Journal of Cleaner Production 241 (2019) 118295

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Exploring optimal nitrogen management practices within site-specific ecological and socioeconomic conditions

Tingyu Li [a, b, c, 1], Xin Zhang [d, 1], Huaxin Gao [a], Bei Li [a], Huan Wang [a], Qiongyu Yan [a], Mary Ollenburger [d], Weifeng Zhang [a, b, c, *]

[a] College of Resources & Environmental Sciences, China Agricultural University, Beijing, 100193, China
[b] National Academy of Agriculture Green Development, China Agricultural University, Beijing, 100193, China
[c] School of Agriculture Green Development, China Agricultural University, Beijing, 100193, China
[d] Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD, 21532, USA

ARTICLE INFO

Article history:
Received 25 February 2019
Received in revised form
12 August 2019
Accepted 4 September 2019
Available online 9 September 2019

Handling Editor: Dr Sandra Caeiro

Keywords:
Agricultural sustainability
4R nutrient stewardship
Enhanced efficiency fertilizers
Efficacy
Design principles

ABSTRACT

The “4R” fertilizer management principles of using the right rate, right source, right timing and right place is emergently required for enhancing crop production and improving crop Nitrogen Use Efficiency (NUE) in intensive small farming system. However, the methodology is still vague to design and implement technologies and management practices (TMPs) following the “4R” principles in these regions. This study designs various TMPs and evaluates their agronomic, environmental, and economic impacts in two typical intensive cereals cropping systems in China to explore how TMPs interact with biophysical conditions, and finally establish methodologies to recommend local optimal TMPs. Among 5 designed TMPs, the optimal TMPs for each site and cropping system were selected, which achieved the sustainable targets for productivity (80% of the achievable yield potential), NUE (0.60), and economic profitability. But several TMPs failed to satisfy the integrated targets, which implied the TMPs must be carefully designed to fit site-specific biophysical contexts. This work provided some basic guidelines for determining each “R”: The *“Right rate”* can be determined by balancing with crop aboveground N uptake where soil testing is not always available. The “*Right timing*” must consider the fertilizer products and local climatic features. Split application is not always better than one-time application, e.g., applying urea at 11th-leaf stage decreased spring maize yield by 9% at Lishu due to a 20-day sustained high temperature and drought condition. For the *“Right source”*, the adoption of enhanced efficiency fertilizers should take soil properties (especially soil pH) into consideration, e.g., urease inhibitors are effective in increasing NUE (by 44%) on alkaline soils, but the efficacy on acid soils is greatly reduced (by 19%). The *“Right place”* needs to be designed according to characteristics of crop root distribution and fertilizer sources, e.g., surface application of urease inhibitors in winter wheat gained greater NUE (0.62) and grain yield (8.3 $Mg\ ha^{-1}$) than deep placement of urea and calcium ammonium nitrate. Considering the biophysical condition variations and its great influence on TMPs, a long-term trial research network to design, test and reshape the site-specific optimal TMPs following “4R” principles will be necessary.

1. Introduction

Chemical nitrogen (N) fertilizer is critical for food security but its overuse has threatened human health and environmental sustainability (Davidson et al., 2015; Galloway et al., 2008). Nearly half of the reactive nitrogen applied to cropland is lost to the environment in various forms of pollutants, such as nitrate oxides and nitrate (Galloway et al., 2003; Lassaletta et al., 2014). China accounts for one third of global N fertilizer consumption, and nitrogen use efficiency (NUE, the fraction of nitrogen inputs harvested as crop products) of only 0.25, far from the sustainable target (i.e. 0.60, Zhang et al., 2015a). The high N consumption and low NUE in China resulted in more than 10 million tons of nitrogen loss annually, leading to serious environmental degradation, such as soil acidification, high atmospheric deposition, eutrophication, and nitrate

* Corresponding author. College of Resources & Environmental Sciences, China Agricultural University, Beijing, 100193, China.
E-mail address: wfzhang@cau.edu.cn (W. Zhang).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.jclepro.2019.118295
0959-6526/

accumulation in shallow groundwater (Gu et al., 2013; Guo et al., 2010). Consequently, improving N management in crop production has become urgent and critical issue in China (Zhang et al., 2015a).

