestock forage ^d	217.6	59.9	33.6	40.0	66.6	425.8	361.7	64.9	1270.1
Agricultural harvest losses ^e	15.8	1.9	10.6	15.0	0.9	38.3	10.4	8.8	101.7
Primary harvest ^f	154.1	38.8	173.0	322.4	26.9	683.2	196.4	184.6	1779.5
Postharvest losses ^g	16.2	1.2	8.5	7.1	0.6	56.1	6.6	7.0	103.2
Net change in food reserves ^h	3.2	−0.5	2.1	6.7	2.5	0.5	−4.5	−2.6	7.4
Crop products food intake	82.0	13.9	37.4	20.7	1.3	234.8	29.0	21.7	440.9
Livestock products food intake	5.0	2.6	8.5	7.9	0.6	24.8	6.1	10.4	65.8
Crop products food waste ⁱ	24.9	4.7	24.0	16.5	1.0	105.4	9.6	18.4	204.4
Livestock products food waste ⁱ	1.4	0.8	4.5	5.8	0.4	12.1	1.8	7.0	33.9
Crop primary harvest for livestock feed ^j	30.3	19.4	70.3	180.1	7.9	135.6	50.0	130.6	624.2
Fiber and tobacco	1.4	0.1	2.4	3.2	0.4	10.2	1.6	0.5	19.8
Biofuels ^k	0.0	0.0	0.0	10.1	0.1	3.9	23.1	3.9	43.7
Imports of primary harvest	32.3	15.2	33.7	10.8	1.3	90.1	12.0	72.9	268.4
Exports of primary harvest	5.5	3.8	26.9	67.7	10.8	48.5	62.0	50.4	275.7
Total supply (primary harvest plus imports)	186.4	54.1	206.7	333.2	28.2	773.3	208.4	257.5	1779.5
Unaccounted supply ^l	22.8	11.6	35.1	21.1	3.6	178.4	31.0	27.5	335.9
Percent unaccounted supply ^l	12.2%	21.4%	17.0%	6.3%	12.9%	23.1%	14.9%	10.7%	18.9%
2009									
Crop plant NPP C	440.7	92.9	510.2	849.0	62.8	2031.8	513.5	506.2	5007.1
Crop plant root biomass ^b	72.2	18.3	84.4	199.1	11.6	326.4	95.9	129.7	937.6
Crop plant residue left on field ^c	146.2	20.6	149.8	283.3	25.4	597.8	127.4	160.6	1511.0
Crop plant residue collected for livestock feed ^c	38.1	10.0	77.7	7.5	0.9	294.3	53.6	9.8	491.9
Livestock forage ^d	239.9	61.9	35.4	51.8	61.6	437.9	360.5	58.7	1307.8
Agricultural harvest losses ^e	17.2	2.1	11.0	15.6	0.9	42.6	10.4	9.0	108.7
Primary harvest ^f	167.0	41.9	187.3	343.5	24.1	770.6	226.1	197.2	1957.8
Postharvest losses ^g	17.6	1.3	8.9	7.5	0.6	63.9	6.6	7.3	113.7
Net change in food reserves ^h	−1.3	−1.1	−0.8	3.2	−0.7	17.7	−8.1	3.0	11.8
Crop products food intake	91.2	14.5	38.9	20.4	1.4	252.5	30.5	22.3	471.7
Livestock products food intake	5.7	2.8	9.2	7.8	0.6	28.9	7.1	10.4	72.6
Crop products food waste ⁱ	27.5	4.8	24.3	16.4	1.1	110.8	10.1	19.0	214.0
Livestock products food waste ⁱ	1.6	0.8	4.9	5.8	0.5	14.0	2.1	7.0	36.6
Crop primary harvest for livestock feed ^j	32.8	21.2	57.4	166.9	7.3	155.5	54.4	132.0	627.4
Fiber and tobacco	1.0	0.1	1.9	1.7	0.2	11.4	1.3	0.3	17.9
Biofuels ^k	0.0	0.0	0.0	26.9	0.1	3.6	38.0	9.2	78.7
Imports of crop products	37.5	15.4	40.4	12.8	1.8	111.5	15.0	81.7	316.1
Exports of crop products	5.4	4.6	47.3	79.5	10.9	54.7	63.9	53.2	319.6
Total supply (primary harvest plus imports)	204.5	57.3	227.7	356.3	25.9	882.1	241.2	278.9	1957.8
Unaccounted supply ^l	30.3	11.9	49.8	33.9	4.9	212.0	44.5	32.7	422.6
Percent unaccounted supply ^l	14.8%	20.7%	21.9%	9.5%	18.9%	24.0%	18.5%	11.7%	21.6%

