doi:10.1038/nature25785

Pursuing sustainable productivity with millions of smallholder farmers

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Sustainably feeding a growing population is a grand challenge[1–3], and one that is particularly difficult in regions that are dominated by smallholder farming. Despite local successes[4–8], mobilizing vast smallholder communities with science- and evidence-based management practices to simultaneously address production and pollution problems has been infeasible. Here we report the outcome of concerted efforts in engaging millions of Chinese smallholder farmers to adopt enhanced management practices for greater yield and environmental performance. First, we conducted field trials across China's major agroecological zones to develop locally applicable recommendations using a comprehensive decision-support program. Engaging farmers to adopt those recommendations involved the collaboration of a core network of 1,152 researchers with numerous extension agents and agribusiness personnel. From 2005 to 2015, about 20.9 million farmers in 452 counties adopted enhanced management practices in fields with a total of 37.7 million cumulative hectares over the years. Average yields (maize, rice and wheat) increased by 10.8–11.5%, generating a net grain output of 33 million tonnes (Mt). At the same time, application of nitrogen decreased by 14.7–18.1%, saving 1.2 Mt of nitrogen fertilizers. The increased grain output and decreased nitrogen fertilizer use were equivalent to US$12.2 billion. Estimated reactive nitrogen losses averaged 4.5–4.7 kg nitrogen per Megagram (Mg) with the intervention compared to 6.0–6.4 kg nitrogen per Mg without. Greenhouse gas emissions were 328 kg, 812 kg and 434 kg CO_2 equivalent per Mg of maize, rice and wheat produced, respectively, compared to 422 kg, 941 kg and 549 kg CO_2 equivalent per Mg without the intervention. On the basis of a large-scale survey (8.6 million farmer participants) and scenario analyses, we further demonstrate the potential impacts of implementing the enhanced management practices on China's food security and sustainability outlook.

Food security, environmental degradation and climate change are grand challenges facing humankind[1,2]. Agriculture is at the heart of these challenges, as food production must be increased by 60–110% (from 2005) to meet the growing demand by 2050[3,9], and at the same time adverse environmental impacts need to be reduced amid climate change and growing competition for natural resources[10,11]. The greatest challenge occurs in regions in which smallholder farming dominates the agricultural landscape, for example, in sub-Saharan Africa, India and China. In these regions, food security and sustainability depend on how smallholders, who are typically resource-limited and knowledge-poor, farm their land[12]. Much effort has endeavoured to enhance smallholder productivity[13–15]. However, mobilizing millions of smallholder farmers and encouraging them to adopt management technologies that simultaneously address production and pollution problems has been infeasible. The need to do so is particularly important in countries in which smallholders operate high-input, low-efficiency systems.

China is a case in point. With 200–300 million households that each farm a few hectares of land, the agricultural system relies heavily on high-to-excessive inputs. For example, nitrogen application averages to 305 kg N ha^{-1} yr^{-1} compared to 74 kg N ha^{-1} yr^{-1} worldwide[16]; nitrogen use efficiency (the fraction of nitrogen input harvested as product) is only 0.25 compared to 0.42 worldwide and 0.65 in North America[17]. Over-application of nitrogen has caused widespread soil acidification[18], devastating water pollution[19] and excessive greenhouse gas (GHG) emissions[20]. For a sustainable food-secure future, China needs a 'great balancing act'[21] to attain high yield and high efficiency with a substantially reduced environmental footprint. This cannot be achieved without the vast smallholder-farming communities.

Here we report the outcome of nationally coordinated efforts over a 10-year period that encouraged 20.9 million smallholders to adopt enhanced management technologies for greater yield and reduced environmental pollution. First we present the results of 13,123 field trials that tested the applicability of a comprehensive decision-support integrated soil–crop system management (ISSM) program for growing maize, rice and wheat across China's vast agroecological zones. We then describe coordinated campaigns, leading to the implementation of ISSM-based management in farmland with a total of 37.7 million cumulative hectares over the years (2005–2015). Finally, we discuss

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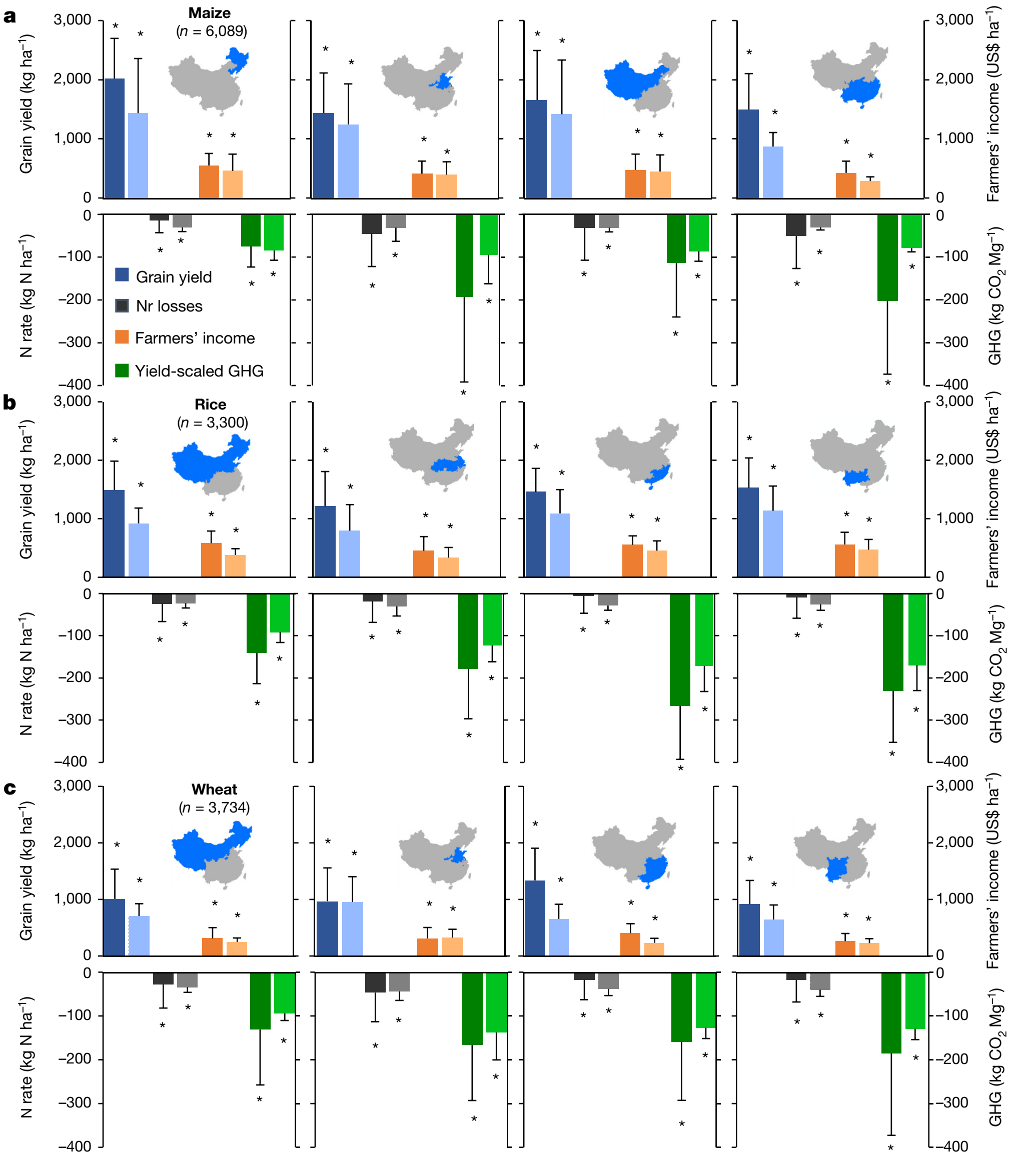

Figure 1 | Production and environmental performance with ISSM-based intervention. a–c, Yield response, nitrogen rate, farmers' net income and GHG emissions of ISSM-based management compared to farmers' practices (0 baseline) for maize (**a**), rice (**b**) and wheat (**c**) in four agroecological zones in China. Dark-coloured bars denote data from field trials ($n = 13{,}123$), light-coloured bars indicate data from the national campaign during 2005–2015. Nr, reactive nitrogen. Data are mean ± s.d. $*P < 0.05$, significant difference between treatment (ISSM) and control (farmers' practice). Chinese map was obtained from the Resource and Environment Data Cloud Platform (http://www.resdc.cn/data.aspx?DATAID=202).

scenarios for pursuing sustainable productivity in the entire country and the potential impacts on grain output and selected environmental indices.

To start, we needed technological tools for designing management practices that can be packaged for making field recommendations. Such technologies need to be comprehensive and include key crop–soil–water–nutrient parameters, as well as adaptive, in order to suit different biophysical conditions. The ISSM framework[4,22] appears to suit these needs. It consists of a crop module from which cropping strategies (for example, crop variety, planting date and density for maize, rice or wheat) can be determined based on crop model simulations for optimal use of solar and thermal resources in a given region; and a resource supply module for the formulation of nutrient and water applications according to soil tests and the needs of the growing crops. Previous studies have demonstrated that following ISSM-based recommendations resulted in greater yields (18–35%), a reduction in nitrogen fertilizer usage (4–14%) and improved nitrogen productivity (kg grain produced per kg nitrogen applied; 32–46%) compared to the conventional practices of the farmers[5].