The “4R” principles for improved crop N management focus on applying fertilizer at the right rate, right time, right place, and from the right source. These general principles for guiding N management have been widely adopted by organizations in both private and public sectors (e.g., fertilizer companies, International Fertilizer Association, International Plant Nutrition Institute). For example, the successful application of “4R” principles in North America through precision fertilizer application and development of enhanced-efficiency fertilizers has improved NUE to 0.68 and increased the crop yield to 85% of the yield potential (Davidson et al., 2016; Snyder et al., 2014; Zhang et al., 2015a). However, the implementation of “4R” principles still faces various challenges, especially in developing countries such as China, including the following.

First, “4R” principles provide only general guidance for fertilizer management, and must be translated into technologies and management practices (TMPs) for implementation. However, many existing TMP recommendations consider only one or two “R″s. For example, some reduce N application rate with split applications (right time) but ignore the fertilizer products (source) or application method (place), therefore limited NUE improvement has been observed (Guo et al., 2016; Li et al., 2017; Wang et al., 2009). Others use enhanced efficiency fertilizers (right source) but use inappropriate application place or time (e.g., use nitrification inhibitors without deep or split application on maize-wheat or rice systems), therefore the highest NUE achieved is still no more than 0.50 (Hartmann et al., 2015; Sun et al., 2015). Few studies have explored integrated technologies considering all of the “4R” components, which could be more effective than those only adopting one “R”. For example, Venterea et al. (2016) explored the impacts of N fertilizer source, rate, and application timing on improving NUE and reducing N_2O emission in corn production. They found that the only treatment decreased N_2O emission and increased NUE to 0.7 was a combination of split nitrogen application, use of nitrification inhibitors, and reduced N rate. In contrast, changing application timing only has no such effect. Similarly, Maharjan and Venterea (2013) observed that applying enhanced efficiency fertilizers alone had no effect on improving NUE during a two-years experiment. Therefore, we hypothesize that achieving the NUE target in China requires the integration of all “4R” principles.

Secondly, the right fertilizer application practices are site-specific and their effectiveness vary based on site conditions including climate, soil, cropping system and management pattern (IFA, 2009). For example, the effectiveness of enhanced efficiency fertilizers for improving productivity and environmental benefit varies greatly in different biophysical conditions. Polymer coated fertilizer has only showed a positive effect where temperature and water conditions were favorable for growth, and the nitrification inhibitors component of stabilized fertilizers would be degraded on alkaline soils, reducing their efficacy (Li et al., 2018). Deep placement of N fertilizer will help reduce NH_3 loss, but it has been reported to increase N_2O emission in some soils (Engel et al., 2010; Yan et al., 2001). Therefore, the design of TMPs need to consider these site-specific soil and climate conditions.

Lastly, widespread implementation of TMPs designed with “4R” principles is still a major challenge mainly due to the lack of socioeconomic incentives (Zhang et al., 2016; Zhang, 2017). In China, scientists have been exploring TMPs to improve NUE to the 0.60 national target. While some limited progress has been made by providing farm-specific fertilizer products based on soil testing, many N-efficient TMPs have failed to be implemented by farmers. For example, it is reported that a 30% reduction in N fertilizer application will not decrease yield in China, but farmers have few incentives to adopt technologies with no yield increase (Ju et al., 2009). Other integrated technologies, such as ISSM (integrated soil and plant system management), can elevate grain yield to its yield potential and improve NUE to the target level (Chen et al., 2014), but the increased cost and intensive testing work have hindered adoption by farmers. Therefore, in addition to the “4R” principles, TMPs should have the “right cost” to incentivize adoption.

These three major challenges—translating “4R” principles into specific technologies and management practices, designing TMPs to fit site-specific conditions, and insuring that TMPs are cost-effective for farmers to implement—must be overcome in order to implement “4R” principles in China. To address these challenges, this study designed TMPs for two typical cropping systems (a summer maize-winter wheat rotation system and a spring maize system) following “4R” principles, then measured and evaluated the performance of each TMP in production (yield), environmental impact (NUE, N_2O and NH_3 emissions, N loss) and economic impact (farmer's net benefit) through a two-year field experiment. This study also explored how ecological and socioeconomic conditions affect the performance of TMPs, and finally provides recommendations for applying “4R” principles at different sites. The major objective of this study is to provide a practical framework and a case study for designing and identifying site-specific TMPs that integrate “4R” principles, and to illustrate principles for TMP design at different sites.

2. Materials and methods

This study follows three sequential steps (Fig. 1): 1. Design of TMPs based on “4R” principles and site-specific conditions; 2. Field measurements to test and quantify the agronomic and environmental impacts of TMPs; 3. Integrated assessment to evaluate the performance of TMPs using multiple indicators and identify the optimal TMPs for specific sites. In this section, we first give an overview of the experimental sites, and then describe each step in detail.

