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SUPPLEMENTARY INFORMATION
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TITLE: Greenhouse gas emissions intensity of global croplands

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1. Supplementary Methods

For rice emission factors, rice conversion factors, and peat emission factors, we converted 95% confidence intervals and sample sizes reported by IPCC [1], Yan, et al. [2], and Yan, et al. [3] into mean and standard deviation. We used these values to create lognormal (rice emission scaling factors) or normal (peat emission factors) distributions. For peat harvested area fraction and rice conversion factors, we constructed triangular distributions. For peat, distributions were created from the naïve (crops planted on peatlands in proportion to the area of a grid cell occupied by peatlands), minimum, and maximum potential overlap of peat and crop area in a grid cell. For rice conversion factors, we used the default factor and error range to construct the distributions. For indirect N_2O emissions, we constructed beta distributions from low, center, and high fractions leached or volatilized, and emissions factors. When no uncertainty or error value was provided, we assumed a normal distribution and a standard deviation of 50% around the mean value.

For N_2O emissions from fertilizer application, we obtained the distribution of emissions factors by randomly sampling a correlated set of model parameters and analytically averaging over the ensemble of emissions factors associated with those model parameters. Our analysis is based on Equation 1 presented in Gerber, et al. [4]; here, we removed subscripts and the error term ϵ:

$$Y(X) = exp(\alpha_0 + \alpha_1 X + \beta Z) \quad (1)$$

In Equation 4, X is the N fertilizer rate (kg ha^{-1}), Z is a dummy variable set to 1 for paddy rice and 0 for all other crops, β is a "discount factor" for flooded rice, and α_0 and α_1 are random variables such that $\alpha_0 \sim N(\mu_0, \sigma_0^2)$ and $\alpha_1 \sim N(\mu_1, \sigma_1^2)$, where N denotes a normal distribution. If we hold the parameters μ_0 and μ_1 fixed, the uncertainty due to random values of α_0 and α_1 corresponds to site/year variability. In addition to this uncertainty, there is uncertainty of the parameters themselves (including β). To derive mean emissions results for crops other than flooded rice, we fixed μ_0 and μ_1 at their mean values (Table S9), and averaged over the normal distributions of α_0 and α_1 to get the following expression for the site-year-averaged emissions response $Y_{\overline{sy}}(X)$ of the model:

$$Y_{\overline{sy}}(X) = I(X) - I(0) \quad (2)$$

Where:

$$I(X) = exp\left[\frac{((\mu_0 + \sigma_0^2)^2 - \mu_0^2)}{(2\sigma_0^2)}\right] exp\left[\frac{((\mu_1 + \sigma_1^2 X)^2 - \mu_1^2)}{(2\sigma_1^2)}\right] \quad (3)$$

Parameters in Equation 6 are available in Supplementary Table 10. To derive mean emissions results for flooded rice, we replaced μ_0 in Equation 6 with $\mu_0 + \beta$. To determine confidence intervals for N_2O emissions estimates, we repeatedly sampled new values of the parameters μ_0, μ_1, and β according to their distributions and correlation properties. For each new set of values μ_0, μ_1, and β, we applied the procedure above. Repeating this procedure, we developed a distribution of N_2O responses from which we derived mean and standard deviation.

2. Supplementary Discussion

2.1. Comparisons with Previous Estimates

2.1.1. Rice Methane

We compared our rice CH_4 emissions results to recent 2000-era global scale estimates (Supplementary Table 11), as well country-scale estimates[2,5] and national communications to the UNFCCC (Supplementary Data 6). Our total global emissions estimate of 28.3 Tg CH_4 yr^{-1} aligns closely with other recent studies that estimate rice CH_4 emissions of 22-34 Tg CH_4 yr^{-1} [2,5-8]. On a country basis, coefficients of determination (r^2) of 0.80-0.96 also suggest similarity of our spatially-explicit models with these three sources of aggregated rice CH_4 emissions estimates.

2.1.2. Peatland Extent, Drainage, and Emission Estimates

We estimate 3.4 M km^2 of global peatlands, and 3.3 M km^2 within the country boundaries considered in this study. Combining previous country-level peatland estimates[9-12] yields a best estimate of ~2.7 M km^2 within these countries (range 2.6-3.9 M km^2, Supplementary Data 3).

The coefficients of determination between our country-level peatland estimates and these "best estimates" is $r^2 = 0.88$.

Our assessment indicates that ~4% of global peatlands are drained for crop agriculture circa year 2000. Only a few studies have quantified carbon emissions from global drained peatlands. Joosten [9] accounts for the extent and status of peatlands in 1990 and 2008 for all nations for which peat data are available, and estimates 3.9 M km^2 of global peatlands in 1990, with ~12% draining. Frolking, et al. [13] reviews global and regional studies across tropical and non-tropical regions to derive a rough estimate of ~4.0 M km^2 of peatlands, with ~13% "disturbed". These studies do not differentiate draining for croplands from other causes of disturbance[9,10,14]. As a result of our relatively lower total peatland area as well as a focus on cropland drainage compared to these other studies, our mean cropland peat emissions estimate is ~51-80% of estimates that account for all peat disturbance[15], or disturbance due to agriculture including livestock[9] (Supplementary Table 12).

2.1.3. Fertilizer N_2O

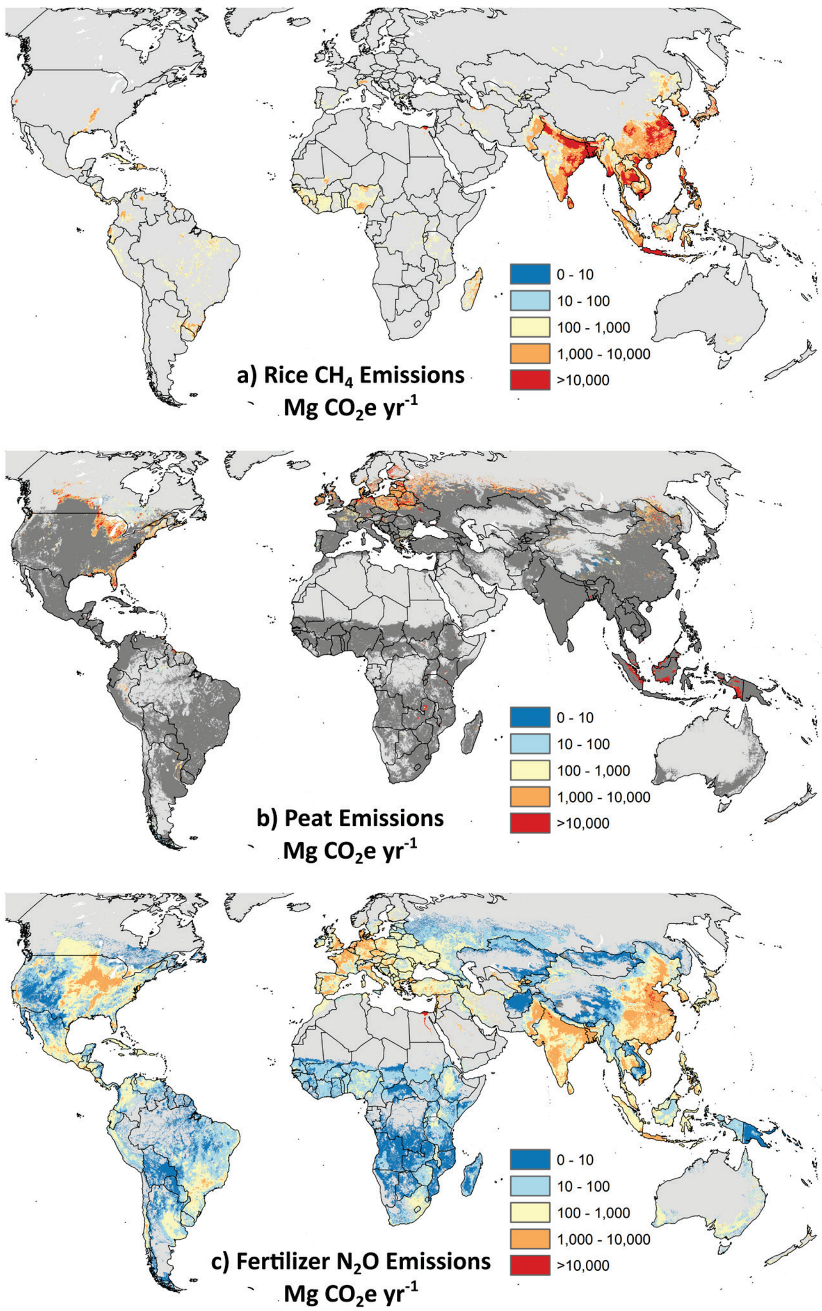
The FAO publishes comparable direct and indirect N_2O emissions estimates at the national level using a 1% emissions factor[5]. However, these estimates do not limit leaching to regions where soil water holding capacity is exceeded, and they assume that all managed manure not leached or volatilized is applied to soils[5]. In 2000, FAO estimates suggest 81 Tg synthetic N applied to croplands (103% of our 79 Tg synthetic N), as well as 24 Tg manure N (324% of our 7.4 Tg manure N), totaling 105 Tg N applied to agricultural soils (122% of our 86 Tg N). By applying a non-linear direct N_2O emissions model with a mean global emissions factor of 0.77%, we generate global N_2O emissions estimates substantially less than when applying a 1% fixed emissions factor[4] (Supplementary Table 13). Notably, our negative concave N_2O emissions model generates underestimates of N_2O emissions when N fertilizer application data are aggregated in space[64,80], leading to conservatively low emissions estimates[4,16,17]. Largely as a result of the FAO's greater assumed total N applied, but also due to our non-linear direct N_2O emissions model and indirect leaching methods that identify regions where soil water holding capacity is surpassed, the FAO estimates direct N_2O emissions 160% greater than our 0.66 Tg N_2O-N yr^{-1}, and indirect emissions 179% greater than our 0.20 Tg N_2O-N yr^{-1}. On a country-level basis, the coefficients of determination between year 2000 FAO N_2O emission estimates (synthetic + manure applied to soils) and our results is $r^2 = 0.98$ (Supplementary Data 7).

