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Improving yield and nitrogen use efficiency through alternative fertilization options for rice in China: A meta-analysis

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ABSTRACT

Applying alternative fertilization practices instead of conventional fertilizers might improve rice yield and nutrient use efficiency in rice cropping systems. However, the results range widely among individual studies, making generalizations difficult. Here, we investigated five alternative fertilization options (slow-release nitrogen fertilizer, SRF; organic fertilizer, OF; straw return, SR; green manure, GM; secondary/micronutrient fertilizer, SMF) and performed a meta-analysis to quantify their effects on rice yield and nitrogen (N) use efficiency across different rice types in China. Yield responses were significantly positive under all alternative fertilization options relative to those obtained with conventional fertilization, and the magnitude of yield increase exhibited the following the order: OF (7.8%) > SRF (7.4%) > GM (6.7%) > SR (5.4%) > SMF (4.6%). Furthermore, the recovery efficiency (REN), agronomic efficiency (AEN), and the partial factor productivity of nitrogen (PFPN) were increased by 6.0–34.8%, 10.2–29.5%, and 4.7–6.9%, respectively under the alternative fertilization options relative to conventional fertilization. The application of SRF and SMF generated higher yield responses in single rice than in other rice types, whereas OF and SR application resulted in better performance in early and middle rice. The rice yield response was maximized when approximately 70% slow-release N was combined with approximately 30% conventional N according to the quadratic relationship between the percentage of slow-release N substituting conventional N and the yield response. It was estimated that the total N rate could be reduced by up to 32% without yield loss with the application of slow-release N fertilizer instead of conventional N fertilizer. When organic N fully or partially substituted inorganic N, yield response declined with increasing substitution level, and the substitution proportion needed to be controlled below 20% to maintain rice yield. The meta-analysis results clearly demonstrate that appropriate alternative fertilization options can increase both rice yield and nitrogen use efficiency, and that conventional chemical fertilizers can be partially replaced with alternative ones without negatively affecting rice productivity.

1. Introduction

Rice (*Oryza sativa* L.), which is one of the most important food crops and is considered as a major source of calories for more than half of the global population (Carrijo et al., 2017), covers 11% of total arable land (Khush, 2005). China is the leading rice-cultivation country, accounting for 28.1% of the world's total rice production and 18.8% of the total rice harvested area worldwide (FAOSTAT, 2014). There are diverse rice paddy ecosystems extending from the cold to the tropical zones of China, and the agronomic practices in these ecosystems vary considerably (Guo et al., 2017). However, China still needs to produce approximately 20% more rice by 2030 to meet the demand of the rising population if rice consumption per capita remains at the current level (Peng et al., 2009). Due to agricultural restructuring, rural industrialization, urbanization and economic reforms, the area of paddy fields is unlikely to expand in the near future in China (Khan et al., 2009). Therefore, achieving additional rice production will rely mainly on sustainable increases in yield.

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Achieving high productivity and high nitrogen use efficiency (NUE) simultaneously in agricultural production has become a major challenge with increasing food demand, natural resource depletion, and environmental deterioration. China accounts for 37% of the global inorganic N fertilizer input in rice production (Xu et al., 2013). In China, farmers commonly apply excessive inorganic fertilizer to ensure high crop yield (Cui et al., 2008; Zhang et al., 2016), leading to additional greenhouse gas emissions (Zheng et al., 2004), eutrophication of surface and ground water (Fang et al., 2006; Le et al., 2010), soil degradation (Guo et al., 2010), and consequently, a decline in crop productivity (Zhang et al., 2008). Thus, many optimized agronomic practices including a series of alternative fertilization options have been applied in Chinese rice cultivation during the last several decades, aiming to produce higher yields as well as to achieve a higher NUE. These alternative fertilization options include the application of slow-release fertilizers, inorganic fertilizer combined with organic fertilizers, and straw return, among other approaches.

Slow-release N fertilizers are one type of enhanced-efficiency fertilizers that were developed to reduce N losses and increase NUE by allowing better synchrony between the release of N in the soil-water matrix and crop N demand, as well as to reduce the labor cost (Geng et al., 2015). A meta-analysis revealed that enhanced-efficiency N fertilizers resulted in a 5.7% increase in yield and an 8.0% increase in N uptake (Linquist et al., 2013). The application of organic fertilizers such as commercial manure and farmyard manure not only sustains crop productivity (Steiner et al., 2007), but also improves soil fertility (Diacono and Montemurro, 2010). In addition, relative to mineral fertilizer application, manure application can create a larger capacity to mitigate environmental N loss (Bouwman et al., 2010; Smith et al., 2001; Zhou et al., 2016) and to enhance soil carbon sequestration in paddy fields (Zhu et al., 2015) compared with mineral fertilizers. Substituting chemical N fertilizers with organic fertilizers has been suggested as an effective option to reduce environmental pollution as well as to sustain crop yield in agricultural production (Smith et al., 2008). Straw return is commonly applied in China as a measure of sustainable agriculture. In situ retention of crop straw plays important roles in nutrient balance and the supply of organic matter to the soil; it thereby improves soil fertility and is conducive to sustainable rice production (Huang et al., 2013; Yadvinder-Singh et al., 2005). The application of secondary and micronutrient fertilizers is critical for replenishing soil nutrients and for continuously improving production because a large amount of secondary and micronutrients have been harvested from the soil due to the significant yield increase experienced during the past decades. The lack of secondary nutrients and micronutrients is of great concern for moderate- and low-yield fields in China; 5.0%, 6.9%, 21.3%, 46.8%, 34.5%, and 51.5% of such fields suffer from insufficient iron, copper, molybdenum, manganese, boron, and zinc, respectively (Liu et al., 2000).

