Equations and coefficients for calculating agricultural carbon emissions

In this study, carbon emissions from agricultural production were predominantly derived from five sources. These were, agricultural materials, rice cultivation, soil management, and straw burning. The carbon effects of various activities in agricultural production and the data required for calculations were collated, as shown in Table S1.

Table S1 Carbon effects of agricultural production and data required for calculation

Source	Cause	Factor	Data required	Reference
Agricultural materials	①The production, transportation, and application of agricultural materials bring about carbon emissions.	Fertilizer	Consumption of fertilizer	Li et al., 2011
		Pesticide	Consumption of pesticide	
		Mulch	Consumption of mulch	
	②The consumption of diesel by machinery leads to carbon emissions.	Diesel	Consumption of diesel fuel in agriculture	
	③The fossil fuels consumed for generating electricity in irrigation result in carbon emissions indirectly.	Irrigation	Irrigated area	
Rice cultivation	Methanogens in rice fields utilize organic matter from the roots of rice plants to form CH_4.	Rice field	Planting area of early rice, medium rice, late rice	PRC National Development and Reform Commission, 2011
Soil management	N_2O from cropland due to fertilizer nitrogen, straw return, atmospheric nitrogen deposition, runoff leaching nitrogen, etc.	Soil	Application of nitrogen fertilizer and yields of various crops	
Straw burning	Burning straw emits CO_2, CH_4, etc.	Straw	Yield of various crops, such as rice, wheat, maize, pulses, vegetables	Cheng et al., 2018
Livestock breeding	N_2O and CH_4 emissions arise from livestock breeding from enteric fermentation and feces management.	Livestock	The number of cows, steer, buffalo, goats, sheep, horses, donkeys, mules, camels, and pigs	

The total carbon emissions are the sum of the emissions from carbon sources, which is expressed as follows:

$$E = E_{material}+E_{rice}+E_{soil}+E_{straw}+E_{livestock}\ , \tag{1}$$

where E is the total agricultural carbon emissions, $E_{material}$ is the carbon emissions from agricultural materials, E_{rice} is the carbon emissions from rice cultivation, E_{soil} is the carbon emissions from soil management, E_{straw} is the carbon emissions from straw burning, and $E_{livestock}$ is the carbon emissions from livestock breeding. CH_4 and N_2O will be expressed in carbon equivalents (C-eq) according to global warmth potential, as the effect of 1 kg CH_4 is equivalent to 9.2727 kg C-eq, and that of 1 kg N_2O is equivalent to 81.2727 kg C-eq (Cubasch et al., 2013).

1 Carbon emissions from agricultural materials

Carbon emissions from agricultural materials involve five factors, which are fertilizer, pesticides, mulch, diesel, and electricity used in irrigation, and is expressed as:

$$E_{\text{material}} = \sum_{i=1}^{I}\sum_{m=1}^{M} E_{im} = \sum_{i=1}^{I}\sum_{m=1}^{M} h_{im} \cdot \delta_m , \quad (2)$$

where E_{im} denotes the carbon emissions from factor m of province i, h_{im} is the activity data of factor m of province i, and δ_m is the carbon coefficient of factor m. The coefficients were obtained from Li et al. (2011), as shown in Table S2.

Table S2 Specific factors and coefficients of carbon emissions from agricultural materials

Agricultural material	Coefficient
Fertilizer	0.8956 kg(C)·kg^{-1}
Pesticide	4.9341 kg(C)·kg^{-1}
Mulch	5.1800 kg(C)·kg^{-1}
Diesel	0.5927 kg(C)·kg-1
Irrigation	266.4800 kg(C)·hm^{-2}

2 CH_4 emissions from rice cultivation

The second carbon source was rice cultivation. The coefficients vary spatially, and provincial differences need to be considered, which is expressed as:

$$E_{\text{rice}} = \sum_{i=1}^{I} E_{\text{rice},i} = \sum_{i=1}^{I} q_i \cdot f_i , \quad (3)$$

where E_{rice} is the CH_4 emissions from rice cultivation, $E_{rice,i}$ is the emissions of province i, q_i is the rice planting area of province i, and f_i is the coefficient of CH_4 from rice cultivation in province i, which is divided into three categories, namely, early-season rice, late-season rice, and mid-season rice. The coefficients were obtained from PRC National Development and Reform Commission (2011), as shown in

Table S3.