2.2. Temporal Limitation

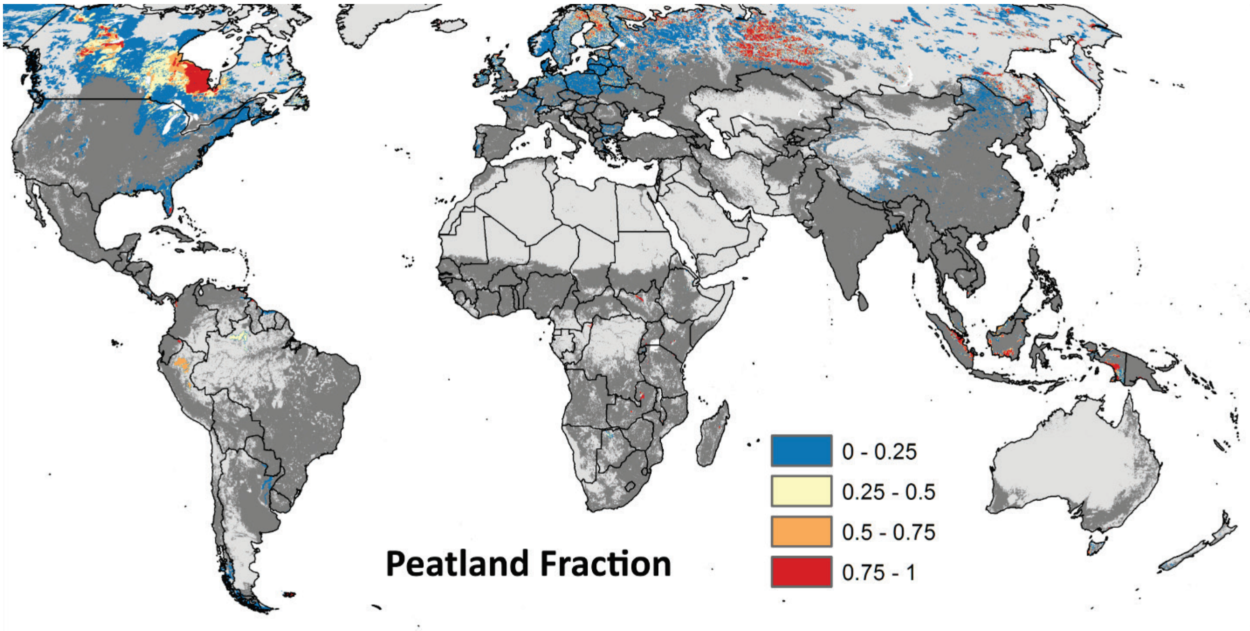
Many of the year 2000 input datasets applied here have not been updated to the current era. Global agriculture has changed considerably since 2000, with substantial peatland clearing and draining in Southeast Asia[18], crop intensification in South America[19], and increasing prevalence of biofuels and feed crops[20]. Quantifying current cropland emissions and intensities would support policy formulation to create a climate-effective food system, balancing GHG emissions mitigation with farmer adaptation to changing climate, biodiversity conservation, socio-economic conditions, cultural norms, and nutritional requirements.

3. Supplementary Figures

Supplementary Figure 1. Total emissions (Mg CO_2e yr^{-1}) from paddy rice, peatland drainage, and N fertilizer. Emissions are per grid cell, and consist of: a) CH_4 emissions from paddy rice cultivation; b) CO_2, CH_4, and N_2O emissions from peatland draining for agriculture; and c) N_2O emissions from fertilizer application. Dark grey areas in (b) indicate 2000-era cropland locations.



Supplementary Figure 2. Fraction of each grid cell occupied by peatlands. Dark grey areas indicate 2000-era cropland locations.



