A steady-state N balance approach for sustainable smallholder farming

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Hundreds of millions of smallholders in emerging countries substantially overuse nitrogen (N) fertilizers, driving local environmental pollution and global climate change. Despite local demonstration-scale successes, widespread mobilization of smallholders to adopt precise N management practices remains a challenge, largely due to associated high costs and complicated sampling and calculations. Here, we propose a long-term steady-state N balance (SSNB) approach without these complications that is suitable for sustainable smallholder farming. The hypothesis underpinning the concept of SSNB is that an intensively cultivated soil–crop system with excessive N inputs and high N losses can be transformed into a steady-state system with minimal losses while maintaining high yields. Based on SSNB, we estimate the optimized N application range across 3,824 crop counties for the three staple crops in China. We evaluated SSNB first in ca. 18,000 researcher-managed on-farm trials followed by testing in on-farm trials with 13,760 smallholders who applied SSNB-optimized N rates under the guidance of local extension staff. Results showed that SSNB could significantly reduce N fertilizer use by 21 to 28% while maintaining or increasing yields by 6 to 7%, compared to current smallholder practices. The SSNB approach could become an effective tool contributing to the global N sustainability of smallholder agriculture.

smallholders | long-term steady-state N balance approach | high yields | sustainability

Humanity has exceeded the planetary boundary for nitrogen (N), and agriculture is the primary driver owing to the intensive use of N fertilizer (1, 2). N fertilizer has been crucial to improving crop yields worldwide, but the N uptake by crops needed to increase yield enhances N biochemical cycling in the soil and often causes significant N losses in various forms (3–7). Agriculture, for example, accounts for ∼80 to 90% of total atmospheric NH_3 emissions and >70% of global N_2O emissions (8–11). Reducing global agricultural N loss remains a major challenge, especially for the hundreds of millions of smallholders in India and China, who tend to overfertilize as an "insurance" to avoid yield losses because of limited access to advanced N management information and technologies (12–15). From year 2001 to 2015, ∼60% of the global increase in N fertilizer consumption occurred in China and India (16). Thus, mobilizing these smallholders to adopt advanced N technologies for significant N reduction is a priority for global sustainable development goals (13, 17, 18).

China's agricultural land is dominated by 200 to 300 million smallholders, most of whom cultivate <1 ha of farmland (19). High-to-excessive N use by these smallholders has resulted in widespread air and water pollution across the country and also contribute significantly to global climate change (20–22). Realizing the severity of these issues, China has recently invested heavily in agricultural Research & Development to improve N management. Many advanced N management technologies (e.g., soil and plant diagnostic laboratory tests, remote-sensing technologies, and handheld leaf N sensors) have been developed and locally demonstrated to significantly reduce N inputs while increasing N use efficiency (23–25). However, the adoption rate of these improved methods by Chinese smallholders is extremely low partly because they are complex and costly and require frequent real-time in situ field monitoring and complicated calculations and partly because they are site specific and difficult to scale up across regions. To promote sustainable intensification among the smallholders in China, it is critical that improved N management methods are easy to implement, inexpensive, flexible, and require little additional labor.

Here, we demonstrated that a steady-state N balance (SSNB) approach can significantly improve smallholder farming for sustainable development. The hypothesis underpinning the concept of SSNB is that an intensively cultivated soil can reach a steady state where soil N pools change slowly and external N inputs equal roughly to N outputs (3, 26, 27). For intensive agricultural production, some N losses are inevitable but can be minimized at levels that do not compromise local environmental integrity. Therefore, when N losses are minimal, external N inputs that exceed crop N uptake can be considered as excess N and then removed without yield loss (Fig. 1).

Here, we first describe the long-term experiments from which our SSNB conceptual framework was derived (*Materials and Methods*). Then, we formalized the SSNB approach and applied it to cereal

Significance

Smallholder farmers in China tend to overuse N fertilizer as an "insurance" to avoid yield loss. Better management can be achieved but lack resources to adopt advanced technologies that improve N use efficiency. Our study proposes a simplified but effective N management approach without sampling. This new approach based on steady-state N balance could significantly reduce N fertilizer use while maintaining or even increasing yields compared to the local farmers' practice. Demonstrations in Chinese cereal production indicate the potential of the new N management approach to become an effective tool for policy guidance and to contribute to global N sustainability.

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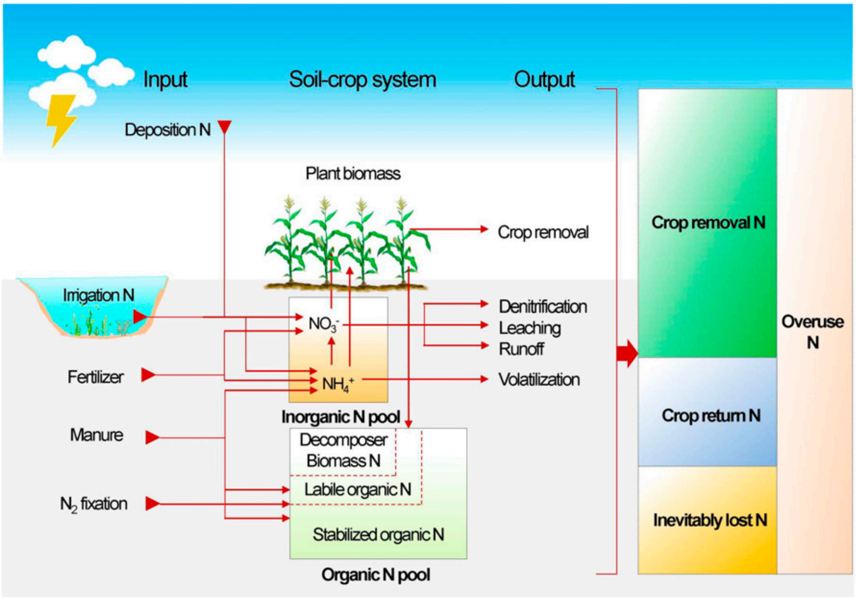

