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Can knowledge-based N management produce more staple grain with lower greenhouse gas emission and reactive nitrogen pollution? A meta-analysis

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Abstract

Knowledge-based nitrogen (N) management, which is designed for a better synchronization of crop N demand with N supply, is critical for global food security and environmental sustainability. Yet, a comprehensive assessment on how these N management practices affect food production, greenhouse gas emission (GHG), and N pollution in China is lacking. We compiled the results of 376 studies (1166 observations) to evaluate the overall effects of seven knowledge-based N management practices on crop productivity, nitrous oxide (N_2O) emission, and major reactive N (Nr) losses (ammonia, NH_3; N leaching and runoff), for staple grain (rice, wheat, and corn) production in China. These practices included the application of controlled-release N fertilizer, nitrification inhibitor (NI) and urease inhibitor (UI), higher splitting frequency of fertilizer N application, lower basal N fertilizer (BF) proportion, deep placement of N fertilizer, and optimal N rate based on soil N test. Our results showed that, compared to traditional N management, these knowledge-based N practices significantly increased grain yields by 1.3–10.0%, which is attributed to the higher aboveground N uptake (5.1–12.1%) and N use efficiency in grain (8.0–48.2%). Moreover, these N management practices overall reduced GHG emission and Nr losses, by 5.4–39.8% for N_2O emission, 30.7–61.5% for NH_3 emission (except for the NI application), 13.6–37.3% for N leaching, and 15.5–45.0% for N runoff. The use of NI increased NH_3 emission by 27.5% (9.0–56.0%), which deserves extra-attention. The cost and benefit analysis indicated that the yield profit of these N management practices exceeded the corresponding input cost, which resulted in a significant increase of the net economic benefit by 2.9–12.6%. These results suggest that knowledge-based N management practice can be considered an effective way to ensure food security and improve environmental sustainability, while increasing economic return.

Keywords: cost and benefit, grain yield, greenhouse gas, knowledge-based N management, reactive N losses

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Introduction

Feeding the increasing population without devastating the environment is challenging (Chen *et al*., 2014). As the largest N fertilizer consumer in the world, China plays a major role in global food security, but simultaneously contributes to global greenhouse gas (GHG) emission and alters the nitrogen (N) cycle (Galloway *et al*., 2008; Oita *et al*., 2016). About 27 Tg of fertilizer N was used annually for food production during 2001–2010 in China, and more than 60% of that was applied for staple grain (rice, wheat, and corn) production (Yan *et al*., 2014; Xia *et al*., 2016). However, around 20–50% of the fertilizer is lost to the environment as GHG (e.g., nitrous oxide, N_2O) and other reactive N species (e.g., ammonia, NH_3; N leaching and runoff). This has created a cascade of environmental problems (e.g., global warming, air pollution, and eutrophication) that threaten ecosystems and human health (Sutton *et al*., 2011; Gu *et al*., 2015). In 2015, the Ministry of Agriculture in China announced a 'Zero Increase Action Plan' for national fertilizer use by 2020, which aimed to reduce the environmental costs associated with food production (Liu *et al*., 2015). This 'Zero Increase' plan highlights the need to adopt reasonable N management to improve the nitrogen use efficiency (NUE), a key step to reduce the unintended climate and environment changes induced by fertilizer N application (Chen *et al*., 2014).

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To produce more grains while minimizing N_2O emission and major Nr losses, knowledge-based N management practices were recommended, such as the use of enhanced efficiency N fertilizers (controlled-release fertilizer, CRF; nitrification inhibitors, NI; urease inhibitors, UI), and optimum N application methods (increasing splitting frequency and deep placement) (Zhang *et al.*, 2011; Cui *et al.*, 2013a; Chen *et al.*, 2014). Knowledge-based N management practices generally improve the NUE by providing better synchronization of crop N demand with N supply and therefore have been adopted for increasing yield while decreasing N_2O emission and other Nr losses (Ju *et al.*, 2009; Zhang *et al.*, 2012). While some knowledge-based N management practices (e.g., NI application) increase yield (Abalos *et al.*, 2014) and reduce one type of N loss (e.g., N_2O emission), they can increase N loss via other pathways (e.g., NH_3 emission) (Lam *et al.*, 2016). Yet, a comprehensive assessment on the agronomic and environmental impacts of these N management practices is lacking.

Some knowledge-based N management practices (e.g., deep placement and NI application) require additional economic input costs (Zhang *et al.*, 2012; Wang *et al.*, 2014). However, few studies have assessed the net economic benefit (NEB, balance between the input cost and yield profit) of the knowledge-based N management practices, which is the important factor for adopting the N practices (Wang *et al.*, 2014; Zhang *et al.*, 2015). We therefore conducted a comprehensive meta-analysis for staple grain (rice, wheat, and corn) production in China and assessed the responses to knowledge-based N management practice of crop productivity (yield; NUE; aboveground N uptake), N_2O emission and major Nr losses (NH_3 emission, N leaching and runoff), and economic indicators (input cost, yield profit, and NEB). We focused on seven knowledge-based N management practices, including the applications of CRF, NI, and UI, increasing splitting frequency of fertilizer N application, lower basal N fertilizer (BF) proportion, deep placement of N fertilizer, and optimal N rate based on soil N test.

