

Online Supplemental Material

A generic methodological framework for accurately quantifying greenhouse gas footprints of crop cultivation systems

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Supplementary Text S1, Equations S1–S6, Tables S1–S3, and Figure S1

Text S1 Detailed descriptions for Equations (3)–(27) in the text

In Equations (4) and (18) in the text, the integer numbers 12, 44, 16, and 28 are the carbon atomic weight, the molecular weight of CO₂ or N₂O, the molecular weight of CH₄ and the double atomic weights of nitrogen in a N₂O molecule, respectively. The parameters GWP_m and GWP_n involved in the equations denote the global warming potential (GWP) of CH₄ and N₂O, respectively. Both are dimensionless factors and involved to convert the net emission quantities of the two non-CO₂ GHGs to CO₂eq quantities. The Intergovernmental Panel on Climate Change (IPCC) provided the GWP_m values of 23, 25, and 34 and the GWP_n values of 296, 298, and 298 for the 100-year time horizon in its assessment reports on climate change published in 2001, 2007, and 2013, respectively (IPCC 2001, 2007, 2013). In a study, it is required to specify the used value(s) of the parameters though the GWP values provided by the latest IPCC reports are taken in most cases.

The subscripts as serial numbers (Equations (5)–(6), (14), and (20)–(23) in the text), i_1 (1, 2, ..., n_1), i_2 (1, 2, ..., n_2), ..., i_5 (1, 2, ..., n_5), j (1, 2, ..., m), and k (1, 2, ..., q), encode the types of machinery operations, synthetic fertilizers, organic manure, agricultural chemicals, other inputs excluding electricity, sub-categories of farmland operations, and fertilization practices, respectively.

As variables for activity levels, the MO_{i_1} , A_j , N_k , N_{i_2} , N_{i_3} , N_{i_4} and N_{i_5} (Equations (5)–(6), (14), and (20)–(23) in the text) denote the quantities for fossil fuel consumed on-farm in machinery, acreages of farmland sub-categories, nitrogen fertilizer types or application methods, nutrients of synthetic fertilizers, fresh mass of organic manures, active gradients of agricultural chemicals, and other inputs excluding fossil fuels and electricity, respectively. And the L , D , U , A_w , A_d , R_b , A_e , N_{iii} , N_{rs} , N_{il} and N_{ig} (Equations (7), (9)–(11), (15)–(16), (24), and (26)–(27) in the text) represent the amounts of calcic limestone (CaCO₃), dolomite (CaMg(CO₃)₂) and urea (CO (NH₂)₂), the areas of wetland and upland, the amount of on-farm burned biomass in crop residues management, the amount of electricity consumed on-farm, the nitrogen quantities of unintentional input, fertilizer residual in soils, fertilizer losses by leaching/runoff and reactive nitrogenous emissions, respectively.

The EF with different subscripts are variables denoting net GHG emission factors in CO₂eq, pure carbon of CH₄ or pure nitrogen of N₂O. Meanwhile, the UF with subscripts of C, SOC and M denotes the net CO₂ uptake factors of cropland ecosystems with woody perennials and the cultivated soils, and the CH₄ uptake factor of the upland ecosystems, respectively.

Equations S1–S6

$$UF_C = UF_{C_AB} + UF_{C_BB} + UF_{C_DW} + UF_{C_LI} + UF_{C_HWP} + UF_{SOC}, \quad (S1)$$

where the AB, BB, DW, LI, HWP and SOC denote aboveground biomass, belowground biomass, deadwood, litter, harvested wood products and soil organic matter, respectively (IPCC, 2006).

$$f = 1.260 t / (3.37 + t) \quad (10 \text{ observations, } R^2 = 0.963). \quad (S2)$$

In Equation S2, which is adapted from Shao et al. (2017) and Shao (2017), f denotes an adaption factor, namely a normalized annual CH₄ emission (dimensionless), and t represents years (yr) since conversion of a long-term upland to consecutive paddy rice cultivation. The numerator parameter represents the maximum adaptation factor, which indicates the annually cumulated methane emission from a paddy rice field at the equilibrium. The denominator parameter is a half-saturation value, which represents the time when the annually cumulated methane emission reaches a half of the maximum. More details for this supplementary equation are referred to the footnotes of Figure S1.