^aAll quantities are Tg C yr^{−1} unless otherwise specified.

^bCrop root biomass excludes harvested belowground storage organs.

^cResidue is assumed to be either left on the field or collected for livestock feed.

^dLivestock forage (i.e., grazing and scavenging) is calculated as the difference between total livestock intake and total fodder, which includes market feeds, hay and fodder crops, and residue collected for feed.

^eAgricultural production harvest losses are assumed to be left on the field and are included with total residue.

^fPrimary harvest denotes the main harvested commodity, excluding collected residue.

^gPostharvest losses occur between farm gate and distribution or processing.

^hA negative value indicates that reserves decreased, and a positive value indicates that reserves increased.

ⁱFood waste includes processing, distribution, and postconsumer waste.

^jTotal national supply of market feeds (e.g., grains, seeds, brans, and byproducts) plus fodder crops (i.e., hay, haylage, and silage).

^kIncludes bioethanol production reported by the *Energy Alternative Fuels Data Center* [2014] and biodiesel production reported by *Lamers* [2011]. Global totals exceed regional sums because production in unnamed nations is included in the global total.

^lUnaccounted supply is calculated as primary harvest plus imports minus postharvest losses, crop products food intake and food waste, net change in food reserves, and primary harvest used for livestock feed, fiber, tobacco, biofuels, and exports.

Figure 13. Global agricultural carbon budget for 2009. All quantities are Tg C yr^{-1} . Box sizes are proportional within sectors. Note the different scales. Quantities rounded to the nearest Tg.

4. Conclusions

We present estimates of global cropland carbon fluxes which consistently account for carbon production and consumption across crop, livestock, and human domains. Our results agree well with other studies that have focused on individual NCE components, thereby providing a positive evaluation of the total NCE flux estimates. Development of these estimates has highlighted recent trends, such as changes over time in the global suite of crops and livestock, increasing human consumption of meat and fats, increasing global per capita food intake, and regional differences in NCE. Development of annual cropland carbon budgets indicates that 78%–81% of all harvested crop carbon is accounted for globally in our flux estimates. The downscaling and spatial distribution of carbon uptake, release, and NCE associated with cropland biogenic carbon illustrates the individual and net carbon fluxes at a subprovince level. More importantly, a geospatial data set was developed and documented here that applies similar carbon coefficients across regions and across disparate data sets for livestock, humans, and cropland production. The result of this effort is a spatially and methodologically consistent data set of carbon uptake and release from global croplands.

Acknowledgments

Results presented here can be recreated from the publicly available inventory and remote sensing data sources identified in section 2, in combination with the information provided in the supporting information tables and text. The global gridded flux data presented here are available online from Oak Ridge National Laboratory Distributed Active Archive Center at <http://dx.doi.org/10.3334/ORNLDAAC/1279>. This research was conducted with support from the National Aeronautics and Space Administration Carbon Monitoring System program under projects NNH12AU351 and NNH13AW581. We thank Celia Wilkinson Enns (U.S. Department of Agriculture) for providing information on U.S. and international food intake survey data.

