SUPPORTING INFORMATION

Nitrogen surplus benchmarks for controlling N pollution in the main cropping systems of China

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The Supporting Information contains:

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Text S1 Calculating N surplus under farmers' conventional N management

Fertilizer N and grain yield (N harvest) for wheat, rice and maize were obtained from several surveys (4552, 6611 and 5406 individual farmers for wheat, rice, and maize, respectively from 2008 to 2009) across different Chinese regions.[1-3] For rapeseed, fertilizer N and grain yield were obtained from Xu[4] who conducted 1848 farmer surveys in the upper, middle, lower Yangtze River Basin from 2010 to 2011. Fertilizer N and yield for the SW region in the present study were derived from the upper Yangtze River Basin of Xu.[4] We calculated fertilizer N and yield for the middle and lower Yangtze River Basin region in the present study based on cultivation area−weighted average method and the fertilizer N and yield in the middle, lower Yangtze River Basin of Xu.[4] Other N input (atmospheric deposition and biological N fixation) and grain N content for calculating N surplus under farmers' conventional N management were the same as that for calculating the N surplus benchmarks.

Text S2 Calculating reactive N (Nr) losses

Nr losses for wheat, rice and maize under economic optimum and conventional N management were calculated by using regional N loss models directly cited from Cui et al.[5] (Table S2), based on the relationships between NH_3 volatilization, N_2O emission, N leaching, N runoff and N application rates.[5] NH_3 volatilization and N leaching for rapeseed under economic optimum N management were obtained from the field data measured by Li et al.[6] Since there were no reliable data for NH_3 volatilization and N leaching under conventional N management in Li et al.[6] and other studies, we estimated the NH_3 volatilization and N leaching under conventional N management by multiplying fertilizer N application rate by NH_3 volatilization and N leaching per fertilizer N input from economic optimal N management in Li et al.[6] N_2O emissions under economic optimal and conventional management were estimated by using the IPCC default emission factor[7] for direct N_2O emissions of rapeseed.

Text S3 Merging the regional data from literatures to the present study

When a region in the present study was included in a region in literatures, we directly use the data or parameter in the literatures. When a region in the present study includes several regions in the literature, we averaged the data of the regions from literature by using the area-weighted average. For instance, when we collected the N rate and yield for wheat, rice and maize under optimum and farmer's conventional N management, each above crop included several sub-regions (1 to 4) of the previous studies.[1-3, 5, 8]

Table S1. Models for calculating crop yields (N harvest) under simulated N rates (Derived from Wu,[1] Wu et al.[2, 3] and Li et al.[9] by using response curve of averaged yield to N rate)

Crops	Regions in the present study [a]	Regions in above published studies	n [b]	Recommend N rates (RN, kg N ha^{-1})	Averaged yield at different N rates (kg ha^{-1})				Yield response to N rates curves [c]
					0	50%RN	RN	150%RN	
Wheat	Northwest	Northwest China 1	101	171	4240	5000	5550	5220	$Y=-0.0373x^2+13.643x+4206.5$
		Northwest China 2	60	172	4560	6050	6720	6300	$Y=-0.0646x^2+23.506x+4546.5$
	North China Plain	North China Plain 1	1165	199	5250	6240	6950	6550	$Y=-0.0351x^2+15.111x+5208.5$
		North China Plain 2	50	196	4000	5950	6750	6310	$Y=-0.0622x^2+26.179x+3995.5$
	Middle and lower Yangtze River	Middle and lower Yangtze River	112	182	3200	4920	6000	5550	$Y=-0.0655x^2+26.819x+3155.5$
	Southwest	Southwest	73	144	2810	3840	4630	4050	$Y=-0.0776x^2+23.035x+2753.5$
Maize	Northeast	Northeast China 1	132	153	6400	8070	8980	8390	$Y=-0.0965x^2+31.15x+6363$
		Northeast China 2	62	147	6820	8350	9050	8780	$Y=-0.0833x^2+27.32x+6813$
		Northeast China 3	126	162	6500	8130	9480	8690	$Y=-0.0922x^2+32.185x+6407$
		Northeast China 4	77	204	6920	8200	8930	8460	$Y=-0.0421x^2+18.113x+6887.5$
	North China Plain	North China Plain 1	348	194	6580	7680	8230	7830	$Y=-0.0399x^2+16.031x+6560$
		North China Plain 2	59	213	6910	6950	8670	7150	$Y=-0.0344x^2+13.277x+6664$
	Northwest	Northwest 1	100	190	6300	7550	8350	7910	$Y=-0.0468x^2+19.268x+6260.5$
		Northwest 2	309	190	8120	9690	10530	9890	$Y=-0.0612x^2+23.921x+8082.5$
		Northwest 3	7	221	7230	8820	10330	9500	$Y=-0.0495x^2+23.955x+7117$
	Southwest	Southwest 1	78	217	5700	6990	7630	7110	$Y=-0.0384x^2+17x+5674.5$
		Southwest 2	368	195	5590	7090	7720	7300	$Y=-0.0505x^2+20.677x+5581$
		Southwest 3	60	207	6000	7520	8290	7660	$Y=-0.0502x^2+21.135x+5967.5$
Rice	Northeast (SR)	Northeast China 1 (SR)	47	102	4740	6750	7820	7510	$Y=-0.223x^2+52.51x+4718$
		Northeast China 2 (SR)	89	153	6710	7960	9170	8270	$Y=-0.0918x^2+28.778x+6606.5$