Fig. 1. The N cycle in soil–crop system. N flows include major inputs, outputs, and pools of organic and inorganic (3). The long-term fate of external N inputs includes crop N uptake (crop removal plus N return), inevitable N loss, and overapplied N.

crops (wheat, rice, and maize) in ∼3,000 counties of China, taking into account each county's particular geographic soil and climate conditions. Next, we tested this SSNB approach more broadly in ∼18,000 trials across China. Finally, we tested the applicability of SSNB at scale by enrolling 13,760 smallholders in 1,468 of counties who implemented the SSNB approach. Results indicated the SSNB approach is agronomically and environmentally acceptable, and it has the potential to provide effective policy guidance for regional or local governments worldwide to reduce N-related pollution while ensuring food security.

Results

Optimized N Rate Based on Soil Testing. Understanding driving factors for field variations in optimized N rate (ONR) is critical when establishing region-specific N management. From 2003 to 2006, we conducted 269 on-farm trials in central-eastern China (*Materials and Methods*) to optimize N management for wheat and maize. An ONR was determined for each field monitoring soil NO_3^-–N levels in the root zone and a target N requirement value for the corresponding crop growth period. The ONRs varied from 38 to 280 kg N ha^{-1}, which represented a 40 to 60% decrease compared to local farmers' typical N application rates for wheat and maize. Grain yields increased by 4 to 5% with an ONR (*SI Appendix*, Fig. S1). We further found indigenous N supplies had a large influence on observed variation in ONR (*SI Appendix*, Fig. S1). In practice, robust estimation of indigenous N supply in the field is a complicated and costly process that requires frequent real-time soil or plant testing (28). The costs of soil NO_3^-–N testing and labor in these 269 sites were about $9 per site per season, and professional sampling and laboratory measurement were needed, which limited the widespread adoption by smallholders.

Development of the SSNB Approach. Consistently achieving a tight N balance, with minimal excess N, can eventually result in a quasi–steady-state system as soil organic matter turnover also reaches steady state (29). Our SSNB concept was derived from an 8-y experiment for 16 consecutive seasons of a wheat–maize cropping system was conducted at Dongbeiwang, Beijing. The ONR based on soil testing substantially reduced the N rate without yield losses compared to the local farmers' practices. The N fertilizer rate in the ONR treatment can be classified into two phases: an increasing phase during the first 4 y from 97 kg N ha^{-1} $year^{-1}$ in the first year to 226 kg N ha^{-1} $year^{-1}$ in the fifth year and a steady-state phase afterward during which the ONR varied within a narrow range (200 to 230 kg N ha^{-1} $year^{-1}$), close to N uptake by the harvested crop (Fig. 2*B*).

We measured the N flows from external N inputs, outputs with crop N uptake, N losses, and N pools in the soil in this experiment. In the steady-state phase, organic and inorganic N pools changed slowly, while soil N supplies were mainly from environmental N inputs from atmospheric deposition, biological N_2 fixation, and irrigation water. Soil N supplies at the steady-state phase, determined by crop N uptake from soils in the control plot that received no N, were constant at ∼87 kg N ha^{-1} $year^{-1}$ (ranging from 84 to 93 kg N ha^{-1} $year^{-1}$). Total reactive N losses in the ONR treatments from N_2O emissions, NH_3 volatilization, and N leaching were 75 kg N ha^{-1} $year^{-1}$, which was similar to environmental N inputs. This implied that an ONR equal to crop N removal resulted in a steady-state system (Fig. 2*E*). By contrast, the local farmers' N practices were to apply 600 kg N fertilizer ha^{-1} $year^{-1}$ for a wheat–maize double cropping system, exceeding outputs by 169 kg N ha^{-1} and resulting in a total reactive N loss of 288 kg N ha^{-1} $year^{-1}$, fourfold greater than that with the ONR (Fig. 2*D*).

Based on the field observations above, a schematic of SSNB was developed to seek a long-term N steady state that achieves optimal yields, balances N exports with additions, maintains soil N reservoirs, and minimizes N transfer to losses. Under this steady-state condition, residual soil mineral N becomes stable, and the N cycle in the soil organic N pool changes slowly. Thus, we estimated an ONR for each county, reflecting the difference between N supplies from all sources except N fertilizer and the sum of crop N removal and inevitable N losses (see *Materials and Methods*). Although the SSNB seeks a long-term steady state, the N flows still depend on local management, climate, and soil properties. The SSNB could maximize crop N uptake and achieve high yield through improved soil and crop management (13). It could minimize N losses by managing the N cycle, such as maintaining inorganic N pools at ∼90 to 100 kg N ha^{-1} in the 0 to 1 m soil layer after the crop harvest (30). Thus, the SSNB approach is an integrated, comprehensive approach but flexible and easy to implement for smallholders. It differs from the simple N balance and

