Supplementary Information

Optimizing nitrogen fertilizer use for more grain and less pollution

Keyu Ren[1#], Minggang Xu[1#], Rong Li[2], Lei Zheng[2], Shaogui Liu[3], Stefan Reis[4,5], Huiying Wang[2], Changai Lu[1], Wenju Zhang[1], Hui Gao[3], Yinghua Duan[1*], Baojing Gu[6*]

[1]Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[2]Arable Land Quality Monitoring and Protection Center, Ministry of Agriculture, Beijing 100125, China
[3]Yangzhou Station of Farmland Quality Protection, Yangzhou 225100, China
[4]UK Centre for Ecology & Hydrology, Penicuik, EH26 0QB, United Kingdom
[5]University of Exeter Medical School, Knowledge Spa, Truro, TR1 3HD, United Kingdom
[6]College of Environmental & Resource Sciences, Zhejiang University, Hangzhou 310058, China

[#]These authors contributed equally to this work
[*]duanyinghua@caas.cn (Y.D.), bjgu@zju.edu.cn (B.G.)

Supplementary figures and tables

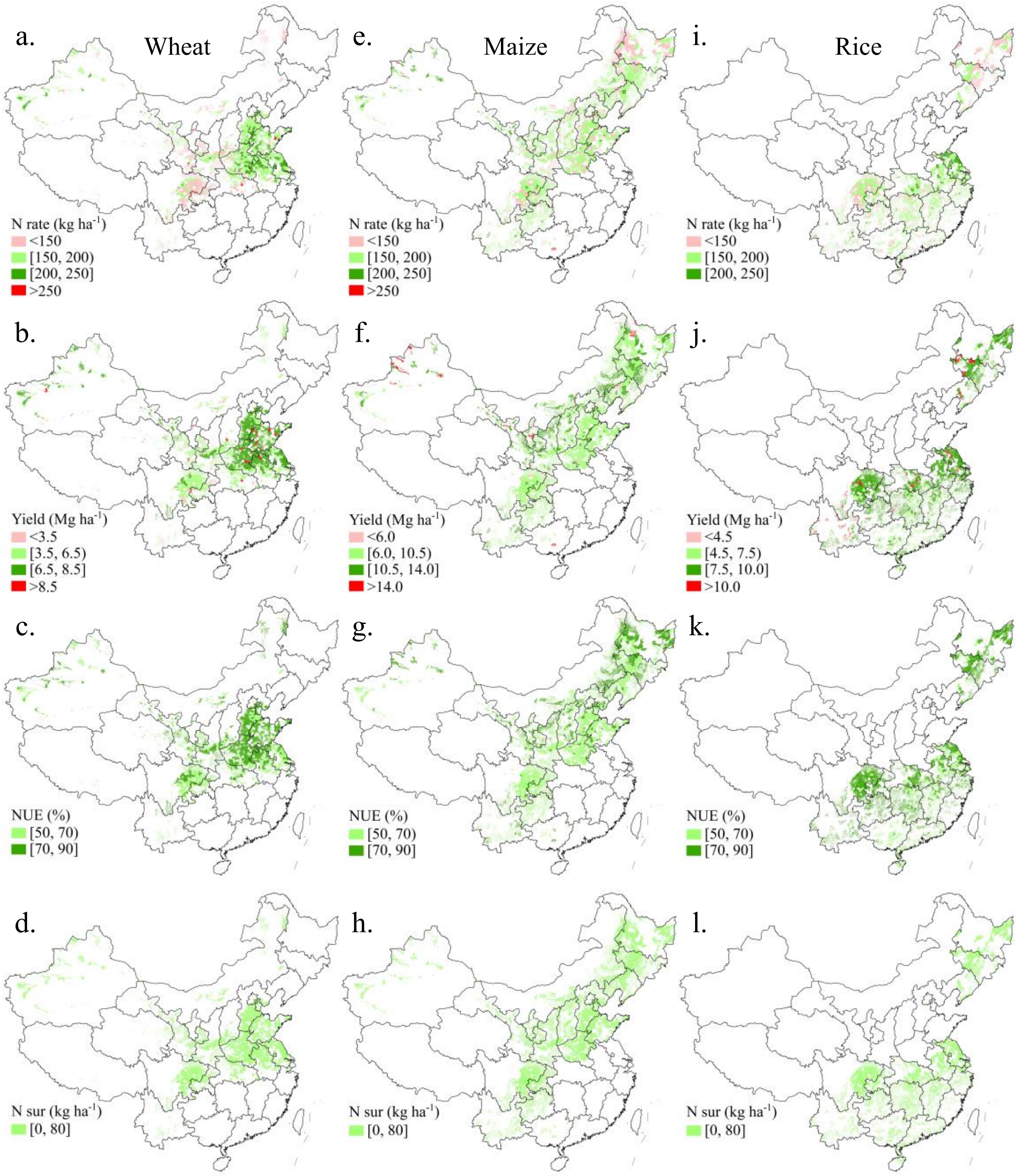

Fig. S1 Nitrogen application rate (N rate) and corresponding yield, nitrogen use efficiency (NUE) and nitrogen surplus (N_{sur}) of three grain crops under the best nitrogen management. (a)–(d) wheat, (e)–(h) maize, (i)–(l) rice.

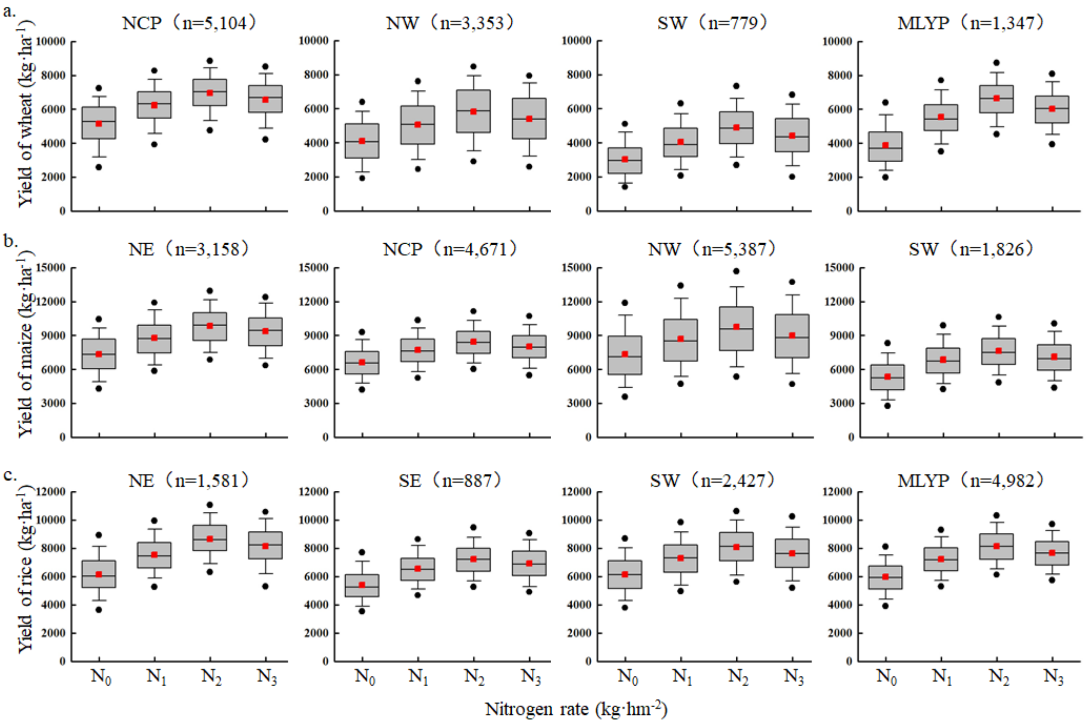

Fig. S2 Yields at different nitrogen application rates in each region of wheat (a), maize(b) and rice (c). n indicates experimental sites number. NCP: North China Plain; NW: Northwest; SW: Southwest; MLYP: Middle-Lower Yangtze Plain; NE: Northeast; SE: Southeast.