References

- Abiven, S., S. Recous, V. Reyes, and R. Oliver (2005), Mineralisation of C and N from root, stem and leaf residues in soil and role of their biochemical quality, *Biol. Fertil. Soils*, 42(2), 119–128, doi:10.1007/s00374-005-0006-0.
- Amos, B., and D. T. Walters (2006), Maize root biomass and net rhizodeposited carbon, *Soil Sci. Soc. Am. J.*, 70(5), 1489–1503, doi:10.2136/sssaj2005.0216.
- Bolinder, M. A., H. H. Janzen, E. G. Gregorich, D. A. Angers, and A. J. VandenBygaart (2007), An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada, *Agric. Ecosyst. Environ.*, 118(1–4), 29–42, doi:10.1016/j.agee.2006.05.013.
- Bouwman, A. F., K. W. Van der Hoek, B. Eickhout, and I. Soenarso (2005), Exploring changes in world ruminant production systems, *Agric. Syst.*, 84(2), 121–153, doi:10.1016/j.agry.2004.05.006.
- Bowman, S., C. Martin, J. Carlson, J. Clemens, B.-H. Lin, and A. Moshfegh (2013), Retail food commodity intakes: Mean amounts of retail commodities per individual 2003–2013, USDA-ARS, Beltsville, MD and USDA-ERS, Washington, D. C.
- Buckmaster, D. (1990), Cooperative Extension Fact Sheet Listing I-107: Forage losses equal economic losses, so minimize them Penn State College of Agricultural Sciences, Agricultural and Biological Engineering, Univ. Park, Pa.
- Ciais, P., P. Bousquet, A. Freibauer, and T. Naegler (2007), Horizontal displacement of carbon associated with agriculture and its impacts on atmospheric CO₂, *Global Biogeochem. Cycles*, 21, GB2014, doi:10.1029/2006GB002741.
- EPA (2010), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008 Reports and Assessments, U.S. Environmental Protection Agency, Climate Change Division, Washington, D. C.
- European Food Safety Authority (2014), EFSA: The EFSA Comprehensive European Food Consumption Database. [Available at <http://www.efsa.europa.eu/en/datexfoodcdb/datexfooddb.htm>, Accessed 24 February 2014.]
- Food and Agriculture Organization (FAO) (2013), Food and Agriculture Organization of the United Nations Statistics Division (FAOSTAT). [Available at <http://faostat.fao.org/>, Accessed 2 December 2013.]
- Food and Agriculture Organization (FAO) (2014a), Food and Agriculture Organization of the United Nations Statistics Division (FAOSTAT). [Available at <http://faostat.fao.org/>, Accessed 1 September 2014.]
- Food and Agriculture Organization (FAO) (2014b), Global Livestock Production and Health Atlas (GLiPHA) Food Agric. Organ. U. N. Anim. Prod. Health Div. Glob. Livest. Prod. Health Atlas GLiPHA. [Available at <http://kids.fao.org/glipha/>, Accessed 1 January 2014.]
- Gale, F. (2002), China's statistics: Are they reliable? China's Food and Agriculture: Issues for the 21st Century, USDA Economic Research Service, Market and Trade Economics Division.
- Gray, A. (2007), *Report ID-341: Is biodiesel as Attractive an Economic Alternative as Ethanol?*, Purdue Univ. Extension, West Lafayette, Ind.
- Gunders, D. (2012), Wasted: How America is losing up to 40 percent of its food from farm to fork to landfill NRDC Issue Paper, Natl. Resources Defense Council, New York.
- Gustavsson, J., C. Cederberg, U. Sonesson, R. van Otterdijk, and A. Meybeck (2011), *Global Food Losses and Food Waste: Extent, Causes, and Prevention*, Food and Agriculture Organization, Rome.
- Gustavsson, J., C. Cederberg, U. Sonesson, and A. Emanuelsson (2013), *The Methodology of the FAO Study: "Global Food Losses and Food Waste—Extent, Causes, and Prevention"*, SIK (Swedish Institute for Food and Biotechnology), Göteborg, Sweden.
- Hayes, D. J., et al. (2012), Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions, and a new approach for estimating net ecosystem exchange from inventory-based data, *Global Change Biol.*, 18(4), 1282–1299, doi:10.1111/j.1365-2486.2011.02627.x.