	Middle and lower Yangtze River (ER)	Middle Yangtze River (ER)	202	165	4500	6020	6840	6430	$Y=-0.0709x^2+25.558x+4473.5$
	Middle and lower Yangtze River (LR)	Middle Yangtze River (LR)	177	174	4990	6410	7220	6690	$Y=-0.0644x^2+23.603x+4953.5$
	Middle and lower Yangtze River (SR)	Middle Yangtze River (SR)	51	182	6110	7250	7990	7510	$Y=-0.0489x^2+18.78x+6069$
		Lower Yangtze River (SR)	36	226	5950	7990	9100	8430	$Y=-0.0531x^2+25.553x+5907.5$
	Southwest (SR)	Upper Yangtze River (SR)	77	162	6390	7660	8530	8050	$Y=-0.0667x^2+23.426x+6342.5$
		Southwest China (SR)	164	165	5200	6540	7230	6880	$Y=-0.0621x^2+22.309x+5180.5$
	Southeast (ER)	South China 1 (ER)	67	159	5170	6350	7110	6750	$Y=-0.0609x^2+21.447x+5135$
		South China 2 (ER)	61	171	5500	6210	6780	6300	$Y=-0.0407x^2+13.912x+5454.5$
	Southeast (LR)	South China 1 (LR)	82	160	5340	6370	7030	6760	$Y=-0.0508x^2+18.337x+5312$
		South China 2 (LR)	77	165	4990	6190	6750	6700	$Y=-0.0459x^2+18.261x+4991.5$
Rapeseed	Southwest	Yangtze River	1457	180	1482	2088	2610	2478	$Y=-0.0228x^2+10.05x+1453.5$
	Middle and Yangtze River	Yangtze River	1457	180	1482	2088	2610	2478	$Y=-0.0228x^2+10.05x+1453.5$

[a] ER, LR, SR denotes early rice, late rice and single rice, respectively.

[b] n: number of observations

[c] R^2 for the curve in North China Plain 2 is 0.43**, and R^2 values for the other curves are >0.90**