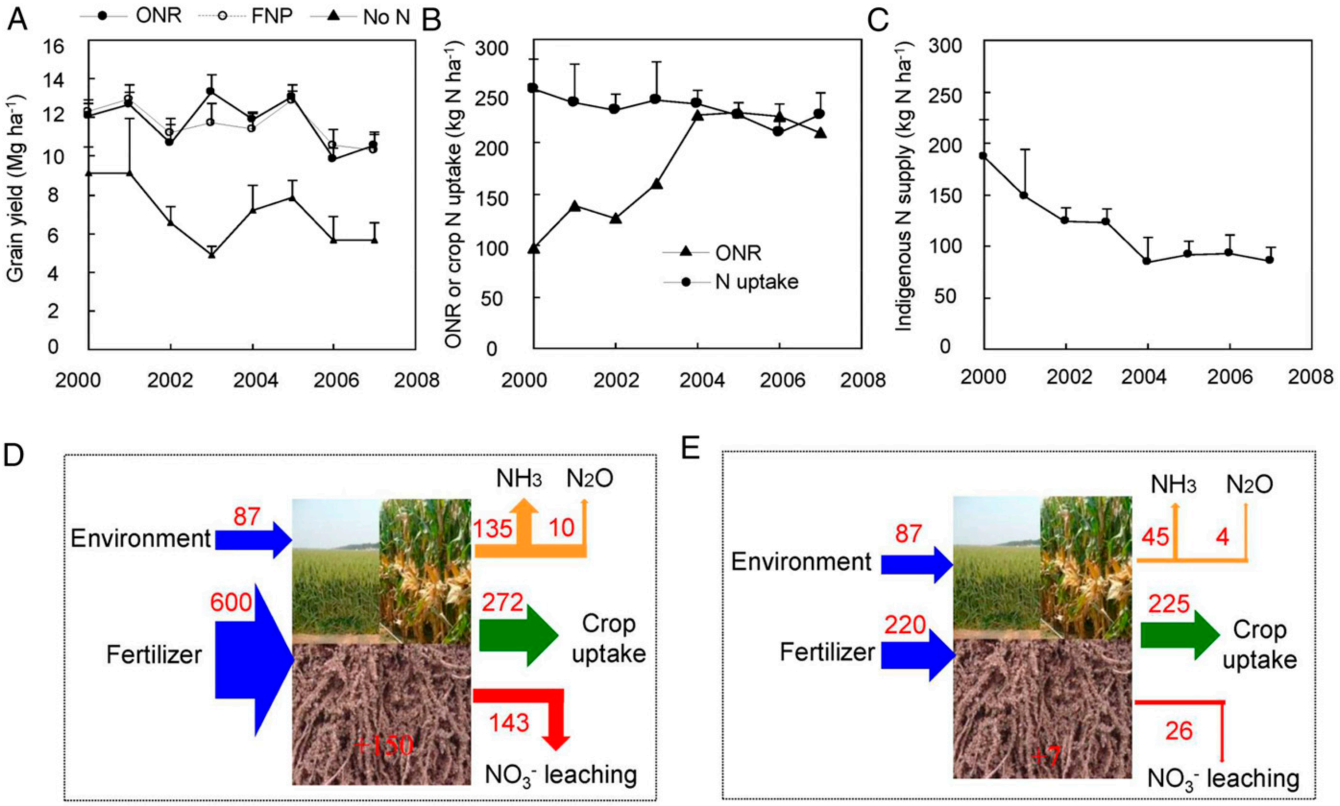

Fig. 2. Crop yield, N rate and crop N uptake, indigenous N supply, and N cycle in a steady-state system. The system was a wheat–maize double cropping system, and data were averaged across both crops per year. Grain yield (*A*), N rate and crop N uptake (*B*), and indigenous N supply (*C*) in ONR-treated plots from 2000 to 2008 at Dongbeiwang. The numbers showed the amount of N cycle (kg N ha^{-1}) with the farmer practice (FNP) (*D*) or ONR treatment (*E*) when the system reached a steady state.

yield-goal approach, which ignores environmental outcomes and location-specific soil N cycles (31, 32).

Development of County-Specific SSNB Mode. We estimated the SSNB-ONR in China at the county level. First, we created a random forest regression model by applying machine learning techniques to compute N losses (including NH_3 volatilization, N_2O emissions, N leaching and runoff, and N_2 emissions; 33–35) using 3,007 field observations in China (*SI Appendix*, Fig. S2). The model computed in situ N losses, integrating 10 parameters from 1 × 1 km grids with total precipitation, potential evapotranspiration, daily average temperature during the crop growth, soil texture (clay, silt, and sand percentage in soil), pH, soil organic carbon, soil total N, and soil bulk density (*Materials and Methods*). Our developed model performed well, having adjusted coefficients of determination (R^2) of 0.85 to 0.93 for each N loss pathway (*SI Appendix*, Fig. S9). The estimated total N loss factors (the ratio of total N fertilizer inputs) for maize, rice, and wheat were 23.8, 30.3, and 27.4%, respectively (*SI Appendix*, Figs. S3 and S4). Then, we estimated environmental N supplied from atmospheric deposition (1 × 1 km grid resolution), irrigation N (irrigation water rate multiplied by N concentration), and biological N fixation. The estimated environmental N supplies for each crop in China were 16 kg N ha^{-1} for maize, 56 kg N ha^{-1}for rice, and 24 kg N ha^{-1}for wheat, respectively. All environmental N sources and N losses were estimated at the county level.

Yield ranges in each county were estimated based on all producers' mean yields and the top 10% of producers (*SI Appendix*, Fig. S5). County-specific yields were determined via surveys of 8.64 million farmers conducted during 2005 to 2014 (*Materials and Methods*). Crop N removal was estimated based on N uptake from grain yields and ratios of straw return (*SI Appendix*, Table S1). The SSNB-ONR ranged from the mean-yield system as the lower bound to the top 10% of producers as the upper bound. Finally, we mapped county-specific SSNBs for 3,824 crop counties for the three staple crops in China. The SSNBs over all counties averaged 168 kg N ha^{-1} (ranging from 146 to 190 kg N ha^{-1} for lower and upper bounds) for maize, 155 kg N ha^{-1} (ranging from 132 to 177 kg N ha^{-1}) for rice, and 151 kg N ha^{-1} (ranging from 130 to 171 kg N ha^{-1}) for wheat, respectively (Fig. 3 and *SI Appendix*, Fig. S6). The N fertilizer was applied in split doses with the largest rate applied at the beginning of the crop rapid growth stages (e.g., ∼70% of N fertilizer was applied during the stem elongation of wheat and rice and 10-leaf stage of maize).