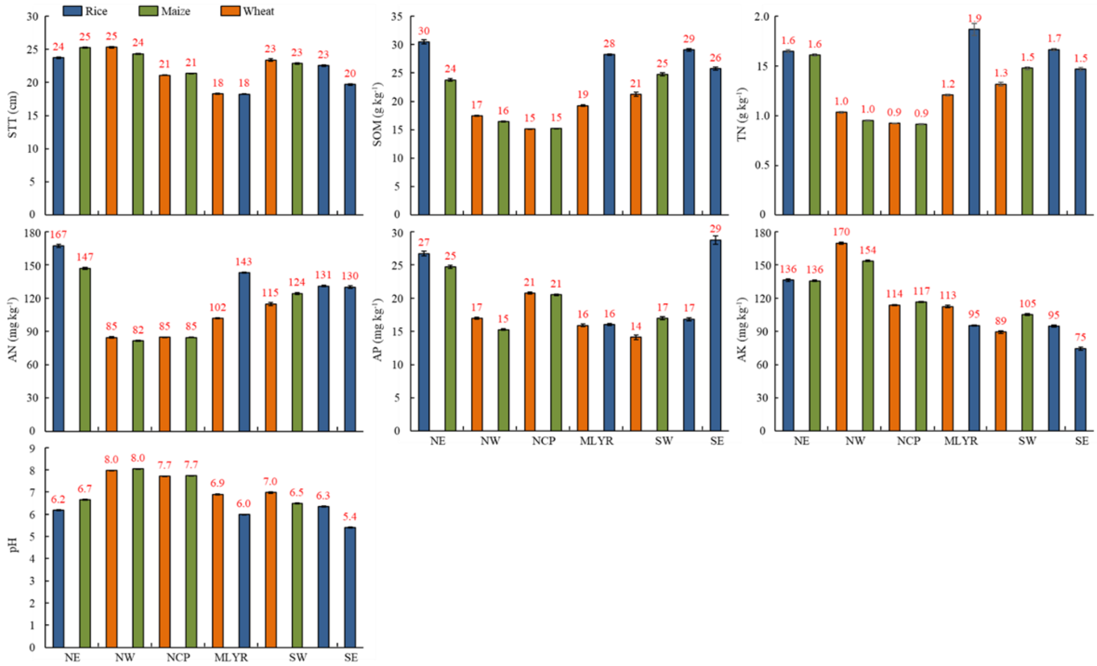

Fig. S3 Soil nutrients prior to planting of crops in various regions. The red number represents the mean of each region; The error bar represents the standard error of the mean (SE). STT: soil tillage thickness; SOM: soil organic matter content; TN: soil total nitrogen content; AN: soil alkali nitrogen content; AP: soil available phosphorus content; AK: soil available potassium content; NE: Northeast; NW: Northwest; NCP: North China Plain, MLYP: Middle-Lower Yangtze Plain; SW: Southwest; SE: Southeast.