We investigated whether ISSM could be used across China's major agroecological zones, which range from frigid to subtropical, and from arid to semi-arid to humid, to obtain similar outcomes across all regions. We conducted field trials, with a total of 13,123 site years between 2005 and 2015 across agroecological zones (Extended Data Fig. 1). Each trial included ISSM-based recommendations (treatment) compared to the conventional practice of the farmers (control), with the participating farmer carrying out field operations and campaign collaborators providing on-site guidance (Methods and Extended Data Table 1). Yield response to treatment varied for different crops in different agroecological zones. But in all cases ISSM-based treatment enhanced yield, nitrogen productivity, and farmer profitability and reduced nitrogen losses. Averaged over all site years, grain yields increased from 7.83 to 9.54 Mg ha^{-1} for maize ($n = 6{,}089$), from 7.03 to 8.41 Mg ha^{-1} for rice ($n = 3{,}300$) and from 5.69 to 6.73 Mg ha^{-1} for wheat ($n = 3{,}734$). At the same time, nitrogen rate (amount of nitrogen applied per unit area (kg N ha^{-1})) decreased by 8.5–15.6% (Fig. 1). As expected, ISSM-based treatment led to greater nitrogen use efficiency, net income and environmental performance. Nitrogen productivity

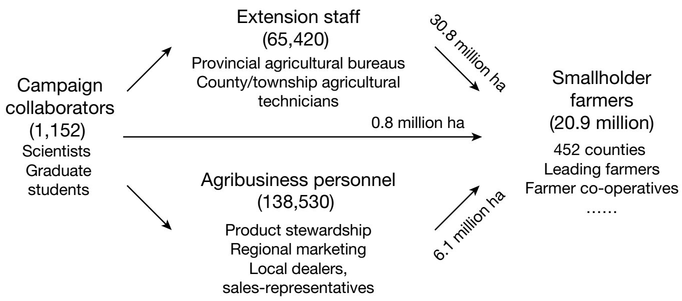

Figure 2 | The national campaign network. The campaigns were conducted to encourage smallholder farmers to implement ISSM-based management practices for high yield, high efficiency and low pollution. Campaign collaborators (scientists and graduate students at agricultural universities or research institutions) developed locally applicable ISSM-based recommendations and provided training to extension staff (agricultural technicians and field agents at various governmental agencies) and agribusiness personnel (agricultural production supply and services, including headquarters business/product development, regional marketing, and local dealers and sales representatives). All three entities worked with farmers. Numbers in parentheses indicate the number of individuals involved in the campaign.

increased by 26.0–33.1%. Calculated reactive nitrogen losses (Methods) decreased by 22.9–34.9% and GHG emissions were reduced by 18.6–29.1% (Fig. 1).

The expansive field trials provided strong evidence that the ISSM program is robust and versatile and could be used nationwide for developing management practices to simultaneously enhance productivity and environmental performance. Once ISSM-based recommendations were derived from the field trials of a given region, we led and coordinated campaign activities to promote their adoption throughout the region (Methods). The national campaign consisted of more than 1,000 collaborators, 65,000 extension agents and 130,000 agribusiness personnel (Fig. 2), who engaged 20.9 million farmers in 452 counties to implement ISSM-based practices in fields with a total of 37.7 million cumulative hectares over the years (2005–2015).

Production and environmental outcomes from the national campaign were in line with expectations. Aggregated 10-year data showed an overall yield improvement of 10.8–11.5% and a reduction in the use of nitrogen fertilizers of 14.7–18.1%, when comparing ISSM-based interventions and the prevailing practices of the farmers (Table 1 and Methods). This led to a net increase of 33 Mt grains and a decrease of 1.2 Mt nitrogen fertilizer use during the 10-year period, equivalent to US$12.2 billion (Table 1). To put the numbers in perspective, Malawi's total grain output was 31.5 Mt during 2005–2014[23]; nitrogen fertilizer use in the entire sub-Saharan Africa was 4.6 Mt during 2005–2015[23].

We assessed relevant environmental impacts by calculating reactive nitrogen losses (N_2O emission, NH_3 volatilization, NO_3^- leaching and nitrogen runoff losses) and GHG emissions (Methods). Results varied widely, depending on crop type, nitrogen rate, biophysical conditions and other factors. Aggregated results showed that ISSM-based interventions reduced reactive nitrogen losses by 13.3–21.9% and GHG emissions by 4.6–13.2%. The yield-scaled nitrogen footprint averaged 4.6, 4.7 and 4.5 kg reactive nitrogen loss per Mg of maize, rice and wheat produced, respectively, compared to 6.1, 6.0 and 6.4 kg Mg^{-1} without intervention. Similarly, yield-scaled GHG emissions were 328 kg, 812 kg and 434 kg compared to 422 kg, 941 kg and 549 kg CO_2 equivalent per Mg for maize, rice and wheat, respectively (Table 1).

Changing farmer behaviour requires more than scientifically sound and evidence-based technologies[24,25]. Building trust, participatory innovation, developing human capacity and strengthening the coherence of the farming communities are critical for sustainable changes; we pursued these goals vigorously throughout the campaign (Methods). Examples include providing basic knowledge to progressive farmers and increasing their problem-solving skills, enabling these farmers

Table 1 | Comparison of grain output, nitrogen fertilizer use, nitrogen productivity, reactive nitrogen losses, GHG emissions and net economic gains

		Maize	Rice	Wheat	Total
Area (million ha)		12.8	17.0	7.9	37.7
Grain output (Mt)	FP	108	133	51	292
	ISSM	120	147	56	324
	Difference	11.5%	11.1%	10.8%	11.2%
N fertilizer use (Mt)	FP	2.9	3.3	1.8	8.0
	ISSM	2.5	2.8	1.5	6.8
	Difference	−14.7%	−15.1%	−18.1%	−15.6%
N productivity (kg N per kg grain)	FP	40.0	41.9	28.4	NA
	ISSM	53.4	55.1	38.5	NA
	Difference	33.4%	31.5%	35.7%	NA
Nr losses* (Mt)	FP	0.65	0.79	0.33	1.8
	ISSM	0.55	0.69	0.25	1.5
	Difference	−15.0%	−13.3%	−21.9%	−15.5%
CO_2-equivalent emission† (Mt)	FP	45	125	28	198
	ISSM	39	119	24	183
	Difference	−12.9%	−4.6%	−13.2%	−7.7%
Net economic gain‡ (billion US$)	FP	18.0	28.0	7.2	53.2
	ISSM	22.1	34.2	9.2	65.5
	Difference	22.7%	22.1%	27.2%	23.0%

Comparison between ISSM-based management technologies (ISSM) and conventional practices of the farmers (FP) for maize, rice and wheat during the national campaign from 2006 to 2015. Difference indicates the percentage increase of ISSM-based recommendations over the conventional practice.

*Reactive nitrogen losses include NH_3 volatilization, NO_3^- leaching, N_2O emissions and nitrogen runoff. See Methods for calculations.

†GHG emissions include CO_2, CH_4 and N_2O from the whole life cycle of crop production. See Methods for calculations.

‡Net economic gain from increased yield and decreased nitrogen fertilizer use, calculated as 0.31, 0.40, 0.32 and 0.62 US$ per kg of maize, rice, wheat and nitrogen, respectively.

to lead fellow villagers[26]; fostering farmer cooperatives to give smallholders a collective voice for negotiating purchases or marketing their products at better price as well as influencing local agricultural policies (Supplementary Information). Campaign collaboration, engagement mechanisms, socioeconomic factors and relevant impacts are described in the Methods.

For China's vast numbers of smallholder farmers, we wanted to understand how varied their productivity and environmental performances were. We therefore extracted results from a large-scale survey (8.6 million participants from 1,944 counties covering 73% of total acreage of the three crops; Methods). Our analysis indicates that the majority of smallholder farmers (61%) had yields at least 10% (up to 50%) below the ISSM-based yields, while their nitrogen rates were comparable to or higher than ISSM-based rates. County-level performance scores show considerable gaps in most cases, comparing county-average yield and nitrogen rate with ISSM-based benchmarks (Fig. 3), indicating that there is room for improvement.

We then conducted scenario analyses to assess the potential impacts if all surveyed counties were to adopt ISSM-based technologies. Counties in each agroecological zone were categorized as 'low yield and high nitrogen rate', 'low yield and low nitrogen rate', 'high yield and high nitrogen rate' and 'high yield and low nitrogen rate' (Extended Data Tables 2–4). Scenario 1 targets the low yield and high nitrogen rate group with the ISSM-based yield and nitrogen rate as benchmark; scenario 2 included the low yield and high nitrogen and the low yield and low nitrogen group; and scenario 3 further added the high yield and high nitrogen rate group. Our analysis shows that compared to business as usual (that is, prevailing practices without intervention)[27], implementing ISSM-based technologies would increase annual grain output by 19.3, 70.5 and 82.4 Mt for scenarios 1, 2 and 3, respectively. Taken together (that is, including scenario 3), there would be an annual reduction of nitrogen fertilizer use by 1.10 Mt (8.5% compared to business as usual), reactive nitrogen losses by 0.45 Mt (16.0%) and CO_2-equivalent emissions by 23.4 Mt (7.6%; Extended Data Table 5). The feasibility for a nationwide scale-up is discussed in

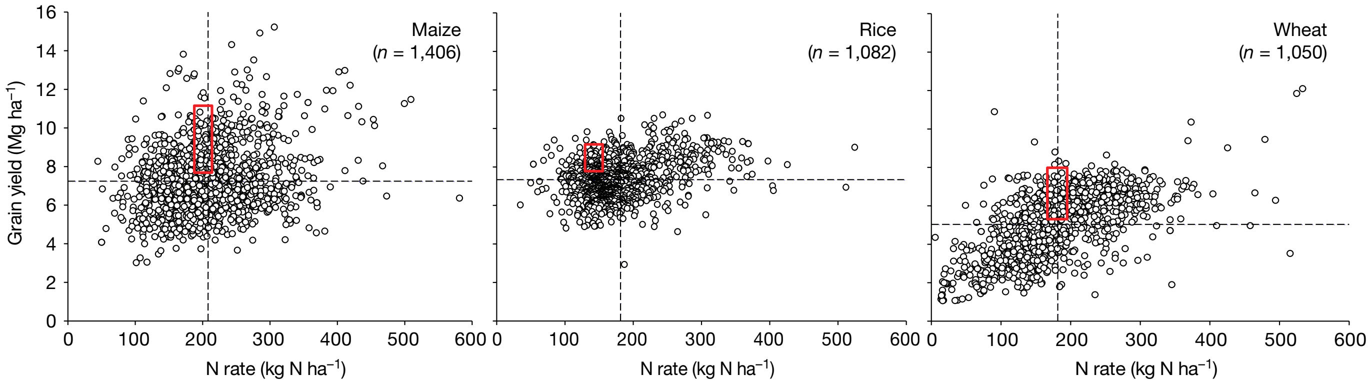

Figure 3 | National performance scores based on surveys of farmers during 2005–2014 for maize, rice and wheat. County-level performance scores (yield and nitrogen application rate) based on survey results of 8.6 million farmers in 1,944 counties during 2005–2014. **a**, Maize. **b**, Rice. **c**, Wheat. Dashed lines denote means of the total in yields and nitrogen rates, 7.2 Mg ha^{-1} and 208 kg N ha^{-1} for maize, 7.3 Mg ha^{-1} and 181 kg N ha^{-1} for rice, 5.0 Mg ha^{-1} and 181 kg N ha^{-1} for wheat, respectively. Rectangular boxes indicate ranges of ISSM-based performance. Numbers in parentheses indicate the number of counties.

the Supplementary Information, along with potential limitations and possible barriers.