2.1. Experiment sites

Maize and wheat are essential for food security in China, but high yields have been achieved at the cost of excess application of N fertilizer in recent years (Cui et al., 2010; Ju et al., 2009). We chose two experimental sites in intensive maize and wheat production regions. The two sites are at Quzhou (3652′28″N, 11501′18″E) and

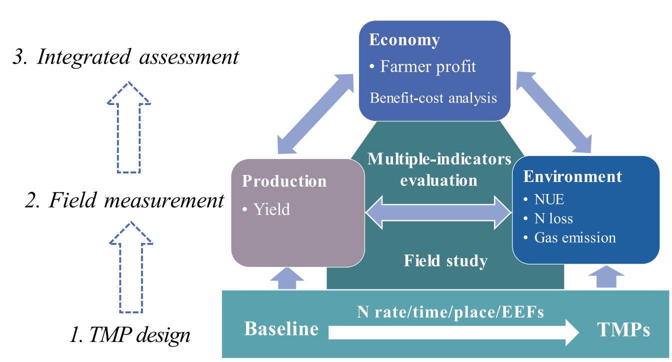

Fig. 1. The framework of optimizing site-specific N management following “4R” principles. EEFs and TMPs are the abbreviation of enhanced efficiency fertilizers and technologies and management practices.

Table 1
Characteristics of topsoils at the two experimental sites.

Sites	Soil texture	Soil pH (H_2O)	SOC g kg^{-1}	Total N g kg^{-1}
Quzhou	Sandy loam	8.2	12.3	0.8
Lishu	Clay	5.7	18.9	1.3

Lishu (43º16′48″N, 124º26′43″E) counties, located in North China Plain and Northeast China respectively, Fig. S1. The production system in Quzhou is predominantly a summer maize and winter wheat rotation system. The area has an average air temperature of 13.1 °C and mean annual precipitation of 556 mm, and a calcareous fluvo-aquic soil (Fluvisols in the World Reference Base for Soil Resources classification). In Lishu, a single spring maize cropping system is most common, and black soil is predominant (according to the Chinese soil classification, it is typic Chernozems in the World Reference Base for Soil Resources classification). The average air temperature is 6.5 °C and mean annual precipitation is 569 mm. The field experiments were conducted for two consecutive years at the Campus Experimental Stations of China Agriculture University at both sites (2013−2015 two years' rotation at Quzhou, 2014−2015 at Lishu). Soil properties for two sites are listed in Table 1.

Conventional treatment consistent with local farmer practice was used at each site to be compared with experimental TMPs. There were three replicates distributed in strips with a size of 100 m^2 per plot to enable machinery operation. Crop management (tillage, irrigation and pesticides application) at the two sites was consistent with local advanced farmer practices. At Quzhou site, summer maize was sown on 10th June at a density of 75,000 plant ha^{-1} in 2013 and 90,000 plant ha^{-1} in 2014 adapting to local technology improvement, and harvested in early October. Winter wheat was sown at a rate of 200 kg ha^{-1} several days after summer maize harvest and harvested on 5th June. At Lishu, spring maize was sown in late April at 60,000 plant ha^{-1} and harvested in early October.

2.2. Design of TMPs

Following "4R" principles, we designed five TMPs for each cropping system. Each TMP considers more than one "R" (Table 2) and has potential to achieve three specific targets for sustainable agriculture. Those targets are 1) yield increases to 80% of the local attainable yield potential in order to meet the food demand target in China in 2030 (Chen et al., 2014). 2) NUE increases to 0.60 (Zhang et al., 2015a), a national target to address environmental pressure, but below 0.90 to avoid "soil mining" (EU Nitrogen Expert Panel, 2015). 3) The profitability of TMPs is equal to or higher than the conventional treatment to encourage adoption. The designed TMPs are feasible to implement but have not yet been widely adopted by farmers in China.

More specifically, the five designed TMPs for Quzhou summer maize were: 1. PCF, one-time application of polymer coated fertilizer applied at 10 cm depth; 2. SU, split application with compound fertilizer (formula) applied at 10 cm depth at the first fertilization and urea broadcasted at the 6th-leaf stage of maize; 3. SUI, same as SU but using urea amended with urease inhibitors at topdressing; 4. SDU, same as SU but incorporate urea with machinery (10 cm below soil surface) at 11th-leaf stage; 5. SDCAN, same as SDU but using calcium ammonium nitrate at topdressing (Table S2). For winter wheat in Quzhou, the designed TMPs were the same as for summer maize except the topdressing timing, which was at shooting stage for all treatments (Table S3).