$$EF_w = f \cdot EF_{we}, \quad (S3)$$

where EF_{we} and EF_w (kg CH₄-C ha⁻¹ yr⁻¹) denotes the area-based emission factors of methane (CH₄) from a managed wetland at non-equilibrium and equilibrium stages, respectively, and f the adaptation factor (dimensionless) which is given by Equation S2.

$$EF_{mb} = -28.73CE + 28.41 \quad (R^2 = 999 \text{ for } CE > 80\%), \quad (S4)$$

where EF_{mb} denotes CH₄ emission factor in biomass burning (kg CH₄-C Mg⁻¹ dry matter), and CE is combustion efficiency (%). This supplementary equation is an empirical function adapted from IPCC (2000).

$$N_2O_t = 1.44 + e^{0.044N_{surplus}}, \quad (S5)$$

where N_2O_t denotes the annual or seasonal on-farm biogenic nitrous oxide (N₂O) emission from a cropland (kg N₂O-N ha⁻¹ yr⁻¹) per unit area or of certain given area, and $N_{surplus}$ is the nitrogen surplus (kg N ha⁻¹). This supplementary equation is an empirical function developed by Van Groenigen et al. (2010). The independent variable $N_{surplus}$ is defined by agronomists as $N_{surplus} = F_N - N_{accum}$, wherein F_N denotes the intentional nitrogen input in the current year (kg N ha⁻¹ yr⁻¹) and N_{accum} is the amount of nitrogen contained in the aboveground biomass at crop physiological maturity (kg N ha⁻¹ yr⁻¹).

$$N_{accum} = e^{1.667 \ln(\frac{ADM}{861})}, \quad (S6)$$

where ADM denotes the aboveground biomass at crop physiological maturity (kg dry matter ha⁻¹). This supplementary equation is adapted from Grassini and Cassman (2012).

Table S1a Category of the greenhouse gas (GHG) emissions in the life cycle of a crop cultivation system: On-farm.

Variable	Description	Unit
GHG _{total}	Total net GHG emission from a crop cultivation system, namely a sum of the on- and off-farm emissions	[1]
GHG _{on}	On-farm anthropogenic GHG emission from a crop cultivation system	[1]
Δ OC	Multi-year average rate of the increase in cropland carbon stock including organic carbon in both standing biomass and soil	[2]
$-\Delta$ OC	The opposite of Δ OC, i.e., multi-year average rate of the reduction in cropland carbon stock	[2]
Δ SOC	Multi-year average rate of the increase in soil organic carbon (SOC) stock of a cropland, with Δ OC \approx Δ SOC for a farmland free from woody perennial	[2]
$-\Delta$ SOC	The opposite of Δ SOC, i.e., multi-year average rate of the reduction in SOC stock of a cropland	[2]
IC	Abiotic carbon dioxide (CO ₂) emission from chemical reactions of applied calcic lime (CaCO ₃), dolomite (CaMg(CO ₃) ₂) and urea (CO(NH ₂) ₂)	[2]
CH _{4b}	Net biogenic methane (CH ₄) emission from a cropland	[2]
CH _{4bu}	Atmospheric CH ₄ uptake by upland soil	[2]
CH _{4bc}	Biogenic CH ₄ emission from wetland in association with human activities, like paddy rice field	[2]
CH _{4bb}	CH ₄ emission from biomass burning in crop residue management	[2]
N ₂ O _{on}	On-farm nitrous oxide (N ₂ O) emission from a cropland, excluding that occurring during fossil fuel combustion to drive on-farm machinery operation	[3]
N ₂ O _{bt}	Total biogenic N ₂ O emission from a cropland due to intentional and unintentional nitrogen inputs	[3]
N ₂ O _{bdc}	Direct biogenic N ₂ O emission from a cropland due to nitrogen input on purpose in the current year	[3]
N ₂ O _{bdp}	Direct biogenic N ₂ O emission from a cropland due to nitrogen input on purpose in the previous years	[3]
N ₂ O _{bif}	Indirect biogenic N ₂ O emission occurring in a cropland due to unintentional input of anthropogenic nitrogen via irrigation/runoff and/or atmospheric deposition	[3]
N ₂ O _{bb}	N ₂ O emission from biomass burning in crop residue management	[3]
GHG _{ono}	Emissions of GHGs (CO ₂ , CH ₄ and/or N ₂ O) due to direct and/or indirect fossil energy consumption in field machinery operations	[1]