To improve yield and nutrient use efficiency, numerous short- and long-term experiments have been conducted on paddy soils during the past decades, with most studies focusing on the effects of only one or two types of alternative fertilization options on crop yields or NUE at the field scale. However, yield responses varied widely among different sites due to differences in rice types, regional climate characteristics, tillage and fertilization. Unlike a narrative review, meta-analysis is a formal statistical technique that can be used to summarize the results of independent experiments to quantitatively estimate the trend and magnitude of a treatment effect (Abalos et al., 2014; Chakraborty et al., 2017; Hedges et al., 1999). Therefore, we conducted a meta-analysis to analyze the effects of five alternative fertilization options on rice: slow-release N fertilizer, organic fertilizer, straw return, green manure, and secondary/micronutrient fertilizer. The meta-analysis was conducted (1) to comprehensively evaluate the effect of different alternative fertilization options on rice yield and NUE relative to conventional chemical fertilizer application in Chinese rice cultivation, (2) to investigate how the magnitude of the yield response varies with rice type (early, middle, late, and single season rice), and (3) to determine the maximum proportion of conventional chemical nitrogen input that can be substituted with alternative fertilization options without causing a decrease in rice yield.

2. Materials and methods

2.1. Data collection

The meta-analysis was based on published and unpublished data. The unpublished studies were conducted by the International Plant Nutrient Institute (IPNI) China Program, and a comprehensive literature survey of peer-reviewed papers from Chinese rice field studies published from January 2000 to December 2016 was conducted using the China Knowledge Resource Integrated Database and Web of Science. The following search terms and their variations were used: rice yield, controlled or slow release fertilizer, organic fertilizer, green manure, crop residue, and secondary or micronutrients. Published papers were scrutinized and selected if they met the following criteria:

(1) The fertilization measures were conducted under field conditions in China; no pot or greenhouse experiments were included.
(2) The study reported yield and the number of field replication.
(3) Conventional chemical fertilizer application was included as a control treatment.
(4) The experimental and control treatments had to be applied to the same agricultural system and site.

In total, the database consisted of 489 studies involving 1635 paired observations from 2000 to 2016 (Appendix. A), of which were 339 published studies (Appendix. B). The studies were divided into five separate datasets according to the types of alternative fertilization options: slow-release N fertilizer (SRF), organic fertilizer (OF), straw return (SR), green manure (GM), and secondary/micronutrient fertilizer (SMF). The geographic distribution of the experimental sites is shown in Fig. 1. The SRF dataset was divided into three categories: (i) studies in which the effects of slow-release N were compared to those of the same amount of conventional N, (ii) studies in which the effects of slow-release N combined with conventional N were compared to those of conventional N under the same total N rate, and (iii) studies in which the effects of the reduced rate of slow-release N were compared to those of the full rate of conventional N. The OF included commercial manure, farmyard manure, biogas manure, and cake manure. The OF dataset was divided into two categories: (i) studies in which the additional application of organic fertilizers was compared to chemical fertilizers alone and (ii) studies in which full or partial substitution of inorganic N by organic N was compared to inorganic N alone under the same total N rate. The SR dataset included studies with only in situ straw return, in which early, late and single rice received rice straw, and middle rice received other crop straw (wheat, oilseed rape or maize straw) depending on the rotation system. Green manure crops included in the GM dataset were Chinese milk vetch, oilseed rape and ryegrass. In the studies included in the SR, GM, and SMF datasets, the experimental and control treatments in each study received the same amount of inorganic NPK fertilizer. From each study, we extracted the rice yield (kg ha^{-1}), N application rate (kg ha^{-1}) and total N uptake (kg ha^{-1}) for alternative fertilizer application treatments (the experimental treatments), conventional chemical fertilizer application treatments (the control treatments), and N omission treatments.

2.2. Meta-analysis

The meta-analysis was performed using MetaWin 2.1 software (Rosenberg et al., 2000). The analysis was divided into two main stages:

First, we used the natural log of the response ratio (ln*R*) as a measure of effect size due to the high variability of responses between