For Lishu spring maize, the five TMPs were similar: 1. PCF, one-time application of polymer coated fertilizer; 2. UI or NI, one-time application of urease inhibitors in year of 2014 and nitrification inhibitors in year of 2015 (several one-time application treatments at Lishu were designed considering the labor shortage and farmer preference); 3. SDU_1, split application of formula compounds as base and deep placement of urea (10 cm below soil surface) at 6th-leaf stage; 4. SDU_2, as with SDU_1 but different topdressing timing, 11th-leaf stage; 5. SDCAN, same as SDU_2 but using calcium ammonium nitrate at topdressing (Table S4).

The design of TMPs considered a combination of "4R" principles. The ***"Right rate"*** for the TMPs were 180 kg N ha^{-1} at Quzhou and 200 kg N ha^{-1} at Lishu. Rates were calculated by matching fertilizer N input to target crop N uptake, because this method is simple enough to implement among farmers without complex testing work (Ju and Christie, 2011; Rajkovich et al., 2015). Split application of fertilizer was tested to meet crop's N demand at the ***"Right time"***. For the ***"Right source"***, three types of enhanced efficiency fertilizers were tested, namely polymer coated fertilizer (PCF), nitrification inhibitors (NI, consisting dimethyl-phenyl-piperazinium-DMPP), and urease inhibitors (UI, consisting of 75% N-(n-butyl) thiophosphoric triamide-NBPT and 25% N-(n-propyl) thiophosphoric triamide-NPPT). In addition, we also tested calcium ammonium nitrate (CAN), a more environmentally friendly product compared to urea, to explore its potential on reducing N loss (Brentrup et al., 2001; Forrestal et al., 2017). For the ***"Right place"***, we tested surface and subsurface application of urea during topdressing, while keeping the application method for the base fertilization consistent with the conventional treatment, which applies fertilizer at 10 cm below soil surface with machinery.

2.3. Indicators and measurements

We chose six indicators to evaluate each TMP's performance in production, environmental, and economic dimensions of agricultural sustainability. Grain yield was recorded as the indicator for TMP's productivity performance. The environmental performance was assessed using four indicators, namely N loss, NUE and gaseous emissions of N_2O and NH_3. N loss was calculated as total N input minus N removed in crop products and changes in mineral N content in soil (Ju and Gu, 2017). NUE was defined as the proportion of all N removed in harvest crop products divided by the sum of all N inputs including N from chemical fertilizer, manure, bio-fixation and deposition (Conant et al., 2013). The measurements of gaseous emissions were conducted across the growing season using the closed chamber method (N_2O) and Dräger Tube Method (NH_3). Detailed measurement methods are provided in Supplementary

Table 2
The detail and rationale for TMPs design.

TMPs	Details	4R components	Other consideration
1.EEFs	Polymer coated urea or stabilized fertilizer in one-time application	Right rate, source, place and time	Saving labor
2.SU	Split application, urea surface placement at topdressing	Right rate and time	Low cost
3.SUI	Split application (urease inhibitors surface placement at topdressing)	Right rate, source, place and time	Reduce ammonia loss
4.SDU	Split application (urea deep placement at topdressing)	Right rate, place and time	Medium cost
5.SDCAN	Split application (calcium ammonium nitrate deep placement at topdressing)	Right rate, source, place and time	More efficient

Information.

To assess the economic performance of TMPs, farmers' net profit was calculated by benefit-cost analysis method (Brouwer and Van Ek, 2004). The cost included expense for fertilizer, machinery (rental costs), and labor input, while the benefit consisted of income from harvested grain. The prices of maize and wheat changed marginally between years because of the protective purchase price policy, while the price of enhanced-efficiency fertilizer varied greatly due to different manufacturing techniques. To assess the impacts of variable enhanced-efficiency fertilizer prices on farmers' net profit, we set four price scenarios for each fertilizer product based on the information collected from the China Fertilizer Industry Association. More specifically, we tested PCF price as 1.5, 2, 2.5, 3 times of the price of urea (considering the unit N price), NI and UI prices as 1.2, 1.5, 2, 2.5 times and CAN price as 1.2, 1.5, 2, 3 times of the urea price. The upper and lower bounds were determined according to the price range of each enhanced-efficiency fertilizer found in local fertilizer market excluding extreme values. The prices of grains and fertilizers are shown in Table S1.