Materials and methods

Database compilation

The Web of Science (http://apps.webofknowledge.com/) and China National Knowledge Infrastructure database (http://www.cnki.net/) were employed to search peer-reviewed studies published before March 2016. The following criteria were set for a study to be included in the present analysis. First, only the field, pot, and lysimeter studies on rice, wheat, or corn growth were included. The crop grain had to be harvested and weighted at the physiological mature stage. Second, means and samples size had to be reported with a minimum of three replicates. Third, the application rates of agricultural materials had to be reported, such as fertilizers (N, P, and K) and inhibitors (NI and UI), for the consideration of the cost–benefit analysis. A total of 1166 observations from 376 peer-reviewed studies were included in our analysis (Fig. S1). All studies were divided into three groups:

1. Enhanced efficiency N fertilizers: CRF application (332 observations), and NI (151 observations) and UI application (80 observations). N fertilizer (e.g., urea) application (control) was compared with N fertilizer treated with CRF (NI or UI) application (treatment). The CRF mainly included those coated or encapsulated fertilizers, such as sulfur-coated urea and polymer-coated urea. The NI mainly included dicyandiamide (DCD), 3,4-dimethylpyrazole phosphate (DMPP), and nitrapyrin (CP), while the UI mainly comprised hydroquinone (HQ) and N-(n-butyl) thiophosphoric triamide (NBPT).
2. Optimizing N fertilizer application method, including three aspects: increasing splitting frequency of fertilizer N application (241 observations), reducing BF proportion (92 observations), and employing deep placement (38 observations). Using the method of Huang *et al.* (2016) for N split, N fertilizer treated with a higher splitting frequency was set as the treatment, such as two split applications (treatment) vs. a single application (control). For BF proportion reduction, N fertilizer treated with a traditional proportion of BF (control) was compared with the BF proportion reduction (treatment). The minimum percentage of BF reduction for 'reducing BF proportion' was 10% in this study. For N placement, N fertilizer treated with surface broadcast (control) was compared with deep placement (treatment). The minimum depth of the deep placement of fertilizer N was 5 cm below the soil surface.
3. Optimizing N rate (232 observations). Traditional N application rate (control) was compared with optimal N rate (treatment). The optimal N rate refers to the N application rate determined based on the soil N test, which was calculated by the difference between crop N demand and soil N supply, that is the target crop N demand minus the soil NH_4^+ and NO_3^- present in the root zone (Ju *et al.*, 2009; Huang *et al.*, 2013). On average, the optimal N rate was 28% lower than the traditional N rate of the studies included in this meta-analysis. The optimal rates in some studies were determined based on the recommendation of local agronomists (Cui *et al.*, 2013b; Yao *et al.*, 2013) according to the results of 'National Soil N Tests Project' (Zhang *et al.*, 2012).

Treatment and control in above database, except for the 'optimizing N rate', have identical N application rates. Effects of these knowledge-based N management practices were evaluated by the following three categories with 10 variables, including (1) crop productivity: yield, total aboveground N uptake and NUE; (2) N_2O emission and other major Nr losses (NH_3 emission, N leaching and N runoff); (3) economic indicators: input cost, yield profit, and NEB. The NUE in this study refers to the grain NUE, calculated by dividing the difference in the grain N uptake between the treatments with and without fertilization by fertilizer N rate. In addition, the effects of these practices were categorized, according to crop species (rice, wheat, and corn), soil organic carbon (SOC) content (≤10, 10–20 and ≥20, g kg^{-1}), soil TN content (≤1, 1–2 and ≥2, g kg^{-1}), pH (≤6, 6–8 and ≥8), and N application rate (≤200, 200–300 and ≥300, kg N ha^{-1}). Due to the lack of data, the effects of UI application on N leaching and runoff, reducing BF proportion on N_2O emission and N runoff, and deep placement on N leaching were unable to be assessed in this study.

Meta-analysis

Impacts of knowledge-based N management practices on the values of variables (X_t) were evaluated against their corresponding control (X_c) using the following equation:

$$\ln R = \ln\left(\frac{X_t}{X_c}\right), \tag{1}$$

where ln *R* represents the natural log of response ratio which is the effect size. The results were presented as the percentage changes ((*R*-1)×100) under knowledge-based N management practices. Positive percentage changes denote an increase due to N managements, whereas negative values indicate a decrease in the variables.