Table S1b Category of the greenhouse gas (GHG) emissions in the life cycle of a crop cultivation system: Off-farm.

Variable	Description	Unit
GHG _{of}	The off-farm GHG releases in association with crop production in a farmland	[1]
N ₂ O _{ofbi}	Indirect biogenic N ₂ O emission from applied anthropogenic nitrogen for crop cultivation, which occurs off-farm due to runoff/leaching and gaseous nitrogen loss	[3]
N ₂ O _{ofbil}	Indirect biogenic N ₂ O emission occurring off-farm due to runoff/leaching of applied nitrogen	[3]
N ₂ O _{ofbig}	Indirect biogenic N ₂ O emission occurring off-farm due to gaseous nitrogen loss of applied nitrogen	[3]
GHG _{ofi}	Overall off-farm indirect GHG emissions due to manufacturing, storage and transportation of agricultural inputs to a farmland	[1]
GHG _{ofis}	Off-farm indirect GHG emissions due to manufacturing, storage and transportation of synthetic fertilizers	[1]
GHG _{ofim}	Off-farm indirect GHG emissions due to manufacturing, storage and transportation of organic manure	[1]
GHG _{ofic}	Off-farm indirect GHG emissions due to manufacturing, storage and transportation of agricultural chemicals	[1]
GHG _{ofif}	Off-farm indirect GHG emissions due to manufacturing, storage and transportation of fossil fuels	[1]
GHG _{ofie}	Off-farm indirect GHG emissions due to manufacturing, storage and transportation of electricity	[1]
GHG _{ofio}	Off-farm indirect GHG emissions due to manufacturing, storage and transportation of other input materials	[1]

Notes: 1 Mg = 10⁶ g. CO₂eq, carbon dioxide (CO₂) equivalent (at the 100-year time horizon if not specified). UA, unit land area, e.g., ha⁻¹, km⁻², grid⁻¹ or region⁻¹. [1] Mg or kg CO₂eq UA⁻¹ yr⁻¹. [2] Mg or kg C UA⁻¹ yr⁻¹. [3] Mg or kg N UA⁻¹ yr⁻¹. For the variables ΔOC, ΔSOC and CH_{4bu} (on uptake), values greater and less than 0 indicate sink and source fluxes, respectively, while for the other variables (on emission), values greater and less than 0 indicate source and sink fluxes, respectively.

Table S2a Greenhouse gas emission factors of on-farm machinery operations: Soil preparation/tillage and irrigation.