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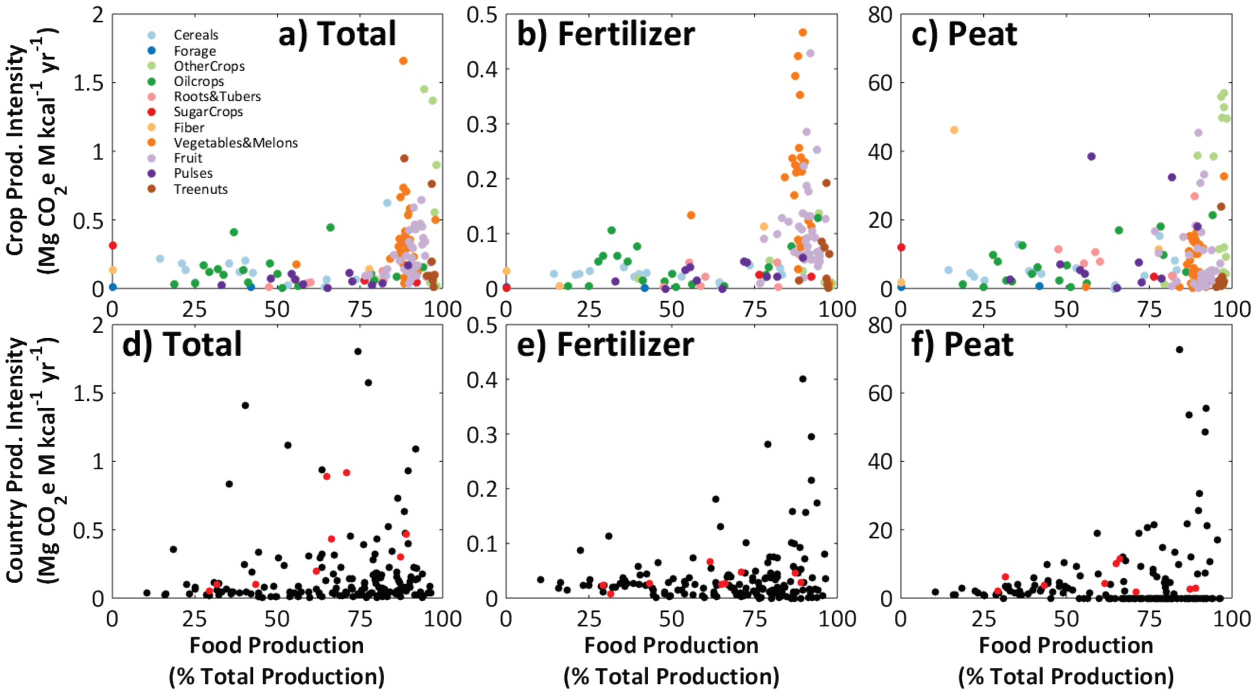
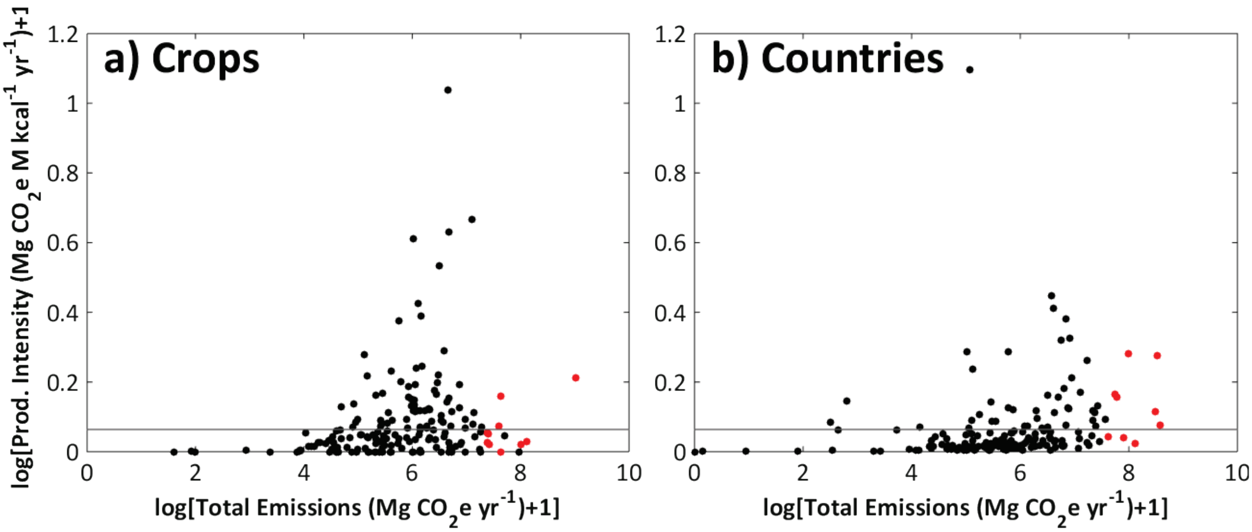
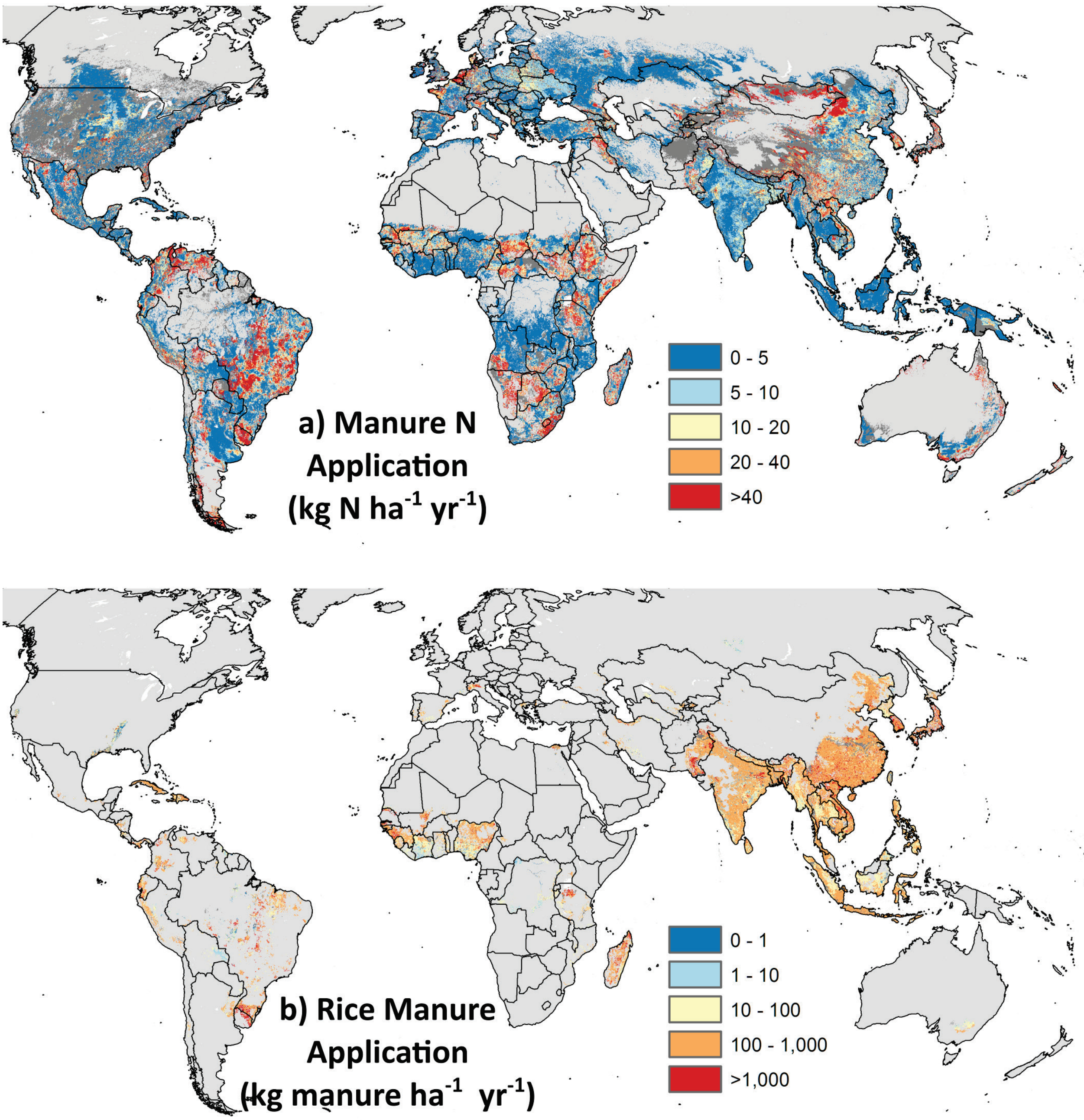
Supplementary Figure 3. Cropland production intensity contrasted with the contribution of food to total production for crops (a-c) and countries (d-f). At the crop level, overall crop production intensity (a) tends to be highest for crops that are mostly produced for food; this trend holds for fertilizer production intensity (b) and peat production intensity (c). Crops including vegetables, fruits, and tree nuts tend to have the highest production intensity, while cereals and pulses often have lower intensity. Similar trends are observed at a country level, including overall production intensity (d), fertilizer (e) and peat (f) production intensity. In d-f, red circles indicate the top nine emitting countries; individual European countries, rather than the European region, are displayed. Production intensity includes crop calories destined to any use. Food intensity excludes calories dedicated to industrial and non-food uses, and assumes that 12% of the calories used as livestock feed are available in foods for human consumption[20].



