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Extended reference list for establishing the reactive N loss models for maize, wheat, and rice systems (including 462 published references with 3,374 observations, references 1–462), and relevant CH_4 emission parameters for rice systems (including 85 published references with 464 observations, references 101, 103, 105, 139–141, 142–157, 159–175, 183–207, 210–211,230–233, 326, 412, 463–475).

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Supplementary Discussion: Description of China's agroecological zones for maize, rice and wheat

Maize. In China, maize is cultivated across the nation, including Northeast, Center, Northwest and South China [1]. The Northeast China zone is located between 40–55°N and 110–135°E, and has a warm–temperate, frigid–humid, or sub–humid continental monsoon climate with warm, wet summers and long, cold winters. In most parts, single–cropped maize grows in rainfed conditions; the average maize cycle is 130–150 days. Average annual precipitation varies from 400 to 700 mm. The Center China zone is located between 32–41°N and 113–120°E and has a warm, semi–humid continental monsoon climate, where maize grows in rainfed conditions. The maize is often directly sowed after winter wheat in a double cropping system. The maize cycle is 100–115 days, and average annual precipitation varies from 500 to 800 mm.

The Northwest China zone is located between 34–40°N and 95–115°E. It has an arid and semi–arid continental monsoon climate with a cold winter and dry, warm summer. The single–cropped maize is grown in rainfed conditions in part of the area, and under irrigation in mid–temperate and warm–temperate sections. The Southwest zone is located between 21–34°N and 97–112°E. It has a humid or sub–humid, subtropical climate, with moist, hot summers and cold winters. The most notable type of terrain consists of plains in part of the area, and hills, mountains and highlands in other areas.

Rice. The North China zone is located between 38°45’–53°27’N and 121°40’E–131°01’E, and has a frigid–humid, or sub–humid climate with warm, wet summers and long, cold winters. Annual precipitation varies from 400–1000 mm. The Yangtze River Basin zone is located between 27°20’–34°55’N and 102°19’E–122°17’E and has a warm, humid subtropical monsoon climate. In the upper Yangtze River, rice is typically planted in early April and harvested in late August, with 800–1600 mm precipitation during the rice–growing period. The middle Yangtze River has a humid warm monsoon climate with 900–1500 mm of rain during the rice–growing period, allowing either a single rice crop from early May to late September or two rice crops from early April to mid–October. In the lower Yangtze River, rice is grown from June to October in a paddy–upland rotation, with 700–1300 mm precipitation during the rice–growing period [2].

The Southeast China zone is located between 18°18’–29°41’N and 106°36’E–122°16’E. It has a subtropical to tropical monsoon climate with cool, dry winters and hot, humid summers. Annual precipitation varies from 800–2000 mm, allowing a single rice crop from early May to late September or two rice crops from mid–March to late October [2]. The Southwest zone is located between 18°12’–29°43’N and 97°39’E–112°01’E. It has a humid, subtropical monsoon climate, with hot, humid summers and cool, dry winters. A single crop of rice is planted in late May and harvested in late September, with 500–800 mm precipitation during the rice–growing period [2].

Wheat. The wheat cultivation zone includes Northeast, Center, Northwest, the Yangtze River basin, and Southwest China. The Northeast China zone has a continental monsoon climate. The average annual precipitation is about 400–800 mm, with 60% of the precipitation occurring during June to August. The average precipitation is 200–300 mm during the wheat–growing period, allowing a single wheat crop. Soil types include chernozem, chestnut, meadow, swampy, and cinnamon soils. The Northwest China zone is situated in the warm temperate zone of the monsoon area, and has a continental monsoon climate. Annual precipitation varies from 200–700 mm, with most of the precipitation occurring during July to September. A single crop of wheat is planted in this region.

The Center China zone for wheat is the same as Center China of maize, and has a continental monsoon climate. Annual precipitation varies from 500–950 mm, with about 60% of the precipitation occurring from July to September. Wheat is planted after maize in early October and harvested in mid–June. Soil types include brown, cinnamon, moisture, solonchak, shajiang black, and sandy soils. The Yangtze River basin has a northern subtropical monsoon climate. Annual precipitation varies from 830–1870 mm, allowing either two or three crops a year. Wheat–rice is the primary crop rotation scheme used in this region. The Southwest China zone has a subtropical humid monsoon. The average precipitation is about 800–1100 mm, allowing either a single or double rice crop per year.