To compare the performance difference between TMPs and conventional treatment, Response ratio, constructed by calculating the value for each TMP divided by that from conventional treatment for each indicator (Y_{TMP}/Y_{Conv}), was used to evaluate the performance of TMPs (Coleman, 2012). One-way analysis of variance (ANOVA) and multiple comparisons of Tukey test were conducted to identify the variation from treatments and years which are commonly used in similar research (Li et al., 2015; Hu et al., 2013). T test was also performed to examine the robustness of TMPs between two years (Tables S8-S18). All the statistical analysis was conducted using SPSS 2.0 software.

2.4. Optimal TMP determination

The optimal TMP will be the treatment which is most effective at enhancing productivity, NUE and farmer profit simultaneously, and should meet all three aspects' targets. However, the performance of TMPs is not always consistent across multiple indicators, and trade-offs often exist. Consequently, an assessment integrating each TMP's performance in various indicators is necessary to identify the optimal TMP for specific sites and management priorities. In this study, we used the "Technique for Order Performance by Similarity to Ideal Solution" (TOPSIS) method, a classical multiple criteria decision-making method. It is based on the concept that the optimal choice should have the shortest distance from the Positive Ideal Solution (PIS) (the solution which minimizes the cost criteria and maximizes the benefit criteria) (Baky and Abo-Sinna, 2013). Accordingly, we calculated the distance from PIS (d_{PIS}) for each TMP and defined those with shortest d_{PIS} as the optimal practices (Lai et al., 1994). d_{PIS} is calculated by specific equation with a weight coefficient for each dimension and detailed information is provided in Supplementary Information.

3. Results

In order to evaluate TMPs following "4R" principles, it is important to quantify their efficacy with respect to improving productivity, reducing environmental impact, and providing economic benefits. The efficacy of TMPs at each of the two sites depends as well on how each TMP fits specific ecological and economic conditions. Because of the complexity of these interrelationships, a set of integrated performance indicators should be used to give an overview of each option and determine which is optimal.

3.1. TMPs' impact on productivity, environment, and economy

Most TMPs at both sites achieved the productivity target. They produced equal or greater quantities of grain when compared to conventional treatment, even after reducing N input by 20%–30%. In the maize-wheat rotation cropping system at Quzhou, the average yield of all experimental TMPs over two years were 12.0 Mg ha^{-1} and 7.9 Mg ha^{-1} for summer maize and winter wheat. All TMPs achieved the target yield except split surface placement of urea (SU) for summer maize and split subsurface placement of urea (SDU) for winter wheat (Fig. 2a and b; Tables S5 and S6). At Lishu site, the average yield of the TMPs was 13.0 Mg ha^{-1}, which was higher than the target yield (12.0 Mg ha^{-1}), but not significantly different from conventional treatment. The exception was SDU_2 in which grain yield decreased by 9% in the second year (Fig. 2c; Tables S7 and S9). The yield loss from SDU_2 may be due to a 20-day sustained high temperature and drought condition, which was aggravated by urea hydrolysis.

With regard to environmental impact, all TMPs increased NUE while few achieved the national target (0.60). For summer maize, all TMPs significantly increased NUE from 0.42 to 0.54–0.60 (Fig. 3a). However, only split application with deep placement of