Effect sizes were weighted by the inverse of pooled variance (Yang *et al.*, 2016) or replications (Lam *et al.*, 2012) in previous meta-analyses, depending on the integrity of the reported standard deviations in the database. In this study, around 50% studies did not report the standard deviations of the mean values. In addition, extreme weights may be generated by variance-based weighting function but not for replication-based one (Van Groenigen *et al.*, 2011). Therefore, the replication-based weighting was adopted in the analysis using the following equation (Lam *et al.*, 2012):

$$\text{weight} = \frac{n_t \times n_c}{n_t + n_c}, \tag{2}$$

where n_t and n_c represent the numbers of replicates of the treatment and control groups, respectively.

Mean effect sizes and the 95% confidence intervals (CIs) were generated by a bootstrapping procedure with 4999 iterations, using METAWIN 2.1 (Rosenberg *et al.*, 2000). Effects of knowledge-based N management practices were considered significant if the 95% CIs did not overlap with zero. Means of categorical variables were considered significantly different from each other if their 95% CIs did not overlap.

Cost–benefit analysis

To evaluate whether the knowledge-based N management practices are economically viable, a cost–benefit analysis was conducted by incorporating in this analysis the input cost, yield profit, and NEB. Input cost included the cost of agricultural materials (fertilizers, NI, and UI), and labor cost associated with fertilizer application and the management practice (e.g., increasing splitting frequency, deep placement, and soil N test). Yield profit was the gross economic benefit from crop grains. Price of fertilizers and labor cost were listed in the Supporting information (Table S1). The NEB represented the net economic benefit, calculated by subtracting the input cost from the yield profit.

Results

Grain yield

Overall, grain yield was significantly increased by 8.0% for CRF application (Fig. 1a), 10.0% for NI application (Fig. 1b), 7.1% for UI application (Fig. 1c), 5.9% for increasing splitting frequency of fertilizer N

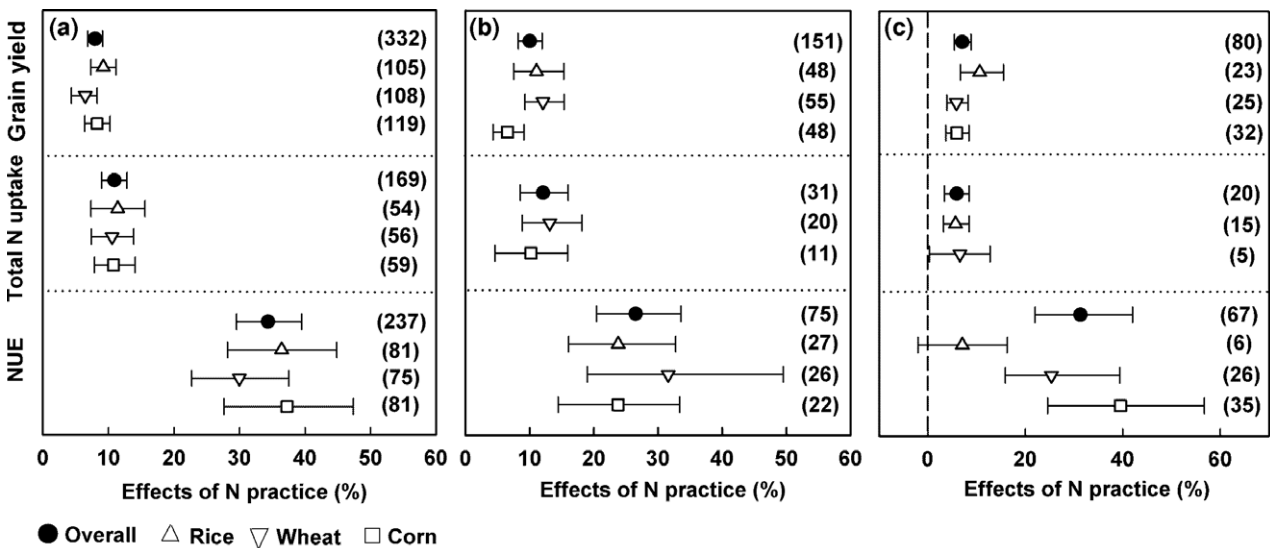

Fig. 1 Changes in grain yield, total aboveground N uptake, and nitrogen use efficiency (NUE) induced by the applications of controlled-release fertilizer (a), nitrification inhibitor (b), and urease inhibitor (c). Numbers of experimental observation are in parentheses.