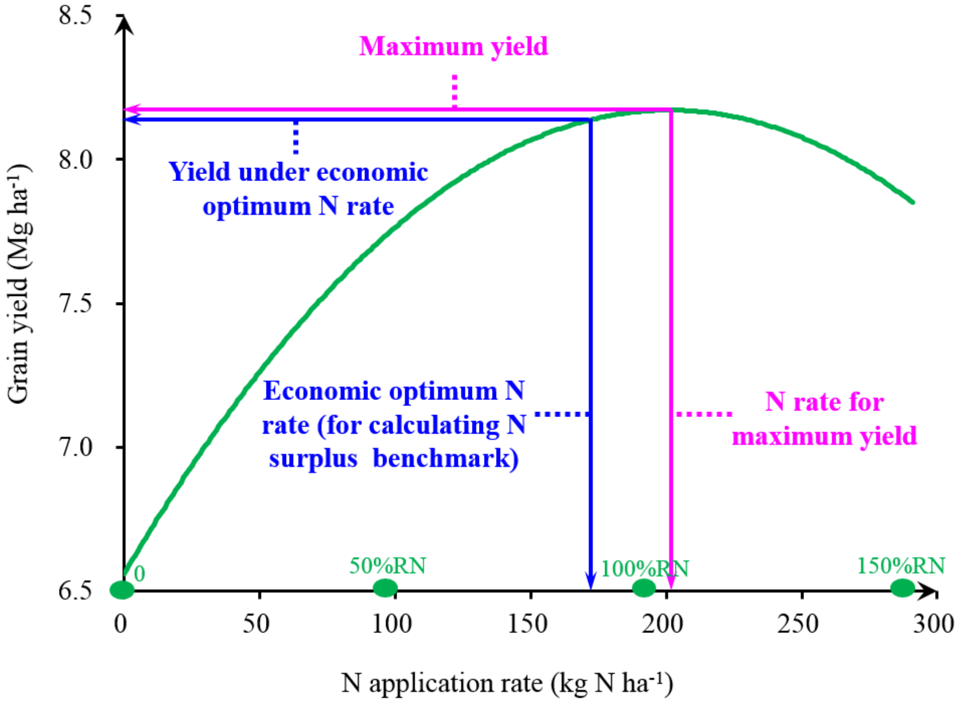

Figure S1. A yield response curve to illustrate the relationships among economic optimum N rate (for calculating N surplus benchmark), maximum yield N rate and the recommended N rate (RN).Data was derived from the maize season in North China Plain[2].

Table S2. Models for calculating reactive nitrogen (Nr) losses under optimum and conventional N managements for wheat, maize and rice (Cited from Cui et al.[5]) [a]