Table S3 Coefficients of CH_4 emissions from rice fields in different provinces Unit: g·m^{-2}

Province	Early-season rice	Late-season rice	Mid-season rice	Province	Early-season rice	Late-season rice	Mid-season rice
Beijing	0	0	13.23	Henan	0	0	17.85
Tianjin	0	0	11.34	Hubei	17.51	39	58.17
Hebei	0	0	15.33	Hunan	14.71	34.1	56.28
Shanxi	0	0	6.62	Guangdong	15.05	51.6	57.02
Inner Mongolia	0	0	8.93	Guangxi	12.41	49.1	47.78
Liaoning	0	0	9.24	Hainan	13.43	49.4	52.29
Jilin	0	0	5.57	Chongqing	6.55	18.5	25.73
Heilongjiang	0	0	8.31	Sichuan	6.55	18.5	25.73
Shanghai	12.41	27.5	53.87	Guizhou	5.1	21	22.05
Jiangsu	16.07	27.6	53.55	Yunnan	2.38	7.6	7.25
Zhejiang	14.37	34.5	57.96	Shaanxi	0	0	12.51
Anhui	16.75	27.6	51.24	Gansu	0	0	6.83
Fujian	7.74	52.6	43.47	Qinghai	0	0	0
Jiangxi	15.47	45.8	65.42	Ningxia	0	0	7
Shandong	0	0	21	Xinjiang	0	0	10

3 N_2O emissions from soil management

N_2O emissions from soil management include both direct and indirect sources. Direct emissions are caused by in-season N input to agricultural land, including fertilizer, manure, and straw. In view of the difficulty in obtaining data on manure application, only fertilizer and straw were considered. Indirect emissions originate from atmospheric nitrogen deposition and nitrogen loss through leaching and runoff:

$$E_{soil} = E_{sd} + E_{si}, \tag{4}$$

where E_{soil} is the N_2O emissions from soil management and E_{sd} and E_{si} are the direct and indirect N_2O emissions, respectively.

3.1 Direct N_2O emissions from soil management

Nitrogen input from fertilizer and straw in croplands was considered. Measuring the direct emissions is expressed as:

$$E_{sd} = (N_{fer} + N_{straw}) \times ef_{sd}, \tag{5}$$

where N_{fer} is the quantity of nitrogen in the fertilizer, N_{straw} is the quantity of nitrogen in straw returned to the field, and ef_{sd} is the coefficient of direct N_2O emission, which is assigned according to PRC National Development and Reform Commission (2011), as shown in Table S4.

Table S4 Coefficients of direct N_2O emission from soil management by province Unit: kg(N_2O) ·kg^{-1})

Province	Recommended value	Range
Xinjiang, Gansu, Inner Mongolia, Qinghai, Ningxia, Shaanxi, Shanxi	0.0056	0.0015–0.0085
Heilongjiang, Jilin, Liaoning	0.0114	0.0021–0.0258
Beijing, Tianjin, Hebei, Henan, Shandong	0.0057	0.0014–0.0081
Jiangsu, Shanghai, Zhejiang, Jiangxi, Anhui, Hubei, Hunan, Sichuan, Chongqing	0.0109	0.0026–0.0220
Fujian, Guangdong, Guangxi, Hainan	0.0178	0.0046–0.0228
Guizhou, Yunnan	0.0106	0.0025–0.0218