Worldwide, 2.5 billion smallholders farm 60% of the world's arable land[28]. How they perform directly determines their own livelihood, and at the same time these farmers collectively impact the global food, resources and ecosystem health as a whole. Empowering smallholder farmers with enhanced management technologies to help them attain greater productivity and environmental performance is critical as we pursue an equitable world with a sustainable future. Towards this end, this study can be a valuable addition to the range of viable solutions.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

Received 8 March 2017; accepted 19 January 2018.
Published online 7 March 2018.

1. Foley, J. A. *et al.* Solutions for a cultivated planet. *Nature* **478,** 337–342 (2011).
2. Matson, P. A., Parton, W. J., Power, A. G. & Swift, M. J. Agricultural intensification and ecosystem properties. *Science* **277,** 504–509 (1997).
3. Tilman, D., Balzer, C., Hill, J. & Befort, B. L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl Acad. Sci. USA* **108,** 20260–20264 (2011).
4. Chen, X. P. *et al.* Integrated soil–crop system management for food security. *Proc. Natl Acad. Sci. USA* **108,** 6399–6404 (2011).
5. Chen, X. *et al.* Producing more grain with lower environmental costs. *Nature* **514,** 486–489 (2014).
6. Cui, Z. *et al.* Closing the yield gap could reduce projected greenhouse gas emissions: a case study of maize production in China. *Glob. Change Biol.* **19,** 2467–2477 (2013).
7. Ladha, J. K. *et al.* Agronomic improvements can make future cereal systems in South Asia far more productive and result in a lower environmental footprint. *Glob. Change Biol.* **22,** 1054–1074 (2016).
8. Liu, Y. *et al.* Net global warming potential and greenhouse gas intensity from the double rice system with integrated soil–crop system management: a three-year field study. *Atmos. Environ.* **116,** 92–101 (2015).
9. Alexandratos, N. How to feed the world in 2050. In *The Proceedings of a Technical Meeting of Experts* 1–32 (FAO, 2009).
10. Garnett, T. *et al.* Sustainable intensification in agriculture: premises and policies. *Science* **341,** 33–34 (2013).
11. Gunton, R. M., Firbank, L. G., Inman, A. & Winter, D. M. How scalable is sustainable intensification? *Nat. Plants* **2,** 16065 (2016).
12. Sanchez, P. A. En route to plentiful food production in Africa. *Nat. Plants* **1,** 14014 (2015).
13. Dixon, J., Gulliver, A. & Gibbon, D. *Farming Systems and Poverty (*FAO, 2001).
14. Pretty, J. Agricultural sustainability: concepts, principles and evidence. *Phil. Trans. R. Soc. B* **363,** 447–465 (2008).
15. Denning, G. *et al.* Input subsidies to improve smallholder maize productivity in Malawi: toward an african green revolution. *PLoS Biol.* **7,** e1000023 (2009).
16. IFA. IFADATA http://ifadata.fertilizer.org/ucSearch.aspx (International Fertilizer Industry Association, 2011).
17. Zhang, X. *et al.* Managing nitrogen for sustainable development. *Nature* **528,** 51–59 (2015).
18. Guo, J. H. *et al.* Significant acidification in major Chinese croplands. *Science* **327,** 1008–1010 (2010).
19. Diaz, R. J. & Rosenberg, R. Spreading dead zones and consequences for marine ecosystems. *Science* **321,** 926–929 (2008).
20. Zhang, W. *et al.* Closing yield gaps in China by empowering smallholder farmers. *Nature* **537,** 671–674 (2016).
21. Searchinger, T. *et al.* The great balancing act. Installment 1 of creating a sustainable food future. *World Resources Institute* http://www.worldresourcesreport.org (2013).
22. Zhang, F., Chen, X. & Vitousek, P. Chinese agriculture: an experiment for the world. *Nature* **497,** 33–35 (2013).
23. FAO. FAOSTAT. *Statistics Division of the Food and Agriculture Organization of the United Nations* http://www.fao.org/faostat/en/#home (FAO, 2016).
24. Spielman, D. J., Byerlee, D., Alemu, D. & Kelemework, D. Policies to promote cereal intensification in Ethiopia: the search for appropriate public and private roles. *Food Policy* **35,** 185–194 (2010).
25. Matson, P., Clark, W. C. & Andersson, K. *Pursuing Sustainability: a Guide to the Science and Practice* (Princeton Univ. Press, 2016).
26. Zhao, P. F. *et al.* Training and organization programs increases maize yield and nitrogen-use efficiency in smallholder agriculture in China. *Agron. J.* **108,** 1944–1950 (2016).
27. National Bureau of Statistics of China. *China Statistical Yearbook* (China Statistics Press, 2016).
28. IFAD & UNEP. *Smallholders, Food Security and the Environment* (International Fund for Agricultural Development, 2013).

Supplementary Information is available in the online version of the paper.

Acknowledgements We acknowledge all those who provided local assistance or technical help during the national campaign. We also thank J. D. Toth at the University of Pennsylvania for editing assistance. This work was financially supported by the Chinese National Basic Research Program (2015CB150400), the Innovative Group Grant from the NSFC (31421092), the Special Fund for Agro-scientific Research in the Public Interest (201103003), and National Natural Science Foundation—Outstanding Youth Foundation (31522050).

Author Contributions F.Z., X.C. and Z.C. designed the research and F.Z. supervised the project. Z.C., H.Z., G.M., Y.M., X.L., W.M., Q.G., J.Y., Z.W., Y. Ye, S.G., J.L., J.H., S. Lv, Y.S., Y.L., X.P., J.R., S. Li, X.D., X.S., Qia.Z., Z.Y., L.T., C.W., L.J., J.Z., M.H., Y.T., Q.T., X.Z., Z.L., N.C., C.K. and M.F. were key players as regional coordinators or group leaders for the field trials and national campaign; W.M., C.H., C.Z., W.Z., H.Y., Y. Yin, R.J., X.J. and Qin.Z. collected and analysed the data. Z.C., F.Z. and Z.D. wrote the manuscript.

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Reviewer Information *Nature* thanks N. Mueller, D. Powlson, J. Reganold and L. Samberg for their contribution to the peer review of this work.

METHODS

The scope of the work reported here consists of three components: (i) field trials conducted across major agroecological zones to develop locally applicable ISSM-based recommendations; (ii) a 10-year national campaign to promote wide adoption of the enhanced management practices; and (iii) results extracted from a large-scale survey to examine, through scenario analyses, the potential impacts on grain output and environmental footprint of implementing ISSM-based technologies in the entire production systems of rice, wheat and maize in China.

The agroecological zones for maize, rice and wheat. Cereal crops are cultivated across China from frigid to subtropical and from arid to semi-arid and humid regions. On the basis of climatic conditions, geographical location and cropping systems (for example, crop type, rotation, rainfed or irrigation), we categorized the production systems into four agroecological zones for each crop. These are northeast, central, northwest and south China for maize; north, Yangtze River Basin, southeast and southwest for rice; and north, central, Yangtze River Basin and southwest for wheat. More details regarding the climate and cropping system in these zones are shown in Extended Data Fig. 1 and described in the Supplementary Information.

Field trials. A total of 13,123 site years of field trials were conducted from 2005 to 2015 for the three crops ($n = 6,089$ for maize, 3,300 for rice and 3,734 for wheat), with sites spread across all agroecological zones (Extended Data Fig. 1). A network of collaborators chose relevant locations/sites then solicited farmer participants based on willingness, field size, labour availability, land tenure, and so on. Each field trial included two types of management: conventional farmers' practice (control) and ISSM-based recommendations (treatment; developed specifically for a given area). The recommended practices were discussed with local experts and participating farmers. Adjustments were made when necessary. Finally, the agreed-upon management technologies were implemented in the fields by the farmer; the collaborators provided guidance on-site during key operations, such as sowing, fertilization, irrigation and harvest. Campaign collaborators recorded fertilizer rate, pesticide and energy use, and calculated nutrient application rate. At maturity, grain yield and aboveground biomass were sampled by the collaborators for plots with a size of $6\,m^2$ for wheat and rice, and $10\,m^2$ for maize. Plant samples were dried at 70 °C in a forced-draft oven to constant weight, and grain yield was standardized at 14% moisture for all crops.