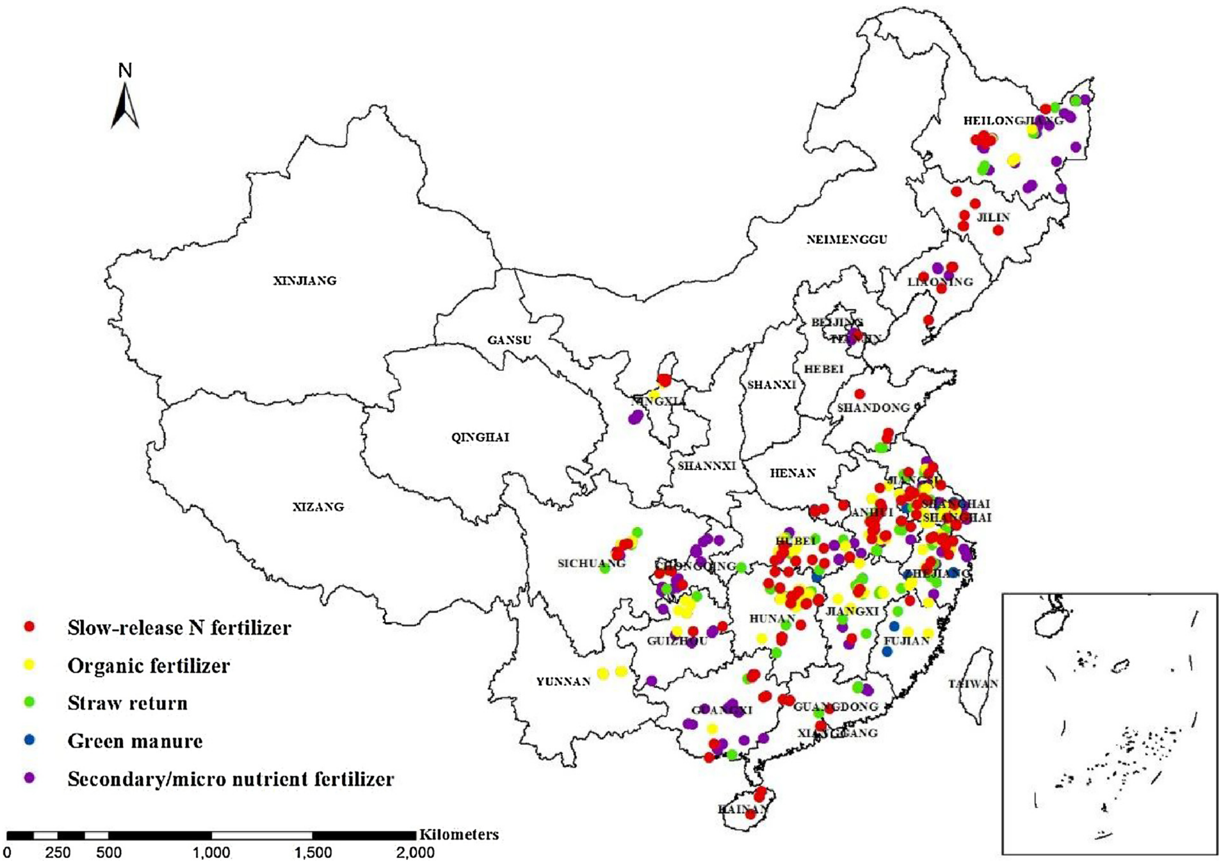

Fig. 1. Geographic locations of five types of alternative fertilization experiments in China.

studies. Individual effect sizes and their associated variances ($V_{\ln R}$) were calculated for each study to place the data from the primary studies on a common scale (Hedges et al., 1999):

$$\ln R = \ln\left(\frac{\overline{X_e}}{\overline{X_c}}\right)$$

$$V_{\ln R} = \frac{{S_e}^2}{N_e \times \overline{X_e}^2} + \frac{{S_c}^2}{N_c \times \overline{X_c}^2}$$

where $\overline{X_e}$ is the mean value of the experimental group and $\overline{X_c}$ is the mean value of the control group. S_e and S_c are the standard deviations of the experimental and control groups, respectively, and N_e and N_c are the number of field replications in the experimental and control groups, respectively. The standard deviation (SD), which was used as a measure of variance, was calculated from the published measure of variance in each study if available. When no measure of variance was given, standard deviation was calculated from two to five experiments located close to each other using similar rates of fertilizers to include as many studies as possible (Valkama et al., 2009).

Subsequently, the log response ratios were combined across the studies using a weighting procedure. The cumulative effect size ($\overline{\overline{E}}$) was calculated as follows:

$$\overline{\overline{E}} = \frac{\sum_{i=1}^{n} w_i E_i}{\sum_{i=1}^{n} w_i}$$

where n is the number of studies, E_i is the effect size (ln$R$) for the i^{th} study, and w_i is the weight for the i^{th} study, defined by the reciprocal of the sample variance (Rosenberg et al., 2000).

We also calculated the recovery efficiency (REN) and agronomic efficiency of nitrogen (AEN) if studies included nitrogen omission treatments and the partial factor productivity of nitrogen (PFPN) to estimate the alternative fertilizer options effect on NUE:

$$\text{REN} = \frac{U - U0}{F_N}$$

$$\text{AEN} = \frac{Y - Y0}{F_N}$$

$$\text{PFPN} = \frac{Y}{F_N}$$

where Y and U are the yield (kg ha^{-1}) and total plant N uptake in the aboveground biomass, respectively, with N fertilizer application (kg ha^{-1}); $Y0$ and $U0$ are the yield (kg ha^{-1}) and total plant N uptake in the aboveground biomass, respectively, in the N omission treatment (kg ha^{-1}); and F_N is the amount of N fertilizer applied (kg ha^{-1}).

Performance parameters considered in the meta-analysis included (a) grain yield, (b) REN, (c) AEN, and (d) PFPN. Effect sizes from individual studies were combined using a random-effect model to calculate the mean effect size based on the assumption that random variation in yields occurred between observations. Rice was grouped into four categories, i.e., early, middle, late and single rice, to maximize in-group homogenization. We used a categorical random effects model to compare the effect sizes among the categorical groups.