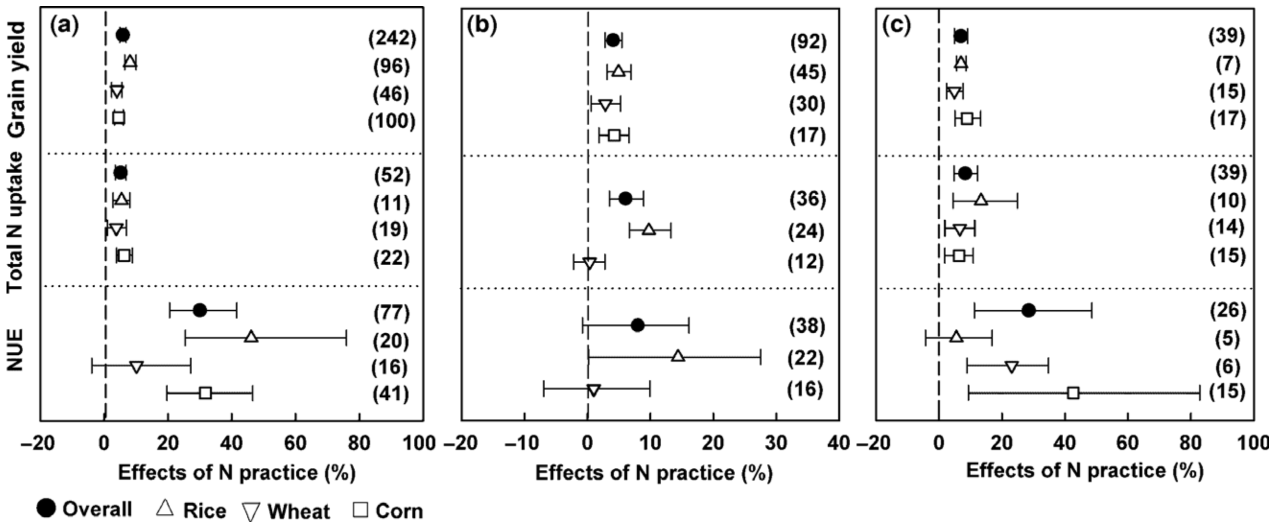

Fig. 2 Changes in grain yield, total aboveground N uptake, and nitrogen use efficiency (NUE) induced by the applications of increasing splitting frequency of fertilizer N application (a), reducing basal N fertilizer proportion (b), and deep placement of N fertilizer (c). Numbers of experimental observation are in parentheses.

application (Fig. 2a), 4.1% for reducing BF proportion (Fig. 2b), 6.9% for deep placement (Fig. 2c), and 1.3% for optimizing N rate (an average N rate reduction of 28%) based on soil N test (Fig. 3a). The effect of NI application on grain yield was stronger in wheat (12.1%) than corn (6.5%) and that of increasing splitting frequency of fertilizer N application was stronger in rice (8.1%) than wheat (4.0%) and corn (4.5%) (Figs 1 and 2). The effect of reduction of BF proportion on grain yield became nonsignificant if the reduction rate was larger than 60% (Table S6). N application rates and soil properties (e.g., SOC, TN, and pH) also changed the yield responses to the knowledge-based N management practices to some extent (Table S10).

Aboveground N uptake and NUE

On average, the aboveground N uptake was significantly reduced by 5.6% when the optimum N rate was used (Fig. 3), but increased by other N management practices, ranging from 5.1% (increasing splitting frequency of fertilizer N application) to 12.1% (NI application) (Figs 1 and 2). The NUE was also significantly improved by employing these N management practices by 26.5% (NI application) to 48.2% (optimizing N rate), except for the practice of reducing BF proportion (Figs 1–3) which led to a nonsignificant increase (8.0%) in NUE (Fig. 2b). Responses of aboveground N uptake and NUE were in general similar for various crops, N application rates, and soil properties (Table S10).

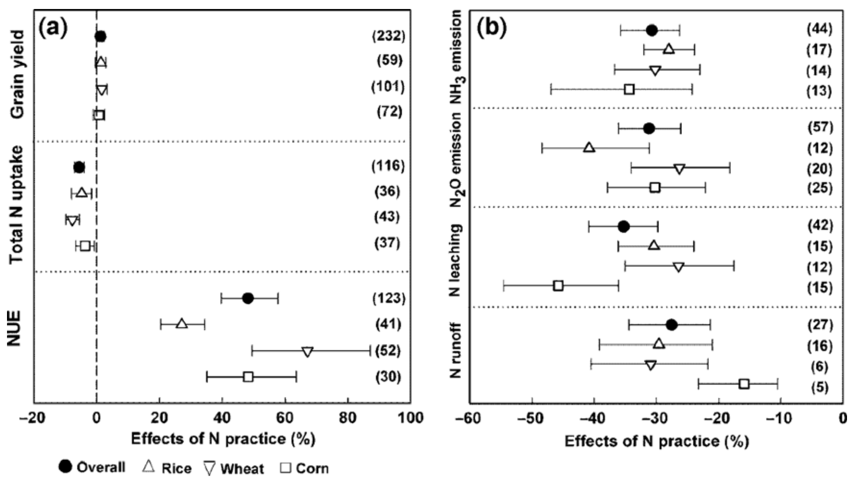

Fig. 3 Changes in grain yield, total aboveground N uptake and nitrogen use efficiency (NUE) (a), and various Nr losses (b) induced by the application of optimizing N rate. Numbers of experimental observation are in parentheses.