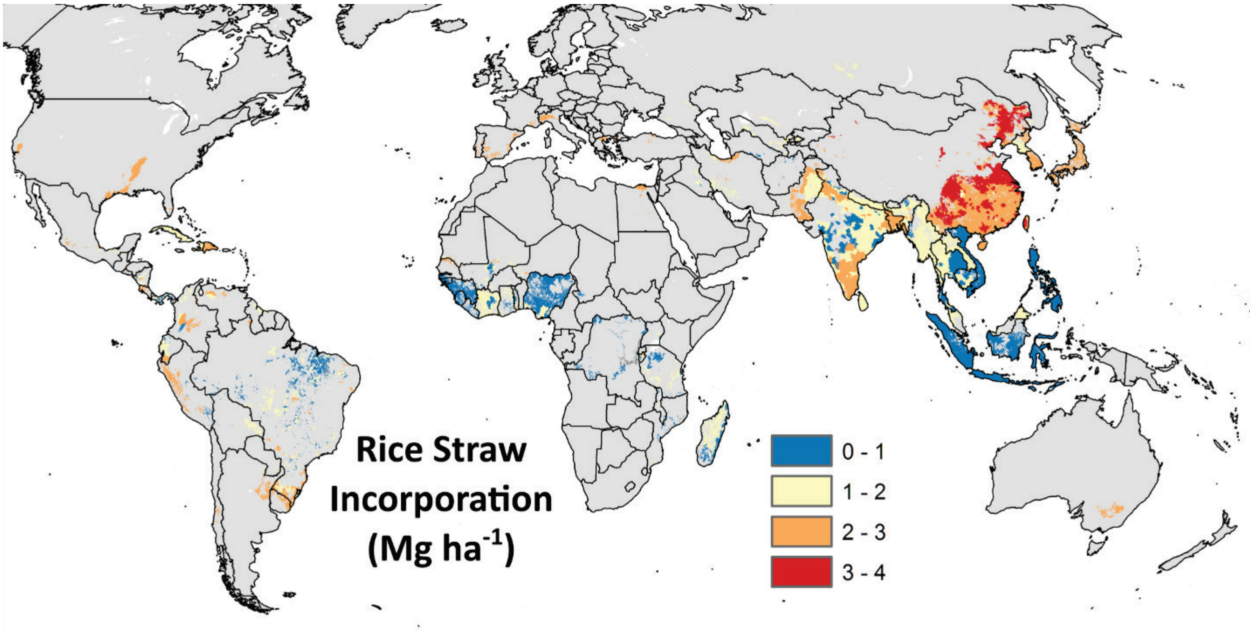
Supplementary Figure 4. Relationship between total emissions and production intensity. Log-transformed total emissions are a poor predictor of production intensity for crops (a, r^2=0.054, p=0.0022) and countries (b, r^2=0.13, p<0.001). Production intensity includes crop calories destined to any use. Food intensity excludes calories dedicated to industrial and non-food uses, and assumes that 12% of the calories used as livestock feed are available in foods for human consumption[20]. Horizontal line denotes mean global production intensity. In (b), red circles indicate the top nine emitting countries and food crops; individual European countries, rather than the European region, are displayed. Data are log-10 transformed.



Supplementary Figure 5. Manure applied to croplands. Manure N application (a, kg N ha^{-1} yr^{-1} averaged across all crops) was used along with synthetic N additions to calculate N_2O emissions from fertilizer application, while manure mass (b, kg manure ha^{-1} yr^{-1}) was used to assess CH_4 emissions from rice. Dark grey areas in (a) indicate 2000-era croplands with zero estimated manure application.



Supplementary Figure 6. Rice straw incorporation rates (Mg ha^{-1}) for single-cropped paddy rice.



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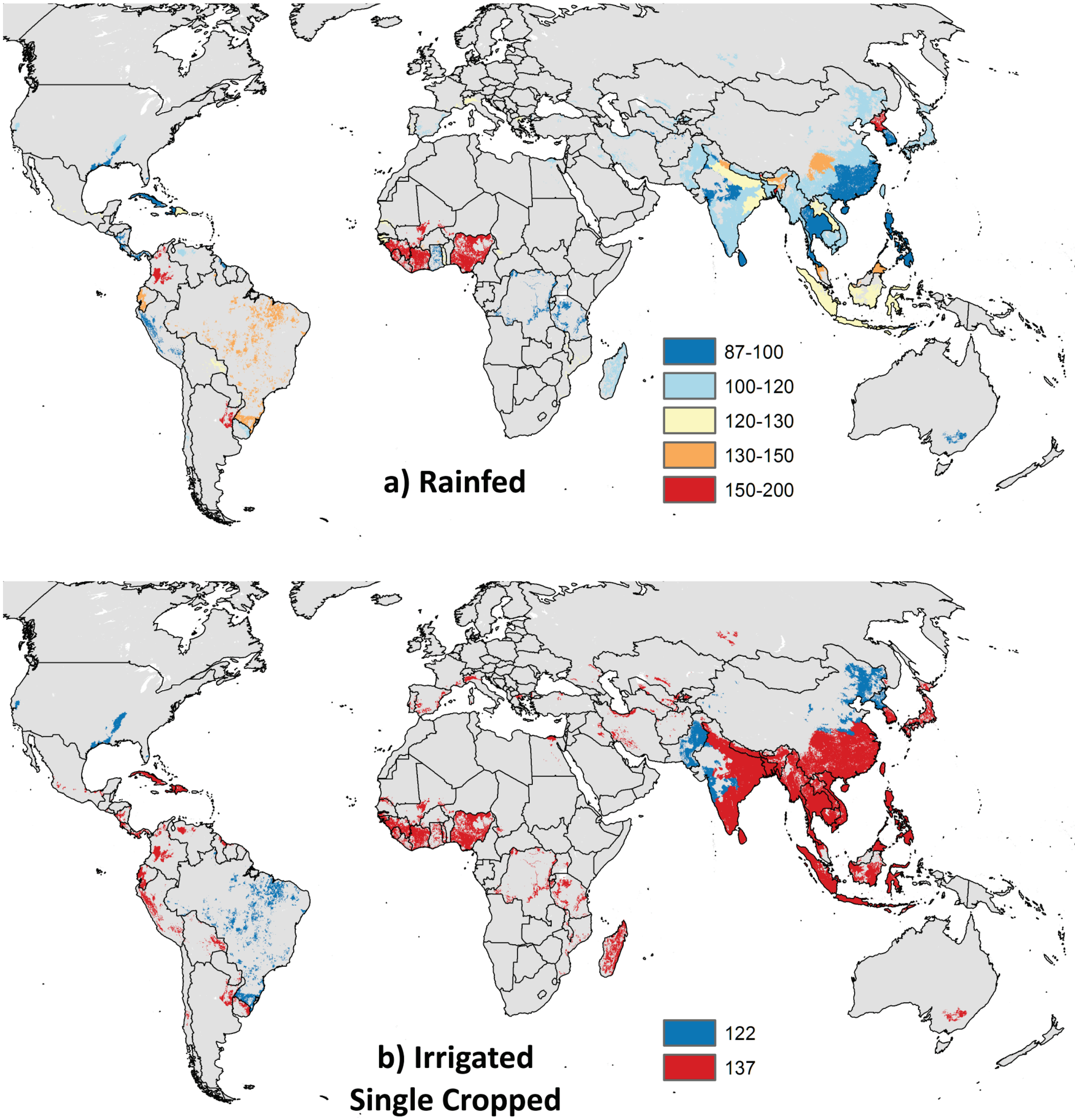
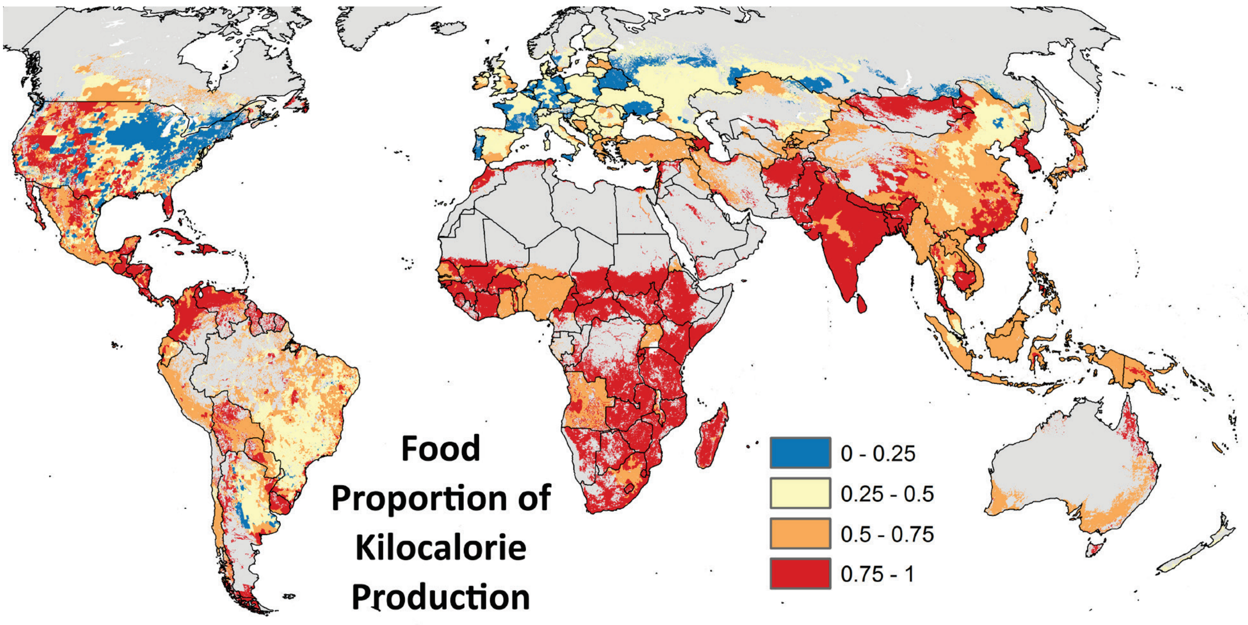
Supplementary Figure 7. Examples of rice cropping season length circa 2000. Maps depict the number of days that rainfed (a) and single-cropped irrigated rice (b) is estimated to be cultivated. We quantified rice growing season length (days crop^{-1}) using MIRCA2000 crop calendars[21].