Crops	Regions [b]	NH_3	N_2O	Leaching	Runoff
Wheat	Northwest	$Y=3.21+0.068x$ ($R^2=0.17^{*}$)	$Y=0.26e^{0.0045x}$ ($R^2=0.19^{*}$)	$Y=4.93^{0.0057x}$ ($R^2=0.50^{**}$)	– [c]
	North China Plain	$Y=2.69+0.069x$ ($R^2=0.24^{**}$)	$Y=0.50e^{0.0032x}$ ($R^2=0.25^{**}$)	$Y=3.63e^{0.0080x}$ ($R^2=0.27^{**}$)	–
	Middle and lower Yangtze River	$Y=-0.61+0.13x$ ($R^2=0.68^{**}$)	$Y=0.59e^{0.0060x}$ ($R^2=0.19^{**}$)	$Y=1.64e^{0.0078x}$ ($R^2=0.53^{**}$)	–
	Southwest	$Y=-0.61+0.13x$ ($R^2=0.68^{**}$)	$Y=0.59e^{0.0060x}$ ($R^2=0.19^{**}$)	$Y=1.64e^{0.0078x}$ ($R^2=0.53^{**}$)	–
Maize	Northeast	$Y=2.53+0.058x$ ($R^2=0.43^{**}$)	$Y=0.68e^{0.0035x}$ ($R^2=0.38^{**}$)	$Y=2.38e^{0.0041x}$ ($R^2=0.63^{**}$)	–
	North China Plain	$Y=7.98+0.099x$ ($R^2=0.23^{**}$)	$Y=0.99e^{0.0047x}$ ($R^2=0.20^{**}$)	$Y=10.7e^{0.0060x}$ ($R^2=0.30^{**}$)	–
	Northwest	$Y=2.53+0.058x$ ($R^2=0.43^{**}$)	$Y=0.68e^{0.0035x}$ ($R^2=0.38^{**}$)	$Y=2.38e^{0.0041x}$ ($R^2=0.63^{**}$)	–
	Southwest	$Y=1.93+0.071x$ ($R^2=0.34^{**}$)	$Y=0.60e^{0.0045x}$ ($R^2=0.39^{**}$)	$Y=8.35e^{0.0059x}$ ($R^2=0.27^{**}$)	–
Rice	Northeast (SR)	$Y=3.83+0.10x$ ($R^2=0.66^{**}$)	$Y=0.32e^{0.0029x}$ ($R^2=0.14^{**}$)	$Y=2.25e^{0.0033x}$ ($R^2=0.20^{**}$)	$Y=1.20e^{0.0037x}$ ($R^2=0.98^{**}$)
	Middle and lower Yangtze River (ER)	$Y=-0.54+0.20x$ ($R^2=0.40^{**}$)	$Y=0.65e^{0.0040x}$ ($R^2=0.14^{**}$)	$Y=2.25e^{0.0033x}$ ($R^2=0.20^{**}$)	$Y=3.05e^{0.0040x}$ ($R^2=0.17^{**}$)
	Middle and lower Yangtze River (LR)	$Y=-0.54+0.20x$ ($R^2=0.40^{**}$)	$Y=0.65e^{0.0040x}$ ($R^2=0.14^{**}$)	$Y=2.25e^{0.0033x}$ ($R^2=0.20^{**}$)	$Y=3.05e^{0.0040x}$ ($R^2=0.17^{**}$)
	Middle and lower Yangtze River (SR)	$Y=-0.54+0.20x$ ($R^2=0.40^{**}$)	$Y=0.65e^{0.0040x}$ ($R^2=0.14^{**}$)	$Y=2.25e^{0.0033x}$ ($R^2=0.20^{**}$)	$Y=3.05e^{0.0040x}$ ($R^2=0.17^{**}$)
	Southwest (SR)	$Y=4.95+0.17x$ ($R^2=0.59^{**}$)	$Y=0.10e^{0.0094x}$ ($R^2=0.20^{**}$)	$Y=2.25e^{0.0033x}$ ($R^2=0.20^{**}$)	$Y=2.62e^{0.0033x}$ ($R^2=0.83^{**}$)
	Southeast (ER)	$Y=4.95+0.17x$ ($R^2=0.59^{**}$)	$Y=0.10e^{0.0094x}$ ($R^2=0.20^{**}$)	$Y=2.25e^{0.0033x}$ ($R^2=0.20^{**}$)	$Y=2.62e^{0.0033x}$ ($R^2=0.83^{**}$)
	Southeast (LR)	$Y=4.95+0.17x$ ($R^2=0.59^{**}$)	$Y=0.10e^{0.0094x}$ ($R^2=0.20^{**}$)	$Y=2.25e^{0.0033x}$ ($R^2=0.20^{**}$)	$Y=2.62e^{0.0033x}$ ($R^2=0.83^{**}$)

[a] Y and x denote N loss (kg N ha^{-1}) and fertilizer N rate (kg N ha^{-1}), respectively. $^{**}P<0.01$ and $^{*}P<0.05$ indicate significance of the regression model.

[b] ER, LR, SR denotes early rice, late rice and single rice, respectively.

[c] "–"denote no available data for upland crops.

Table S3. Fertilizer N, crop yield, N harvest and reactive nitrogen (Nr) losses of different crops in China under economic optimum and conventional N managements