The 95% confidence intervals (95% CI) around the mean effect sizes were estimated through bootstrapping with 999 iterations (Adams et al., 1997). The cumulative effect was considered significant if the 95% CIs did not overlap zero. Effect sizes among the categories were considered significantly different if their 95% CI did not overlap each other ($p < 0.05$) (Hedges et al., 1999). For the sake of expression, the results were back-transformed and reported as percentage changes in rice yield, REN, AEN or PFPN ([R − 1] × 100). Positive percentage changes indicate an increase, while negative values indicate a decrease.

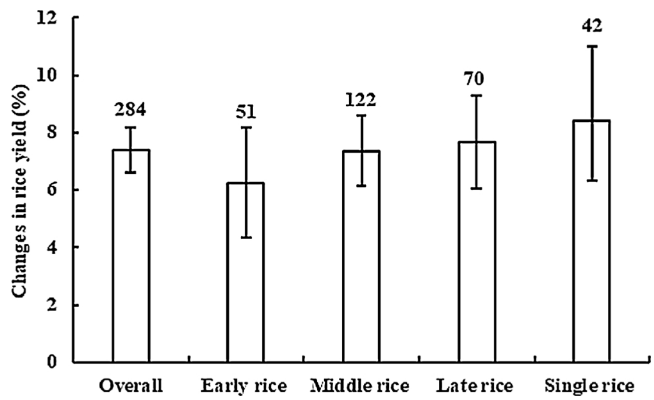

Fig. 2. Influence of slow-release N fertilizers on percentage changes in yield relative to conventional N fertilizer under the same fertilization rate across different rice types. Error bars represent the 95% confidence intervals. The number of observations is indicated above the error bars.

3. Results

3.1. Effect of slow-release N fertilizer application on percentage changes in rice yield

On average, the application of slow-release N fertilizer (SRF) significantly increased yield across all rice types by 7.4%, relative to conventional N fertilizer at the same N rate (Fig. 2); increases of 6.3%, 7.4%, 7.7% and 8.4% were observed for early, middle, late and single rice, respectively. Single rice exhibited the largest yield increase among the rice types.

Rice yield was increased by slow-release N application (1.4%–12.0%) when all or part of conventional chemical N was substituted by slow-release N, and there was a significant quadratic relationship between the proportion of conventional N substituted by slow-release N and the percentage yield changes (Fig. 3). According to the trend line, the highest rice yield can be obtained with approximately 70% slow-release N combined with approximately 30% conventional N.

The slow-release N rate had a significantly negative linear relationship with percentage changes in rice yield (Fig. 4). Yield response remained significantly positive when a low percentage reduction (< 20%) of slow-release N was applied compared to the full rate of conventional N alone. According to the regression analysis results, it was estimated that a decrease in the application of SRF would not result in a loss of rice yield when the SRF rate was reduced by up to 32.0%.

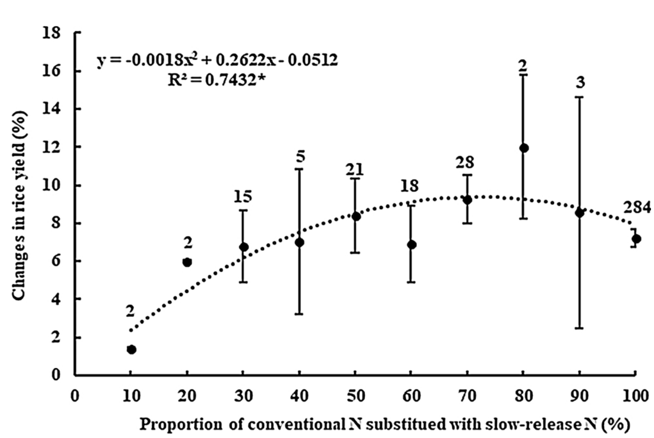

Fig. 3. Relationship between the proportion of conventional N substituted by slow-release N and percentage changes in yield across all rice types. Each point is the mean value of its corresponding interval except the 100% point, the data for which involve only slow-release N application. Error bars represent standard errors. The number of observations is indicated above the error bars. * indicates significance at $p < 0.05$.

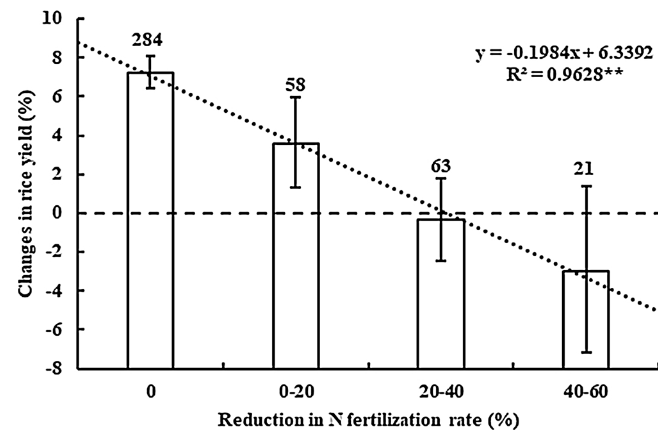

Fig. 4. Influence of the reduction in the slow-release N rate (relative to the full rate of conventional N) on the percentage changes in yield across all rice types. Error bars represent the 95% confidence intervals. The number of observations is indicated above the error bars. ** indicates significance at $p < 0.01$.