National campaign. The campaign was initiated as a national 'high yield high efficiency' (double high) umbrella project, funded via several grants (see Acknowledgements) by government agencies, for example, the Ministry of Agriculture and the Ministry of Science and Technology. The campaign was led by a group of scientists at the China Agricultural University. The core network consisted of 1,152 scientists and graduate students from 33 agricultural universities or research academies, typically at the provincial or regional level. They developed ISSM-based recommendations through field trials (see 'Field trials'), then trained extension agents ($n = 65,420$; mostly county or township agricultural technicians supported by the government) as well as private sector personnel (seed and fertilizer sales representatives, $n = 44,580$; dealers, $n = 93,950$). The extension agents received basic training from campaign collaborators and worked with farmers to promote the adoption of ISSM-based technologies. The private sector personnel participated mainly by providing farmers with the needed supplies such as specific maize cultivars or fertilizer blends based on ISSM recommendations.

Outreach activities. A variety of methods were used to disseminate ISSM-based recommendations to the farming communities. Main mechanisms included the following: (i) workshops to discuss details of ISSM-based recommendations, with (already) participating farmers sharing their experience and outcomes; (ii) on-site guidance was provided in a timely manner when needed; (iii) high-quality production materials, for example, seeds, fertilizers and other agricultural chemicals, were uniformly supplied to some sites; (iv) field day and harvest time meetings were organized to demonstrate the outcomes of the advanced management technologies; (v) ISSM-based recommendations were printed and distributed free to extension personnel and farming households, such as leaflets and customized calendars. Industry investments in advertising also communicated information about key products and practices. During the campaign, about 14,000 training workshops, 21,000 field days, and more than 6,000 site demonstrations were organized by campaign staff; more than 337,000 pamphlets were distributed.

Engaging farmers and changing behaviour. Our experience and approaches in persuading farmers to change their conventional practices can be summarized into the following aspects. First, participatory innovation is an essential step to initiate changes at any a given site. Scientifically sound and evidence-based management practices must be effectively communicated to farmers; often some modifications were made to address the specific needs of the local communities. Participatory innovation is attained through dialogues and close interactions between campaign collaborators and farmers, frequently involving local extension agents as well. These processes have been described in a previous study[20]. Second, enabling leading farmers to lead, the followers will follow. Lead farmers are those who have good farming skills and are open-minded to new ideas. They are recognized by fellow villagers as the smart and successful individuals whose actions inspire others. Lead farmers are active players in the participatory innovation processes during our campaign, providing inputs and feedbacks. They were the early adopters of the advanced management technologies. They influenced others by example, and helped during field days or site demonstrations by answering questions and explaining to fellow farmers what practices they adopted, why, and the attained or expected benefits. This is important, because sometimes information-driven outreach activities organized by campaign personnel, for example, training workshops or distribution of printed materials, may have limited impact on some farmers who were simply uninterested in learning the information per se. However, these farmers were willing to follow the steps of successful (lead) farmers. Third, changing behaviour requires building trust, which takes time and effort. For example, when starting at a new site/location, we were often asked by farmers whether we were trying to sell them something (seeds or fertilizers). Once we gained a solid foothold with demonstrated greater yield and less fertilizer use, typically in the fields of leading farmers, and with no hidden agenda, they became willing participants.

It is worth noting that farmers are not blindly following the recommendations of the scientists. Instead, they do perform, in their own way, the act of balancing potential benefits against risks as well as conforming to farming reality (for example, many farmers are only temporarily returning from their cash-earning jobs in the city to carry out tasks of agricultural operations). A recent publication[20] includes detailed information on specific concerns related to farmers' risk-aversion; certain compromises had to be made between farmers and the researchers involving plant density, fertilization frequency (number of split applications) and nutrient sourcing (inorganic versus organic fertilizers).

During the campaign, we also encountered barriers and experienced challenges. For example, we observed that some farmers appeared indifferent during some outreach events. We later learned that it was mainly, because they could not comprehend the scientific content that we were trying to deliver. We solved the problem by having local (county or township) agents acting as an on-site 'interpreter' in ways that speaks/connects with those farmers. Furthermore, not all recommended practices were uniformly adopted by all participating farmers. One particular challenge was rural labour shortage, because those that are young and able-bodied have gone to take city jobs[29]. This made some of the recommended best nutrient management practices (for example, in-season fertilizer applications) difficult to implement. It is also worth noting that the interests of agribusinesses do not always align with those of our campaign staff. For example, one of our main strategies used in the campaign was to select a site (for example, a village) for a given area, establish the base with field demonstrations of ISSM-based practices, then attract and engage more farmers from the same as well as neighbouring villages, creating a snowballing and lasting effect. But sometimes, our partners in the private sector were more interested in changing sites so as to reach more farmer-clients. Vigorous debates and discussion ensued. Eventually, the private sector personnel conformed to our reasoned schemes while using the established sites as demonstrations for visitors from other areas. Notably, we have not encountered nor received negative feedbacks regarding risks projected onto farmers due to agribusinesses involvement in the high yield high efficiency project. Farmers are not obliged to purchase seeds or other production inputs from designated suppliers, although oftentimes they opt to do so for the benefit of group discount. Furthermore, those suppliers are typically large and reputable enterprises that are interested in doing long-term business.

Data collection. Farmers conducted all field operations. Campaign collaborators and/or extension agents were responsible for information and data collection. Typically, 10–30 farmers were randomly selected per ISSM-adopting site; another group of randomly selected 10–30 farmers from a nearby village without ISSM intervention served as a control/comparison. From the selected pool of farmers (roughly 14,600 paired data points), information on key management practices were obtained through a questionnaire survey, including crop varieties, planting densities, planting dates, fertilizer rates and harvest dates. For some sites, grain yields were directly measured in the same way as the field trials (see 'Field trials') for the selected 10–30 farmers. Yield and nitrogen rate were then averaged for each site.

Campaign cost. Direct costs, including the numerous field trials for developing locally applicable ISSM-based recommendations, approximated 350 million RMB in total (equivalent to US$54 million), funded through various grants (see Acknowledgements). We do not have data on indirect expenditure through, for example, local governments that cost-shared with farmer groups that needed to purchase necessary equipment or agribusinesses that sponsored outreach activities[20]. Direct profit, calculated from increased grain output and reduced nitrogen fertilizer use, was US$12.2 billion (Table 1), which does not include relevant environmental benefits associated with reductions in reactive nitrogen losses and in GHG emissions. On the basis of the rough estimates, the cost:benefit ratio would be 1:226. Note that campaign expenditure was primarily operational. In some cases, participating farmers were paid a small fee for their services. Campaign collaborators, extension staff and agribusiness personnel engaged in the campaign were not compensated for their time or efforts. Their participation in and contribution to the achievement of the campaign stem from a combination of professional duty (it is their job) and personal enthusiasm, as the campaign provided a platform for inspired individuals who desired to make a difference. This is particularly so with extension staff, who were reinvigorated through their participation in and contribution to the campaign, coupled with purposeful professional engagement and campaign outcomes. Estimated person-hours devoted to the campaign are 200–300 per year for campaign collaborators, 250–400 for extension agents and 150–250 for private sector personnel.

Calculation of reactive nitrogen losses. To obtain relevant nitrogen loss parameters, we conducted an exhaustive literature search of peer-reviewed publications using ISI-Web of Science (Thomson Reuters) and the China Knowledge Resource Integrated (CNKI) database. The literature search focused on field measurements of nitrogen losses, including NH_3 volatilization, NO_3^- leaching, N_2O emissions and nitrogen runoff in all major Chinese agricultural regions. All nitrogen losses had to have been measured both during field operations and throughout the entire growing season. The NH_3 volatilization had to have been measured within at least two weeks after nitrogen fertilization[30]. The N_2O emissions had to have been measured daily using the static chamber technique for 7–10 days after nitrogen fertilization and for 3–10 days after other events that may have triggered N_2O gas emissions, such as rainfall, irrigation or tillage, as well as weekly or biweekly during the remaining periods[31]. Nitrogen leaching had to have been measured using the suction cup or lysimeter method[32] or the soil sample method[33].

The final dataset consisted of 462 published references and 3,374 observations (see Supplementary Information for references). All analysed data were from the main agroecological zones. For data limitation, we combined northeast and northwest zones together as north China for reactive nitrogen loss calculations for the maize system, southeast and southwest zones together as south China for rice, and Yangtze River and southwest zones together as south China for wheat (Extended Data Figs 2–5). Across all zones and crops, the N_2O emissions, NO_3^- leaching, and nitrogen runoff (only paddy rice) increased exponentially with increasing nitrogen rate, whereas the relationship between NH_3 volatilization and nitrogen rate followed a linear model. The coefficient of nitrogen losses in response to nitrogen rate varied across the three zones and three crops, depending on climatic conditions, terrain, agricultural management practices (for example, with and without irrigation, cropping system) and soil types (Extended Data Figs 2–5, see Supplementary Information).

Using the exponential or linear models depicting the relationships between nitrogen losses and nitrogen rate (Extended Data Figs 2–5), we calculated N_2O emissions, NO_3^- leaching, nitrogen runoff and NH_3 volatilization relevant to ISSM interventions compared to control on the basis respective nitrogen rates. Total reactive nitrogen loss is reported as the sum of N_2O emissions, NO_3^- leaching, nitrogen runoff and NH_3 volatilization, expressed as kg reactive nitrogen per ha as well as yield-scaled reactive nitrogen loss (kg reactive nitrogen per Mg of grain produced).

Calculation of GHG emissions. The GHG emissions from the whole life cycle of crop production included CO_2, CH_4 and N_2O[34]. The emissions consisted of three components[6]: those occurring after the application of nitrogen fertilizers, including direct and indirect N_2O emissions; those occurring during fertilizer manufacturing and transportation; and those from diesel fuel use in farming operations, such as sowing, tillage and harvesting. Indirect N_2O emissions after the application of nitrogen fertilizers were estimated through two indirect pathways via the volatilization of compounds, such as NH_3 and NO_x, with subsequent re-deposition downwind and N_2O emission there, and through leaching and runoff and subsequent N_2O emission downstream[35,36].