Regions	Crop types [a)]	Economic optimum N management							Conventional N management						
		Fertilizer N [b] (kg N ha^{-1} yr^{-1})	Yield (Mg ha^{-1} yr^{-1})	N harvest (kg N ha^{-1} yr^{-1})	Nr losses (kg N ha^{-1} yr^{-1}) NH_3	N_2O	Leaching	Runoff	Fertilizer N (kg N ha^{-1} yr^{-1})	Yield (Mg ha^{-1} yr^{-1})	N harvest (kg N ha^{-1} yr^{-1})	Nr losses (kg N ha^{-1} yr^{-1}) NH_3	N_2O	Leaching	Runoff
Northeast	Rice (S)	127	8.13	154	16.5	0.5	3.4	1.9	141	7.75	147	17.9	0.5	3.6	2.0
	Maize	160	9.02	126	11.8	1.2	4.6	– [c]	199	8.86	124	14.1	1.4	5.4	–
Northwest	Wheat	166	6.01	138	14.5	0.5	12.7	–	202	4.72	109	16.9	0.6	15.6	–
	Maize	184	9.16	128	13.2	1.3	5.1	–	238	7.42	104	16.3	1.6	6.3	–
North China Plain	Wheat	183	6.76	155	15.3	0.9	15.7	–	228	6.54	150	18.4	1.0	22.5	–
	Maize	178	8.18	115	25.6	2.3	31.1	–	208	7.58	106	28.6	2.6	37.3	–
Middle and lower Yangtze River	Wheat	184	5.84	134	23.3	1.8	6.9	–	200	5.15	118	25.4	2.0	7.8	–
	Rapeseed	180	2.66	104	11.9	1.8	19.4	–	184	1.93	75	12.2	1.8	19.8	–
	Rice (S)	197	8.40	160	38.9	1.4	4.3	6.7	258	7.32	139	51.1	1.8	5.3	8.6
	Rice (E)	167	6.75	128	32.9	1.3	3.9	5.9	197	6.66	127	38.9	1.4	4.3	6.7
	Rice (L)	170	7.10	135	33.5	1.3	3.9	6.0	193	6.94	132	38.1	1.4	4.3	6.6
Southwest	Wheat	131	4.45	102	16.4	1.3	4.6	–	144	3.88	89	18.1	1.4	5.0	–
	Rapeseed	180	2.66	104	11.9	1.8	19.4	–	203	1.90	74	13.4	2.0	21.9	–
	Maize	182	7.80	109	14.9	1.4	24.4	–	251	5.45	76	19.8	1.9	36.7	–
	Rice (S)	163	7.79	148	32.7	0.5	3.9	4.5	201	7.08	135	39.1	0.7	4.4	5.1
Southeast	Rice (E)	162	6.90	131	32.5	0.5	3.8	4.5	210	6.82	130	40.7	0.7	4.5	5.2
	Rice (L)	163	6.86	130	32.7	0.5	3.9	4.5	224	6.71	127	43.0	0.8	4.7	5.5

[a] Rice (S), Rice (E), Rice (L) denotes single rice, early rice and late rice, respectively.

[b] includes synthetic fertilizer and manure

[c] "–"denote no available data for upland crops.

Table S4. N surplus benchmarks for the main cropping systems of China under one thirds of straw removing situation.

Region	Cropping system	Fertilizer N (kg N ha^{-1} yr^{-1})	Other N (kg N ha^{-1} yr^{-1})	Grain N (kg N ha^{-1} yr^{-1})	Straw N (kg N ha^{-1} yr^{-1}) [a]	N Surplus benchmark (kg N ha^{-1} yr^{-1}) [b]
Northeast	Rice	127	65	154	81	11
	Maize	160	45	126	67	57
Northwest	Wheat	166	40	138	53	50
	Maize	184	40	128	68	73
North China Plain	Wheat-Maize	361	71	270	120	122
Middle and lower Yangtze River	Wheat-Rice	381	74	294	135	116
	Rice-Rice	337	94	263	138	122
	Rapeseed-Rice	377	74	264	137	141
Southwest	Wheat-Maize	313	45	211	97	115
	Wheat-Rice	294	65	250	117	70
	Rapeseed-Rice	343	65	252	131	112
	Rapeseed-Maize	362	45	213	111	157
Southeast	Rice-Rice	325	83	261	137	101

a) Straw yield=Grain yield×(1/Harvest Index-1); Straw N=straw yield × straw N content; Grain yield was obtained from Table S3, Harvest Index and straw N content were obtained from Gu et al.[10]

b) N surplus benchmark=Fertilizer N + 2/3×Straw N + Other N – Grain N – Straw N

References

(1) Wu, L. Nitrogen Fertilizer Demand and Greenhouse Gas Mitigation Potential under Nitrogen Limiting Conditions for Chinese Agriculture Production (in Chinese). Doctor Thesis, China Agricultural University, 2014.