Testing of SSNB by Smallholders. The SSNB was tested in on-farm trials during 2005 to 2014 at 5,979, 6,625, and 5,229 sites for maize, rice, and wheat, respectively (*SI Appendix*, Fig. S12*A*). Established plots included four treatments: no N, SSNB-based ONR, 50% ONR, and 150% ONR. The SSNB-based ONRs based on local yield targets were recommended to be 159 to 208 kg N ha^{-1} for maize, 135 to 182 kg N ha^{-1} for rice, and 139 to 183 kg N ha^{-1} for wheat (Fig. 4 *A* and *B*). Local SSNB-based ONRs were determined by local extension staff based on county-specific ranges, resulting in the mean ONR values of 183, 158, and 159 kg N ha^{-1} for maize, rice, and wheat, respectively. Across all sites, when the N application was reduced from a rate within the ONR to 50% ONR, yields decreased substantially from 8.85 to 7.92 Mg ha^{-1} for maize, 7.80 to 6.99 Mg ha^{-1} for rice, and 5.96 to 5.19 Mg ha^{-1} for wheat. When excessive N fertilizers were applied under the 150% ONR condition, no yield gains were achieved relative to the ONR condition (Fig. 4*B*).

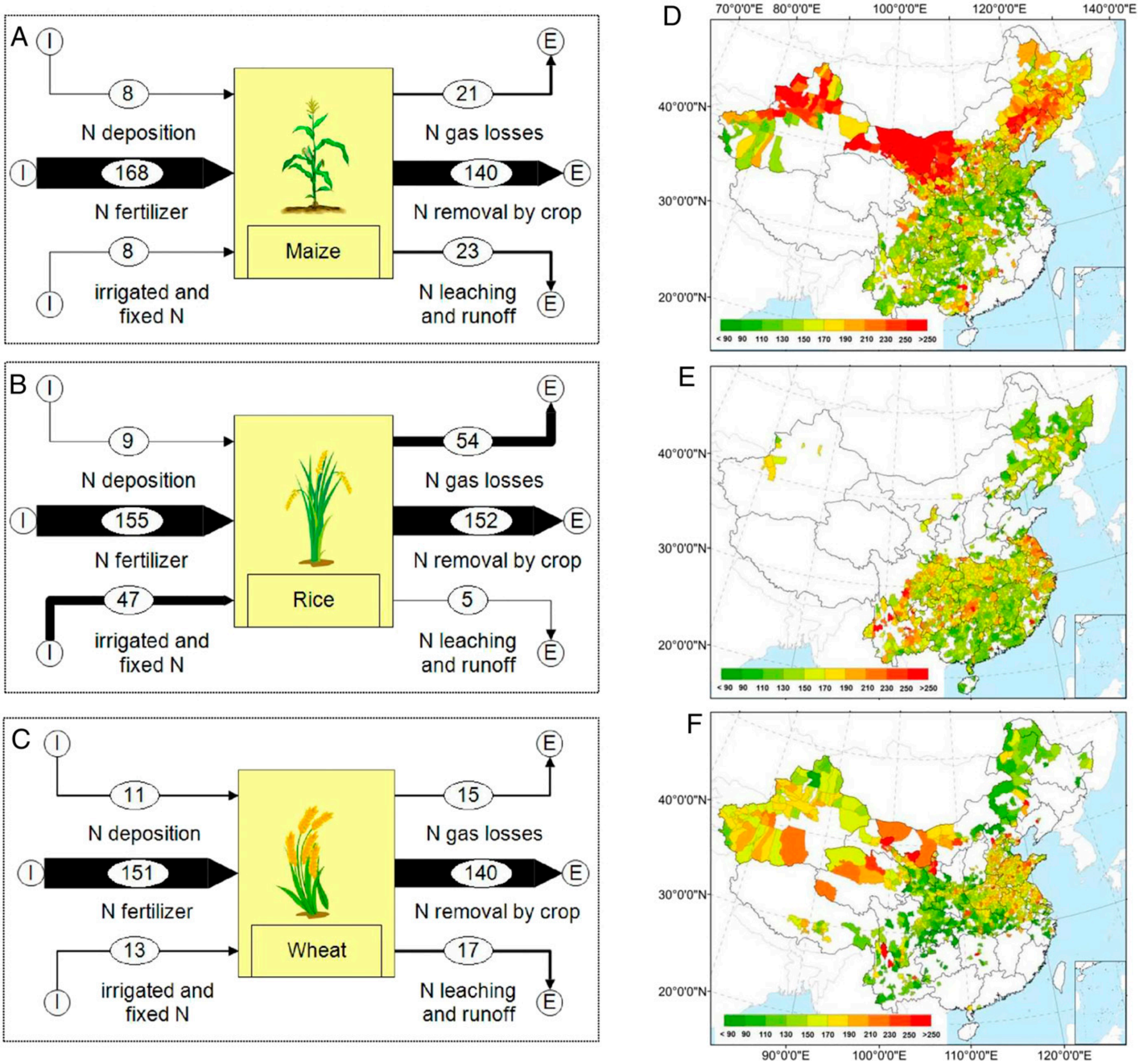

Fig. 3. The mean N flows and SSNB-ONR across China. The amounts of N inputs and outputs within the national means for maize (*A*), rice (*B*), and wheat (*C*) (kg N ha^{-1}). These SSNBs are the mean of lower bounds and upper bounds calculated for 1,419, 1,316, and 1,091 counties of maize (*D*), rice (*E*), and wheat (*F*), respectively.