Supplementary Discussion: Reduction in N rate was not uniform in China

In our present study, reductions in N application rate were 14.1% (195 vs. 227 kg N ha^{-1}), 8.5% (from 158 vs. 173 kg N ha^{-1}) and 15.6% (181 vs. 215 kg N ha^{-1}) for maize, rice and wheat, comparing the treatment vs. control (Fig. 1; Extended Data Table 2–4). Similar reduction in N rate was also observed during the national campaign (covering 37.7 million ha). A large number of early studies reported that the average N application rate in China exceeded the maximum N requirement for Chinese crop production [3, 4]. However, N application rate varied with famers in different zones, and some low income farmers or those in remote areas have deficient N application rates. In 13,123 field trial site–years, not all farmers reduced N use, and N application rates were increased or maintained (± 1 kg N ha^{-1}) by 29% and 5% of all farmers, respectively.

With our scenario analysis (Extended Data Fig. 8 and Tables 6–8), the farmers in the low yield–low N category covered 29% of the entire survey area, cultivating 19.7 million ha. Except for some production constraints, N deficiency places important limits on achieving high yield. In the scenario analysis, N applications in the low yield–low N category averaged 151, 145 and 138 kg N ha^{-1}, which are 22%, 13% and 25% lower than the ISSM–based N rate from the national campaign for maize, rice and wheat, respectively. As a result, grain yield in these counties was substantially (27%, 22% and 39%) lower than ISSM–based yield for the three grains. In the future, higher crop yields are likely to be achieved through a combination of increased N application in regions with low N fertilizer use, and improved nitrogen use efficiency in regions where N fertilizer use is already high [5–7].

Supplementary Discussion: Examples of dissemination of ISSM–based recommendations across different zones

The dissemination of ISSM–based recommendations varied regionally and were very much dependent on mitigating factors such as farm size, technological, intellectual, or socioeconomic factors. In Lishu County (Northeastern China) with relatively large–scale farming operations (often 1–2 ha per household), the government and scientists together organized farmer yield contests, trained lead farmers and hosted large–scale farm demonstration projects with seed and chemical companies (e.g. fertilizers and pesticides), which increased maize yields by 23%, compared to local farmers. Participation in large–scale demonstration events has increased farmers' communication and negotiation skills, increasing farm income and providing beneficial services such as high prices for grain and low price of better–quality fertilizer. These sociocultural strengths have built trust among extension alliances, and promoted them to adopt the ISSM practices.

In Quzhou County, for wheat–maize double–crop systems in the Center China, with 0.3–0.5 ha per household and fields worked only by older men and women, scientists formulated and demonstrated NPK fertilizer use with the cooperation of agricultural chemical companies, and the government allocated a subsidy to service the main management practices (e.g. $2,000,000 for deep–plough acquisition by farmer cooperatives). These combined actions increased yield by 32% and 24% across the whole county (2009–2013) for maize and wheat systems, respectively [8]. In Jiangjin County with rice cultivation in South China, with remote mountainous terrain and lack of mechanization, farmers integrated machine transplanting (purchasing machines using government subsidies) and formulated NPK fertilizer with industry assistance, which increased yield by 28% in 2010 [9].

Supplementary Discussion: Public and private partnership are pulled closer to area farmers with cooperative, collaborative, and improved support services

In most smallholder regions, agricultural extension is still considered to be a "government responsibility," and is the primary channel for technology transfer. Governmental extension programs have unique strengths. Government extension specialists have access to university research before it is published, which allows for rapid sharing of new methods or technologies [10]. They also have access to a local network of county or regional Extension offices, with coverage that reaches into all areas within a province (or county). In China, a series of national programs have been initiated for scientists to collaborate across disciplines and to accelerate extension of ISSM practices. For example, based on success of demonstrating ISSM concepts and related research, the Chinese Ministry of Agriculture initiated a national Soil–Testing and Fertilizer Recommendation Program to optimize fertilizer management. They covered all agricultural counties with total funding of nearly 6 billion yuan until 2010