Item	Emission factor *				Unit	Refs.
	Low	High	Mean	SD		
Soil preparation or tillage						
Moldboard plowing ^a	49.13	73.70	55.73	15.03	A	[1]
Chisel plowing ^a	16.50	40.70	28.97	8.43	A	[1]
Heavy tandem disking ^a	16.87	41.07	30.43	9.17	A	[1]
Standard tandem disking ^a	14.67	26.03	21.27	6.23	A	[1]
Sub-soiling ^a	31.17	51.70	41.43	10.27	A	[1]
Field cultivation ^a	11.00	31.53	14.67	6.97	A	[1]
Rotary hoeing ^a	4.40	10.63	7.33	3.30	A	[1]
Disking ^a			22.02		A	[2]
Plant (disk) ^a			13.52		A	[2]
Plant (reduced or no tillage) ^a			18.77		A	[2]
Row crop cultivation ^a			15.15		A	[2]
Ridge cultivation and hoe ^a			27.12		A	[2]
Ploughing ^a			15.20		B	[3]
Harrowing ^a			1.70		B	[3]
Discing ^a			5.80		B	[3]
Direct drilling ^a			3.20		B	[3]
Combo drilling ^a			3.20		B	[3]
Other soil preparation ^a			6.40		B	[3]
Rolling ^a			1.70		B	[3]
Subsoiling ^a			11.30		B	[3]
Direct drilling on sand soil ^a			34.73		A	[4]
Ploughing on clay ^a			384.9		A	[4]
Irrigation						
Irrigation ^b			0.92		D	[6]
Irrigation ^c			41.37		E	[2]
Irrigation ^a	26.60	36.56	31.68	4.11	E	[2]
Irrigation ^d	26.60	28.65	27.62	1.45	E	[2]
Irrigation (wheat, NCP) ^d	35.83	358.3	177.8	81.71	A	[8]
Irrigation (maize, NCP) ^d	24.46	228.0	93.24	29.63	A	[8]
Irrigating (wheat/maize, NCP) ^d			0.31		F	[9]
By pumping groundwater ^b			550		A	[5]
Surface water without IRRS ^b			34.47		C	[1]
Surface water with IRRS ^b			90.20		C	[1]
Sprinkler irrigation ^b			14.68		E	[7]
Solid set sprinkle ^b			444.8		C	[1]

Permanent sprinkle ^b	130.2	c	[1]
Hand moved sprinkle ^b	59.77	c	[1]
Solid roll sprinkle ^b	85.43	c	[1]
Center-pivot sprinkle ^b	79.20	c	[1]
Traveler sprinkle ^b	61.97	c	[1]
Trickle ^b	311.3	c	[1]

Table S2b Greenhouse gas emission factors of on-farm machinery operations: Harvest.

Item	Emission factor *				Unit	Refs.
	Low	High	Mean	SD		
Potato ^a			232.0		A	[4]
Grain crop (combine + carting) ^a			18.77		A	[2]
Combine with straw chopping ^a			83.49		A	[4]
Wheat (combine + carting) ^a	16.52	37	24.10	11.23	A	[10]
Wheat (combining) ^a			33.30		A	[3]
Wheat (carting) ^a			1.44		A	[3]
Wheat (baling) ^a			19.30		A	[3]
Grain (building for storage, UK) ^b			0.81		G	[4]
Wheat (cooling, UK) ^d			0.09		G	[4]
Rape/wheat (grain drying, UK) ^d	9.83	11.67	10.75	1.31	G	[4]
Rape (cooling, UK) ^d			0.30		G	[4]
Soybean (combine) ^a	22.73	31.53	27.13	4.40	C	[1]
Maize (combine) ^a	31.17	42.17	36.67	5.50	C	[1]
Maize: cob threshing ^b			7.13		C	[11]
Maize: shred stalk ^a	12.83	19.43	16.13	3.30	C	[1]
Chop stalks ^a			13.82		A	[2]
Windrower ^a	15.03	20.17	17.60	2.57	C	[1]
Rake ^a	3.67	8.80	6.23	2.57	C	[1]
Baler (rectangle) ^a	5.87	18.33	12.10	6.23	C	[1]
Baler (large round) ^b	10.27	32.27	21.27	11.00	C	[1]
Maize (silage) ^a	48.40	97.53	71.87	23.47	C	[1]
Forage harvesting ^a	33.73	68.93	49.87	16.13	C	[1]
Grain drying ^d			0.006		H	[2]
Grain drying ^d			0.35		I	[4]

Table S2c Greenhouse gas emission factors of on-farm machinery operations: Fertilizer and agrochemical applications and others.