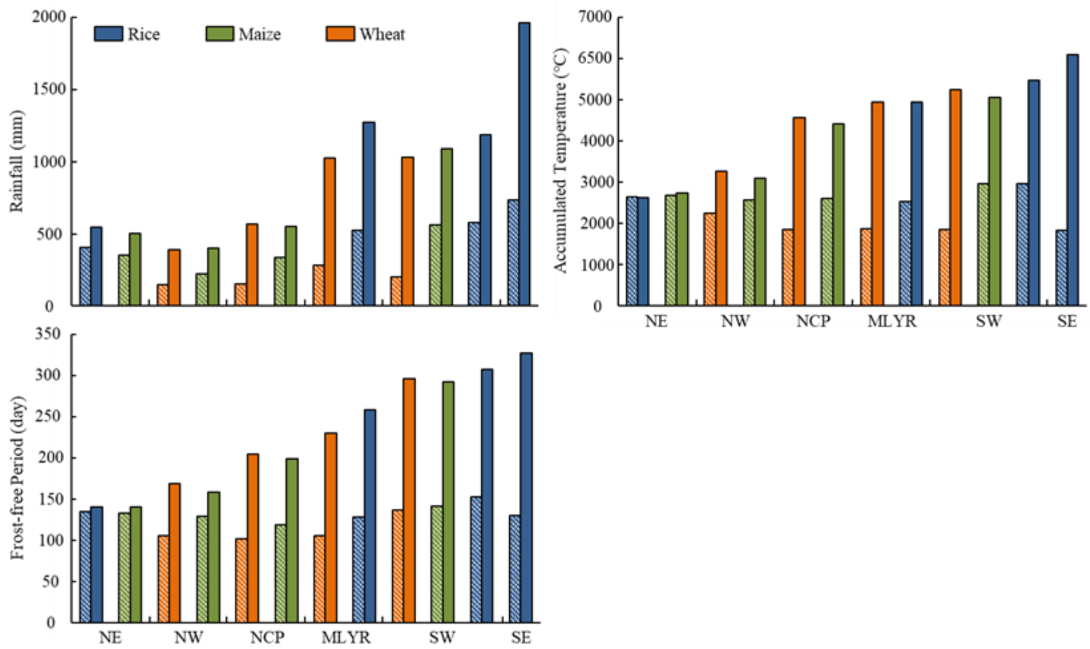

Fig. S4 Rainfall, accumulated temperature and frost-free period during each crop growth season (pattern column) and each year (monochromatic column) in various regions, average of the study period. NE: Northeast; NW: Northwest; NCP: North China Plain, MLYP: Middle-Lower Yangtze Plain; SW: Southwest; SE: Southeast.

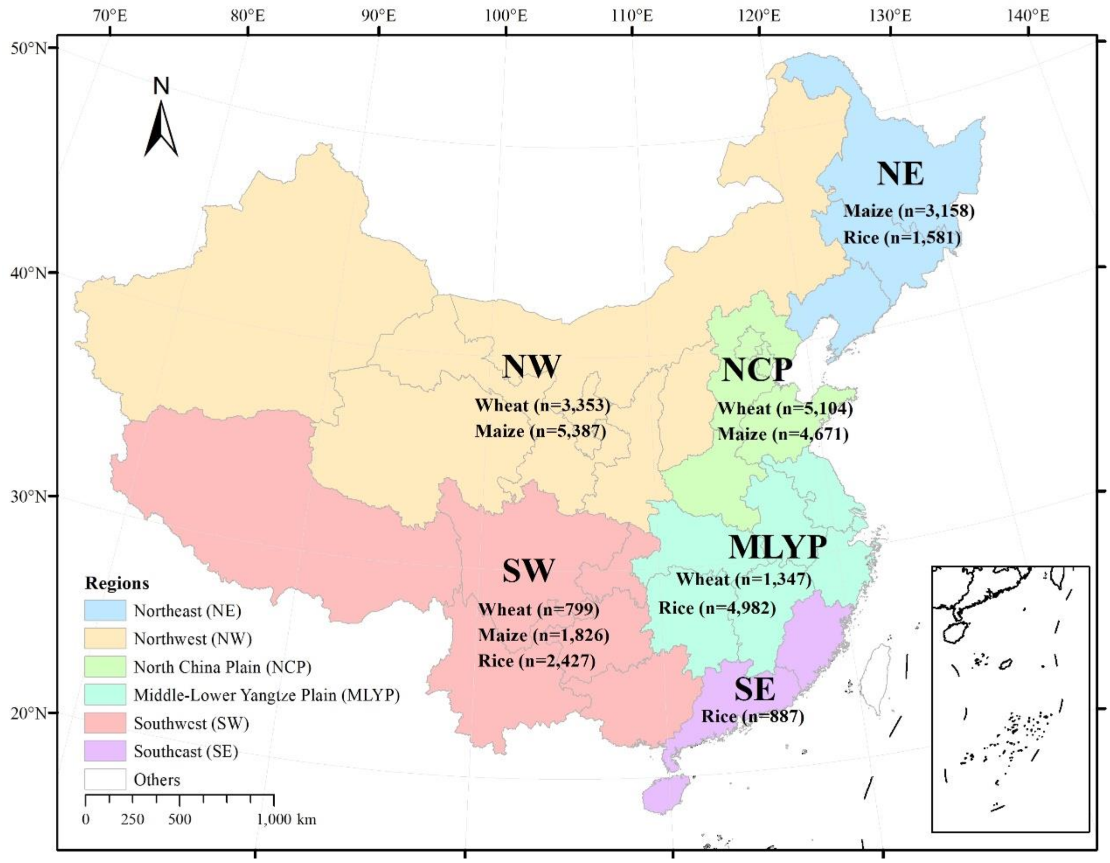

Fig. S5 Regional division and crop distribution of China in this study. n indicates experimental sites number.