In Equation (5), the nitrogen input from straw is not available from statistical data, which needs to be calculated, and the expression is shown as Equation (6):

$$N_{\text{straw}} = \sum_{i=1}^{I}\sum_{k=1}^{K} N_{\text{straw},i,k} = \sum_{i=1}^{I}\sum_{k=1}^{K}\left(\left(\frac{Y_{ik}}{H_k} - Y_{ik}\right)\times r_k \times J_i \times b_k + \frac{Y_{ik}}{H_k}\times r_k \times g_k \times b_k\right), \quad (6)$$

where N_{straw} is the nitrogen from straw returned to the field, K is the number of crops. For crop k in province i, $N_{straw,i,k}$ is the nitrogen from straw returned to the field, Y_{ik} is the economic yield. J_i is the rate of straw return in province i. For crop k, H_k is the economic coefficient, which is the ratio of crop economic yield to biological yield, g_k is the root-to-crown ratio, and b_k is the dry weight ratio of the economic part. The coefficients were obtained from PRC National Development and Reform Commission (2011) and Cheng (2018), as shown in Table S5 and Table S6.

Table S5 Coefficient for measuring nitrogen of straw returned to the field by crop

Crop	Dry weight ratio	Proportion of nitrogen in seeds	Proportion of nitrogen in straw	Economic coefficient	Root-to-crown ratio
Rice	0.855	0.01	0.00753	0.489	0.125
Wheat	0.87	0.014	0.00516	0.434	0.166
Maize	0.86	0.017	0.0058	0.438	0.17
Sorghum	0.87	0.017	0.0073	0.393	0.185
Grain	0.83	0.007	0.0085	0.385	0.166
Other cereals	0.83	0.014	0.0056	0.455	0.166
Soybeans	0.86	0.06	0.0181	0.425	0.13

Other pulses	0.82	0.05	0.022	0.385	0.13
Rapeseed	0.82	0.00548	0.00548	0.271	0.15
Peanuts	0.9	0.05	0.0182	0.556	0.2
Seed cotton	0.83	0.00548	0.00548	0.383	0.2
Potatoes	0.45	0.004	0.011	0.667	0.05
Sesame	0.9	0.05	0.0131	0.417	0.2
Hemp	0.83	0.0131	0.0131	0.83	0.2
Sugar cane	0.32	0.004	0.0058	0.75	0.26
Sugar beet	0.4	0.004	0.00507	0.667	0.05
Vegetables	0.15	0.008	0.008	0.83	0.25
Tobacco leaf	0.83	0.041	0.0144	0.83	0.2

Table S6 Straw return rates for major crops by province Unit: %

Province	Straw return rates	Province	Straw return rates	Province	Straw return rates
Beijing	68.3	Zhejiang	46.0	Hainan	31.6
Tianjin	43.3	Anhui	19.2	Chongqing	24.2
Hebei	65.1	Fujian	39.2	Sichuan	24.2
Shanxi	42.9	Jiangxi	46.9	Guizhou	31.2
Inner Mongolia	18.5	Shandong	56.0	Yunnan	24.8
Liaoning	3.4	Henan	62.9	Shaanxi	40.6
Jilin	4.2	Hubei	21.2	Gansu	3.4
Heilongjiang	7.0	Hunan	45.6	Qinghai	3.3
Shanghai	29.6	Guangdong	29.0	Ningxia	7.4
Jiangsu	25.2	Guangxi	53.2	Xinjiang	27.6

3.2 Indirect N_2O emissions from soil management

Indirect N_2O emissions are caused by the volatilization of NO_X and NH_3 from fertilized soils through atmospheric nitrogen deposition, and by soil nitrogen leaching or runoff losses into water bodies, which can be estimated by:

$$\begin{aligned} E_{si} &= E_{sedi} + E_{leach} \\ &= (N_{fer} + N_{straw}) \times V \times ef_{sedi} + (N_{fer} + N_{straw}) \times L \times ef_{leach}, \end{aligned} \quad (7)$$

where E_{atmos} indicates the N_2O emissions caused by atmospheric nitrogen deposition and V and ef_{atmos} is the ratio of volatilization and the coefficient of emission, respectively, set as 10% and 0.01 kg(N_2O)·kg^{-1} recommended by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007). E_{leach} is the N_2O emissions from soil nitrogen leaching and runoff losses, L is the rate of nitrogen loss, estimated as 20% of the total nitrogen input to the cropland, and ef_{leach} is the corresponding coefficient of emission, suggested to be 0.0075 kg (N_2O) ·kg^{-1} by the IPCC.