Supplementary Figure 8. Proportion of total kilocalorie production available as food based on spatial allocation of national estimates by crop or crop group. We used the FAOSTAT Food Balance Sheets to calculate the fraction of total calories used for food in each crop and country. We followed an approach similar to Cassidy, et al. [20] to partition calories in the "food manufacturing" category and the calories derived from oilseeds to either food or non-food uses. We also used detailed bilateral crop trade data from MacDonald, et al. [22] to link the use of imported crops to calorie production in the producing countries. Following Cassidy, et al. [20], we assumed that 12% of total "feed" calories are available for human consumption in foods globally.



4. Supplementary Tables

Supplementary Table 1. Total global emissions and emissions intensities for peat, fertilizer, paddy rice, and from all sources of emissions ("All").

Type	Total ($Tg\ CO_2e\ yr^{-1}$)		Area Intensity ($Mg\ CO_2e\ ha^{-1}\ yr^{-1}$)		Production Intensity [2] ($Mg\ CO_2e\ M\ kcal^{-1}\ yr^{-1}$)		Food Intensity [3] ($Mg\ CO_2e\ M\ kcal^{-1}\ yr^{-1}$)	
	mean [1]	*SD [1]*	*mean [1]*	*SD [1]*	*mean [1]*	*SD [1]*	*mean [1]*	*SD [1]*
Peat CO_2e	630	90	61	32	3.7	6.5	8.8	17
Fertilizer N_2O	403	74	0.31	0.20	0.033	0.044	0.046	0.066
Rice CH_4	962	2,170	6.3	14	0.58	1.3	0.66	1.4
All	1,994	2,172	1.5	2.1	0.16	0.23	0.25	0.31

[1] Mean and standard deviation (SD) were calculated from 200 model runs.

[2] Production intensity includes all crop calories.

[3] Food intensity excludes calories dedicated to industrial and non-food uses, and assumes that 12% of the calories used as livestock feed are available in foods for human consumption[20].

Supplementary Table 2. Emission and conversion factors for rice methane (CH_4) emissions.

Type		Mean	SD [1]	Range	Distribution	Source
Default Emission Factor		1.3	2.5		lognormal	IPCC [23] Table 5.11
Cultivation Period Water Regime	Irrigated - Continuously Flooded	1.0	0.85		lognormal	IPCC [23] Table 5.12
	Irrigated - Single Drainage	0.60	0.62		lognormal	IPCC [23] Table 5.12
	Irrigated - Multiple Drainage	0.52	0.45		lognormal	IPCC [23] Table 5.12
	Rainfed - Regular	0.28	0.29		lognormal	IPCC [23] Table 5.12
	Rainfed - Drought	0.25	0.33		lognormal	IPCC [23] Table 5.12
	Rainfed - Deepwater	0.31	0.16		lognormal	IPCC [23] Table 5.12
Pre-Cultivation Water Regime	Short Drainage	1.0	0.47		lognormal	IPCC [23] Table 5.13
	Long Drainage	0.68	0.40		lognormal	IPCC [23] Table 5.13
	Flooded	1.9	0.96		lognormal	IPCC [23] Table 5.13
Conversion Factor	Rice Straw <30 days	1.0		0.97 - 1.0	triangle	IPCC [23] Table 5.14
	Rice Straw >30 days	0.29		0.20 - 0.40	triangle	IPCC [23] Table 5.14
	Manure	0.14		0.069 - 0.21	triangle	Yan, et al. [2] Table 3

[1] Standard deviation (SD) was calculated from the number of sites sampled (*n* = 53, Yan, et al. [3]) and 95% confidence intervals, except for deepwater rainfed rice, where SD was assumed to be 50% of the mean value.

Supplementary Table 3. Irrigated rice water regime during cultivation period.

Country	Continuous Flooding (%)	Single Drainage (%)	Multiple Drainage (%)	Source
Bangladesh	4.0	0	96	ALGAS[24]
Cambodia	100	0	0	2nd National Communication[25]
China	20	0	80	Li et al. [26]
India	30	43	26	ALGAS[24]
Indonesia	43	22	35	ALGAS[24]
Japan	20	0	80	Assumed same as China[27]
Korea	9.0	0	91	ALGAS[24]
Myanmar	0	0	100	ALGAS[24]
Pakistan	100	0	0	ALGAS[24]
Philippines	100	0	0	ALGAS[24]
Thailand	100	0	0	ALGAS[24]
United States	100	0	0	Assumed single drainage[27]
Vietnam	100	0	0	ALGAS[24]
Rest of World [1]	68	6.5	26	Mean of above countries except China, Japan, and Korea

[1] Rest of world values were determined from relative mean proportions of continuous flooding, single drainage, and multiple drainage for all countries in this table, excluding China, Japan, and Korea.

Supplementary Table 4. Percent of pre-season drainage practices (long, short, none) for irrigated and rainfed rice, including multiple cropping [1].

Type	Drainage	Single Cropped (%)	Multi-Cropped (%)		
			1st	*2nd*	*3rd*
irrigated	long	95	0	0	0
	short	0	90	20	0
	none	5	10	80	100
deepwater	long	0			
	short	0			
	none	100			
regular rainfed & drought-prone	long	5			
	short	5			
	none	90			

[1] We applied the method of Yan et al. [2] to determine pre-cultivation water regimes.

Supplementary Table 5. Rainfed rice areas in Asian countries [1].

Country	Upland (%)	Deepwater (%)	Rainfed Shallow (%)	Rainfed Deep (%)
Bangladesh	8.7	15	41	36
Cambodia	1.5	10	67	22
China	20	0	80	0
India	22	6	52	19
Indonesia	24	0	56	20
Korea	0	0	100	0
North Korea	39	0	61	0
Laos	39	0	61	0
Malaysia	35	0	59	6.5
Myanmar	6.9	12	66	15
Nepal	9.0	16	54	22
Philippines	12	0	64	24
Sri Lanka	0	0	89	11
Thailand	2.3	3.9	73	20
Vietnam	10	5.7	63	21
Rest of World [2]	21	1.5	67	10

[1] We translated the rice cultivated areas defined by Huke and Huke [28] into IPCC non-irrigated rice categories (upland, regular rainfed, drought-prone, and deepwater) for these countries.

[2] Rest of world values were determined from estimated proportional area in each category, derived from all individual countries in this table.

Supplementary Table 6. Percent of straw production left on field [1].

Country	Straw Left on Field (%)
Indonesia	14
Thailand	33
Bangladesh	59
Vietnam	14
Philippines	20
Myanmar	38
Afghanistan	30
Pakistan	66
Turkey	42
China	56
India	52
Rest of World	45

[1] The proportion of straw left on the field was derived from Yan, et al. [29] for China, and Yevich and Logan [30] for other Asian countries. For all other countries ("Rest of World"), we applied the weighted mean for Asia (excluding China and India) reported by Yevich and Logan [30].

Supplementary Table 7. Inputs to global peat soil map [1].