Item	Emission factor *				Unit	Refs.
	Low	High	Mean	SD		
Fertilization						
Mineral fertilizer application ^a			8.13		A	[4]
Fertilizer spraying ^a			0.90		B	[3]
Fertilizer spraying ^a	1.83	4.77	3.30	1.47	C	[1]
Fertilizer spreading ^a	18.70	37.03	27.87	9.17	C	[1]
Anhydrous ammonia application ^a			24.01		A	[2]
Knife-down ammonia ^a			37.03		C	[1]
UAN solution application ^a			3.69		A	[2]
Manure application ^a			0.14		A	[2]
Chemical application						
Chemical incorporation ^a	13.20	28.60	20.90	7.70	C	[1]
Chemicals spraying ^a			22.02		A	[2]
Pesticide spraying (wheat, Canada) ^a			5.00		A	[12]
Pesticide spraying ^a			1.40		B	[3]
Herbicide spraying ^a	2.57	8.07	5.13	4.77	C	[1]
Others						
Wheat planting (Canada) ^a			14		A	[12]
Plant/sow/drill ^a	8.07	14.30	11.73	2.93	C	[1]
No-till planting ^a	13.57	14.30	13.93	0.37	C	[1]
Potato planter ^a	20.53	30.07	25.30	4.77	C	[1]
Potato planter ^a			6.90		B	[3]
Mechanization (wheat, NCP) ^a	187.4	301.9	225.6	27.76	A	[11]
Mechanization (maize, NCP) ^a	301.9	510.1	367.8	45.11	A	[11]
Crop scouting ^a			13.52		A	[2]

Notes: * Factor for integrative emissions of all greenhouse gases (including carbon dioxide, methane and nitrous oxide) in the “cradle-to-grave” life cycle, which occur off-farm in mining, storage and transportation of the fossil fuels (diesel, coal, liquefied petroleum gas or natural gas) to farm gate and on-farm in their combustion. IRRS, irrigation runoff return system. NCP, north China Plain. UAN, urea-ammonium-nitrate. CO₂eq, carbon dioxide equivalent at the 100-year time horizon. ^a Diesel as consumed energy. ^b Diesel or electricity as consumed energy. ^c Natural gas as consumed energy. ^d electricity as consumed energy. ^A kg CO₂eq ha⁻¹ per crop season. ^B kg CO₂eq ha⁻¹ event⁻¹. ^C kg CO₂eq ha⁻¹ yr⁻¹. ^D kg CO₂eq kWh⁻¹. ^E kg CO₂eq cm⁻¹ water. ^F kg CO₂eq MJ⁻¹. ^G kg CO₂eq kg⁻¹ grain, on the basis of fresh matter that is dried to the standard moisture contents (maize, wheat and rape are 85%, 86% and 92.5% dry matter, respectively). ^H kg CO₂eq per moisture percentage point removed from per kg grain. ^I kg CO₂eq kg⁻¹ water loss. [1] Lal (2004a). [2] Adapted from Grassini and Cassman (2012) and

Lal (2004a). [3] Hiller et al. (2009), and references therein. [4] Adapted from Williams et al. (2010) and Lal (2004a). [5] Lal (2004b) and references therein. [6] Yan et al. (2015) and references therein. [7] Bayer et al. (2016) and references therein. [8] Adapted from Ha et al. (2015) and Lal (2004a). [9] Ha et al. (2015) and references therein. [10] Adapted from Gan et al. (2014), Grassini and Cassman (2012) and Lal (2004a). [11] Adapted from Ha et al. (2015) and references therein. [12] Gan et al. (2014) and references therein.

Table S3a Greenhouse gas emission factors of agricultural inputs in off-farm manufacturing, storage and/or transportation: Fertilizers with single essential nutrient.