Next, we enrolled a total of 13,760 smallholder fields from 1,173 counties across China to investigate whether the SSNB approach could be easily implemented by Chinese smallholders for simultaneously enhancing productivity and environmental performance (*SI Appendix*, Fig. S12*B* and Table 1). The smallholders adopted the SSNB approach under the guidance of local extension staff, and results were compared with local farmers' own practices. Although yield responses to treatments varied among crops and counties, the SSNB-based treatments consistently reduced N rates from 230 to 178 kg N ha^{-1} for maize (n = 4,090), 190 to 157 kg N ha^{-1} for rice (n = 6,319), and 210 to 164 kg N ha^{-1} for wheat (n = 3,351) (*SI Appendix*, Fig. S7 and Table 1). More importantly, grain yields increased by 6 to 7% averaged for these three crops. As a result, N productivity (yield/N fertilizer) increased by 26.0 to 33.2%, and calculated yield-scaled reactive N losses (*Materials and Methods*) decreased by 23.2 to 28.9%, in comparison to results from local farmers (Table 1). These results provided strong evidence that the SSNB approach is robust and realistic for China's major crop-producing counties.

Discussion

Long-term results from high yield large-scale cropping systems in developed countries lend support to the concept of SSNB proposed in this study. For example, the average N application rate in the United Kingdom based on farming surveys has remained stable at 185 kg N ha^{-1} year^{-1} since 1983, a rate equal to wheat N removal (*SI Appendix*, Fig. S8*A*). In the United States, maize grain yield had increased from 5.5 Mg ha^{-1} to 9.6 Mg ha^{-1} from 1976 to 2010, but the N application rate had remained stable at ~170 kg N ha^{-1}. The crop N removal was slightly more than N rate with an N deficit of

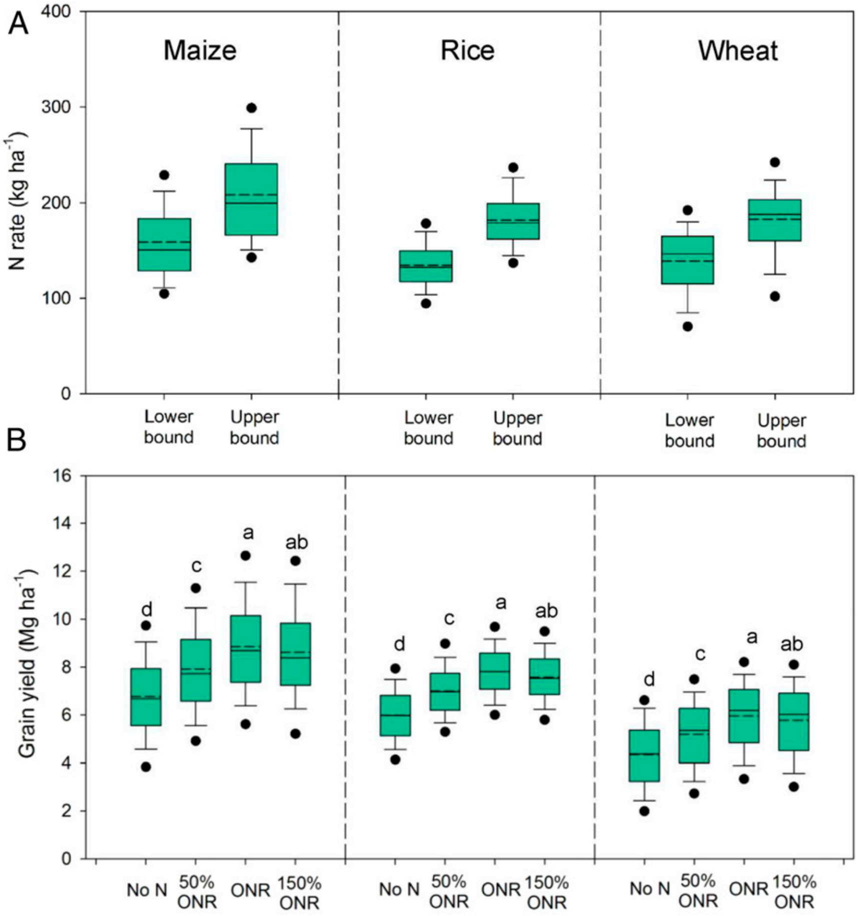

Fig. 4. The N rate and grain yield for on-farm trials of the SSNB approach. The ONR range based upon the SSNB approach for 5,979, 6,625, and 5,229 sites of maize, rice, and wheat, respectively (*A*). Grain yield with different N treatments (no N control, 50, 100, and 150% ONR) (*B*).

10 kg N ha^{-1} from 2001 to 2010 (*SI Appendix*, Fig. S8*B*). Similar evidence was also observed from an irrigated rice long-term experiment in Asia, suggesting that many of those systems have reached a near-steady state (29).

The SSNB approach is agronomically robust and relatively flexible and easy for smallholders to adopt and implement, although the management practices employed for SSNB vary across different crops and locations. The system does not require multifarious soil–plant sampling and processing efforts. In contrast, the costs of soil NO_3^-–N testing and labor in our previous studies were about \$9 per site per season, and professional sampling and laboratory measurement were needed, which limited the widespread adoption by smallholders. The direct cost of implementing SSNB approach in this study was related to training the local extension staff and producers. Some participating staff and farmers were paid a small fee for their services to provide an incentive for training and organization programs (36, 37).