Location	Primary Source	Secondary Source	Method	Data Type & Resolution
Africa	Soil Atlas of Africa[31]		histosols (HS) from the dominant World Reference Base Reference Soil Group	ESRI shapefile
Australia (excluding Tasmania)	Digital Atlas of Australian Soils [32]		peatlands (class Z, organosols)	ESRI shapefile
Australia (Tasmania)	Tasmanian Vegetation Monitoring and Mapping Program (TASVEG 2.0)[33]		Moorland, Sedgeland, Rushland and Peatland vegetation codes MBE, MBP, MBS, MBU, MBW, MRR, MSP and MSW	ESRI shapefile
Canada	Peatlands of Canada[34]		bog and fen features of with ≥30 cm depth and ≥30% organic carbon content	ESRI shapefile
China	Yu, et al. [14]	Niu, et al. [35]	Inland Marshes Feature (Code 24); ESRI shapefile	ESRI shapefile
Finland	Geological Survey of Finland's 1:1,000,000 Soils Map[36]		peat deposits ('Turvekerrostuma', code Tu)	ESRI shapefile
French Guinea	Cubizolle, et al. [37]		digitized in ArcGIS	ESRI shapefile
Iceland	Circumpolar Active-Layer Permafrost System Version 2.0 (CAPS 2)[38]		gelisols with >1% histel coverage	ESRI shapefile
Iceland	Harmonized World Soil Database (HWSD)[39]		proportion of Histosols (HS) in each cell	30 arc-second raster
Indonesia (Kalimantan)	Wahyunto, et al. [40]		polygons with a 'peat id'	ESRI shapefile
Indonesia (Papua)	Wahyunto, et al. [41]		polygons with a 'peat id'	ESRI shapefile
Indonesia (Sumatra)	Wahyunto, et al. [42]		polygons with a 'peat id'	ESRI shapefile
Ireland	Yu, et al. [14]	Connolly, et al. [43]	RB, LLA and HLM layers; ESRI raster dataset	ESRI shapefile
Ireland	Yu, et al. [14]	[44]	Extent of peatlands in Fennoscandia from Fig. 1, >5% visual coverage; Digitized in ArcGIS	ESRI shapefile
Malaysia (Borneo)	Koh, et al. [45]		digitized in ArcGIS	ESRI shapefile
Malaysia (Peninsular)	Wetlands International [46]		digitized in ArcGIS	ESRI shapefile
New Zealand	Yu, et al. [14]	Ausseil, et al. [47]	Current Extent feature of Bogs and Fens from wetland typology; ESRI shapefile	ESRI shapefile
Patagonia	Yu, et al. [14]	Heusser [48]	Extent of Magellanic Moorland from Fig. 1; Digitized in ArcGIS	ESRI shapefile
Patagonia	Yu, et al. [14]	Pisano [49]	Extent of 1) Sphagnum magellanicum and other	ESRI shapefile

			ombrotrophic bogs in area of deciduous forest, 2) Low altitude cushion-plant, herbaceous, woodland and shrubby bogs mostly in area or evergreen coastal forests, and 3) Montane cushion-plant herbaceous bogs; Digitized in ArcGIS	
Sweden	Geological Survey of Sweden's 1:1,000,000 Soils Map (Jordarter)[50]		peat ('torv') areas	ESRI shapefile
United Kingdom	Yu, et al. [14]	British Geological Survey [51]	Peat feature from Surficial Deposits V1.0 digital map DiGMapGB-625; ESRI shapefile	ESRI shapefile
United States (Alaska)	Circumpolar Active-Layer Permafrost System Version 2.0 (CAPS 2)[38]		gelisols with >1% histel coverage	ESRI shapefile
United States (including Puerto Rico and the U.S. Virgin Islands)	Digital General Soil Map (DGSM)[52]		histosols with ≥30 cm depth	ESRI shapefile
Rest of World	Harmonized World Soil Database (HWSD)[39]		proportion of Histosols (HS) in each cell	30 arc-second raster

[1] We generated a peatland map based on the Harmonized World Soil Database[39]. In regions known to have extensive peatlands, we replaced or supplemented the HWSD with more resolved data.

Supplementary Table 8. Emissions factors for cultivated peatland soils derived from IPCC [1].

GHG	Units	Location	Climate	Land Use	Mean	SD [1]	Source
CO_2	Mg CO_2 ha^{-1} yr^{-1}	soil	Boreal	crop	29	16	Table 2.1
			Temperate	crop	29	16	Table 2.1
			Tropical	crop	51	50	Table 2.1
			Tropical	rice	34	35	Table 2.1
			Tropical	oil palm	40	29	Table 2.1
			Tropical	sago [3]	5.5	11	Table 2.1
		offsite	Boreal	crop	0.44	0.31	Table 2.2
			Temperate	crop	1.1	0.78	Table 2.2
			Tropical	crop	3.0	0.67	Table 2.2
CH_4	Mg CH_4 ha^{-1} yr^{-1}	soil	Boreal	crop	0	0.0085	Table 2.3
			Temperate	crop	0	0.0085	Table 2.3
			Tropical	crop	0.0070	0.0054	Table 2.3
			Boreal	rice	0	0	Table 2.3
			Temperate	rice	0	0	Table 2.3
			Tropical	rice	0	0	Table 2.3
			Tropical	oil palm	0	0	Table 2.3
			Tropical	sago [3]	0.026	0.018	Table 2.3
		ditch [2]	Boreal	crop	0.058	0.79	Table 2.4
			Temperate	crop	0.058	0.79	Table 2.4
			Tropical	crop	0.045	0.18	Table 2.4
N_2O	Mg N_2O ha^{-1} yr^{-1}	soil	Boreal	crop	0.020	0.023	Table 2.5
			Temperate	crop	0.020	0.023	Table 2.5
			Tropical	crop	0.0079	0.0051	Table 2.5
			Tropical	rice	0.00063	0.00067	Table 2.5
			Tropical	oil palm	0.0019	0.00094	Table 2.5
			Tropical	sago [3]	0.0052	0.0026	Table 2.5

[1] Standard deviation (SD) was calculated from the number of samples and 95% confidence intervals. We assumed normal distribution for all factors.

[2] Following IPCC [1] ditch fraction was taken to be 5% for boreal and temperate climates, and 2% for tropical climates.

[3] Sago is not included in the individual crops considered in our models.

Supplementary Table 9. Indirect N_2O emissions factors and N loss fractions for synthetic and organic fertilizer application derived from IPCC [23] (Table 11.3).

Description	Units	Mid	Low	High
N volatilization and re-deposition	kg N_2O-N	0.010	0.0020	0.050
Leaching and runoff	kg N_2O-N	0.0075	0.00050	0.025
Volatilization from synthetic fertilizer		0.10	0.030	0.30
Volatilization from organic fertilizer		0.20	0.050	0.50
N losses by leaching/runoff [1]		0.30	0.10	0.80

[1] In regions where the difference between rainy season precipitation and potential evapotranspiration is greater than soil water holding capacity, or where irrigation is employed.

Supplementary Table 10. Estimated model parameter values and variance-covariance matrix for N_2O emissions estimation.

Parameter	Value
μ_0	0.303
σ_0	0.707
μ_1	0.00339
σ_1	0.00195
β	-0.972
τ	2.32
Variance-covariance matrix of the estimator of μ_0, μ_1, and β:	
$$\begin{pmatrix} 5.72E-03 & -1.26E-05 & -1.44E-03 \\ -1.26E-05 & 8.98E-08 & -7.55E-06 \\ -1.44E-03 & -7.55E-06 & 1.04E-02 \end{pmatrix}$$	

[1] The N_2O emissions model is explained fully in Gerber, et al. [4].

Supplementary Table 11. Global rice CH_4 emission estimates compared across 2000-era studies.

Source	Year	CH_4 Emissions (Tg CH_4 yr^{-1})
Linquist et al. 2012 [6]	2004	21.6
FAO [5]	2000	23.3
Yan et al. 2009 [2]	2000	25.6
Yan el al. 2003 [7]	2000	28.2
This Study	2000	28.3
Spahni et al. 2011[8]	1995	33.7

Supplementary Table 12. Global peatland extent, drainage, and GHG emissions estimates across contemporary studies.