- Hels, O., N. Hassan, I. Tetens, and S. H. Thilsted (2003), Food consumption, energy and nutrient intake and nutritional status in rural Bangladesh: Changes from 1981–1982 to 1995–96, *Eur. J. Clin. Nutr.*, 57(4), 586–594, doi:10.1038/sj.ejcn.1601535.
- Herrero, M., P. K. Thornton, R. Kruska, and R. S. Reid (2008), Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030, *Agric. Ecosyst. Environ.*, 126(1–2), 122–137, doi:10.1016/j.agee.2008.01.017.
- Herrero, M., P. Havlik, H. Valin, A. Notenbaert, M. C. Rufino, P. K. Thornton, M. Bluemmel, F. Weiss, D. Grace, and M. Obersteiner (2013), Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems, *Proc. Natl. Acad. Sci. U.S.A.*, 110(52), 20,888–20,893, doi:10.1073/pnas.1308149110.
- Hicke, J. A., and D. B. Lobell (2004), Spatiotemporal patterns of cropland area and net primary production in the central United States estimated from USDA agricultural information, *Geophys. Res. Lett.*, 31, L20502, doi:10.1029/2004GL020927.
- Hicke, J. A., D. B. Lobell, and G. P. Asner (2004), Cropland area and net primary production computed from 30 years of USDA agricultural harvest data, *Earth Interact.*, 8(10), 1–20, doi:10.1175/1087-3562(2004)008<0001:CAANPP>2.0.CO;2.
- Imhoff, M. L., and L. Bounoua (2006), Exploring global patterns of net primary production carbon supply and demand using satellite observations and statistical data, *J. Geophys. Res.*, 111, D22S12, doi:10.1029/2006JD007377.
- Institution of Mechanical Engineers (2013), *Global Food: Waste Not, Want Not*, pp. 36, Inst. of Mechanical Engineers, London.
- Intergovernmental Panel on Climate Change (IPCC) (1996), *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Reference Manual (Volume 3)*, Hadley Centre, Bracknell, U. K.
- Intergovernmental Panel on Climate Change (IPCC) (2006), *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use*, Inst. for Global Environmental Strategies, Kanagawa, Japan.
- Jensen, L. S., T. Salo, F. Palmason, T. A. Brelund, T. M. Henriksen, B. Stenborg, A. Pedersen, C. Lundström, and M. Esala (2005), Influence of biochemical quality on C and N mineralisation from a broad variety of plant materials in soil, *Plant Soil*, 273(1–2), 307–326, doi:10.1007/s11104-004-8128-y.
- Johnson, J. M. F., J. M. Novak, G. E. Varvel, D. E. Stott, S. L. Osborne, D. L. Karlen, J. A. Lamb, J. Baker, and P. R. Adler (2014), Crop residue mass needed to maintain soil organic carbon levels: Can it be determined?, *Bioenergy Res.*, 7(2), 481–490, doi:10.1007/s12155-013-9402-8.
- Johnson, J. M. F., R. R. Allmaras, and D. C. Reicosky (2006), Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database, *Agron. J.*, 98(3), 622–636, doi:10.2134/agronj2005.0179.
- Jones, A. D., et al. (2013), Greenhouse gas policy influences climate via direct effects of land-use change, *J. Clim.*, 26(11), 3657–3670, doi:10.1175/JCLI-D-12-00377.1.
- Jones, B., and B. C. O'Neill (2013), Historically grounded spatial population projections for the continental United States, *Environ. Res. Lett.*, 8(4), 044021, doi:10.1088/1748-9326/8/4/044021.
- Kim, Y., N. S. Mosier, R. Hendrickson, T. Ezeji, H. Blaschek, B. Dien, M. Cotta, B. Dale, and M. R. Ladisch (2008), Composition of corn dry-grind ethanol by-products: DDGS, wet cake, and thin stillage, *Bioresour. Technol.*, 99(12), 5165–5176, doi:10.1016/j.biortech.2007.09.028.
- King, A. W., et al. (2014), North America's net terrestrial carbon exchange with the atmosphere 1990–2009, *Biogeosci. Discuss.*, 11(7), 11,027–11,059, doi:10.5194/bgd-11-11027-2014.