($923 million) (http://www.farmer.com.cn/xwpd/tjyd/201205/t20120521_718544.htm). In 2015, the Ministry of Agriculture formally announced a "Zero Increase Action Plan" for national fertilizer use by 2020. This plan requires that the annual increase in total fertilizer use will be less than 1% from 2015 to 2019, with no further increase after 2020. This plan was strongly supported by research–based ISSM recommendations, showing that it is possible to produce more grain with more efficient use of fertilizer inputs and less environmental costs. In our present study, government agricultural extension is still is the primary channel for technology dissemination (Fig. 2). Combining national programs and research projects, a rapid increase extended the area employing ISSM recommendations, with 3.08 million ha per year (total 30.8 million ha–yrs) coming on board since 2006. Aggregated data showed an average yield enhancement with ISSM–based management practices, of 11–12% and an N rate reduction of 15–17%, compared to prevailing farmer practices (Table 1).

Recently, the private sector has promoted the deployment of ISSM–based recommendations using their extensive network of regional employees and industry investment in advertising [10]. Optimal nutrient management practices, the key of ISSM, have been designed for specialized fertilizer with cooperation by private sector firms (e.g. chemical fertilizer companies). Sales representatives and retail dealers, who are trained in local ISSM management practices, can cultivate close ties with local farmers and other agricultural professionals. In addition, private companies devote significant resources toward market research to understand their customers' (e.g., farmers') needs, resulting in development of novel ISSM practices and products. Feedback from marketers often promote the capability to create new technological products (such as slow/controlled–release fertilizers, and integration of water into fertilizer management). Importantly, these firms recover the cost of technology transfer and production inputs at the time the commodity is sold, thus ensuring the economic sustainability of this alternative technology transfer system.

Since 2011, the private sector had extended ISSM practices to 6.1 million ha–yrs. The yield improvement from the three crops has been slightly lower than values from government–extended systems, with 11–12% vs 8–10 %, although reduction in N application rates has been substantial (by 12–20%). In the future, promoting the role of the private sector in technology transfer activities should be a central component of a government's agricultural development policy. Synergistic public–private extension efforts could ensure that farmers receive the most current and balanced information available to help with their management decisions [10].

Supplementary Discussion: Reactive N losses for different crops and zones in China

Estimating all of the various Nr losses (NH_3 volatilization, NO_3^- leaching, run–off and N_2O emission) were developed for a large–scale area using empirical models [11,12]. Our early studies have established empirical Nr loss models based on N surplus in China [13]. In addition to N rate or N surplus, however, Nr losses also depend on specific local conditions and other management practices; together these include topography, soil type, climate, application method, and fertilizer type [14,15]. Here, Nr loss models based primarily on N rate were separated into three zones per crop based on measured in–situ flux data in broad multi–site/year experiments in China (Extended Data Fig. 3–6). Aggregated results showed the N_2O emissions, NO_3^- leaching, and N runoff, defined using data from the literature meta–analysis, increased exponentially with increasing N application rate in the maize, wheat, and rice systems ($P < 0.01$; Extended Data Fig. 3–5). In contrast, NH_3 volatilization increased linearly with increasing N application rate ($P < 0.01$; Extended Data Fig. 6).