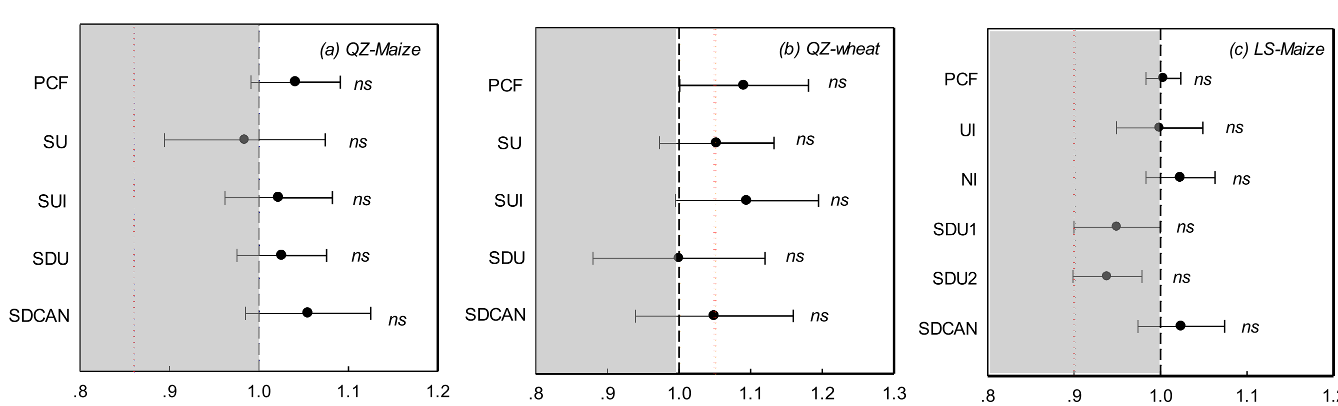

Fig. 2. The impact of technologies and practices (TMPs) on grain yield at two sites, shown as average response ratio with standard deviation from the two-year observation (Grain yield from conventional treatment = 1, shown as short dash). The red dotted line denotes the target yield. The notation on the right side of each error bar denotes the significance of the difference between TMP and conventional treatment: * indicates $P < 0.05$, ** $P < 0.01$, ns-no significance (Tukey test, $P < 0.05$). QZ and LS are the abbreviation of Quzhou and Lishu sites.

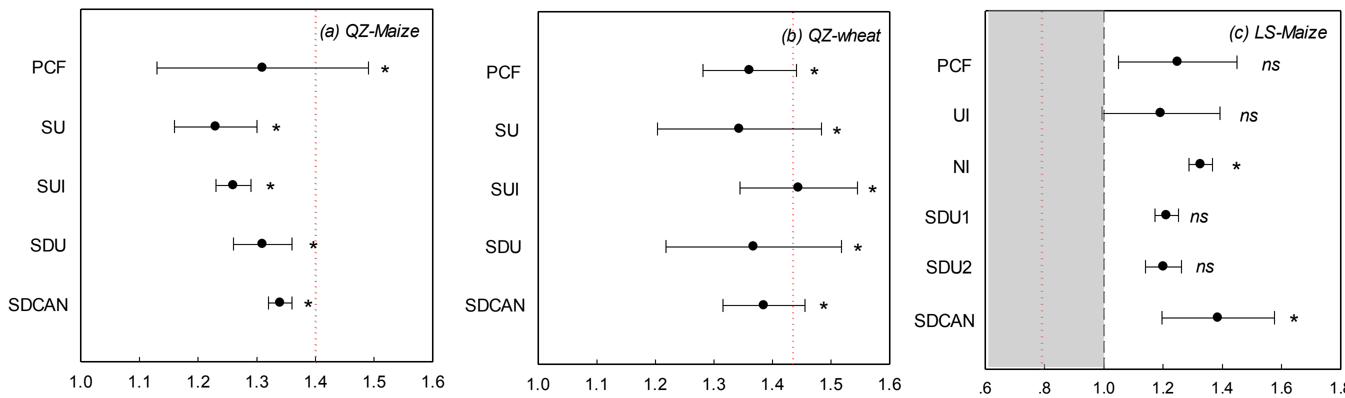

Fig. 3. The impact of technologies and practices (TMPs) on nitrogen use efficiency (NUE) at two sites. Shown as average response ratio with standard deviation of two years (NUE from conventional treatment = 1, shown as short dash). The red dotted line denotes the target NUE (0.60). The notation on the right side of each error bar denotes the significance of the difference between TMP and conventional treatment: *indicates $P < 0.05$, **$P < 0.01$, ns-no significance (Tukey test, $P < 0.05$). QZ and LS are the abbreviation of Quzhou and Lishu sites.

calcium ammonium nitrate (SDCAN) treatment reached the target efficiency of 0.60, and only in the second year. Similarly, the NUE from TMPs in winter wheat was between 0.54 and 0.61, significantly higher than traditional practices (0.43). However, the proposed target was only realized by three TMPs: PCF, SUI and SDCAN, and only in the second year (Table S12). For Lishu spring maize, all TMPs met the NUE target (Fig. 3c), and some even exceeded 0.90 (PCF, NI and SDCAN treatments). This high NUE level indicated a potential "soil mining" (EU Nitrogen Expert Panel, 2015), occurring when the N removed by grain and stover exceed N input.