We also conducted an exhaustive literature search of peer-reviewed publications for relevant CH_4 emission parameters in the rice system using ISI-Web of Science and the CNKI database. The final dataset consisted of 85 published references and 464 observations according to the following criteria: the CH_4 emission data had to have been measured under field conditions, the measurement data had to have been conducted over an entire growth period of rice. For the rice system, the CO_2 equivalent of the CH_4 emission factor was 137 and 114 kg CH_4 ha^{-1} for single-cropped rice in south and north China, respectively, and 212 kg CH_4 ha^{-1} for double-cropped rice in south China. The 100-year global warming potential of CH_4 and N_2O were 25 and 298 times the intensity of CO_2 on a mass basis, respectively. In our work, soil CO_2 flux was not included because of data limitation and lower impacts on a global scale[36]. We calculated the climate footprint, expressed as kg CO_2 equivalent per ha, and as kg CO_2 equivalent per Mg grain.

Survey of prevailing farmer practices. To better understand what was happening in the Chinese agricultural landscape regarding productivity, resource management and various practices, a nationwide farmer survey was carried out during 2005–2014. A total of 1,944 counties were included, encompassing 66.4 million ha, which accounted for 73% of the total acreage planted for the three grains nationwide[27]. In each county, 3–10 villages were selected; in each village, 30–120 farmers were randomly chosen as survey targets. The grand total of survey recipients, 8,630,079 individual farmers, included 2,891,694 farmers of maize, 3,505,004 farmers of rice and 2,233,381 farmers of wheat. The survey was conducted via face-to-face interviews by local (county and/or township) agricultural extension agents. The questionnaire was prescribed with non-open ended questions encompassing a variety of variables covering yield, crop varieties and fertilization practices (application rate, timing, product type, and so on). Only the yields and nitrogen rate data were extracted in the present study for the scenario analysis described below.

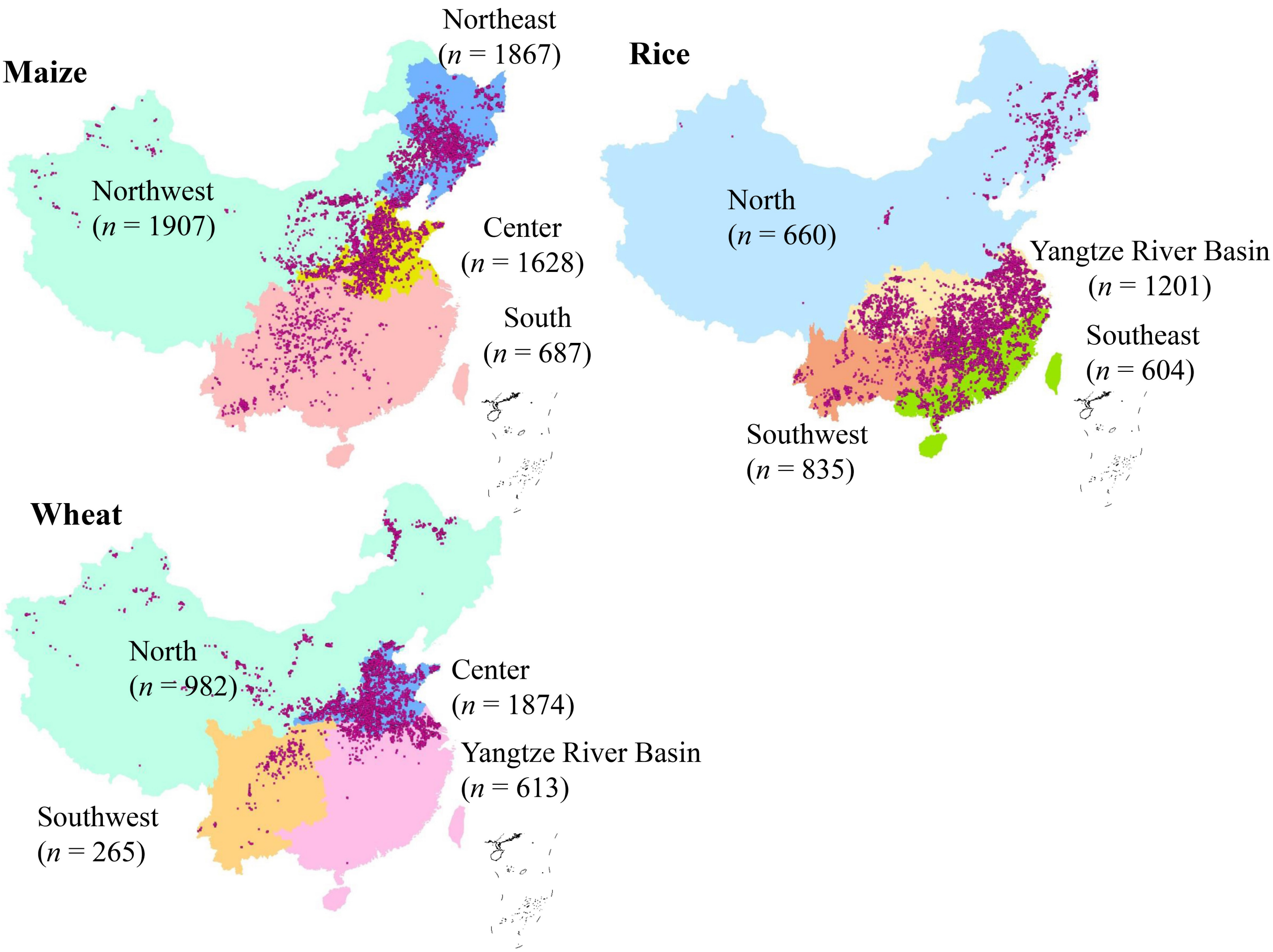
Scenario analysis. Considering the large variation in yield and nitrogen rate in the agroecological zones, we separately examined counties in their respective zones. For each crop zone, counties were grouped based on zone-average yield and nitrogen rate into high yield and high nitrogen, high yield and low nitrogen, low yield and low nitrogen, and low yield and high nitrogen (Extended Data Tables 2–4).

Scenario 1: counties with low yields and high nitrogen rates attain the benchmark (that is, ISSM-based yield and nitrogen rate). Scenario 2: counties with low yields and high nitrogen rates, and counties with low yields and low nitrogen rates achieve the benchmark. Scenario 3: counties with low yield and high nitrogen rates, low yields and low nitrogen rates, and high yields and high nitrogen rates attain the benchmark. The benchmarks were based on results from the field trials in the respective zones.

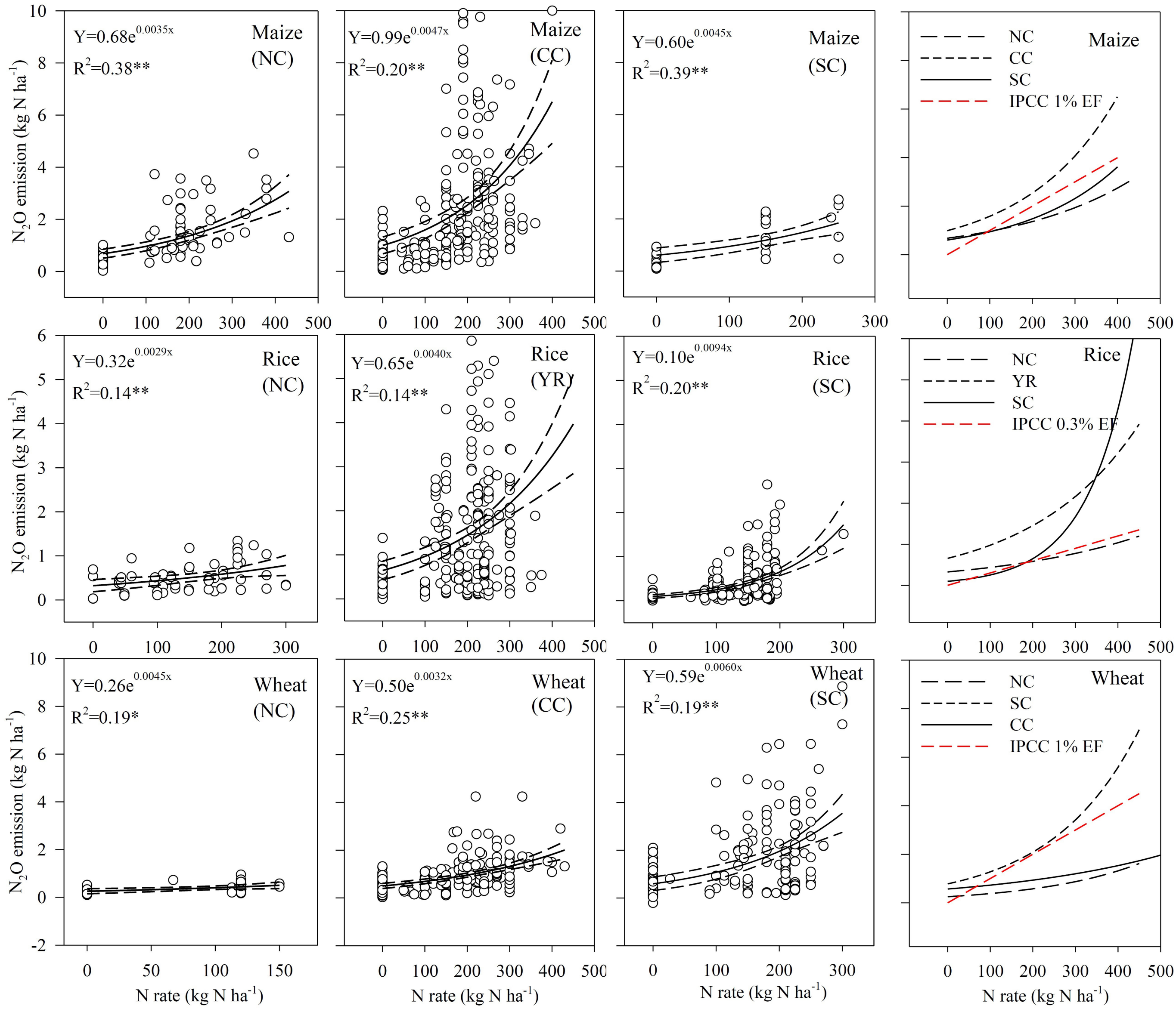
Data management. Raw data for the field trials (13,123 site years) and for the national campaign (37.7 million ha-years) were obtained and maintained by the network of campaign collaborators. At the same time, the raw data were reported to the head group at China Agricultural University, the campaign's lead institution, and entered into a database. The head group maintained the database and conducted summary analyses annually, which were provided to the funding agencies as well as campaign collaborators for feedback. For the current report of the 10-year span, all data analyses were performed at the China Agricultural University using the database. Data from the 13,123 site-year field trials were pooled; data analysis compared two treatments: ISSM-based intervention versus farmers' practices. Treatment effects were evaluated by one-way analysis of variance (ANOVA) using the Statistical Analysis System[37]. Following F-tests in ANOVA, comparisons of means ($P < 0.05$) were made with a Fisher's protected least significant difference (LSD) test. For the national campaign, area-weighted means of crop yield, nitrogen rate, nitrogen productivity, reactive nitrogen losses, GHG emissions and the net economic gain were based on the data from the 14,600 paired sample pools.