3.2. Effect of organic fertilizer application on percentage changes in rice yield

On average, the additional application of organic fertilizer (OF) combined with inorganic fertilizers significantly increased rice yield by 7.8% relative to solely inorganic fertilizers across all sites. The rice yields of early, middle, late and single rice were increased by 10.4%, 8.8%, 7.2% and 0.78%, respectively, under OF application (Fig. 5). The percentage yield changes of single rice showed a slightly positive but insignificant response to OF application due to the large 95% CI range. The magnitude of yield increase with OF addition declined with increasing inorganic N rate, and significantly positive responses were observed under medium and high N rates (Table 1).

A negative relationship was observed between the proportion of inorganic N substituted by organic N and percentage changes in rice yield (Fig. 6). Rice yield declined with an increase in the substitution proportion. There was a significant increase in rice yield (7.3%) when organic N substituted inorganic N, but only when the substitution proportion was less than 20%. In contrast, the effect sizes were negative when the substitution proportion ranged from 20% to 60%, and rice yield decreased significantly (10.4%) under a large substitution proportion (> 60%).

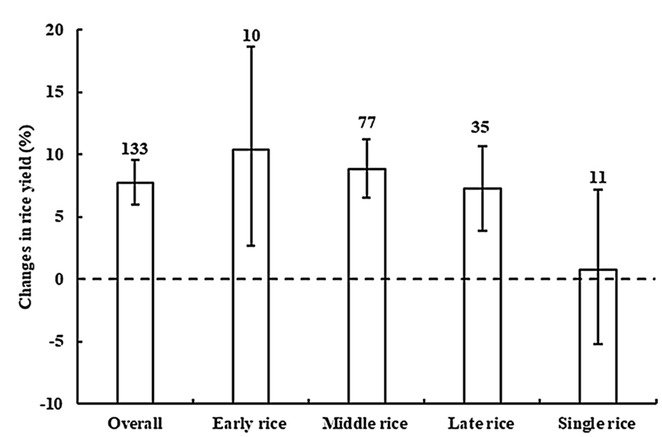

Fig. 5. Influence of additional organic fertilizer application on percentage changes in yield relative to inorganic fertilizer application alone across different rice types. Error bars represent the 95% confidence intervals. The number of observations is indicated above the error bars.

Table 1
The effect of inorganic N input on rice yield response when organic fertilizer, straw return or green manure is applied relative to no organic fertilizer, straw return or green manure application, respectively.

Inorganic N rates (kg ha^{-1})	Organic fertilizer		Straw return		Green manure	
	Changes in yield (%)	95% CI (%)	Changes in yield (%)	95% CI (%)	Changes in yield (%)	95% CI (%)
Low (0-100)	19.8 (3)[a]	-0.6-44.3	3.6 (30)	-4.0-11.8	20.7 (7)	12.5-29.4
Medium (100-200)	8.6 (59)	6.5-10.7	3.1 (177)	0.2-6.1	5.3 (52)	3.2-7.4
High (> 200)	6.4 (70)	4.6-8.2	3.7 (55)	-2.0-9.7	4.5 (27)	1.6-7.5

[a] Number of observations in parentheses.

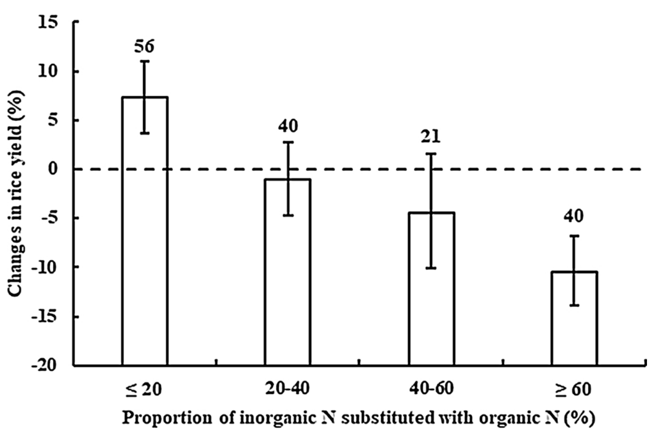

Fig. 6. Influence of organic N substituting inorganic N on percentage changes in rice yield. Error bars represent the 95% confidence intervals. The number of observations is indicated above the error bars.

3.3. Effect of straw or green manure return on percentage changes in rice yield

There was a significantly positive yield response of early, middle, and late rice to straw return relative to straw removal, with percentage changes of 8.4%, 5.1%, and 4.8%, respectively (Fig. 7). The overall magnitude of the yield response to straw return was 5.4%. However, a significant yield increase was observed only under medium inorganic N input (Table 1). The effect size for early rice was significantly higher than that for middle rice. There was no significant yield response of single rice to straw return compared to straw removal, and this trend was also observed in response to the application of organic fertilizers.