- Krausmann, F., K.-H. Erb, S. Gingrich, C. Lauk, and H. Haberl (2008), Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints, *Ecol. Econ.*, **65**(3), 471–487, doi:10.1016/j.ecolecon.2007.07.012.
- Kruska, R. L., R. S. Reid, P. K. Thornton, N. Henninger, and P. M. Kristjanson (2003), Mapping livestock-oriented agricultural production systems for the developing world, *Agric. Syst.*, **77**(1), 39–63, doi:10.1016/S0308-521X(02)00085-9.
- Kyle, P., P. Luckow, K. Calvin, W. Emanuel, M. Nathan, and Y. Zhou (2011), *GCAM 3.0 Agriculture and Land Use: Data Sources and Methods*, Pacific Northwest Natl. Lab., Richland, Wash.
- Lamers, P. (2011), *International Biodiesel Markets: Developments in Production and Trade*, UFOP-Schriften: German Union for the Promotion of Oils and Protein Plants, Berlin.
- Le Quére, C., et al. (2013), Global carbon budget 2013, *Earth Syst. Sci. Data Discuss.*, **6**(2), 689–760, doi:10.5194/essdd-6-689-2013.
- Liu, J., et al. (2014), Carbon monitoring system flux estimation and attribution: Impact of ACOS-GOSAT X CO₂ sampling on the inference of terrestrial biospheric sources and sinks, *Tellus B*, **66**, doi:10.3402/tellusb.v66.22486.
- McKendry, P. (2002), Energy production from biomass (Part 1): Overview of biomass, *Bioresour. Technol.*, **83**(1), 37–46, doi:10.1016/S0960-8524(01)00118-3.
- Meyer, S., J. Schmidhuber, and J. Barreiro-Hurle (2012), ESA Working Paper No. 12–08 Intra-industry trade in biofuels: How environmental legislation fuels resource use and GHG emissions, Food and Agriculture Organization of the United Nations, Agricultural Development Economics Division.
- Miles, N. L., S. J. Richardson, K. J. Davis, T. Lauvaux, A. E. Andrews, T. O. West, V. Bandaru, and E. R. Crosson (2012), Large amplitude spatial and temporal gradients in atmospheric boundary layer CO₂ mole fractions detected with a tower-based network in the U.S. upper Midwest, *J. Geophys. Res.*, **117**, G01019, doi:10.1029/2011JG001781.
- Monfreda, C., N. Ramankutty, and J. A. Foley (2008), Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000, *Global Biogeochem. Cycles*, **22**, GB1022, doi:10.1029/2007GB002947.
- Mueller, N. D., J. S. Gerber, M. Johnston, D. K. Ray, N. Ramankutty, and J. A. Foley (2012), Closing yield gaps through nutrient and water management, *Nature*, **490**(7419), 254–257, doi:10.1038/nature11420.
- North Carolina Soybean Producers Association (2014), Uses of soybeans. [Available at <http://ncsoy.org/media-resources/uses-of-soybeans/>, Accessed 20 November 2014.]
- Organisation for Economic Cooperation and Development/International Energy Agency (2007), IEA Energy Technology Essentials brief ETE02: Biofuel production Organisation for Economic Cooperation and Development/International Energy Agency.
- Osborne, S., and M. Trueblood (2002), Agricultural productivity and efficiency in Russia and Ukraine: Building on a decade of reform Agricultural Economic Report AER813, USDA Economic Research Service.
- Pelletier, N., and P. Tyedmers (2010), Forecasting potential global environmental costs of livestock production 2000–2050, *Proc. Natl. Acad. Sci. U.S.A.*, **107**(43), 18,371–18,374, doi:10.1073/pnas.1004659107.
- Perrin, R. K., N. F. Fretes, and J. P. Sesmero (2009), Efficiency in Midwest U.S. corn ethanol plants: A plant survey, *Energy Policy*, **37**(4), 1309–1316, doi:10.1016/j.enpol.2008.11.022.
- Peters, G. P., S. J. Davis, and R. Andrew (2012), A synthesis of carbon in international trade, *Biogeosciences*, **9**(8), 3247–3276, doi:10.5194/bg-9-3247-2012.
- Potter, C. (2010), The carbon budget of California, *Environ. Sci. Policy*, **13**(5), 373–383, doi:10.1016/j.envsci.2010.04.008.