Item	Emission factor				Unit	Reference
	Low	High	Mean	SD		
Nitrogen (N) fertilizers						
N fertilizer	2.68	10.31*	5.65	2.79	A	[1]
N fertilizer (China, 2005)			10.31*		A	[2]
N fertilizer production (China, 2005) ^a			10.22*		A	[2]
Transportation			0.09		A	[3]
Transportation (China, 2005)			0.10		A	[4]
Urea	3.50	9.70*	5.96	2.36	A	[5]
Urea (China, 2005)			8.20 [#]		A	[4]
Urea production (China, 2005)			8.10 [#]		A	[2]
Urea (China, 2005)			9.70*		A	[4]
Urea production (China, 2005) ^a			9.60*		A	[2]
ABC (China, 2005)			7.30 [#]		A	[4]
ABC production (China, 2005) ^a			7.20 [#]		A	[2]
ABC (China, 2005)			10.90*		A	[4]
ABC production (China, 2005) ^a			10.80*		A	[2]
AN	7.20	12.90	9.10	3.29	A	[6]
AN (China, 2005)	10.70	12.90	11.80	1.55	A	[7]
AN production (China, 2005) ^a			12.80		A	[2]
CAN			7.4		A	[8]
AS			3.0		A	[8]
AC (China, 2005)			7.30		A	[4]
AC production (China, 2005) ^a			7.20		A	[4]
Phosphorous (P) fertilizers						
P fertilizer	0.20	1.65	0.91	0.49	B	[9]
P fertilizers (China, 2005)			1.90		B	[10]
P fertilizer production ^a			0.73		B	[11]
P fertilizer transportation			0.06		B	[3]
Single super phosphate			0.26		B	[12]
Triple super phosphate			0.52		B	[12]
Rock P from 25% P ₂ O ₅ Tunisian			0.48		B	[12]
Potassium (K) fertilizers						
K fertilizer	0.10	0.98	0.49	0.26	C	[13]
K fertilizers (China, 2005)			1.6		C	[10]
K fertilizer production ^a			0.5		C	[8]
K fertilizer transportation			0.05		C	[3]

Rock K	0.71	D	[8]
K fertilzier (Muriate of postash)	0.44	D	[8]

Table S3b Greenhouse gas emission factors of agricultural inputs in off-farm manufacturing, storage and/or transportation: Compound fertilizers and manure.

Item	Emission factor				Unit	Reference
	Low	High	Mean	SD		
Compound fertilizers						
NPK compounds (China, 2005)			7.50		A	[4]
NPK production (China, 2005) ^a			7.40		A	[2]
Compound fertilizer of 15:15:21 ^b			4.81		A	[14]
Compound fertilizer of 22:11:11 ^b			5.75		A	[14]
Compound fertilizer of 9:24:24 ^b			5.18		A	[14]
Compound fertilizer of 17:17:17 ^b			4.88		A	[14]
Different compound fertilizers			5.42		A	[14]
Different compound fertilizers			5.05		A	[14]
Manure						
Production of fresh animal manure	0.026	0.029	0.028	0.003	E	[15]
FYM (fresh, N = 0.48%)			0.008		E	[16]
FYM (fresh, N = 0.48%)			0.15		A	[16]
Chicken manure (N = 1.03%)			0.04		E	[17]

Table S3c Greenhouse gas emission factors of agricultural inputs in off-farm manufacturing, storage and/or transportation: Agricultural chemicals.

Item	Emission factor				Unit	Reference
	Low	High	Mean	SD		
Pesticide production ^a			18.00		F	[18]
Pesticides			19.12		F	[19]
Fungicides/nematicides	3.16	29.33	14.01	9.70	F	[20]
Herbicides	6.23	46.20	18.92	14.02	F	[21]
Insecticides	4.40	29.70	18.70	11.00	F	[14]
Alachlor			20.53		F	[14]
Atrazine			13.93		F	[14]
Benomyl			29.33		F	[14]
Bentazon			31.90		F	[14]
Butylate			10.27		F	[14]
Captan			8.43		F	[14]
Carbaryl			11.37		F	[14]
Carbofuran			33.37		F	[14]
Chloramben			12.47		F	[14]
Chlorodimeform			18.33		F	[14]
Chlorsulfuron			26.77		F	[14]
Cyanazine			14.67		F	[14]
Cypermethrin			42.90		F	[14]
Dicamba			21.63		F	[14]
Dinoseb			5.87		F	[14]
Diquat			29.33		F	[14]
Diuron			19.8		F	[14]
EPTC			11.73		F	[14]
Ferbam			4.40		F	[14]
Fluazifop-butyl			38.13		F	[14]
Fluometuron			26.03		F	[14]
Gasoline			3.12		G	[14]
Glyphosate			33.37		F	[14]
Lindane			4.40		F	[14]
Linuron			21.27		F	[14]
Malathion			16.87		F	[14]
Maneb			7.33		F	[14]
MCPA			9.53		F	[14]
Mechyl parathion			11.73		F	[14]
Methoxychlor			5.13		F	[14]