Although all TMPs significantly increased NUE and reduced N loss, they showed considerable difference in their effects on reactive N gaseous emission. The N loss mitigation potential from TMPs ranged from 32% to 73% (Fig. 4; Tables S5–S7), and the best performance for the three cropping systems were: In Quzhou, SDCAN in summer maize (57%) and PCF in winter wheat (36%); in Lishu, the NI treatment was most effective in spring maize, with a 73% reduction of N loss. The annual N loss measured in experimental TMPs was between 30 and 60 kg ha^{-1} for maize, similar to values for the same crop in the USA (Zhang et al., 2015b). N loss remained high in wheat (around 150 kg ha^{-1}) and requires further improvement. Notably, TMPs showed tradeoffs in mitigating different gaseous emissions (NH_3 and N_2O) and their performance was inconsistent across sites and crop seasons. For Quzhou summer maize, all TMPs significantly reduced N_2O emissions by 29%–57%, but surprisingly, all TMPs increased NH_3 with the exception of the PCF treatment (Fig. 5a). The increased NH_3 emission could be caused by higher fertilization frequency or surface fertilizer application. For example, urea is more likely to be converted to ammonia than ammonium by hydrolysis process on the soil surface due to the upward diffusion of ammoniacal N and is lost to the atmosphere (Sommer et al., 2004). Similarly, in spring maize at Lishu, all TMPs reduced N_2O by 29%–79%, but for NH_3 loss, only PCF reduced NH_3 emission compared to conventional practices. Split application treatments, SDU_1, SDU_2 and SDCAN significantly increased NH_3 losses to varying degrees (Fig. 5c). In contrast, all TMPs could significantly reduce both NH_3 and N_2O emissions in winter wheat, by 11%–67% and 18%–37% respectively (Fig. 5b).

In terms of economic performance, TMPs could increase profit by up to 18% or decrease farmers profit by up to 9%, depending on the price of crops and fertilizers (Fig. 6; Tables S5–S7). For example, PCF and SUI could increase profit in Quzhou summer maize only when the prices of polymer coated fertilizer or urease inhibitors were less than 2.5 and 2 times of urea respectively. SDCAN, however, is profitable in all price scenarios tested, due to high yield improvement (Fig. 6a). In Quzhou winter wheat, PCF and SUI could

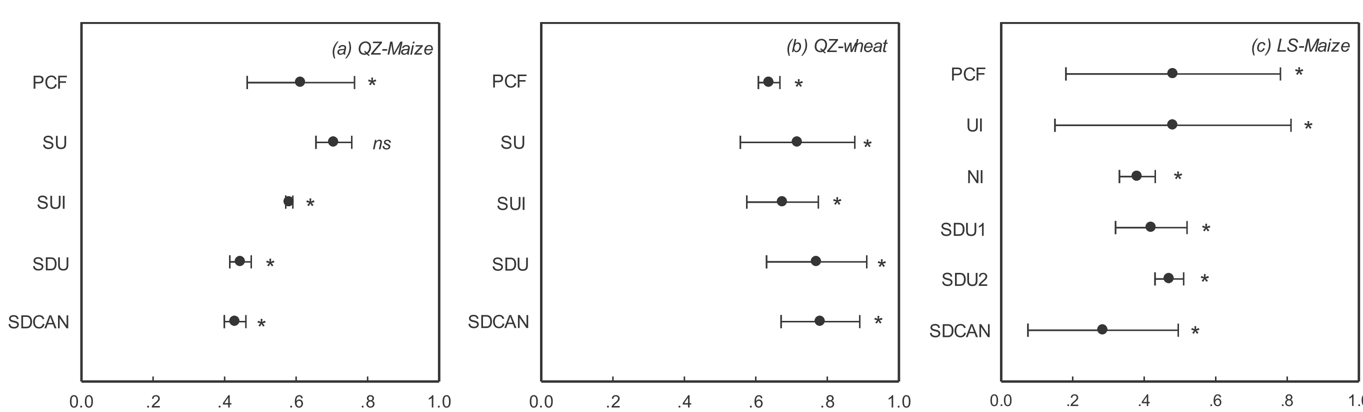

Fig. 4. The impact of technologies and practices (TMPs) on apparent N loss at two sites. Shown as average response ratio with standard deviation of two years (Apparent N loss from conventional treatment = 1). The notation on the right side of each error bar denotes the difference between TMP and conventional treatment: * indicates $P < 0.05$, **$P < 0.01$, ns-no significance (Tukey test, $P < 0.05$). QZ and LS are the abbreviation of Quzhou and Lishu sites.