The SSNB approach will contribute to eliminating overuse of N fertilizer, reduce N-related pollution, and would likely prove useful in other rapidly developing economies such as India, Brazil, Indonesia, and Pakistan that share certain similarities with China (38). As for Sub-Saharan Africa, current agricultural production systems are typically low input and low output. A top priority for these countries is to provide more nutrients and boost judicious production increases in inputs, from current, very low levels, as a first step toward sustainable intensification (39, 40). These benefits are achievable if technologies, trainings, and incentives that are

Table 1. Yield, N rate, N productivity, N balance, and yield-scale N losses for maize, rice, and wheat production systems (SSNB treatment versus farmers' practices [FNP])

Crops	Treatment	Yield	N rate	N productivity	N balance	Yield-scale N losses
		Mg ha^{-1}	kg N ha^{-1}	kg kg^{-1}	kg N ha^{-1}	kg N Mg^{-1}
Maize (*n* = 4,090)	SSNB	8.79a (5.76 to 12.30)	178b (120 to 252)	50.6a (35.7 to 70.8)	24b (−28 to 74)	4.9b (2.4 to 8.9)
	FNP	8.21a (5.28 to 11.48)	230a (150 to 326)	37.3b (22.5 to 54.1)	86a (6 to 191)	6.9a (3.2 to 13.1)
Rice (*n* = 6,139)	SSNB	7.89a (6.09 to 9.77)	157b (120 to 208)	51.3a (38.9 to 67.5)	7b (−30 to 49)	5.3b (3.2 to 7.8)
	FNP	7.37b (5.61 to 9.27)	190a (138 to 270)	39.8b (27.4 to 55.1)	51a (-4 to 124)	6.9a (4.1 to 10.9)
Wheat (*n* = 3,351)	SSNB	6.39a (4.02 to 8.14)	164b (110 to 210)	39.7a (28.8 to 51.2)	7b (−32 to 55)	4.8b (2.9 to 7.7)
	FNP	5.96a (3.56 to 7.65)	210a (134 to 300)	29.3b (19.1 to 40.9)	71a (10 to 158)	6.7a (3.7 to 11.1)

The ranges in parentheses denote 5th to 95th percentile.

keys to the adoption and implementation of SSNB are provided for smallholders.

Uncertainties existed in estimating ONR using the SSNB. A key to the SSNB approach is forming a steady state, whose estimation often requires long-term observations, and such information is currently available for only a limited number of regions. The SSNB might apply more N fertilizer before a soil–crop system achieves a steady state and less N fertilizer when the soil N organic pool needs to be increased (e.g., when immobilization exceeds mineralization). Year to year environmental variations might also affect the N cycle at the steady state, thus changing N inputs (41). The deviations from SSNB-based ONR are smaller in magnitude than the overuse of N in China. For example, there is typically an excess of 200 kg N ha^{-1} $year^{-1}$ for wheat–maize double crop systems in the North China Plain. Overall, the SSNB approach is a useful tool to develop region-specific N management.

Although our study can maintain or improve the average yield and reduce total N losses at a county scale, some smallholders will likely benefit more than others where intracounty variation in climate, soil, and management conditions are large. Additional areas of interest and potential significance include the integration of SSNB with advanced fertilization techniques (e.g., slow-release N fertilizers, nitrification inhibitors, and fertigation) and other practices (such as cropping system patterns, manure inputs, improvements in seed quality/nutrients, conservation tillage, and pest management) (42–45). Therefore, SSNBs should be routinely updated and refined to ensure they are adapted to changes in location, genetics, cropping systems, and climate change. We also note that although reaching the steady state in high-input cropping systems is critical, it does not mean zero N losses. Continuous efforts are needed to minimize N losses, especially in the context of specific soil types and climatic conditions, such as sandy soil and heavy rainfall (46, 47).

In conclusion, how smallholders manage the major N cycle processes in the soil–crop system directly influences local environmental and ecosystem health and collectively impacts global food security and sustainability (13, 17, 48). The SSNB approach developed in this study simplifies the real-world complexities, providing a simple and useful tool to help local farmers manage excess N problems and attain greater productivity and environmental performance. Our study constitutes a valuable addition to the range of viable solutions to ensure a sustainable future and may help inspire a global vision of N sustainability.

Materials and Methods

On-Farm Trials for N Rate Optimization. In total, 269 on-farm trials were conducted to optimize the N rate from 2003 to 2005 in central-eastern China (32 to 41°N, 113 to 120°E). This region is characteristic of temperate, subhumid, continental monsoon climate with cold winters and hot summers. The total precipitation averaged 500 to 700 mm per year, with ∼65 to 75% occurring in the summer. Maize and wheat were cultivated in late June to the end of September and mid-October to mid-June of the following year. The soil in all experiments was calcareous alluvial soil with a bulk density of 1.30 to 1.43 g cm^{-3} for the top 30-cm soil depth, and the organic matter was 7.4 to 25.3 g kg^{-1}, which is typical in central China.

The following three N treatments were applied: no N (control), ONR based on soil N_{min} testing, and local farmers' practices. In this study, crop growth was monitored over two or three periods. The ONR for each crop was determined by the N target value less the measured soil NO_3^-–N content from the root zone. The N target value was obtained from the total N uptake by crop shoots and roots estimated from the target yield and corresponding N content. N was applied as urea. With the exceptions of fertilizer management treatment and the harvest method, other plot management operations were the same as the rest of the fields.

Long-Term Field Experiments. A long-term study was conducted in central China in Beijing from 2000 to 2008. The experiments were comprised of three N fertilizer treatments with four replicates each, including no N (control), application at the ONR based on soil N_{min} testing, and local farmers' practices. The soil was calcareous alluvial with a loamy texture, and the soil characteristics for the 0- to 30-cm soil layer were as follows: pH 8; soil/water pH ratio, 1:2.5; other parameters: organic matter content, total N, Olsen P, exchangeable K were 21.4 g kg^{-1}, 1.17 g kg^{-1}, 34.6 mg kg^{-1}, and 145 mg kg^{-1}.