Metolachlor	20.17	F	[14]
Paraquat	33.73	F	[14]
Parthion	10.27	F	[14]
Phorate	15.40	F	[14]
Propachlor	21.27	F	[14]
Taxaphene	4.40	F	[14]
Trifluralin	11.00	F	[14]
2, 4, 5-T	9.90	F	[14]
2,4-D	6.23	F	[14]

Table S3d Greenhouse gas emission factors of agricultural inputs in off-farm manufacturing, storage and/or transportation: Others.

Item	Emission factor				Unit	Reference
	Low	High	Mean	SD		
Gypsum (quarried)			0.35		^H	[8]
Gypsum (FGSD)			0.11		^H	[8]
Lime	0.11	1.32	0.69	0.44	^I	[22]
Lime			0.16		^J	[8]
Limestone (Ca = 39%) ^c			0.15		^J	[8]
Burnt lime (or chalk, Ca = 60%)			0.23		^J	[8]
Cereal seed	0.19	0.68	0.36	0.27	^I	[23]
Agricultural film			2.50		^I	[25]
Agricultural film (China)			3.17		^I	[24]
Diesel	2.63	3.45	2.97	0.36	^G	[26]
Diesel			3.75		^I	[27]
Grid electricity			0.27		^M	[28]
Grid electricity (China)			0.92		^M	[29]

Notes: ABC, ammonium bicarbonate. AN, ammonium nitrate. CAN, calcium ammonium nitrate. AS, ammonium sulfate. AC, ammonium chloride. FYM, farm yard manure. FGDS, flue gas desulphurization. * Including release of the molecule-fixed fossil carbon in urea or ABC after application. CO₂eq, carbon dioxide equivalent at the 100-year time horizon. # Excluding release of the molecule-fixed fossil carbon. ^a Emission in fertilizer manufacturing exclusively. ^b Nutrient mass ratio of N:P₂O₅:K₂O. ^b Including emission of carbon dioxide (CO₂) from soils once neutralized by lime. ^{A, B, C, D, E, F, H, I, J} kg CO₂eq per kilogram N, P₂O₅, K₂O, K, fresh manure, active ingredient, S, matter and Ca, respectively. ^G kg CO₂eq L⁻¹ product. ^H kg CO₂eq kg⁻¹ S. ^I kg CO₂eq kg⁻¹ matter. ^M kg CO₂eq kWh⁻¹. NBSC, National Bureau of Statistics of China. [1] Adapted from Gao et al. (2015), Grassini and Cassman (2012), Ha et al. (2015), Hiller et al. (2009), Lal (2004a, b), Lu et al. (2009), Macedo et al. (2008), West and Marland (2002), Yang et al. (2014), Zhang et al. (2013), and references therein. [2] Adapted from Zhang et al. (2013). [3] Di et al. (2005), IPCC (2006), NBSC (2011a, b), Wu et al. (2014), Yuan et al. (2006). [4] Adapted from Lal (2004a) and Zhang et al. (2013). [5] Adapted from Ali et al. (2017), Li et al. (2016), Williams et al. (2010), Zhang et al. (2013), and references therein. [6] Adapted from Lal (2004a), Li et al. (2016), Williams et al. (2010), Zhang et al. (2013), and references therein. [7] Adapted from Lal (2004a), Li et al. (2016) and Zhang et al. (2013). [8] Williams et al. (2010). [9] Adapted from Bayer et al. (2016), Gao et al. (2015), Grassini and Cassman (2012), Ha et al. (2015), Hiller et al. (2009), Lal (2004a, b), Macedo et al. (2008), West and Marland (2002), Yang et al. (2014), Yan et al. (2015), and references therein. [10] Li et al. (2016). [11] Brentrup and Pallière (2008). [12] Adapted from Williams et al. (2010). [13] Adapted from Bayer et al. (2016), Grassini and Cassman (2012), Gao et al. (2015), Ha et al. (2015), Hiller et al. (2009), Lal (2004a, b), Macedo et al. (2008), West and Marland (2002), Yang et al. (2014), and references therein. [14] Lal (2004a). [15]