NH_3 emission

NI application overall significantly increased NH_3 emission by 27.5% (Fig. 4b), but other knowledge-based N management practices significantly reduced the emission by 30.7% (optimizing N rate) to 61.5% (reducing BF proportion) (Figs 3–5). Applying CRF in rice and corn showed stronger effect on reducing NH_3 emission than wheat (Fig. 4a). The effect of CRF on NH_3 emission also varied significantly with SOC and TN contents, and N application rate (Tables S2 and S10), and that of deep placement on NH_3 emission varied significantly with crops, TN content, and pH (Tables S7 and S10). For other N management practices, similar responses of NH_3 emission were observed for different crops, N rates, and soil properties (Table S10).

N_2O emission

Averaged across all studies, N_2O emission was significantly reduced by 38.3% for CRF application, 39.8% for NI application, 27.8% for UI application, and 31.2% for optimizing N rate (Figs 3–5). Increasing splitting frequency of fertilizer N application and employing deep placement also reduced N_2O emission by 5.4% and 14.6%, respectively, albeit not significantly (Fig. 5). A higher reduction in N_2O emission was observed in rice (50.4%) than corn (25.3%) for CRF application (Fig. 4a), in rice (51.0%) than wheat (31.8%) for NI application (Fig. 4b), and in corn (37.0%) than wheat (11.9%) for UI application (Fig. 4c), and in wheat (20.4%) than rice (4.0%) for higher splitting frequency of fertilizer N application (Fig. 5a). In general, the responses of N_2O emission to these N managements were not affected by soil properties (Table S10).

N leaching and runoff

N leaching was significantly reduced by 17.3% for CRF application, 37.3% for NI application, 24.7% for increasing splitting frequency of fertilizer N application, 13.6% for reducing BF proportion, and 35.3% for optimizing N rate (Figs 3–5). N runoff was also significantly decreased by these N management practices, by 31.7% for CRF application, 45.0% for NI application, 36.5% for increasing splitting frequency of fertilizer N application, 15.5% for deep placement, and 27.6% for optimizing N rate. A higher reduction in N leaching was observed in corn (45.8%) than wheat (26.4%) for optimizing N rate (Fig. 3a), while a stronger reduction in N runoff was shown in rice (45.7%) than wheat (24.5%) for increasing splitting frequency of fertilizer N application (Fig. 5a). Responses of N leaching and runoff were in general similar for different soil properties (Table S10).

Cost–benefit analysis

The input cost was significantly reduced (by 3.2%) when the optimum N rate was used, but was not affected by reducing BF proportion (Table 1). Other N management practices significantly increased the input cost, ranging from 6.4% for CRF application to 21.4% for increasing splitting frequency of fertilizer N

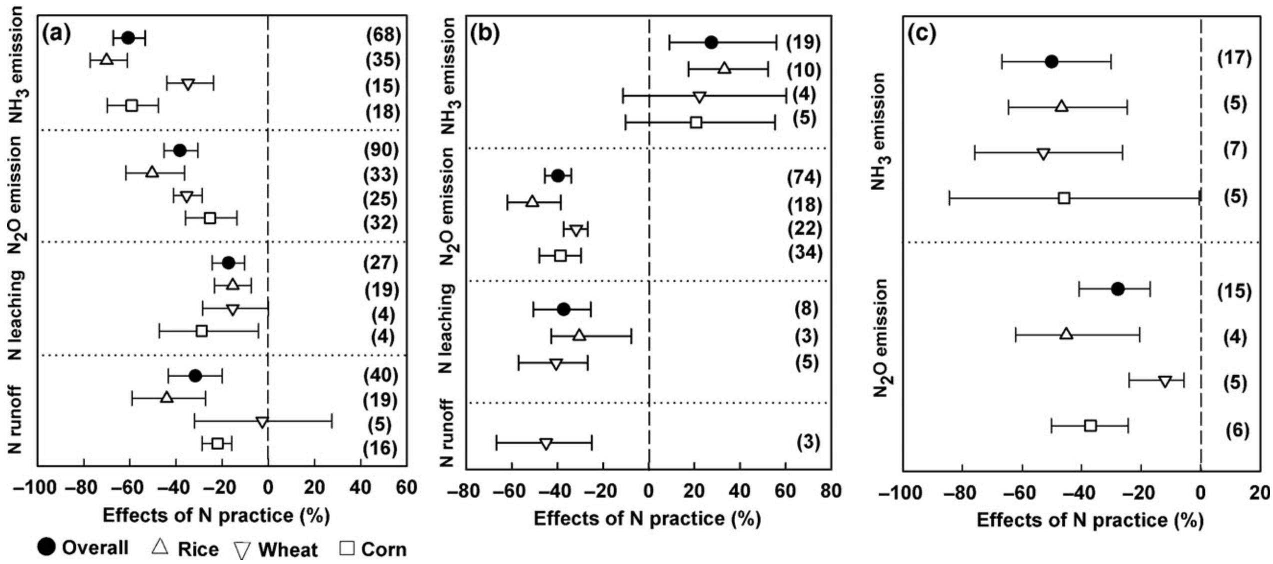

Fig. 4 Changes in various N losses induced by the applications of controlled-release fertilizer (a), nitrification inhibitor (b), and urease inhibitor (c). Numbers of experimental observation are in parentheses.