(2) Wu, L.; Chen, X.; Cui, Z.; Zhang, W.; Zhang, F., Establishing a regional nitrogen management approach to mitigate greenhouse gas emission intensity from intensive smallholder maize production. *PLoS One* **2014,** *9* (5), e98481.

(3) Wu, L.; Chen, X. P.; Cui, Z. L.; Wang, G. L.; Zhang, W. F., Improving nitrogen management via a regional management plan for Chinese rice production. *Environ. Res. Lett.* **2015,** *10* (9), 11.

(4) Xu, H. L. Investigation on fertilization and effect of formulated fertilization of winter rapeseed in yangtze river basin (in Chinese). Master Thesis, China Agricultural University, 2012.

(5) Cui, Z.; Zhang, H.; Chen, X.; Zhang, C.; Ma, W.; Huang, C.; Zhang, W.; Mi, G.; Miao, Y.; Li, X.; Gao, Q.; Yang, J.; Wang, Z.; Ye, Y.; Guo, S.; Lu, J.; Huang, J.; Lv, S.; Sun, Y.; Liu, Y.; Peng, X.; Ren, J.; Li, S.; Deng, X.; Shi, X.; Zhang, Q.; Yang, Z.; Tang, L.; Wei, C.; Jia, L.; Zhang, J.; He, M.; Tong, Y.; Tang, Q.; Zhong, X.; Liu, Z.; Cao, N.; Kou, C.; Ying, H.; Yin, Y.; Jiao, X.; Zhang, Q.; Fan, M.; Jiang, R.; Zhang, F.; Dou, Z., Pursuing sustainable productivity with millions of smallholder farmers. *Nature* **2018,** *555* (7696), 363-366.

(6) Li, H.; Chen, Y.; Liang, X.; Lian, Y.; Li, W., Mineral-nitrogen leaching and ammonia volatilization from a rice-rapeseed system as affected by 3,4-dimethylpyrazole phosphate. *J. Environ. Qual.* **2009,** *38* (5), 2131-2137.

(7) De Klein, C.; Novoa, R. S.; Ogle, S.; Smith, K. A.; Rochette, P.; Wirth, T. C.; McConkey, B.; Mosier, A.; Rypdal, K.; Walsh, M., N2O emissions from managed soils, and CO2 emissions from lime and urea application. *IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme* **2006,** *4*, 1-54.

(8) Xu, W.; Luo, X. S.; Pan, Y. P.; Zhang, L.; Tang, A. H.; Shen, J. L.; Zhang, Y.; Li, K. H.;

Wu, Q. H.; Yang, D. W.; Zhang, Y. Y.; Xue, J.; Li, W. Q.; Li, Q. Q.; Tang, L.; Lu, S. H.; Liang, T.; Tong, Y. A.; Liu, P.; Zhang, Q.; Xiong, Z. Q.; Shi, X. J.; Wu, L. H.; Shi, W. Q.; Tian, K.; Zhong, X. H.; Shi, K.; Tang, Q. Y.; Zhang, L. J.; Huang, J. L.; He, C. E.; Kuang, F. H.; Zhu, B.; Liu, H.; Jin, X.; Xin, Y. J.; Shi, X. K.; Du, E. Z.; Dore, A. J.; Tang, S.; Collett, J. L.; Goulding, K.; Sun, Y. X.; Ren, J.; Zhang, F. S.; Liu, X. J., Quantifying atmospheric nitrogen deposition through a nationwide monitoring network across China. *Atmos. Chem. Phys.* **2015,** *15* (21), 12345-12360.

(9) Li, H.; Cong, R. H.; Ren, T.; Li, X. K.; Ma, C. B.; Zheng, L.; Zhang, Z.; Lu, J. W., Yield response to N fertilizer and optimum N rate of winter oilseed rape under different soil indigenous N supplies. *Field Crops Research* **2015,** *181*, 52-59.

(10) Gu, B.; Ju, X.; Chang, J.; Ge, Y.; Vitousek, P. M., Integrated reactive nitrogen budgets and future trends in China. *Proc. Natl. Acad. Sci. U. S. A.* **2015,** *112* (28), 8792-8797.