NO_3^- leaching and runoff. NO_3^- leaching was the largest pathway of environmental N losses for the major cereal crops, followed by NH_3 volatilization and N_2O emission. NO_3^- leaching from maize following N fertilization was in the order: summer maize in Center China (CC) > maize in South China (SC) > spring maize in North China (NC). In the wheat system, the order was: winter wheat in CC > spring wheat in NC ＞winter wheat in SC (Extended Data Fig. 5–6). A further effect of excessive N application was the loss of NO_3–N by leaching, which was aggravated through the common practice of flood irrigation as well as the monsoon–influenced rainfall pattern of the CC [14]. In the wheat−maize system in the CC, NO_3–N accumulation in the soil profile and gradual leaching below the root zone were the important N loss pathways under conventional agricultural N management practices because of concentrated rainfall in the summer and flood irrigation [16]. The average annual precipitation was 697 mm in CC, with most (60–75%) of the precipitation occurring in the summer months (June through August), which coincides with maize growth. In the rice system, a hardpan formed below the plow layer after the paddy soil had been plowed, due to clay deposition and low redox status, and this appeared to reduce NO_3^- leaching from the rice crop [16,17]. The N runoff from rice following N fertilization was in the order: single cropping rice in the Yangtze River Basin (YR) > double cropping rice in South China (SC) > single cropping rice in NC. N runoff is affected both by rainfall characteristics, soil characteristics, and topographic features [18, 19], and higher N runoff occurred in the heavy rainfall zones of YR and SC.

NH_3 volatilization. In China, summer maize in CC had the highest NH_3 volatilization, followed by maize in SC and spring maize in NC. Winter wheat in CC and SC had the highest NH_3 volatilization, followed by spring wheat in NC. Similarly, single cropping rice in YR and double cropping rice in SC were the highest, followed by single cropping rice in NC (Extended Data Fig. 7). The results were similar to Gu *et al* [20,21], who noted that the CC and SC zones have high NH_3 volatilization because of high precipitation and temperature. In a previous study evaluating an irrigated wheat–maize rotation system in central China, high NH_3 volatilization was attributed to the high pH (around 8) of calcareous soils, together with the surface broadcasting of urea before either irrigation or rainfall [14]. In rice systems, the traditional practice of applying urea to the soil surface has resulted in high NH_3 volatilization [11, 22].

N_2O emission. The calculated N_2O emission from maize systems following N fertilization was in the order: summer maize in CC > maize in SC > spring maize in NC. In the wheat system, the order was: winter wheat in SC > winter wheat in CC > spring wheat in NC. Similarly, in the rice system, the order was: single cropping rice in YR > double cropping rice in SC > single cropping rice in NC (Extended Data Fig. 3). The result was similar to Lu *et al.* [23], Gu *et al.* [20] and Zhang *et al.* [15], who found agriculture–dominated zones, such as the CC and YR, have higher N_2O emissions than other zones. Such a spatial pattern is affected both by climate, soil features, cropping systems, and human activities. High temperatures and humidity, such as in CC and YR, can enhance the activities of microorganisms (e.g., nitrification and denitrification) that promote biogenic N_2O emission [24]. In the CC, irrigation during the upland crop season also promotes N_2O emissions [25], particularly irrigation with fertilization [26]. And, dry–wet alteration in the rice paddy is proven to favor nitrification and denitrification processes where rice–based cropping systems alternate with a rice–upland crop rotation [27,28]. Meanwhile, human activities in CC and YR increase chemical N inputs that can also enhance the activities of microorganisms [29,30].

Compared to IPCC models. Here, we compare modeled estimates derived from measurements in three zones and three crops in China, with the IPCC model (N_2O emission, NO_3^- leaching and NH_3 volatilization comprised 1% (0.3% for paddy rice), 30% and 10% of total N applied, respectively) [31]. Aggregated results showed the IPCC method based on a fixed proportion of applied N inputs overestimates N_2O and

NO_3^- leaching for three crops, N_2O emission for maize and wheat, and NH_3 volatilization for the rice system. However, the IPCC method underestimates N_2O emissions for the rice system. For 200 kg fertilizer N ha^{-1} scenarios, the N_2O emissions were overestimated by 10%, 41% and 56% for maize, wheat and rice, respectively. And, the N_2O emissions were underestimated by 48% for the rice system. Similarly, the NO_3^- leaching and runoff were overestimated by 62%, 77% and 85% for maize, wheat and rice, respectively. The NH_3 volatilization, for 200 kg N ha^{-1} scenarios, was 19 and 20 kg N ha^{-1}, for maize and wheat systems, which were similar to 20 kg N ha^{-1} suggested by the IPCC. The NH_3 volatilization in the rice system was underestimated by 70% with IPCC methodology [31].