Source	Year	Peat Area (km^2)	Drained or Disturbed (%)	CO_2 (Pg yr^{-1})	CH_4 (Pg yr^{-1})	N_2O (Pg yr^{-1})
This Study [1]	2000	3,354,080	4.1	0.56	0.000025	0.00023
Joosten 2009 [9] [2]	1990	3,850,773	12	0.70		
Frolking et al. 2011 [13]	contemporary	4,000,000	13	1.1	0.00016	0.00063
Yu et al. 2010 [14]	contemporary	4,413,500				

[1] Draining and emissions from crop cultivation.

[2] Emissions represent those from agriculture alone, but draining is total drained area.

Supplementary Table 13. Direct N_2O emissions estimates associated with N application across 2000-era studies.

Source	Year	Synthetic Fertilizer N Application (Tg yr^{-1})	Manure N Application (Tg yr^{-1})	Manure + Synthetic N Application (Tg yr^{-1})	Synthetic Direct N_2O-N (Tg yr^{-1})	Manure Direct N_2O-N (Tg yr^{-1})	Manure + Synthetic Direct N_2O-N (Tg yr^{-1})
This Study	2000	79	7.4	86			0.66
FAO	2000	81	24	104	0.81	0.24	1.0
Syakila 2011 [53]	2006				0.90	0.40	1.3
Flynn 2010 [54]	2005	93			0.92		
Verge 2007 [55]	2000				0.95		

Supplementary Data 1. Greenhouse gas emissions, greenhouse gas emissions intensities, harvested area, and kilocalorie production by crop.

2000-era emissions from a 200-iteration Monte Carlo simulation include CH_4 emissions from rice paddies, CO_2, N_2O, and CH_4 emissions from peatland drainage, and N_2O emissions from manure and synthetic N application. The 172 crops included were presented by Monfreda, et al. [56]. Production intensity includes all crop calories. Food intensity excludes calories dedicated to industrial and non-food uses, and assumes that 12% of the calories used as livestock feed are available in foods for human consumption[20].

Supplementary Data 2. Greenhouse gas emissions, greenhouse gas emissions intensities, harvested area, and kilocalorie production by country, for 236 countries.

2000-era emissions from a 200-iteration Monte Carlo simulation include CH_4 emissions from rice paddies, CO_2, N_2O, and CH_4 emissions from peatland drainage, and N_2O emissions from manure and synthetic N application. Production intensity includes all crop calories. Food intensity excludes calories dedicated to industrial and non-food uses, and assumes that 12% of the calories used as livestock feed are available in foods for human consumption[20].

Supplementary Data 3. Peatland area (km^2) by country.

The total best estimate of peatland extent from the literature was calculated from four other studies, ranked by degree of attention given to individual countries: 1) Page, et al. [10]; 2) Joosten [12]; 3) Lappalainen [11]; and 4) Joosten [9]. In this study, we adapted total peat area by country to conform to these best estimate areas to the degree possible. We also report peat crop area (actual area of croplands on peat) as well as peat crop harvested area, which excludes fallow lands and accounts for areas that are double cropped.

Supplementary Data 4. Manure management data.

These data consist of livestock-specific, regional estimates of manure management across livestock systems for bovines and sheep/goats[57] and across smallholder and industrial systems for poultry and pigs[58]. We computed the mass of manure (MA, kg yr^{-1}) and manure N (NA, kg yr^{-1}) applied to croplands. M is total manure mass produced (kg yr^{-1}), N is total nitrogen produced (kg yr^{-1}), F_{MS} is the fraction of total manure managed, F_{MSO} is the fraction of managed manure destined to other uses, and F_{LossMS} is the fraction of managed manure N lost prior to application to croplands (e.g., leaching). LGA = Livestock Grazing Arid/semiarid; LGH = Livestock Grazing Humid-subhumid tropics and subtropics: LGT = Livestock Grazing Temperate/tropical highlands; MIA = Mixed farming Irrigated Arid/semiarid; MIH = Mixed farming Irrigated Humid-subhumid tropics and subtropics; MIT = Mixed farming Temperate/tropical highlands; MRA = Mixed farming Rainfed Arid/semiarid; MRH = Mixed farming Rainfed Humid-subhumid tropics and subtropics; MRT = Mixed farming Rainfed Temperate/tropical highlands.

Supplementary Data 5. Post-intensification greenhouse gas emissions, greenhouse gas emissions intensities, harvested area, and kilocalorie production by crop.
Intensified emissions include CH_4 emissions from rice paddies, CO_2, N_2O, and CH_4 emissions from peatland drainage, and N_2O emissions from manure and synthetic N application. Emissions are from a single model run using mean/center values. Production intensity includes all crop calories. Food intensity excludes calories dedicated to industrial and non-food uses, and assumes that 12% of the calories used as livestock feed are available in foods for human consumption[20].

Supplementary Data 6. National paddy rice CH_4 emissions from four sources.
Sources include National Communications to the UNFCCC (http://unfccc.int/di/FlexibleQueries.do), FAO [5], Yan, et al. [2], and this study's Monte Carlo 200-repetation simulation.

Supplementary Data 7. National fertilizer N_2O emissions from three sources.
Sources include National Communications to the UNFCCC (http://unfccc.int/di/FlexibleQueries.do), FAO [5], and this study's Monte Carlo 200-repetation simulation.

5. Supplementary References

1 IPCC. 2013 Supplement to the 2006 IPCC guidelines for National Greenhouse Gas Inventories: Wetlands. (Switzerland, 2013).

2 Yan, X. Y., Akiyama, H., Yagi, K. & Akimoto, H. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Global Biogeochem Cy* **23**, doi:10.1029/2008gb003299 (2009).

3 Yan, X. Y., Yagi, K., Akiyama, H. & Akimoto, H. Statistical analysis of the major variables controlling methane emission from rice fields. *Global Change Biology* **11**, 1131-1141, doi:10.1111/J.1365-2486.2005.00976.X (2005).

4 Gerber, J. S. *et al.* Spatially explicit estimates of N_2O emissions from croplands suggest climate mitigation opportunities from improved fertilizer management. *Global Change Biology*, Early Online, doi:10.1111/gcb.13341 (2016).

5 FAO. FAOSTAT Online Statistical Service. (Food and Agriculture Oranization (FAO), http://faostat3.fao.org/, 2016).

6 Linquist, B., van Groenigen, K. J., Adviento-Borbe, M. A., Pittelkow, C. & van Kessel, C. An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology* **18**, 194-209, doi:10.1111/J.1365-2486.2011.02502.X (2012).

7 Yan, X., Ohara, T. & Akimoto, H. Development of region-specific emission factors and estimation of methane emission from rice fields in the East, Southeast, and South Asian countries. *Global Change Biology* **9**, 237-254, doi:10.1046/j.1365-2486.2003.00564.x (2003).

8 Spahni, R. *et al.* Constraining global methane emissions and uptake by ecosystems. *Biogeosciences* **8**, 1643-1665, doi:10.5194/Bg-8-1643-2011 (2011).

9 Joosten, H. The Global Peatland CO_2 Picture: Peatland status and drainage related emissions in all countries of the world 35 (Wetlands International, 2009).

10 Page, S. E., Rieley, J. O. & Banks, C. J. Global and regional importance of the tropical peatland carbon pool. *Global Change Biology* **17**, 798–818, doi:10.1111/j.1365-2486.2010.02279.x (2011).

11 Lappalainen, E. *Global Peat Resources*. 359 (International Peat Society, 1996).

12 Joosten, H. *Wise Use of Mires and Peatlands*. 304 (International Mire Conservation Group and International Peat Society, 2002).

13 Frolking, S. *et al.* Peatlands in the Earth's 21st century climate system. *Environ Rev* **19**, 371-396, doi:10.1139/A11-014 (2011).

14 Yu, Z. C., Loisel, J., Brosseau, D. P., Beilman, D. W. & Hunt, S. J. Global peatland dynamics since the Last Glacial Maximum. *Geophys Res Lett* **37**, doi:10.1029/2010gl043584 (2010).

15 Frolking, S. *et al.* A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation. *Earth Syst Dynam* **1**, 1-21, doi:10.5194/Esd-1-1-2010 (2010).