4 Carbon emissions from straw burning

Carbon emissions from straw burning are calculated by:

$$E_{\text{straw}} = \sum_{i=1}^{I}\sum_{k=1}^{K} E_{\text{straw},i,k} = \sum_{i=1}^{I}\sum_{k=1}^{K}\left(Y_{ik} \times s_k \times o_{ik} \times l_k \times ef_k\right), \tag{8}$$

In Equation (8), for crop k, l_k is the burning efficiency, ef_k is the coefficient of emissions from straw burning, and s_k is the straw-to-grain ratio. For crop k in province i, $E_{\text{straw},i,k}$ is the emissions from straw burning, Y_{ik} is the economic yield, o_{ik} is the proportion of straw burning. All the coefficients were obtained from PRC National Development and Reform Commission (2011) and Cheng (2018), as shown in Table S7 to Table S9.

Table S7 Straw-to-grain ratio of different crops by province

Province	Rice	Wheat	Maize
Beijing, Tianjin, Hebei, Inner Mongolia, Shanxi, Shandong, Henan	0.93	1.34	1.73
Heilongjiang, Jilin, Liaoning	0.97	0.93	1.86
Jiangsu, Shanghai, Zhejiang, Jiangxi, Anhui, Hubei, Hunan	1.28	1.38	2.05
Shaanxi, Gansu, Ningxia, Qinghai, Xinjiang	0.68	1.23	1.52
Sichuan, Chongqing, Guizhou, Yunnan	1.00	0.97	1.29
Fujian, Guangdong, Guangxi, Hainan	1.06	1.27	1.32

Table S8 Proportion of straw burning by crop Unit: %

Province	Rice	Wheat	Maize	Province	Rice	Wheat	Maize	Province	Rice	Wheat	Maize
Beijing	0	3.1	12.1	Zhejiang	25.9	31.4	33.7	Hainan	34.8	0	31.1
Tianjin	4.1	13.2	16	Anhui	42.3	28.9	35.9	Chongqing	18.6	10.7	12.3
Hebei	5.8	9.9	15.8	Fujian	17.8	35.3	13.9	Sichuan	25.6	16.2	28.8
Shanxi	8.4	36	25.3	Jiangxi	26.8	23.8	17.2	Guizhou	3.4	4.6	4.3
Inner Mongolia	2.2	3.7	10.8	Shandong	9.7	19.7	23.4	Yunnan	36.8	33.2	23.1
Liaoning	9.3	21.9	12.9	Henan	19.7	34.8	19.3	Shaanxi	6.2	13.4	22
Jilin	18.1	12.7	13.5	Hubei	19.1	27.8	21.6	Gansu	8.5	6.7	15.1
Heilongjiang	21.8	33.1	11.9	Hunan	43.2	47.2	39.1	Qinghai	0	8.1	6.5
Shanghai	26.2	27.7	24.6	Guangdong	40.4	42.1	37.7	Ningxia	19.7	20.3	18.2
Jiangsu	34.6	27.3	23.3	Guangxi	28.6	39.8	31.9	Xinjiang	6.3	3.9	11.5

Table S9 Burning efficiency and coefficient of carbon emission for straw open burning by crop

Crop	Rice	Wheat	Maize
Burning efficiency	0.93	0.93	0.92
CH_4	3.2	3.4	4.4

CO_2	1460	1460	1350

5 Carbon emissions from livestock breeding

N_2O and CH_4 emissions arise from livestock breeding from enteric fermentation and feces management, which can be expressed by:

$$E_{\text{livestock}} = E_{\text{enteric}} + E_{\text{manure}} \ , \tag{9}$$

where $E_{\text{livestock}}$ indicates the emissions caused by livestock breeding, E_{enteric} is the emissions of enteric fermentation, and E_{manure} is the emissions of feces management.