Supplementary Discussion: Sustaining campaign outcomes

We anticipate that major campaign outcomes (enhanced yield, reduced N rate, lower GHG emissions) will be sustained for years to come, based on the following considerations. First, the self-sustaining factor – greater harvest with less input expenditure – will be the fundamental incentive for farmers to continue the implementation of enhanced management practices. Second, the inspired and dedicated agricultural scientists and extension agents will keep the momentum going forward. Third, improvement in agricultural support services and infrastructure, such as fertilizer products packaged according to soil test results, or new machineries developed to ease the rural labor shortage, will help foster greater adoption of ISSM-based management practices. Fourth, there are strong social and political forces pushing for “green development”. For example, the core principle of China’s agricultural development policies has shifted from the decades-long single goal of “high yield” [32] to new mandates issued by the central government that emphasize double high (high yield and high efficiency). The “zero increase action plan” (referring to zero increase in national fertilizer use by 2020) is an example of the latest move [33]. It is worth noting that the recent environment-strengthening policies are accompanied with concrete measures that are emerging (instead of sitting on the shelf as in some past cases). For example, relevant environmental performance started to be taken into account when government officials are evaluated for promotion [34].

On the other hand, there are uncertainties that may impact the sustainability of campaign outcomes, in one way or another. This is largely related to the changing landscape in rural China, e.g. better-educated young people leaving for cities, resulting in brain drains and eroding the social foundation of the farming communities. In the meanwhile, new land-managing formats are emerging, e.g. various farmer co-operatives [35]. These changes may favor the adoption of advanced agricultural technologies, thus promoting sustainable productivity.

Supplementary Discussion: Potential limitation and unintended consequences

The national campaigns focused on areas where the collective mass of smallholders is relatively concentrated. Remote areas with sparse population or with farming households scattered, typically in mountainous regions with biophysical conditions less favorable for growing maize, rice, or wheat, were ‘left behind’. The selective strategy was mainly for efficient use of resources. However, smallholders 'left behind' may need help the most. Furthermore, in areas affected by the campaigns, participation was not uniform and less than 100%. Some of those who did not participate in the program are most likely in the bracket of 'weak and vulnerable' in their communities, owing to chronic health issues or other constraints or problems. In this sense, the high-yield high-efficiency campaign might be associated with an unintended consequence of expanding the inequality in the rural community.

There are uncertainties that may impact the sustainability of campaign outcomes and/or future intervention efforts, in one way or another. This is largely related to the changing landscape in rural China. First, better-educated young people are leaving rural areas for cities, resulting in brain drains and eroding the social foundation of the farming communities. Second, land use has been changing and new formats are emerging, e.g. land-leasing policies and various farmer co-operatives [35]. The dynamic changes may favor the adoption of advanced agricultural technologies, thus promoting sustainable productivity. On the other hand, they may bring forth unexpected challenges that require innovative technologies and/or management solutions.

Supplementary Discussion: Going forward

To scale up and cover the entire production systems with advanced management practices, what resources would be needed? We estimated that 30,000 agricultural research and service personnel are necessary to cover the 92 million ha of rice, wheat, and maize production zones. This is possible, since there are approximately 716,000 agricultural research and extension personals (2008 data), covering all provinces [36]. Annual operational cost is estimated to be 8.5 billion RMB ($ 1.3 billion equivalent), which is a reasonable sum and a small fraction of the $70 billion annual investment for grain production allocated by the Chinese government (2011 data [37]). Anticipated benefits would be $294billion annually, using the cost/benefit ratio of 1/226. Steadfast and forward-looking policies and sustained efforts with actions are critical for such a scale-up. In addition to the high-yield-high-efficiency policy and project-oriented funding mechanisms, supports with incentive-driven policies and measures at all levels (central, provincial, and local governments and organizations) designed to strengthen relevant human resources (e.g. attracting young intellectuals in agricultural research and services), along with innovative reward systems (e.g. double high instead of simply high yield based subsidy programs) would be essential. Furthermore, a step-wise scale-up strategy would be logical, with priorities given to the improvement in LH (low yield high input) counties/regions first, then LL (low yield low input), and HH (high yield and high input) ones.

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