Data availability. All data are available from the corresponding authors upon reasonable request.

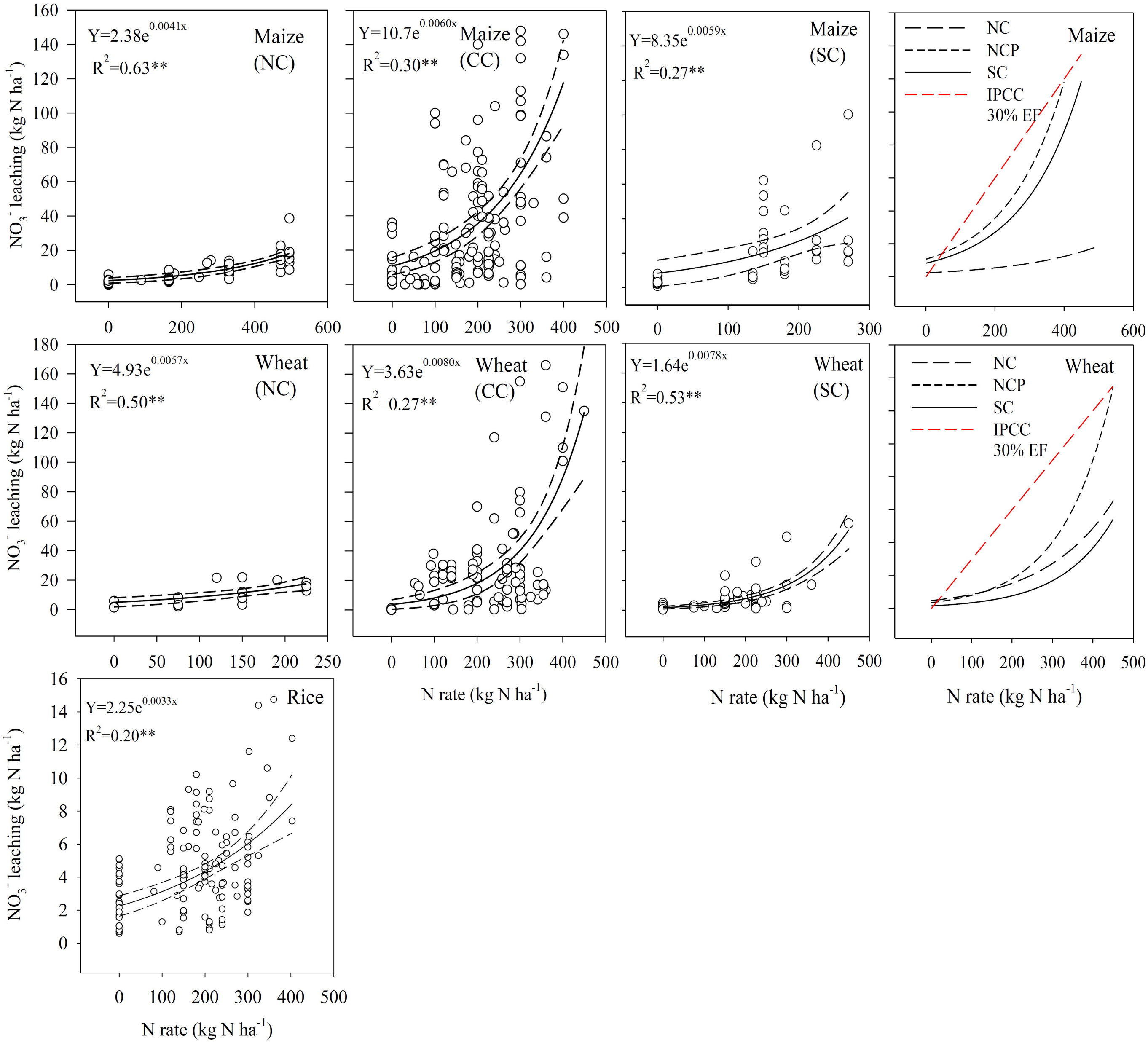
29. Li, Q., Huang, J. K., Luo, R. F. & Liu, C. F. China's labor transition and the future of China's rural wages and employment. *China World Econ.* **21,** 4–24 (2013).
30. Braschkat, J., Mannheim, T., Horlacher, D. & Marschner, H. Measurement of ammonia emissions after liquid manure application: I. Construction of a wind tunnel system for measurements under field conditions. *Z. Pflanz. Bodenkunde* **156,** 393–396 (1993).
31. Holland, E. *et al.* in *Standard Soil Methods for Long-Term Ecological Research* (eds Robertson, G. P. *et al.*), 185–201 (Oxford Univ. Press, 1999).
32. Lehmann, J. & Schroth, G. in *Trees, Crops and Soil Fertility — Concepts and Research Methods* (eds Schroth, G. & Sinclair, F.) Ch. 7 151–165 (CAB International, 2003).
33. Zhao, R., Chen, X. & Zhang, F. Nitrogen cycling and balance in winter-wheat–summer-maize rotation system in Northern China. *Acta Pedol. Sin. (In Chinese)* **46,** 684–697 (2009).
34. Audsley, E. *et al.* Harmonisation of environmental life cycle assessment for agriculture. Final Report. Concerted Action MR3-CT94-2028. Silsoe Research Institute, Silsoe, UK (1997).
35. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories* (eds Eggelston, S. *et al.*) (Cambridge Univ. Press, 2006).
36. Smith, P. *et al.* in *Climate Change 2007: Mitigation of Climate Change* (eds Metz, B. *et al.*) (Cambridge Univ. Press, 2007).
37. SAS Institute. SAS User's Guide: Statistics (SAS Institute, 1998).



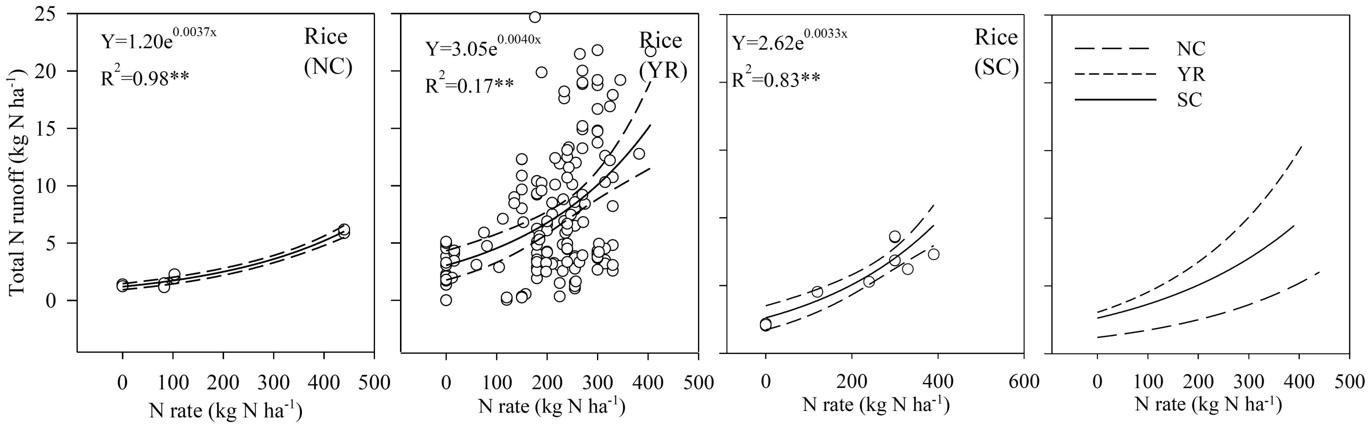
Extended Data Figure 1 | Distribution of field trials for maize, rice and wheat systems from 2005 to 2015 in China. The four coloured regions represent different agroecological zones for maize, rice and wheat. Numbers in brackets are site years. Dots denote individual sites. The Chinese map was obtained from the Resource and Environment Data Cloud Platform (http://www.resdc.cn/data.aspx?DATAID=202).