5.1 Carbon emissions from livestock breeding

Carbon emissions from livestock breeding can be calculated as:

$$E_{\text{enteric}} = \sum ef_{\text{enteric},p} \times AP_p \ , \tag{10}$$

where $ef_{\text{enteric},p}$ is the coefficient of CH_4 emissions from enteric fermentation of animals p, and AP_p is the number of animals p. The coefficients were obtained from Cheng (2018), as shown in Table S10.

Table S10 CH_4 emission coefficients in enteric fermentation of livestock Unit: $kg{\cdot}Capita^{-1}$

Livestock	Coefficient	Livestock	Coefficient	Livestock	Coefficient
Cow	85	Sheep	8.6	/Donkey/Mule	10
Buffalo	88.5	Goat	8.9	Camel	46
Other cattle	71	Horse	18	Pig	1.5

5.2 Carbon emissions from enteric fermentation

Feces management can cause N_2O and CH_4 emissions, which can be estimated as Equations (11) and (12).

$$E_{\text{manure, CH4}} = \sum ef_{\text{manure,CH4},p} \times AP_p \tag{11}$$

$$E_{\text{manure, N2O}} = \sum ef_{\text{manure,N2O},p} \times AP_p \tag{12}$$

where $E_{\text{manure, N2O}}$ is the CH_4 emissions and $E_{\text{manure, N2O}}$ is the N_2O emissions caused by enteric fermentation, $ef_{\text{manure,CH4},p}$ and $ef_{\text{manure,N2O},p}$ denote the coefficient of CH_4 emissions and N_2O emissions from manure management of animals p, respectively, and AP_p is the number of animals p. The coefficients were obtained from Cheng (2018), as shown in Table S11 and Table S12.

Table S11 CH_4 emission coefficients in manure management of livestock Unit: kg·Capita^{-1}

Province	Cow	Other cattle	Sheep	Goat	Pig	Poultry	Horse	Donkey/Mule	Camel
Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia	7.46	2.82	0.15	0.17	3.12	0.01	1.09	0.6	1.28
Heilongjiang, Jilin, Liaoning	2.23	1.02	0.15	0.16	1.12	0.01	1.09	0.6	1.28
Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong	8.33	3.31	0.26	0.28	5.08	0.02	1.64	0.9	1.92
Henan, Hebei, Hunan, Guangdong, Guangxi, Hainan	8.45	4.72	0.34	0.31	5.85	0.02	1.64	0.9	1.92
Chongqing, Sichuan, Guizhou, Yunnan	6.51	3.21	0.48	0.53	4.18	0.02	1.64	0.9	1.92
Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang	5.93	1.86	0.28	0.32	1.38	0.01	1.09	0.6	1.28

Table S12 N_2O emission coefficients in manure management of livestock Unit: kg·Capita^{-1}

Province	Cow	Other cattle	Sheep	Goat	Pig	Poultry	Horse	Donkey/Mule	Camel
Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia	1.846	0.794	0.093	0.093	0.227	0.007	0.33	0.188	0.33
Heilongjiang, Jilin, Liaoning	1.096	0.913	0.057	0.057	0.266	0.007	0.33	0.188	0.33
Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong	2.065	0.846	0.113	0.113	0.175	0.007	0.33	0.188	0.33
Henan, Hebei, Hunan, Guangdong, Guangxi, Hainan	1.71	0.805	0.106	0.106	0.157	0.007	0.33	0.188	0.33
Chongqing, Sichuan, Guizhou, Yunnan	1.884	0.691	0.064	0.064	0.159	0.007	0.33	0.188	0.33
Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang	1.447	0.545	0.074	0.074	0.195	0.007	0.33	0.188	0.33

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