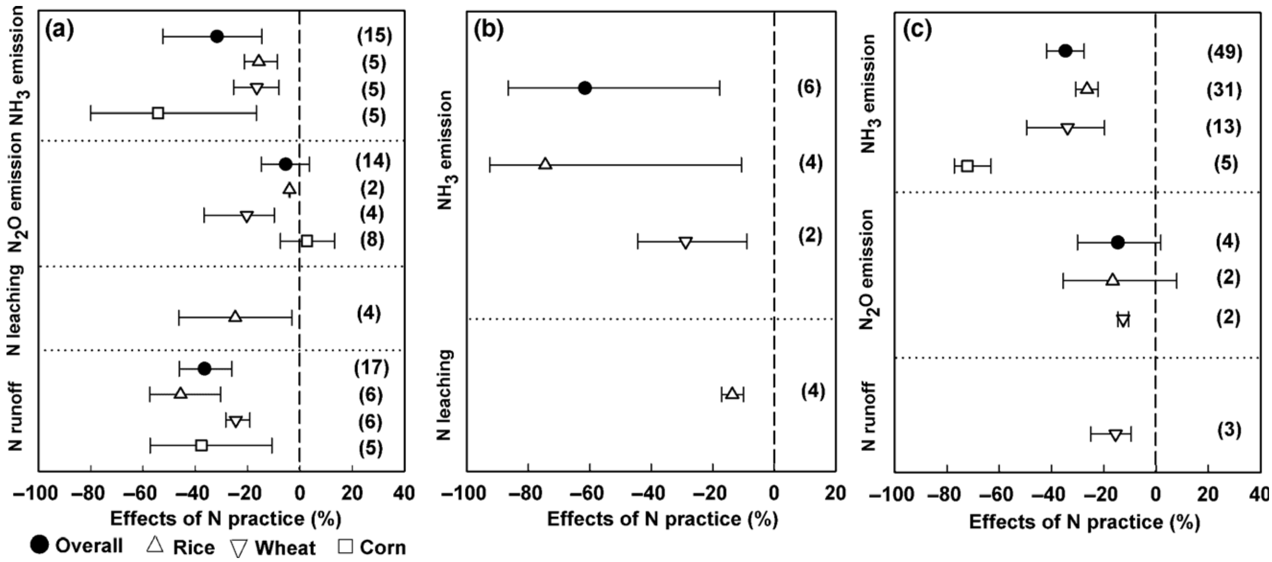

Fig. 5 Changes in various N losses induced by the applications of increasing splitting frequency of fertilizer N application (a), reducing basal N fertilizer proportion (b), and deep placement of N fertilizer (c). Numbers of experimental observation are in parentheses.

application, due to the additional financial cost associated with deep placement, extra topdressing, and the higher price of enhanced efficiency N fertilizers than traditional fertilizers (Table S1). All these N management practices significantly improved the yield profit, ranging from 1.3% (optimizing N rate) to 10.0% (NI application). Likewise, these N management practices significantly increased the NEB by 2.9% for optimizing N rate to 12.6% for NI application.

Discussion

Crop productivity and N loss to environment

The global population is projected to reach 9 billion by 2050, with food demand likely to be doubled (Tilman *et al.*, 2011). Can the increase in food production be achieved on the existing farmland? Based on the meta-analysis of 376 studies, we found that the application of single knowledge-based N management practice significantly increased staple grain production (1.3–10%) in China (Fig. 6). Moreover, applying combination of these N management practices would result in much higher (18–35%) increase in the grain yield, as reported by Chen *et al.* (2014). This increase in yield was largely attributed to greater plant N uptake and higher NUE (Fig. 6), because the knowledge-based N management practice generally resulted in a better synchronization between crop N demand and N supply throughout the crop growing season (Ju *et al.*, 2009; Yang *et al.*, 2012). For instance, a lower BF proportion reduces N rate applied to early growth stage of crop and satisfies the

Table 1 Changes (%) in the input cost, yield profit, and net economic benefit (NEB) induced by the application of knowledge-based N management practices

	Input cost		Yield profit		NEB	
Knowledge-based N practice*	Mean	95% CI	Mean	95% CI	Mean	95% CI
CRF application	6.4	4.9–7.8	7.7	6.5–8.8	7.8	6.3–9.2
NI application	9.8	8.1–11.5	10.0	8.2–12.1	12.6	9.0–17.1
UI application	7.1	5.5–8.7	7.1	5.5–8.9	5.9	2.2–9.3
Increasing splitting frequency	21.4	20.1–22.8	5.8	4.8–6.8	3.6	2.4–4.7
Reducing BF proportion	0	0	4.1	2.7–5.4	5.0	3.5–6.7
Applying deep placement	8.2	7.5–9.0	6.6	4.7–8.9	6.1	3.8–8.6
Optimizing N rate	−3.2†	−(4.6–1.9)	1.3	0.3–2.3	2.9	1.4–4.5

*CRF, controlled-release fertilizer; NI, nitrification inhibitor; UI, urease inhibitor; BF, basal N fertilizer.
†The negative value denotes that optimizing N rate reduced the input cost by 3.2 (95% CI: 1.9–4.6).