The NH_3 volatilization was measured using an automatic wind tunnel system (49, 50). Denitrification losses in the field from both N_2 and N_2O emissions were monitored with a soil core incubation system using the acetylene inhibition method. N_2O fluxes over 2 y were measured using an automatic measurement system with a static chamber and gas chromatograph (49). NO_3^- leaching was quantified using TerrAquat passive samplers filled with ion-exchange resin that were placed at a depth of 130 cm, which was assumed to be below the zone of active NO_3^- uptake by roots (51).

Wet N deposition was measured using automatic wet-only samplers (APS series; Wuhan Tianhong Inc.), and particulate dry N deposition was measured using a 0.5 m^2 polyethylene sheet-based sampler (52). For both wheat and maize, plant-available N from atmospheric deposition was measured using an integrated total N input system (53). All information was used to estimate the N balance for Fig. 2 *D* and *E*.

SSNB Approach. The ONR using the SSNB approach for each county was estimated as follows:

$$\mathrm{ONR} = (N_{removal} - N_{env})/(1 - EF_s), \qquad [1]$$

where EF_s are N loss factors (%), $N_{removal}$ is the crop N removal rate (kg N ha^{-1}), and N_{env} is the environmental N inputs (kg N ha^{-1}).

The crop N removal rate ($N_{removal}$) was calculated as follows:

$$N_{removal} = N_{uptake} - N_{sr}, \qquad [2]$$

$$N_{uptake} = 23.3 \times Y^{0.887} \text{ for maize}, \qquad [3]$$

$$N_{uptake} = 24.9 \times Y^{0.851} \text{ for rice}, \qquad [4]$$

$$N_{uptake} = -14 + 41 \times Y^{0.77} \text{ for wheat}, \qquad [5]$$

$$N_{sr} = (Y/HI - Y) \times R \times C_s, \qquad [6]$$

where Y is the crop target grain yield from farmers' surveys (Mg ha^{-1}), N_{uptake} is the crop N uptake (kg N ha^{-1}), which was estimated from crop grain yield, N_{sr} is the crop return N from straw (kg N ha^{-1}), HI is harvest index, R is the proportion of straw return to the field (%), and C_s is the N concentration of crop straw (g N kg^{-1}). See refs. 54, 55, and 56 for Eqs. 3, 4, and 5, respectively. A detailed explanation provided in *SI Appendix*, Table S1.

Environmental N inputs included atmospheric dry and wet N deposition, biological fixation N, and irrigation N. The N deposition data were extracted from global N deposition maps and simulated with Goddard Earth Observing System-Chems (57). We used the first-order conservative interpolation to regrid the data at a resolution of 1 × 1 km grid. Crop distributions in 2010 derived from the Spatial Production Allocation Model were used to calculate N deposition rates (kg ha^{-1}) according to crop growth duration. The biological N fixation rates were estimated to be 5 kg ha^{-1} for maize, 25 kg ha^{-1} for rice, and 5 kg ha^{-1} for wheat, respectively (58). The irrigated N values were estimated to be 3.4, 22 kg ha^{-1}, and 8.1 for maize, rice, and wheat, respectively (59, 60). A detailed explanation is provided in *SI Appendix*, Table S2.

Estimation of N Losses. We first collected articles published during 1990 to 2020 on N_2O, NH_3, NO_3^-, and N_2 losses during the growth of maize, rice, and wheat from the Web of Science and China National Knowledge Infrastructure databases. The studies met the following search criteria: 1) measurement of N losses in fields throughout the growing season and inclusion of a zero N input control in the measurement of N loss, and 2) N fertilizer types were urea or ammonium, excluding slow-release, controlled-release fertilizers, and organic materials (e.g., manure or compost). Data on soil properties were collected, including soil organic carbon, total N, pH, soil bulk density, soil clay, sand, and silt contents. Data on climatic factors including daily temperature, total precipitation, and total potential evapotranspiration during the growth period, the locations of experimental sites, and the descriptions of experimental treatments were also extracted. In total, 536 peer-reviewed studies consisting of 3,007 observations (1,399 from 242 studies concerning N_2O, 710 from 130 studies concerning NH_3, and 819 from 151 studies concerning NO_3^-; 79 from 14 studies concerning N_2; *SI Appendix*, *Fig. S2*) were included. The missing values for the soil and climatic factors at a few sites (< 15%) were either supplemented from the 0.83-km World Inventory of Soil Emission database (http://www.isric.org) (61) or from Climatic Research Unit Timeseries (CRU TS) version

3.23 (https://crudata.uea.ac.uk/cru/data/hrg/), according to the study latitude and longitude location.

In this study, the amounts of N lost via N_2O, NH_3, NO_3^-, and N_2 were obtained using the emission factors of N (EFs, %) multiplied by the N application rate at the county level. The N_2 loss was estimated to be 1.8, 12, and 1.5% for maize, rice, and wheat, respectively, because of limited published observations (*SI Appendix*, Fig. S4). The maize, rice, and wheat EFs of N_2O, NH_3, and NO_3^- were estimated from a random forest regression model that used parameter measurements synthesized from the 524 studies mentioned above to simulate Nr losses (*SI Appendix*, Fig. S9). The model employed ensemble machine learning techniques and presented a set of binary decision rules based on input variables. The model ran procedures with the following three steps. First, create a random forest model comprised of k selected features from a total of n ($k < n$) features, and create the node d and daughter nodes for the selected features. Second, repeat those steps to create a forest with n number of decision trees. Third, apply a test dataset to test the created decision tree and predict new outputs.