In paddy fields, a green manure (GM) crop is generally grown (in the winter season) prior to rice planting, and the straw is generally incorporated into the soil after harvest of the GM crop. Therefore, GM is rarely returned to late or single rice under current agronomic practices. The retention of GM with early and middle rice resulted in a significant yield increase of 6.4% and 6.8%, respectively, relative to no GM retention (Fig. 7). Consequently, the overall effect of GM retention on rice was significantly positive, with a mean yield increase of 6.7%. The magnitude of yield increase with GM addition declined with increasing inorganic N rate (Table 1).

3.4. Effect of secondary and micronutrient fertilizer application on percentage changes in rice yield

The application of secondary/micronutrient fertilizers (SMF) significantly increased rice yield by 4.6% relative to the control (fertilized without secondary or micronutrients) across all comparisons (Fig. 8). Among the four rice types, single rice showed a significantly higher response to the application of SMF, with a yield increase of 7.3% compared with the three other rice types.

However, the magnitude of the yield response to SMF was highly dependent on the types of SMF. For example, the application of boron (B) produced the highest significant yield increase, i.e., an average of 8.1%, while the application of sulfur (S) resulted in the lowest (and insignificant) increase (1.9%) (Fig. 8). The yield response to other nutrients followed the order: silicon (Si) > zinc (Zn) > calcium (Ca) > magnesium (Mg).

3.5. Effect of alternative fertilization options on nitrogen use efficiency

There were significant increases in REN, AEN and PFPN under SRF and SMF relative to that attained under conventional fertilization (Table 2). The magnitude of increases in REN, AEN and PFPN 34.8%, 29.5% and 6.3%, respectively, for SRF and 23.5%, 10.2% and 5.4%, respectively, for SMF. When substituting chemical fertilizer with some proportion of OF, no significant effect was observed in any types of NUE. The AEN and PFPN increases (18.4% and 4.7%) under SR were significant, whereas that of REN under SR was not. Due to the lack of data, only PFPN for GM was analyzed, and its magnitude of increases was 4.9%. Regarding NUE, the application of SRF showed the best

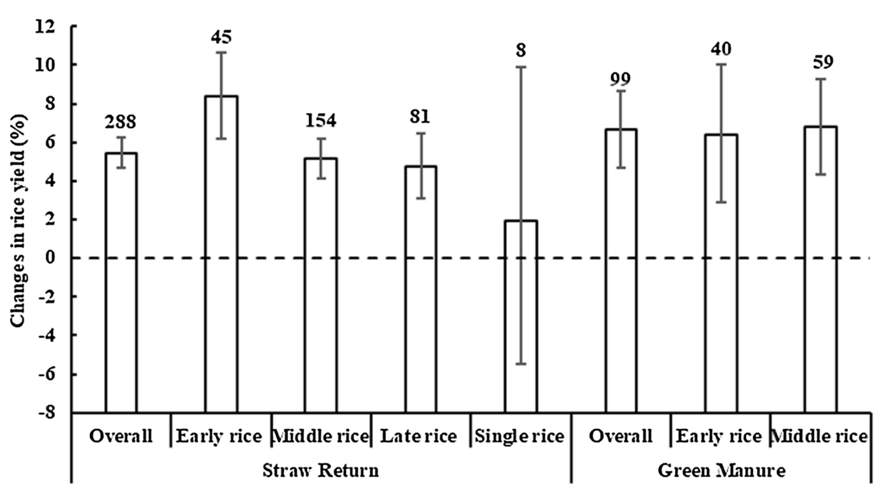

Fig. 7. Influence of straw return and green manure on percentage changes in rice yield across different rice types. Error bars represent the 95% confidence intervals. The number of observations is indicated above the error bars.

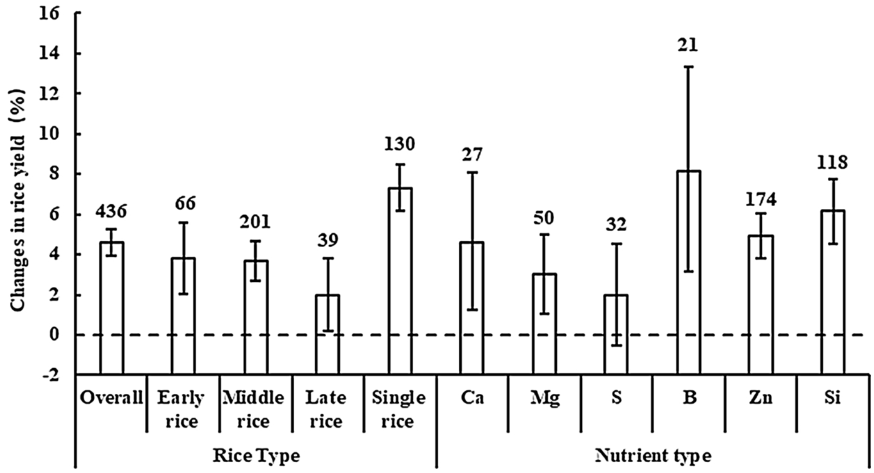

Fig. 8. Influence of secondary/micronutrient fertilizer on percentage changes in yield across different rice types and nutrient types. Error bars represent the 95% confidence intervals. The number of observations is indicated above the error bars.

Table 2
Influence of five alternative fertilization options relative to conventional chemical fertilizer application on percentage changes in recovery efficiency (REN), agronomic efficiency of nitrogen (AEN) and partial factor productivity of nitrogen (PFPN) for all rice types.