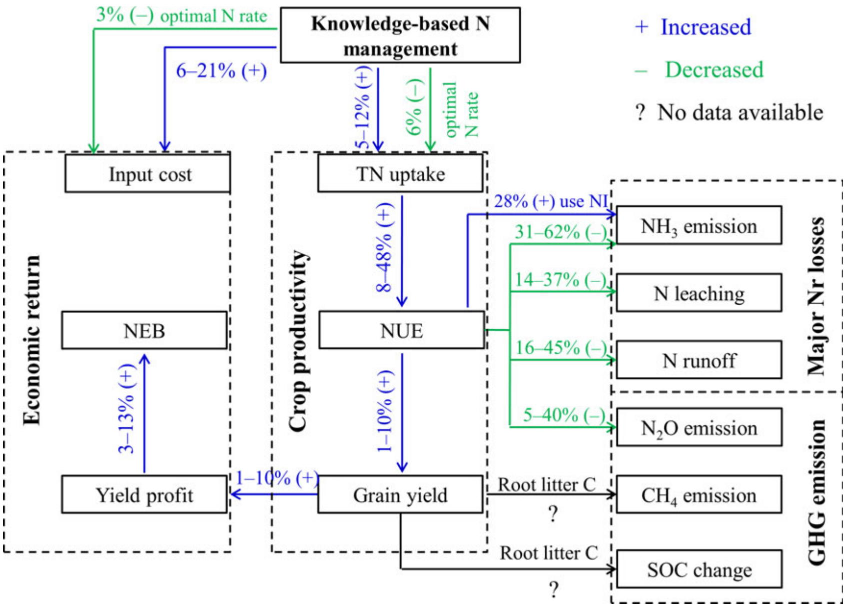

Fig. 6 Effects of knowledge-based N management practices on crop productivity, greenhouse gas (GHG) emission, major Nr losses, and economic return. TN uptake, total aboveground N uptake; NUE, nitrogen use efficiency; NEB, net economic benefit; SOC, soil organic carbon. The percentage closed to the arrow with same color denotes the effect of N management practice on the variable in which the arrow points. The arrows also reflect the reasons that promoted the changes of the variables. [Colour figure can be viewed at wileyonlinelibrary.com].

N requirements for the rapid growth stages (e.g., stem elongation of wheat and expanded leaf stage of maize), thus improving N uptake and NUE (Zhang *et al*., 2012). Nonetheless, there was no significant improvement in grain yield when BF was reduced by more than 60%, which deserves additional attention. This was likely because the insufficient N supply could damage the healthy root growth at the early stage of crop growth (Cui *et al*., 2008).

Because of the traditional belief that higher fertilizer N rates increase yield, farmers often use excessive N fertilizer to pursue high yield profits, particularly in China (Ju *et al*., 2009). However, N losses will be substantial when the availability of N in the soils exceeds crop N demand (Cui *et al*., 2013a). Our study indicated that the use of knowledge-based N management practice largely reduced various N losses while increasing grain yield (Fig. 6). Through better synchronizing crop N demand with N supply (Linquist *et al*., 2013), applying CRF application and optimizing N rate reduced all the N loss pathways targeted in this study (Fig. 6). Through reducing urea hydrolysis (Huang *et al*., 2016), UI application decreased NH_3 emission by 50.0% in this study (Fig. 4c). In contrast to Akiyama *et al*. (2010)'s study, we found that N_2O emission was significantly reduced when UI was applied for staple grain production in China, which is likely due to the difference in the targeted crop species and agricultural systems between these two studies.

Nitrification inhibitors suppress the conversion of NO_3^- from NH_4^+ (Chen *et al*., 2008) and decrease the N_2O emission, N leaching, and runoff (Fig. 4b). However, more NH_4^+ may retain in soils under NI application, which may stimulate NH_3 emission (Lam *et al*., 2016). The increase in NH_3 emission under NI application observed in this study (27.5%) is slightly higher than that reported by others (13–20%) (Qiao *et al*., 2015; Yang *et al*., 2016). Previous studies have demonstrated that the majority of Nr losses (e.g., NH_3 emission, N leaching, and runoff) occurred at the early growth stage of crops when N uptake by roots is limited (Chen *et al*., 2011). Reducing BF proportion and increasing splitting frequency of fertilizer N application avoid over basal N fertilization and increased N uptake along crops growth (Zhang *et al*., 2012), thus reducing NH_3 emission, N leaching, and runoff (Fig. 5a,b). These N losses could also be minimized through the deep placement of N fertilizer (Fig. 5c), which decreases the concentrations of NH_4^+ or NO_3^- in the flooded water (paddy) or surface soils (upland system) (Linquist *et al*., 2013; Xu *et al*., 2013).