N loss EFs served as the dependent variable in the random forest regression model. The independent variables affecting N loss EFs were total precipitation, potential evapotranspiration, and mean daily temperature of growth duration, bulk density, sand content, pH, total N, and organic matter, as determined using random forest modeling with 10-fold cross validation. The climate and soil parameters (*SI Appendix*, Figs. S10 and S11) were imported into the model to obtain the best-fit simulation based on the regression coefficients of determination and variation. In this study, the dataset of each loss pathway was randomly divided into 10 equal size subsets, and 7 of these 10 datasets were used to perform the training of the random forest model. The remaining data were used to test the performance of the trained results. The model's robustness was evaluated by calculating the regression coefficients of determination (R^2) and rms errors. All computations were performed using the "*randomForest*" package in R software version 3.5.1 (R Foundation for Statistical Computing, Vienna, Austria).

Survey of Prevailing Farmer Practices. The survey data were obtained from a 2005 to 2014 nationwide farmer survey campaign and comprised 73% of the total area planted (66.4 million ha) in 1,978 counties for maize, rice, and wheat. A total of 8.64 million individual farmers participated in the survey (3.01, 3.37, and 2.26 million for maize, rice, and wheat, respectively). These farmers were interviewed face-to-face by county extension agents using a questionnaire designed to obtain information on yield and fertilizer use. More details can be found in ref. 13. Only crop yields with county average and 10% of producers were extracted and used as yield targets for the estimation of SSNBs within each county.

On-Farm Testing Trials for the SSNB Approach. In total, 17,840 on-farm trials conducted on 5,986 maize, 6,625 rice, and 5,129 wheat fields were performed by the Ministry of Agriculture and Rural Affairs from 2005 to 2014 throughout China (*SI Appendix*, Fig. S12*A*). Four N treatments were applied to each field: no N (control), application at the ONR calculated based on the SSNB (developed specifically for each county), 50% ONR, and 150% ONR. We included a 50% ONR treatment to explore the potential to further reduce N fertilizer and a 150% ONR treatment to ensure maximum grain yield. In this study, manure was not considered because organic N application rates in cereal crop production in China are low (<15 kg N ha^{-1}; ref. 62). About 40% of the N fertilizer (urea) in wheat and maize was applied at seed sowing, and the remaining 60% N fertilizer was applied as side dressing at the six-leaf and stem-elongation phases. About 50% of the N fertilizer in rice was applied before sowing, and 20 and 30% N fertilizer was applied at tillering and panicle-initiation stage, respectively. P and K fertilizer was applied at recommended rates before sowing with average rates of 97, 73, and 110 kg P_2O_5 ha^{-1} and 95, 103, and 94 kg K_2O ha^{-1} for maize, rice, and wheat, respectively.

National On-Farm Demonstrations. In total, 13,760 field demonstrations were conducted from 2005 to 2014 for the three cereal crops ($n = 4{,}090$ for maize, $n = 6{,}139$ for rice, and $n = 3{,}351$ for wheat). The sites were spread throughout the three cereal crop agroecological zones (*SI Appendix*, Fig. S12*B*). The demonstrations were conducted by local extension staff through solicited farmer participants in the typical locations/sites, based on factors such as willingness, field size, and labor availability. Each field trial received two treatments: the SSNB-based treatment (developed specifically for each county) and local farmers' practices. The extension staff determined N application rates based on the recommend optimized N range from SSNB and then introduced to the participating farmers and helped them implement in their fields. The extension staff provided on-site guidance for key field operations, such as sowing, fertilization, irrigation, and harvesting during crop growth.

The direct cost of implementing SSNB management can be ignored, because it does not require multifarious soil–plant sampling and processing efforts. In China, the core networks of extension personnel are, in essence, government employees; their engagement in the demonstration is considered part of their job. The additional cost was primarily spent on demonstration operations; very little was spent on human capital in the form of salary or wage coverage. In our work, some participating staff and farmers were paid a small fee for their services to provide an incentive for adoption.

Plant and Soil Sampling and Analysis. For all experiments and trials, ≥6 m^2 of maize, ≥4 m^2 of rice, or ≥3 m^2 of wheat was harvested manually from each plot at crop maturity. After samples, aboveground biomass and grain yield were dried to a constant weight at 60 °C to determine weight. Subsamples of grains and straws were ground to pass through a 2-mm sieve and used to determine N content via the Kjeldahl method (63).

Soils in all experiments were sampled to a depth of 90 cm at 30 cm increments before planting and fertilization, as well as after harvest. Fresh subsamples were extracted with a 1:10 ratio of soil to 0.01 mol L^{-1} calcium chloride solution, and ammonium (NH_4^+)-N and NO_3^-–N contents were determined using continuous flow analysis. Air-dried subsamples from the topsoil layer (0 to 30 cm) were analyzed for total N and soil organic matter content.

Data Analysis and Management. One-way ANOVA ($P < 0.05$) was used to compare grain yields among different N treatments. The Student's t test was used to compare the mean grain yield, N rate, N productivity, N balance, and yield-scale N loss between the SSNB-based treatment and farmers' practices ($P < 0.05$). The analyses were performed using the SPSS version 20.0 (SPSS, Inc.). Principal component analysis and correlation analysis were used to clarify the optimal N rate response to the variables of yield, N uptake, nitrogen recovery efficiency (REN), soil nitrate-N content, Nmin, and soil N supply (*SI Appendix*, Fig. S1). These analyses were using ggbioplot in the "*vegan*" package in R (version 3.5.1). N loss databases were created using Excel 2010 software (Microsoft Corp.). Daily weather was analyzed using MATLAB R2017a software (MathWorks Inc.). Data from a survey of 8.64 million farmers were analyzed using SQL Server 2012 software (Microsoft Corp.). Excel 2010 and SigmaPlot version 12.5 software (Systat Software) were used to plot graphs. ArcGIS 10.2 software (https://www.esri.com/en-us/arcgis/products/index) was used to perform map-related operations. The publicly available map of China was obtained from the Resource and Environment Data Cloud Platform (http://www.resdc.cn).

Data Availability. All study data are included in the article and/or *SI Appendix*.

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