- Prince, S. D., J. Haskett, M. Steininger, H. Strand, and R. Wright (2001), Net primary production of U.S. Midwest croplands from agricultural harvested yield data, *Ecol. Appl.*, **11**(4), 1194–1205, doi:10.2307/3061021.
- Quested, T., R. Ingle, and A. Parry (2013), Household food and drink waste in the UK 2012|WRAP UK Banbury, Oxon, U. K.
- Rose, D., L. Bourne, and D. Bradshaw (2002), Food and nutrient availability in South African households: Development of a nationally representative database (technical report) Medical Research Council, South Africa.
- Roy, K. S., P. Bhattacharyya, S. Neogi, K. S. Rao, and T. K. Adhya (2012), Combined effect of elevated CO₂ and temperature on dry matter production, net assimilation rate, C and N allocations in tropical rice (*Oryza sativa* L.), *Field Crops Res.*, **139**, 71–79, doi:10.1016/j.fcr.2012.10.011.
- Russelle, M. (2013), The alfalfa yield gap: A review of the evidence, *Forage Grazinglands*, doi:10.1094/FG-2013-0002-RV.
- Schuh, A. E., et al. (2013), Evaluating atmospheric CO₂ inversions at multiple scales over a highly inventoried agricultural landscape, *Global Change Biol.*, **19**(5), 1424–1439, doi:10.1111/gcb.12141.
- Socioeconomic Data and Applications Center (SEDAC) (2005), *Gridded Population of the World (GPW)*, v3, NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, New York.
- Statistics Canada (2013), CANSIM agriculture: Crops and horticulture. [Available at <http://www5.statcan.gc.ca/cansim/>, Accessed 24 April 2013.]
- Taylor, J. R. (1997), *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*, 2nd ed., Univ. Science Books, Mill Valley, Calif.
- Thomson, A. M., et al. (2011), RCP4.5: A pathway for stabilization of radiative forcing by 2100, *Clim. Change*, **109**(1–2), 77–94, doi:10.1007/s10584-011-0151-4.
- Thomson, A. M., G. P. Jones, X. Zhang, V. Bandaru, T. O. West, M. A. Wise, R. C. Izaurralde, and K. V. Calvin (2014), The contribution of future agricultural trends in the U.S. Midwest to global climate change mitigation, *Glob. Environ. Change-Hum. Policy Dimens.*, **24**, 143–154, doi:10.1016/j.gloenvcha.2013.11.019.
- Tubiello, F. N., M. Salvatore, S. Rossi, A. Ferrara, N. Fitton, and P. Smith (2013), The FAOSTAT database of greenhouse gas emissions from agriculture, *Environ. Res. Lett.*, **8**(1), 015009, doi:10.1088/1748-9326/8/1/015009.
- U.S. Department of Energy (2014), *Global Ethanol Production: Quantity of Ethanol Produced by Country From 2007–2012*, EERE Alternative Fuels Data Center, Washington, D. C.
- U.S. Department of Agriculture (USDA) (2011), Crop explorer for major crop regions Foreign Agric. Serv. [Available at <http://www.pecad.fas.usda.gov/cropeexplorer/>, Accessed 1 January 2013.]
- U.S. Department of Agriculture (USDA) (2013), Quickstats 2.0, Natl. Agric. Stat. Serv. [Available at <http://quickstats.nass.usda.gov/>, Accessed 26 November 2013.]
- U.S. Department of Agriculture (USDA) (2014), *Iowa Ethanol Corn and CO-Products Processing Values*, Market News Service, St Joseph, Mo.
- van Asselen, S., and P. H. Verburg (2013), Land cover change or land-use intensification: Simulating land system change with a global-scale land change model, *Global Change Biol.*, **19**(12), 3648–3667, doi:10.1111/gcb.12331.
- van der Werf, G. R., J. T. Randerson, L. Giglio, G. J. Collatz, M. Mu, P. S. Kasibhatla, D. C. Morton, R. S. DeFries, Y. Jin, and T. T. van Leeuwen (2010), Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), *Atmos. Chem. Phys.*, **10**(23), 11,707–11,735, doi:10.5194/acp-10-11707-2010.
- Wecht, K. J., D. J. Jacob, C. Frankenberg, Z. Jiang, and D. R. Blake (2014), Mapping of North American methane emissions with high spatial resolution by inversion of SCIAMACHY satellite data, *J. Geophys. Res. Atmos.*, **119**, 7741–7756, doi:10.1002/2014JD021551.