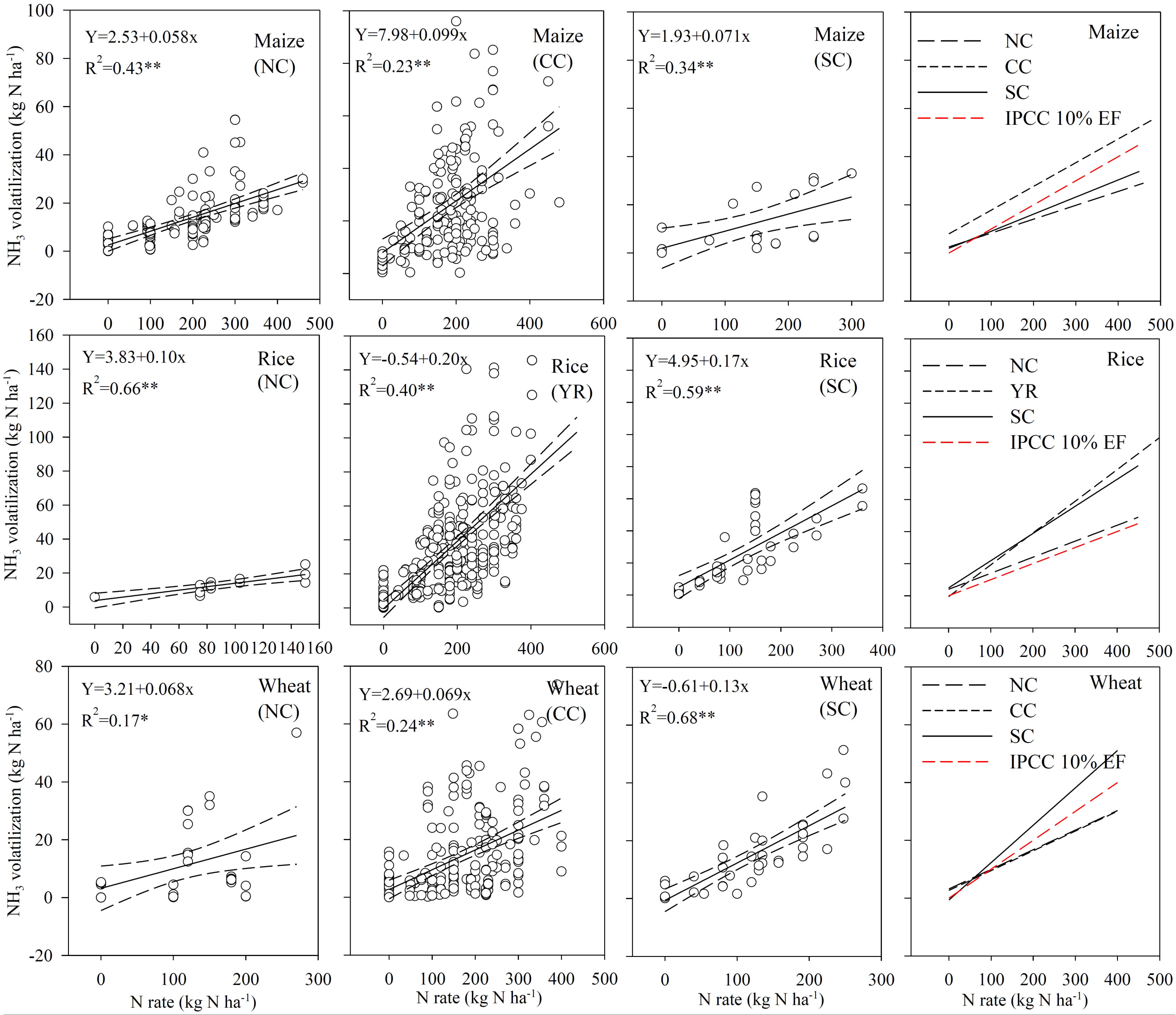
Extended Data Figure 2 | Exponential models describing the relationship between N_2O emissions and nitrogen rate. N_2O–N emissions were plotted against nitrogen rate for maize ($n = 417$), rice ($n = 740$) and wheat ($n = 395$). Red dotted lines are IPCC model-based calculations[35]. NC, CC and SC refer to north China, central China and south China, respectively, for maize and wheat production; NC-R, YR-R and SC-R refer to north China, Yangtze River Basin and south China, respectively, for rice production. $**P < 0.01$ and $*P < 0.05$ indicate the significance of the regression.



Extended Data Figure 3 | Exponential models describing the relationship between NO_3^- leaching and nitrogen rate. The NO_3^- leaching was plotted against nitrogen rate for maize ($n = 238$), rice ($n = 150$) and wheat ($n = 201$). The red dotted line is the IPCC model-based calculation[35]. NC, CC and SC refer to north China, central China and south China, respectively, for maize and wheat production. $^{**}P < 0.01$ indicates the significance of the regression.



Extended Data Figure 4 | Exponential models describing the relationship between nitrogen runoff and nitrogen rate for rice ($n = 216$). NC, YR and SC refer to north China, Yangtze River Basin and south China, respectively, for rice production.



Extended Data Figure 5 | Linear models describing the relationship between NH_3 volatilization and nitrogen rate. NH_3–N volatilization was plotted against nitrogen rate for maize ($n = 315$), rice ($n = 423$) and wheat ($n = 279$) growing seasons, respectively. The red dotted line is the IPCC model[35]. NC, CC and SC refer to north China, central China and south China, respectively, for maize and wheat production; NC, YR and SC refer to north China, Yangtze River Basin and south China, respectively, for rice production. $^{**}P < 0.01$.

Extended Data Table 1 | Conventional farmers' practice compared to ISSM-based recommendations for maize, rice or wheat in different agroecological zones

Region	Crops	Irrigation	Current practice	Critical points of ISSM-based recommendations
Northeast	Maize	Rainfed	Overuse N rate One-time fertilizer application Shallow tillage and poor planting Unsuitable variety Low density	Optimizing N with180~200 kg N ha^{-1} Split before planting and around 6~8-leaf stage Deep tillage and improved planting High yielding variety with resistance to high density and disease Plant density in range of 6.5~7.0 plants m^{-2}
	Rice	Irrigation	Overuse N rate Too much in the early stage Poor planting quality with high seed Low density and more seeding per hole Unsuitable long-term flooding	Reducing N application rate by 20% Increasing the ratio of N application in the late growing season Reducing planting seed rate around 20% Increasing density by 20% and less seeding per hole by 30% Alternate wetting and moderate drying irrigation
Northwest	Maize	Rainfed	Low rainfall with water stress Unsuitable planting date and variety Low density	Increasing soil water retention capacity, and part of film mulching Optimizing sowing date and suitable variety Increased density with 4.8 to 8.5 plants m^{-2}
	Wheat	Rainfed	Low precipitation Low soil fertility Overuse N fertilizer Poor tillage and planting Unsuitable sowing rate and date	Increasing soil water retention capacity Straw return and applied organic manure Reduced N fertilizer application rate by 20% Deep tillage and improved planting Optimal sowing rate and date
Center	Maize	Irrigation	Unsuitable varieties Low density Overuse N and one-time use Harvest early	High-yielding varieties with resistance to high density and disease Increased density with 7.5 to 8.5 plants m^{-2} Optimal N rate and split in 6-leaf stage Harvest later by 5-7 days
	Wheat	Irrigation	Unsuitable sowing, early or late Shallow tillage and poor sowing quality Overuse N before planting Early side dressing in regreening stage Overuse and misused water management	Optimizing sowing date Improved sowing quality with deep tillage Optimal N application rate and 60% of total N use in shooting stage Optimal water management with rate, time, method
Yangtze River Basin	Rice	Irrigation	Overuse N and high use before planting Poor seeding quality Low density Unsuitable long-term flooding	Reduced N use before planting and increased N use in late season Improved seeding quality (reduce seed rate, control soil moisture, transplant seedlings in due time) Increased density Alternate wetting and moderate drying irrigation
	Wheat	Rainfed	Overuse N and high proportion applied in the early growing season Unsuitable sowing early or late Poor sowing quality with shallow tillage Hand broadcasting	Optimal N rate and high use in the mid-late season Suitable seeds sown at suitable time Improved sowing quality with deep tillage Mechanical sowing
South China	Rice	Rainfed	Low density by hand Overuse N and misuse PK fertilizer One-time fertilizer application Poor water and pest management	Increased density with 18-22 hole per m^2 by machine Optimizing N and increased P and K use Split N fertilizer with 30-40% at sidedressing Improve water and pest management
	Maize	Rainfed	Low density with 3.7-4.5 plants m^{-2} Overuse N rate and high N losses Low soil fertility P and Zn deficiency	Increased density with 5-6 per m^2 Optimal N rate with split N fertilization Increased soil fertility with organic manure Added P and Zn use before planting

Extended Data Table 2 | Maize yield, nitrogen rate, nitrogen productivity, reactive nitrogen losses and GHG emissions