16 Philibert, A., Loyce, C. & Makowski, D. Quantifying Uncertainties in N_2O Emission Due to N Fertilizer Application in Cultivated Areas. *Plos One* **7**, e50950, doi:10.1371/journal.pone.0050950 (2012).

17 Davidson, E. A. & Kanter, D. Inventories and scenarios of nitrous oxide emissions. *Environmental Research Letters* **9**, 105012, doi:10.1088/1748-9326/9/10/105012 (2014).

18 Miettinen, J. *et al.* Extent of industrial plantations on Southeast Asian peatlands in 2010 with analysis of historical expansion and future projections. *Global Change Biology - Bioenergy* **4**, 908-918, doi:10.1111/j.1757-1707.2012.01172.x (2012).

19 Spera, S. A. *et al.* Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. *Environmental Research Letters* **9**, 064010, doi:10.1088/1748-9326/9/6/064010 (2014).

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

21 Portmann, F. T. *Global estimation of monthly irrigated and rainfed crop areas on a 5 arc-minute grid* PhD thesis, University of Frankfurt, (2011).

22 MacDonald, G. K. *et al.* Rethinking agricultural trade relationships in an era of globalization. *BioScience* **65**, 275-289, doi:10.1093/biosci/biu225 (2015).

23 IPCC. IPCC Guidelines for National Greenhouse Gas Inventories. (2006).

24 Asian Development Bank, Global Environment Facility & United Nations Development Program (UNDP). Asia Least-cost Greenhouse Gase Abatement Strategy (ALGAS). (1998).

25 Cambodia. Cambodia's Second National Communication Submitted under the United Nationas Framework Convention on Climate Change. (Ministry of Environment, Phnom Penh, 2015).

26 Li, C. S. *et al.* Reduced methane emissions from large-scale changes in water management of China's rice paddies during 1980-2000. *Geophys Res Lett* **29**, 33, doi:10.1029/2002gl015370 (2002).

27 Adhya, T. K., Linquist, B., Searchinger, T., Wassmann, R. & Yan, X. Wetting and Drying: Reducing Greenhouse Gas Emissions and Saving Water from Rice Production. (World Resources Institute, Washington, DC, 2014).

28 Huke, R. E. & Huke, E. H. *Rice Area by Type of Culture: South, Southeast, and East Asia, A Revised and Updated Data Base*. (International Rice Researh Institute, 1997).

29 Yan, X. Y., Ohara, T. & Akimoto, H. Bottom-up estimate of biomass burning in mainland China. *Atmos Environ* **40**, 5262-5273, doi:10.1016/J.Atmosenv.2006.04.040 (2006).

30 Yevich, R. & Logan, J. A. An assessment of biofuel use and burning of agricultural waste in the developing world. *Global Biogeochem Cy* **17**, doi:10.1029/2002gb001952 (2003).

31 Jones, A. *et al. Soil Atlas of Africa*. (European Commission, 2013).

32 National Resource Information Centre. (Canberra, Australia, 1991).

33 Department of Primary Industries and Water. Tasmanian Vegetation Monitoring and Mapping Program. (Resource Management and Conservation Division, 2009).

34 Tarnocai, C., Kettles, I. M. & Lacelle, B. Peatlands of Canada. (Geological Survey of Canada, 2011).

35 Niu, Z. G. *et al.* Geographical characteristics of China's wetlands derived from remotely sensed data. *Sci China Ser D* **52**, 723-738, doi:10.1007/s11430-009-0075-2 (2009).

36 Geological Survey of Finland. Surficial deposit map of Finland 1:1,000,000. (Espoo, Finland, 1993).

37 Cubizolle, H., Mouandza, M. M. & Muller, F. Mires and Histosols in French Guiana (South America): new data relating to location and area. *Mires and Peat* **12** (2013).

38 Tarnocai, C. *et al.* Northern Circumpolar Soils Map. (Research Branch, Agriculture and Agri-Food Canada, Ottawa, Canada, 2002).

39 FAO/IIASA/ISRIC/ISSCAS/JRC. Harmonized World Soil Database (version 1.2). (FAO, Rome, Italy and IIASA, Laxenburg, Austria., 2012).

40 Wahyunto, S., Rintung & Subagjo, H. Peta Luas Sebaran Lahan Gambut dan Kandungan Karbon di Pulau Kalimantan / Maps of Area of Peatland Distribution and Carbon Content in Kalimantan, 2000-2002. (Wetlands International - Indonesia Programme & Wildlife Habitat Canada (WHC), Bogor, Indonesia, 2004).

41 Wahyunto, B. H., Bekti, H. & Widiastuti, F. Peta-Peta Sebaran Lahan Gambut, Luas, dan Kandungan Karbon di Papua / Maps of Peatland Distribution, Area, and Carbon Content in Papua 2000-2001. (Wetlands International - Indonesia Programme & Wildlife Habitat Canada (WHC), Bogor, Indonesia, 2006).

42 Wahyunto, S., Rintung & Subagjo, H. Peta Luas Sebaran Lahan Gambut dan Kandungan Karbon di Pulau Sumatera / Maps of Area of Peatland Distribution and Carbon Content in Sumatera, 1990-2002. (Wetlands International - Indonesia Programme & Wildlife Habitat Canada (WHC), Bogor, Indonesia, 2003).

43 Connolly, J., Holden, N. M. & Ward, S. M. Mapping peatlands in Ireland using a rule-based methodology and digital data. *Soil Sci Soc Am J* **71**, 492-499, doi:10.2136/sssaj2006.0033 (2007).

44 Parviainen, M. & Luoto, M. Climate envelopes of mire complex types in Fennoscandia. *Geografiska Annaler. Series A. Physical Geography*, 137-151 (2007).

45 Koh, L. P., Miettinen, J., Liew, S. C. & Ghazoul, J. Remotely sensed evidence of tropical peatland conversion to oil palm. *Proc Natl Acad Sci USA* **108**, 5127-5132, doi:10.1073/pnas.1018776108 (2011).

46 Wetlands International. A Quick Scan of Peatlands in Malaysia. (Wetlands International - Malaysia, Petaling Jaya, Malaysia, 2010).

47 Ausseil, A.-G. *et al. Wetland ecosystems of national importance for biodiversity: Criteria, methods, and candidate list of nationally important inland wetlands*. (2008).

48 Heusser, C. J. Paleoecology of a Donatia-Astelia Cushion Bog, Magellanic Moorland-Sub-Antarctic Evergreen Forest Transition, Southern Tierra-Del-Fuego, Argentina. *Rev Palaeobot Palyno* **89**, 429-440, doi:10.1016/0034-6667(95)00004-2 (1995).

49 Pisano, E. in *Ecosystems of the world, Volume 4B: Mires, swamp, bog, fen and moor* (ed A.J.P. Gore) 295-329 (Elsevier, 1983).

50 Geological Survey of Sweden. Soil Database (Jordartsdatabas) 1:1,000,000. (Uppsala, Sweden).

51 British Geological Survey. DiGMapGB data at 1:625 000 scale, Surficial deposits V1.0. (2009).

52 U.S. Department of Agriculture & Natural Resources Conservation Service. (Fort Worth, Texas, 2006).

53 Syakila, A. & Kroeze, C. The global nitrous oxide budget revisited. *Greenhouse Gas Measurement and Management* **1**, 17-26, doi:10.3763/ghgmm.2010.0007 (2011).

54 Flynn, H. C. & Smith, P. Greenhouse gas budgets of crop production – current and likely future trends. (International Fertilizer Industry Association, Paris, France, 2010).

55 Verge, X. P. C., Kimpe, C. D. & Desjardins, R. L. Agricultural production, greenhouse gas emissions and mitigation potential. *Agr Forest Meteorol* **142**, 255-269, doi:10.1016/j.agrformet.2006.06.011 (2007).

56 Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochem Cy* **22**, GB1022, doi:10.1029/2007GB002947 (2008).

57 Robinson, T. *et al.* Global livestock production systems. 152 (Food and Agriculture Organization of the United Nations (FAO) and International Livestock Research Institute (ILRI), Rome, 2011).

58 Herrero, M. *et al.* Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *P Natl Acad Sci USA* **110**, 20888-20893, doi:10.1073/Pnas.1308149110 (2013).