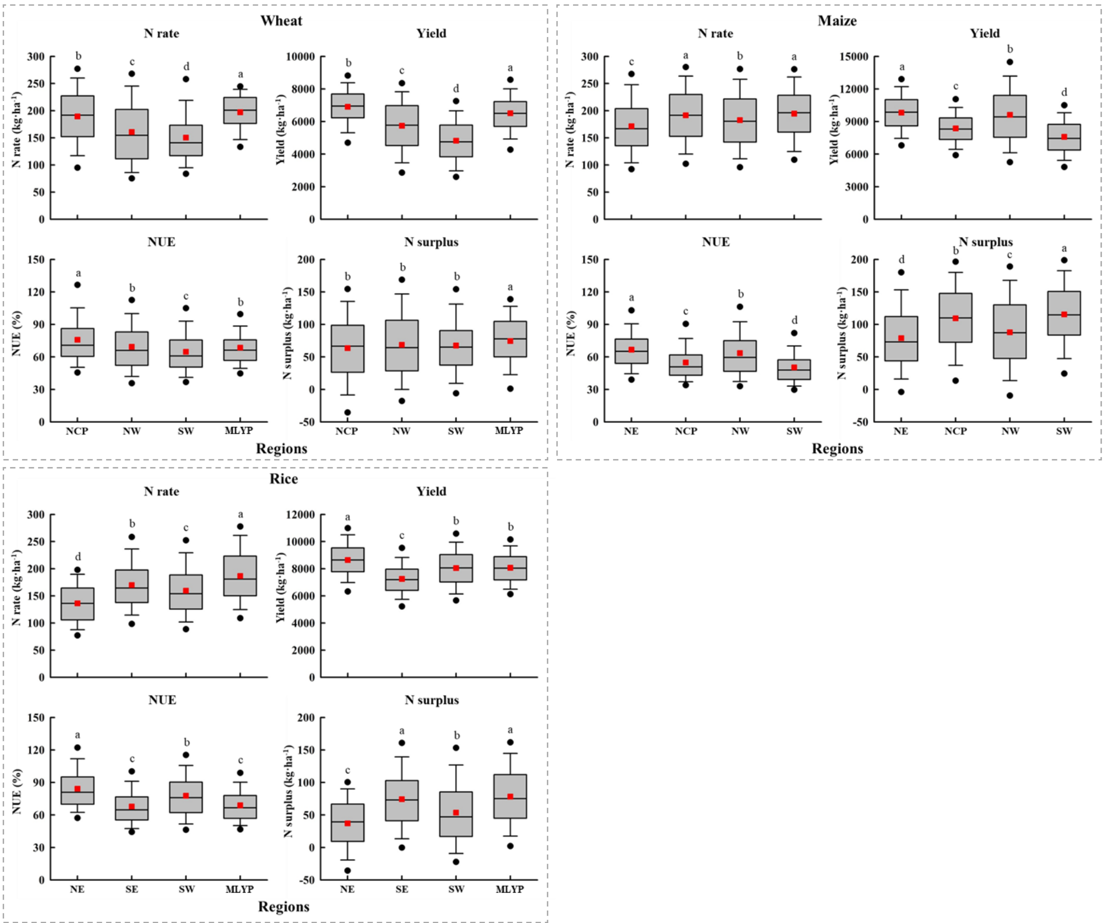

Fig. S6 Optimal nitrogen application rate (N rate) and corresponding yield, nitrogen use efficiency (NUE) and nitrogen surplus for wheat, maize and rice in each region. NCP: North China Plain, NW: Northwest; SW: Southwest; MLYP: Middle-Lower Yangtze Plain; NE: Northeast; SE: Southeast.