Item	Planting area	Grain yield	N rate	N productivity	Nr losses	GHG emission
	Million ha	Mg ha^{-1}	kg ha^{-1}	kg kg^{-1}	kg ha^{-1}	kg CO_2 eq ha^{-1}
Northeast						
HH	3.16	9.63	217	45	22.4	3023
(*n* = 58)		(8.5-10.9)	(180-306)	(31-58)	(19-31)	(2611-4031)
HL	0.0352	9.15	147	66	16.6	2258
(*n* = 17)		(8.6-9.9)	(90-179)	(48-104)	(12-19)	(1639-2583)
LL	2.839	7.29	132	60	15.4	2088
(*n* = 51)		(3.7-8.3)	(45-179)	(23-183)	(8-19)	(1137-2653)
LH	1.355	8.03	206	40	21.5	2909
(*n* = 29)		(7.3-8.5)	(180-371)	(22-46)	(19-37)	(2595-5011)
Center China						
HH	2.419	7.93	257	31	88.9	4374
(*n* = 101)		(7.3-9.5)	(212-468)	(17-41)	(70-240)	(3577-9289)
HL	2.350	8.02	168 (101-211)	50	56.8	2964
(*n* = 110)		(7.2-11.4)		(35-103)	(39-70)	(2033-3611)
LL	1.859	6.41	174	38	58.2	3038
(*n* = 102)		(3.0-7.2)	(70-212)	(24-80)	(33-70)	(1670-3662)
LH	1.907	6.47	256	26	87.9	4344
(*n* = 92)		(4.6-7.2)	(212-382)	(12-33)	(70-158)	(3580-7019)
Northwest						
HH	1.512	10.41	293	37	29.7	3967
(*n* = 102)		(8.3-15.2)	(218-510)	(22-59)	(22-55)	(3035-4850)
HL	0.805	9.83	170	61	18.4	2533
(*n* = 57)		(8.4-13.8)	(81-217)	(40-104)	(11-22)	(1604-3073)
LL	2.391	6.62	156	45	17.3	2369
(*n* = 136)		(3.0-8.2)	(57-217)	(25-113)	(10-22)	(1346-3057)
LH	0.893	6.97	273	26	27.6	3695
(*n* = 62)		(3.6-8.3)	(220-474)	(14-34)	(23-50)	(3048-6331)
South China						
HH	1.353	6.97	268	27	66	3886
(*n* = 121)		(6.7-10.7)	(208-582)	(11-48)	(47-310)	(3034-10273)
HL	0.704	6.87	171	41	38.6	2619
(*n* = 112)		(6.1-9.4)	(84-206)	(31-82)	(22-46)	(1607-3049)
LL	1.252	5.27	162	34	36.7	2484
(*n* = 164)		(3.2-6.1)	(79-207)	(19-67)	(22-46)	(1536-3024)
LH	0.991	5.44	252	22	59.9	3633
(*n* = 92)		(4.2-6.1)	(208-371)	(12-29)	(47-106)	(3033-5589)

Four categories are included: high yield and high nitrogen (HH), high yield and low nitrogen (HL), low yield and low nitrogen (LL), and low yield and high nitrogen (LH) (see Methods). Nr, reactive nitrogen. The values are means and ranges.

Extended Data Table 3 | Rice yield, nitrogen rate, nitrogen productivity, reactive nitrogen losses and GHG emissions

Item	Planting area	Grain yield	N rate	N productivity	Nr losses	GHG emission
	Million ha	Mg ha^{-1}	kg ha^{-1}	kg kg^{-1}	kg ha^{-1}	Kg CO_2 eq ha^{-1}
North						
HH	0.621	9.09	256	37	38.6	6557
(*n* = 52)		(8.3-10.7)	(188-525)	(17-48)	(30-79)	(5885-9487)
HL	0.541	8.97	143	66	24.3	5440
(*n* = 27)		(8.3-10.5)	(74-185)	(47-122)	(12-19)	(4717-5841)
LL	1.361	7.55	130	63	22.8	5322
(*n* = 63)		(6.0-8.3)	(35-185)	(42-171)	(12-29)	(4400-5836)
LH	0.143	7.45	238	33	36.2	6368
(*n* = 23)		(5.5-8.2)	(189-406)	(17-42)	(30-59)	(5910-7993)
Yangtze River						
HH	2.768	8.36	270	32	71.2	8183
(*n* = 110)		(7.5-9.7)	(189-426)	(19-47)	(50-115)	(7151-10523)
HL	2.566	8.03	154	53	41.9	6730
(*n* = 106)		(7.5-9.1)	(98-188)	(41-79)	(29-50)	(6063-7168)
LL	4.330	6.78	148	47	40.6	6666
(*n* = 182)		(2.9-7.5)	(50-188)	(16-142)	(18-50)	(5550-7136)
LH	1.119	6.92	227	32	60.4	7649
(*n* = 48)		(5.7-7.5)	(189-512)	(14-39)	(50-144)	(7148-11922)
Southeast						
HH	1.483	7.21	203	36	49.9	9102
(*n* = 672)		(6.6-10.7)	(169-367)	(20-52)	(43-87)	(8658-11830)
HL	2.089	7.07	146	50	38.154	8411
(*n* = 76)		(6.6-7.9)	(60-168)	(40-111)	(21-43)	(7462-8689)
LL	2.029	6.03	147	42	38.2	8419
(*n* = 78)		(4.9-6.6)	(84-168)	(30-76)	(26-43)	(7725-8682)
LH	1.021	6.07	189	32	46.8	8916
(*n* = 52)		(4.9-6.6)	(169-236)	(21-38)	(43-57)	(8646-9476)
Southwest						
HH	0.257	8.34	225	38	54.4	9362
(*n* = 48)		(7.3-10.5)	(180-304)	(27-46)	(45-72)	(8699-10525)
HL	0.521	8.07	144	58	37.7	8373
(*n* = 46)		(7.3-9.8)	(69-176)	(45-120)	(23-44)	(7599-8754)
LL	0.717	6.42	144	46	37.6	8364
(*n* = 64)		(4.8-7.3)	(63-176)	(32-114)	(22-44)	(7483-8764)
LH	0.424	6.45	222	30	53.7	9319
(*n* = 40)		(4.6-7.3)	(180-348)	(17-39)	(45-82)	(8728-11392)

Four categories are included: high yield and high nitrogen, high yield and low nitrogen, low yield and low nitrogen, and low yield and high nitrogen (see Methods). The values are means and ranges.

Extended Data Table 4 | Wheat yield, nitrogen rate, nitrogen productivity, reactive nitrogen losses and GHG emissions

Item	Planting area	Grain yield	N rate	N productivity	Nr losses	GHG emission
	Million ha	Mg ha^{-1}	kg ha^{-1}	kg kg^{-1}	kg ha^{-1}	Kg CO_2 eq ha^{-1}
North						
HH	1.000	6.17	264	25	47.1	3275
(*n* = 103)		(4.7-12.1)	(172-534)	(11-45)	(29-146)	(2235-6826)
HL	0.443	5.68	132	46	23.3	1850
(*n* = 39)		(4.7-7.6)	(65-171)	(29-93)	(15-28)	(1194-2228)
LL	1.568	3.11	99	40	19.3	1508
(*n* = 122)		(1.0-4.6)	(14-169)	(12-122)	(10-28)	(664-2211)
LH	0.205	4.06	214	19	35.6	2696
(*n* = 19)		(2.8-4.5)	(172-279)	(13-26)	(29-47)	(2232-3599)
Yangtze River						
HH	1.540	5.73	219	27	39.9	3499
(*n* = 66)		(4.7-7.2)	(171-405)	(16-41)	(30-97)	(2735-7370)
HL	0.541	5.74	137	45	23.4	2304
(*n* = 31)		(4.8-9.3)	(50-166)	(29-121)	(9-28)	(1319-2735)
LL	0.615	3.39	128	28	21.9	2168
(*n* = 71)		(1.2-4.6)	(45-169)	(15-58)	(8-29)	(1167-2687)
LH	0.145	3.88	223	18	40.8	3567
(*n* = 18)		(1.9-4.6)	(173-346)	(5-25)	(30-73)	(2745-5778)
Center China						
HH	3.565	7.09	269	27	55.6	4195
(*n* = 119)		(6.5-8.6)	(222-465)	(20-52)	(40-187)	(3630-6769)
HL	3.538	7.01	187	39	33.2	3288
(*n* = 87)		(6.5-10.9)	(91-222)	(30-120)	(17-40)	(2202-3679)
LL	2.517	5.44	166	34	29.3	3063
(*n* = 94)		(2.4-6.4)	(56-221)	(18-81)	(13-40)	(1887-3662)
LH	1.518	5.95	268	23	56.0	4172
(*n* = 59)		(3.5-6.4)	(223-495)	(13-28)	(41-229)	(3679-7341)
Southwest						
HH	0.376	4.58	174	27	30.3	2788
(*n* = 56)		(3.5-7.6)	(139-251)	(16-55)	(24-46)	(2303-3957)
HL	0.439	4.43	117	40	19.9	2020
(*n* = 45)		(3.6-6.6)	(35-138)	(27-120)	(7-23)	(1070-2321)
LL	0.526	2.71	971	33	16.6	1766
(*n* = 80)		(1.1-3.5)	(19-138)	(11-130)	(4-23)	(852-2238)
LH	0.054	2.78	194	15	36.3	3174
(*n* = 41)		(1.4-3.5)	(140-516)	(6-25)	(24-171)	(2256-11502)

Four categories are included: high yield and high nitrogen, high yield and low nitrogen, low yield and low nitrogen, and low yield and high nitrogen (see Methods). The values are means and ranges.

Extended Data Table 5 | Area-weighted yield, nitrogen rate, total amounts of grain output, nitrogen fertilizer use, reactive nitrogen losses, and GHG emissions with scenario analysis using a 3-step progression, compared to prevailing practices, that is, business as usual

Item	unit	BAU	S1	S2	S3
Yield	$Mg\ ha^{-1}$	6.98	7.28 (104%)	8.05 (115%)	8.23 (118%)
N rate	$kg\ N\ ha^{-1}$	195	186 (96%)	197 (102%)	177 (91%)
Crop production	Mt	464	483 (104%)	534 (115%)	546 (118)
N use	Mt	12.9	12.4 (96%)	13.1 (102%)	11.8 (91%)
Nr losses	Mt	2.79	2.64 (94%)	2.70 (99%)	2.35 (84%)
GHG emission	Mt	307	299 (97%)	304 (99%)	284 (92%)

Business as usual (BAU) practices were calculated using county averages from the farmers' surveys and planting acreage from national statistical data. Scenario 1 (S1): counties in the low yield and high nitrogen category (see Methods, Extended Data Tables 2–4) attaining ISSM-based yield and nitrogen rate. Scenario 2 (S2): counties in low yield and low nitrogen category, in addition to those in S1; Scenario 3 (S3): counties in high yield and high nitrogen category plus those in S2. Values in parentheses indicate relevant scenario outcomes as a percentage of BAU.