- West, T. O., G. Marland, N. Singh, B. L. Bhaduri, and A. B. Roddy (2009), The human carbon budget: An estimate of the spatial distribution of metabolic carbon consumption and release in the United States, *Biogeochemistry*, 94(1), 29–41, doi:10.1007/s10533-009-9306-z.
- West, T. O., et al. (2010), Cropland carbon fluxes in the United States: Increasing geospatial resolution of inventory-based carbon accounting, *Ecol. Appl.*, 20(4), 1074–1086, doi:10.1890/08-2352.1.
- West, T. O., V. Bandaru, C. C. Brandt, A. E. Schuh, and S. M. Ogle (2011), Regional uptake and release of crop carbon in the United States, *Biogeosciences*, 8(8), 2037–2046, doi:10.5194/bg-8-2037-2011.
- West, T. O., Y. L. Page, M. Huang, J. Wolf, and A. M. Thomson (2014), Downscaling global land cover projections from an integrated assessment model for use in regional analyses: Results and evaluation for the U.S. from 2005 to 2095, *Environ. Res. Lett.*, 9(6), 064004, doi:10.1088/1748-9326/9/6/064004.
- Wilhelm, W. W., J. M. E. Johnson, D. L. Karlen, and D. T. Lightle (2007), Corn stover to sustain soil organic carbon further constrains biomass supply, *Agron. J.*, 99(6), 1665–1667, doi:10.2134/agronj2007.0150.
- Wint, G., and T. Robinson (2007), *Gridded Livestock of the World 2007*, Food and Agriculture Organization, Rome.
- Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S. J. Smith, A. Janetos, and J. Edmonds (2009), Implications of limiting CO₂ concentrations for land use and energy, *Science*, 324(5931), 1183–1186, doi:10.1126/science.1168475.
- Wolf, J., T. O. West, Y. Le Page, G. Kyle, X. Zhang, G. J. Collatz, and M. L. Imhoff (2015), CMS: Carbon fluxes from global agricultural production and consumption, 2005–2011, ORNL DAAC, Oak Ridge, Tenn., doi:10.3334/ORNLDAAAC/1279.
- World Trade Organization (2011), *Key Developments in 2010: A Snapshot. 2—Merchandise Trade, International Trade Statistics 2011*, World Trade Organization, Geneva, Switzerland.
- Zhao, S., S. Liu, T. Sohl, C. Young, and J. Werner (2013), Land use and carbon dynamics in the southeastern United States from 1992 to 2050, *Environ. Res. Lett.*, 8(4), 044022, doi:10.1088/1748-9326/8/4/044022.