Overall, the use of knowledge-based N management practice is effective in decreasing various N losses to the environment while increasing grain yield (Fig. 6). However, it should be noted that soil properties and crop species might affect the responses of yield and N losses to these practices (Table S10). For instance, the effect of increasing splitting frequency of fertilizer N application on grain yield was stronger in rice than wheat and corn (Fig. 2). The effects of enhanced efficiency N fertilizers on N_2O mitigation and grain yield also varied with crop species and certain soil properties (e.g., pH) (Fig. 4 and Table S10). More studies are needed to uncover the underlying mechanisms before applying these N management practices to a large scale.

Implication of the cost-benefit analysis

By taking the costs of various agricultural inputs (e.g., fertilizers and labors) into consideration, we conducted a preliminary assessment of the NEB associated with the application of the knowledge-based N management practices. Although grain yields were significantly enhanced by these N management practices, the input cost increased accordingly (Table 1). In contrast, the input cost of optimizing N rate based on soil N test was lower, because the cost saved from N fertilizer reduction outweighed that associated with the soil N test. Overall, the yield profit exceeded the corresponding input cost and therefore resulted in a significant increase in the NEB (Fig. 6). The NEB would be even greater if the environmental benefits achieved by the reduction of N loss were included in the cost–benefit analysis (Gu *et al*., 2012; Qiao *et al*., 2015).

Despite their positive NEB, these knowledge-based N management practices are not popular in China. Why are these practices not adopted by the Chinese farmers? Most of the farms in China are tiny, making the large-scale mechanization of these N practices impractical (Zhang *et al*., 2013). In addition, farmers often have part-time jobs in urban areas to source additional income (Ju *et al*., 2009). Therefore, in most instances, the opportunity cost (e.g., labor, time, and education/training costs) of implementing these N practices is very high. Farmers are mostly risk-averse when faced with new agricultural management practices (Wang *et al*., 2014), but more importantly, it is the opportunity cost that impedes the popularity of these new N technologies. To change this situation, national subsidy programs should be established to provide an incentive for farmers to gradually adopt these N practices, such as the 'Carbon Farming Initiative' in Australia (Lam *et al*., 2013). Farmers are reluctant to increase the input cost without realizing the effectiveness of the knowledge-based N practices (Wang *et al*., 2014; Xia *et al*., 2014). More demonstration trials should be conducted in the major areas of staple grain production in China (e.g., North China Plain and Taihu Lake region) to convince farmers of the economic viability of these N practices (Zhang *et al*., 2012, 2013).

Extra-attention should be paid on the NI application, because it considerably increased NH_3 emission. Nonetheless, this problem can be likely solved by the combining NI application with other N management practices (e.g., UI application) (Zhang *et al*., 2012). The use of the NI dicyandiamide has been reported to result in the contamination of milk power in New Zealand (Lucas, 2013). Therefore, the effects of NI (UI) application on staple food security in China should also be taken into consideration in future studies. The effects of these N management practices on the global warming potential (an overall consideration of methane emission, N_2O emission and soil organic carbon change) should be fully assessed, but the current assessment was restricted to N_2O emission due to data deficiency (Fig. 6). Despite this limitation, we demonstrated that knowledge-based N management practice can be considered an effective way to ensure food security and improve environmental sustainability, while increasing economic return.

Acknowledgements

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Fig. S1 Regional distribution of study sites included in this meta-analysis.
Table S1 Price of fertilizers, NI and UI products, crop grains and labor costs used in this meta-analysis.
Table S2 Effects of CRF application on changes of crop productivity and N losses under different categories with 95% bootstrap CI.
Table S3 Effects of NI application on changes of crop productivity and Nr losses under different categories with 95% bootstrap CI.
Table S4. Effects of UI application on changes of crop productivity and Nr losses under different categories with 95% bootstrap CI.
Table S5 Effects of increasing splitting frequency of fertilizer N application on changes of crop productivity and Nr losses under different categories with 95% bootstrap CI.
Table S6 Effects of reducing BF proportion on changes of crop productivity and Nr losses under different categories with 95% bootstrap CI.
Table S7 Effects of fertilizer N deep placement on changes of crop productivity and Nr losses under different categories with 95% bootstrap CI.
Table S8. Effects of optimizing N rate on changes (%) of crop productivity and Nr losses under different categories with 95% bootstrap CI.
Table S9 Changes of input costs, yield profit and NEB induced by the application of various knowledge-based N management practices with 95% bootstrap CI.
Table S10 Effects of knowledge-based N management practices on between group heterogeneity (Qb) for each variable.
Data S1 Source references of all datasets used in this meta-analysis.