Fertilization Options	REN		AEN		PFPN	
	Changes in REN (%)	95% CI (%)	Changes in REN (%)	95% CI (%)	Changes in REN (%)	95% CI (%)
SRF[b]	34.8 (129)[a]	28.3-41.8	29.5 (153)	21.9-37.6	6.3 (281)	6.1-7.8
OF	6.0 (31)	-1.9-14.6	-1.4 (38)	-6.9-4.4	1.3 (126)	-0.3-2.9
SR	11.1 (15)	-3.3-27.6	18.4 (42)	8.0-29.8	4.7 (241)	3.6-5.8
GM	–	–	–	–	4.9 (84)	3.0-6.8
SMF	23.5 (40)	10.2-38.4	10.2 (81)	1.2-20.0	5.4 (361)	4.1-6.7

[a] Number of observations in parentheses.
[b] SRF, OF, SR, GM and SMF represent slow-release N fertilizer, organic fertilizer substituting for chemical fertilizer, straw return, green manure, and secondary/micronutrient fertilizer, respectively.

performance among the alternative fertilization options.

4. Discussion

4.1. Slow-release N fertilizer

Slow-release N fertilizers with a protective, water-insoluble coating are applied to increase yield and NUE by synchronizing N release and demand as well as to minimize N losses associated with ammonia volatilization, nitrification and leaching (Linquist et al., 2012; Snyder et al., 2009). The positive responses of rice yield, REN, AEN and PFPN to slow-release N fertilizer application in our meta-analysis can be attributed to the coating materials, such as polyolefin, which slow N dissolution in water, resulting in less N loss (Shoji and Kanno, 1994; Xu et al., 2013). Recently, a similar result showed that the application of enhanced-efficiency nitrogen fertilizers (including slow-release fertilizers, urease inhibitors and nitrification inhibitors) increased rice yield by 5.7% based on a global meta-analysis (Linquist et al., 2013). In the current study, the yield response of single rice to slow-release fertilizer was higher than that of the three other rice types, which may be because single rice has a longer growth period (usually from early May to late September), and slow-release fertilizer has a greater ability than does conventional fertilizer to supply nitrogen during the whole growth period. Our results indicated that the total N rate can be reduced by 32.0% without yield loss by applying slow-release N fertilizer instead of 100% conventional N fertilizer. This is an effective approach to decrease the input of mineral N fertilizer as well as increase NUE according to Geng et al. (2015), who reported that a 30% decrease in N input with the application of slow-release N fertilizer resulted in the same yield as 100% conventional urea.

Liu et al. (2009) reported that relative to the same amount of conventional urea or slow-release urea applied alone, slow-release urea combined with conventional urea increased single rice yield by 6.0–31.2% and NUE by 20.3–96.5% when slow-release N accounted for 30%–70% of the total N. Our results are in agreement with their findings. Although slow-release N has a longer availability than does conventional N, the application of slow-release N alone may not be able to meet crop N demand at the early growth stages. Therefore, adding a certain percentage of rapid-acting conventional N is appropriate; according to our results, the optimal percentage is approximately 30%.

4.2. Organic fertilizer

Organic fertilizers are important nutrient sources for many rice systems. In our analysis, additional organic fertilizer application increased rice yield by 7.8%, relative to the yield obtained in treatments without organic fertilizer application. This result is consistent with previous studies concluding that rice yield increase due to additional organic fertilizer application was significantly higher than that resulting from only NPK fertilizer application under long-term fixed field experiments conducted for more than ten years (Yadav et al., 2000; Zhang et al., 2009). The additional NPK and micronutrients due to addition of organic fertilizers are the main reason for the yield increase. Furthermore, organic fertilizers have beneficial effects on soil properties, such as an improvement in physical conditions (Haynes and Naidu, 1998). Yield responses of all rice types except single rice were significantly positive (Fig. 4), which can be attributed mainly to the temperature of its cultivated area (in northeastern and northwestern China), where a much lower temperate climate dominates (Xu et al., 2016). Given that the decomposition and mineralization rate of amended organic matters are retarded by low temperatures, the application of organic fertilizer in a cool-temperate area may not be able to supply as much available nutrients as in tropical and subtropical areas. However, since most of the studies included in our meta-analysis were one-season trials, it is not so clear whether significant yield responses to organic fertilizer application as observed with single rice can be realized under multi-seasons.

In studies with treatments in which inorganic N was fully or partially substituted by organic N (Fig. 7), yield response declined as the substitution proportion increased because of a lower availability of organic N relative to that of inorganic N. Our results suggested that when substituting inorganic N with organic N, the substitution proportion needs to be controlled below 20% to maintain rice yield and improve soil fertility at the same time. Meng et al. (2009) estimated that the optimum substitution proportions of commercial organic fertilizer in a paddy field ranged from 10 to 30% across different inorganic N inputs. Their result was similar to ours, which implies that although organic substitution can decrease inorganic fertilizer input, excessive substitution proportions should be avoided to maintain crop yield.