Stout (1990). [16] Hiller et al. (2009) and references therein. [17] Ha et al. (2015) and references therein. [18] West and Marland (2002), Yan et al. (2015). [19] Wu et al. (2014) and references therein. [20] Adapted from Gan et al. (2014), Hiller et al. (2009), Lal (2004a, b), and references therein. [21] Adapted from Gan et al. (2014), Hiller et al. (2009), Lal (2004a), West and Marland (2002), and references therein. [22] Adapted from Bayer et al. (2016), Lal (2004a), and references therein. [23] Adapted from Ali et al. (2017), Ha et al. (2015), and references therein. [24] Qi (2010). [25] Energy Source, China (2009), Yan et al. (2015). [26] Adapted from Ali et al. (2017), Bayer et al. (2016), Lal (2004a), West and Marland (2002), Yan et al. (2015), and references therein. [27] IPCC (2006), NBSC (2011a), Wu et al. (2014), Yuan et al. (2006). [28] Lal (2004a), West and Marland (2002). [29] Yan et al. (2015).

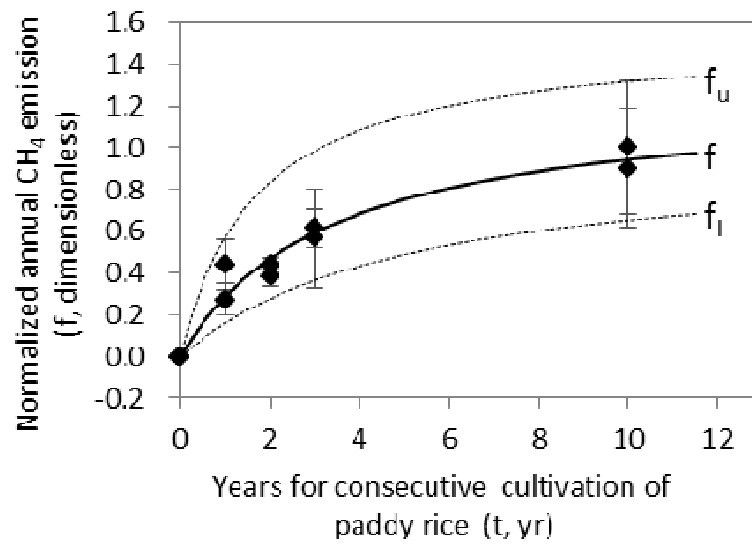


Figure S1 Dependence of normalized annual methane (CH₄) emission upon the years since conversion of subtropical lands long-term growing upland plants to double paddy rice fields (adapted from Shao et al., 2017). The original observations are divided by those of the ten-year treatment, so as to obtain the normalized values. The diamond symbols are means of four spatial replicates, with the vertical bars indicating the standard errors at the 95% confidence interval, irrespective unfertilized or fertilized. The data for the zero year were simultaneously measured in the unconverted lands long-term growing upland plants (Shao, 2017). The solid curve is given by the equation for f while and the lower and upper dashed curves provide the lower (f_l , giving by 0.984 and 5.07 as the numerator and denominator parameters, respectively) and upper bound (f_u , giving by 1.535 and 1.67 as the numerator and denominator parameters, respectively) at the 95% confidence interval.

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