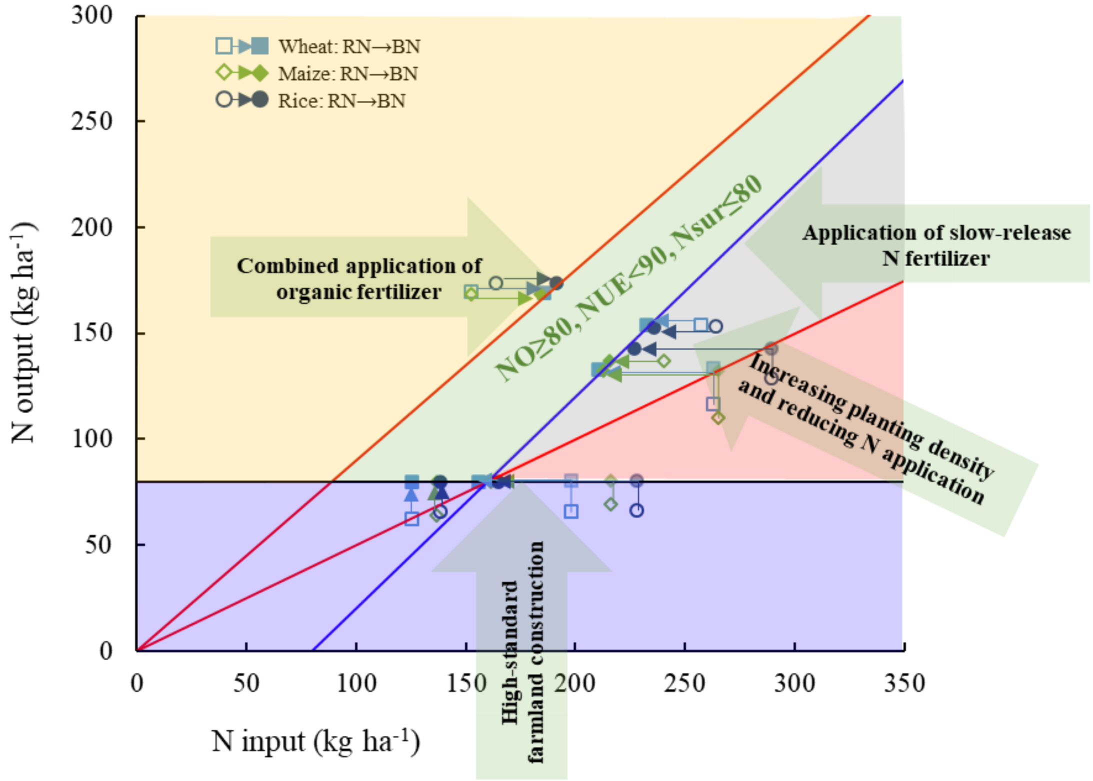

Fig. S7 Schematic diagram of optimizing practices. Different optimization practices were added to each quadrant based on the EU Nitrogen Expert Panel. NO: nitrogen output (unit: kg ha^{-1}); NUE: nitrogen use efficiency (unit: %); Nsur: nitrogen surplus (unit: kg ha^{-1}); RN: optimal N rate; BN: best N management (modified from EU Nitrogen Expert Panel).

Table S1 Nitrogen application rate (Fertilizer N rate), yield, nitrogen use efficiency (NUE) and nitrogen surplus (N_{sur}) of three food crops under different practices.

Crops	Farmer's conventional N application				Optimize N application				Best N management			
	Fertilizer N rate (kg ha^{-1})	Yield (Mg ha^{-1})	NUE (%)	N_{sur} (kg ha^{-1})	Fertilizer N rate (kg ha^{-1})	Yield (Mg ha^{-1})	NUE (%)	N_{sur} (kg ha^{-1})	Fertilizer N rate (kg ha^{-1})	Yield (Mg ha^{-1})	NUE (%)	N_{sur} (kg ha^{-1})
Wheat	210	5.7	55	110	178	6.3	72	67	171	6.4	73	57
Maize	220	7.6	41	151	184	9.0	60	96	162	9.6	67	66
Rice	210	7.1	52	124	170	8.1	73	65	162	8.1	74	56

NUE: nitrogen use efficiency; N_{sur}: nitrogen surplus.

Table S2 Benefits and input under optimization of nitrogen application and optimization of management practices.

Crops	Optimization of N application (F-R)			Optimization of management practices (R-B)				Total income ($\times10^8$ \$)
	N reduction benefits ($\times10^8$ \$)	Yield increase benefits ($\times10^8$ \$)	Environmental benefits ($\times10^5$ t N)	Optimizing practices input ($\times10^8$ \$)	N reduction benefits ($\times10^8$ \$)	Yield increase benefits ($\times10^8$ \$)	Environmental benefits ($\times10^5$ t N)	
Wheat	5.09	24.45	10.16	36.96	1.11	4.77	2.37	-1.53
Maize	9.96	90.98	22.77	64.55	6.09	34.10	12.39	76.58
Rice	7.96	58.19	17.62	16.58	1.59	3.89	2.67	55.05
Total	23.01	173.62	50.55	118.08	8.79	42.76	17.43	130.10

Table S3 Economic inputs for the regions where NUE > 90%.