4.3. Straw return

Straw return is a critical management option in the sustainability of rice production. The effect of straw return on rice yield is still intensively debated; many previous results suggested that rice yield under straw return may be greater than or equivalent to that under straw removal. Our meta-analysis showed that in general, straw return could significantly increase rice yield (5.4%), AEN (18.4%) and PFPN (4.7%) in China. A very similar result was reported by Huang et al. (2013), i.e., overall, crop residue retention significantly increased rice yield by 5.2% in China, in which the yield increase was attributed to increases in the number of spikelets per panicle and grain weight. In contrast, a review showed that only 11 out of 68 comparisons indicated a significant increase in rice yield under straw return in Asia (Bijay-Singh et al., 2008). Variations in experimental conditions, such as soil conditions, fertilization and climate, can influence the results of straw return (Yadvinder-Singh et al., 2009). For example, in our study, there were significant yield responses for all rice types except single rice, which is cultivated in areas dominated by a cool-temperate climate as mentioned previously. Similar to the pattern observed with organic fertilizer, the decomposition and mineralization of returned straw are slowed under a relatively-low temperature. Consequently, returned straw can't supply enough additional nutrients to produce a significant yield increase. Unlike manure, the retention of crop straw, particularly rice straw with higher C:N ratios, may result in microbial immobilization of mineral N in the soil and hence a temporary decline in crop available N (Xu et al., 2010; Yadvinder-Singh et al., 2009). However, this phenomenon can be avoided by increasing inorganic N input (Arshadullah et al., 2012; Thuy et al., 2008), which indicates inorganic N input is another factor responsible for the results observed in response to straw return. Although there was no significant difference between N rates in the present study, the highest increase in rice yield was achieved under high inorganic N input. The variations in other factors within N rates categories, such as rice type and straw type, covered this difference, which deserves to be further investigated under consistent conditions.

4.4. Green manure

Green manures are widely used in many agricultural systems as a source of N fertilizer, and most green manure crops are capable of fixing atmospheric N_2 (Linquist et al., 2012). Our meta-analysis showed that in general, green manure retention significantly increased rice yield (6.7%) and PFPN (4.9%) in China, demonstrating that it can be used as an excellent N fertilizer source by substituting inorganic fertilizer N. Similar to the organic fertilizer, the yield responses to the retention of green manure decreased with increasing inorganic N input, but significant differences between N rates were observed only for green manure. Compared to farmyard manure, fresh green manure not only transfers more available nutrients, but also promotes the decomposition rate of indigenous soil organic N (Xie et al., 2017). In addition, other studies have reported that the retention of green manure enhanced rice productivity by improving the N-supply capacity (Gao et al., 2015; Xie et al., 2016).

4.5. Secondary and micronutrient fertilizers

The emergence of widespread secondary and micronutrient deficiencies has become a major constraint on productivity (Bandita et al., 2016). A balanced supply of NPK and secondary/micronutrients is critical for the improvement of crop growth and yield, and hence, a higher NUE can be achieved. Our meta-analysis confirmed the positive effects of five secondary nutrients (Ca, Mg, and S) and micronutrients (B, Zn, and Si) on rice yield and NUE, whereas the effects varied with rice type and nutrient type. The combination of secondary and micronutrients had significantly greater effects on single rice than on the other rice types, which may be due to greater secondary/micronutrient demands of single rice given their longer growth period and higher yield. Some studies reported that flooding during rice cultivation improved the availability of some nutrients in soil such as sulfur, iron, manganese and molybdenum, while decreasing the availability of other micronutrients, such as zinc, copper and boron (Biswas et al., 2007; Dass et al., 2017; Xu et al., 2015). As our analysis showed, only added sulfur fertilizers failed to have no significant effect on yield response, while boron, silicon and zinc were the three most effective nutrients. This result is consistent with the availability of soil sulfur and zinc being influenced by flooding.

4.6. Study limitations

Although the present meta-analysis included most options of alternative fertilization applied in main rice cultivation areas in China, we did not account for several potential sources of variation within each fertilization category. For instance, variations in fertilization rate, the coating materials of slow-release fertilizer, the proportion of organic substitution for chemical fertilizer and returned-straw types can affect both rice yield and NUE (Huang et al., 2013, 2016; Linquist et al., 2013). These sources of variation might have contributed to the lack of significant differences in the yield responses between rice types for slow-release N fertilizer and green manure. It is possible that one rice type received more fertilizer than the others, although we compared alternative options with conventional fertilizations under the same fertilizer rate. A comparison of alternative fertilization practices among rice types under the same fertilization level would be valuable.

5. Conclusion

We collected results from field studies and used a meta-analysis to assess the effect of various alternative fertilization options (slow-release N fertilizer, organic fertilizer, straw return, green manures, and secondary/micronutrient fertilizer) on rice yield and NUE. All of the studied alternative fertilization options can increase rice yield and NUE relative to conventional chemical fertilizers in China. The magnitudes of the yield responses to each alternative fertilization option depended on the rice type and fertilizer source. The application of slow-release fertilizers or organic fertilizers could substitute for considerable amounts of conventional chemical N fertilizers without negative effects on rice productivity. Yield responses to organic fertilizer, straw return and green manure were affected by the amount of inorganic N input. Our findings highlight the potential of these alternative fertilization options to improve both rice productivity and NUE. In addition, we classified the optimal fertilization options for different rice types. Given the importance of food security in China, the rational application of these fertilization options should receive more attention.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2018.08.001.

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