Category	Purpose	Crops	Increased N input (kg ha^{-1})	Area ($\times 10^6$ ha^{-1})	Measure	Application rate (t ha^{-1})	Price of organic fertilizer (\$ t^{-1})	Government subsidy (\$ ha^{-1})	Economic input ($\times 10^8$ \$)
$N_{output} \geq 80$, NUE > 90	$N_{output} \geq 80$, NUE = 90	Wheat	33.0	4.13	Combined application of organic fertilizer	1.65	168.86	55.06	9.24
		Maize	31.2	3.41		1.56			7.10
		Rice	27.5	5.20		1.38			9.21

N_{output}: nitrogen output (unit: kg ha^{-1}); NUE: nitrogen use efficiency (unit: %).

Table S4 Economic inputs for the regions where NUE ≥ 50% while N_{sur} > 80kg ha^{-1}.

Category	Purpose	Crops	Reduced N input (kg ha^{-1})	Area ($\times10^6$ ha^{-1})	Measure	Application rate (t ha^{-1})	Price of slow-release N fertilizer ($ kg^{-1})	Economic input ($\times10^8$ $)
$N_{output} \geq 80$, NUE ≥ 50, $N_{sur} > 80$	$N_{output} \geq 80$, NUE ≥ 50, $N_{sur} = 80$	Wheat	25.1	6.30	Applying slow-release N fertilizer	200.30	0.97	2.75
		Maize	25.1	10.01		178.50		3.70
		Rice	28.2	8.36		186.20		3.12

N_{output}: nitrogen output (unit: kg ha^{-1}); NUE: nitrogen use efficiency (unit: %); N_{sur}: nitrogen surplus (unit: kg ha^{-1}).

Table S5 Economic inputs for the regions where NUE < 50%.

Category	Purpose	Crops	Increased N output (kg ha^{-1})	Reduced N input (kg ha^{-1})	Area ($\times 10^6$ ha^{-1})	Measure	Increase planting density	Price of seeds (\$ ha^{-1})	Application rate (t ha^{-1})	Price of slow-release N fertilizer (\$ kg^{-1})	Economic input ($\times 10^8$ \$)
$N_{output} \geq 80$, NUE < 50	$N_{output} \geq 80$, NUE ≥ 50, $N_{sur} = 80$	Wheat	16.7	53.00	2.56	Increasing planting density and applying slow-release N fertilizer	30%	155.76	178.30	0.97	1.66
		Maize	22.2	52.30	12.95			122.72	176.10		7.11
		Rice	14.1	62.70	2.41			139.63	177.10		1.28

N_{output}: nitrogen output (unit: kg ha^{-1}); NUE: nitrogen use efficiency (unit: %); N_{sur}: nitrogen surplus (unit: kg ha^{-1})

Table S6 Economic inputs for the regions where N_{output} < 80 kg ha^{-1}.

Category	Purpose	Crops	Area ($\times 10^6$ ha^{-1})	Measure	Input per hectare (\$ ha^{-1})	Economic input ($\times 10^8$ \$)
$N_{output} < 80$	$N_{output} = 80$, $50 \leq NUE \leq 90$, $N_{sur} \leq 80$	Wheat	1.2	High-standard farmland construction	2386.96	23.30
		Maize	2.4			46.64
		Rice	0.2			2.97

N_{output}: nitrogen output (unit: kg ha^{-1}); NUE: nitrogen use efficiency (unit: %); N_{sur}: nitrogen surplus (unit: kg ha^{-1}).

Table S7 Nitrogen inputs from regions of three grain crops

Crops	Regions	n	N_2 rate (kg N ha^{-1})	N_{dep} (kg N ha^{-1})	N_{fix} (kg N ha^{-1})
Wheat	North China Plain (NCP)	5,104	200±35	28	5
	Northwest (NW)	3,353	166±46	35	5
	Southwest (SW)	779	146±33	23	5
	Middle-Lower Yangtze Plain (MLYP)	1,347	199±31	22	5
Maize	Northeast (NE)	3,158	157±35	40	5
	North China Plain (NCP)	4,671	202±34	30	5
	Northwest (NW)	5,387	193±37	35	5
	Southwest (SW)	1,826	207±37	22	5
Rice	Northeast (NE)	1,581	121±31	40	25
	Southeast (SE)	887	164±28	17	25
	Southwest (SW)	2,427	156±44	22	25
	Middle-Lower Yangtze Plain (MLYP)	4,982	182±40	20	25

n indicates experimental sites number. N_{dep} and N_{fix} represent N input by atmospheric deposition and biological N fixation, respectively.