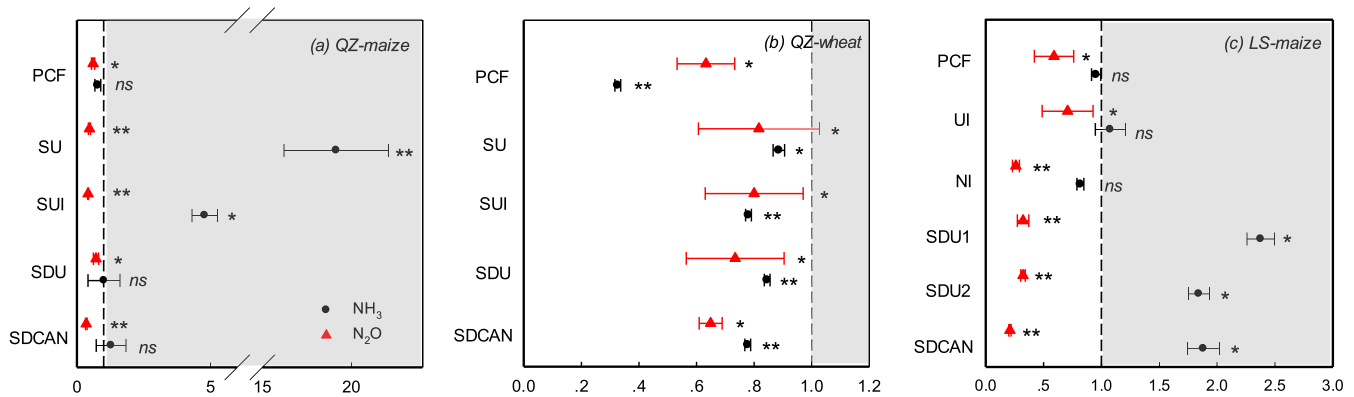

Fig. 5. The impact of different technologies and practices (TMPs) on N_2O and NH_3 emission at two sites. Shown as average response ratio with standard deviation of two years (Profit from conventional treatment = 1). The notation on the right side of each error bar denotes the difference between TMP and conventional treatment: * indicates $P < 0.05$; **$P < 0.01$; ns-no significance (Tukey test, $P < 0.05$). QZ and LS are the abbreviation of Quzhou and Lishu sites.

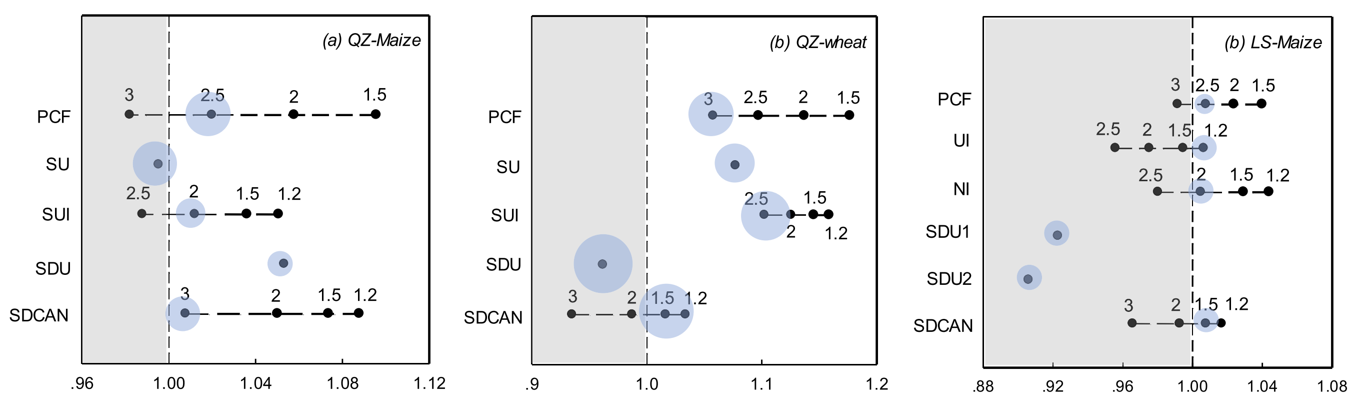

Fig. 6. The impact of technologies and practices (TMPs) on net profit at two sites. Shown as average response ratio (Gas emission from conventional treatment = 1). The numbers indicate different price scenarios for enhanced efficiency fertilizers. For example, "1.5" means the price is 1.5 times of urea. Conventional product of urea has relative stable price therefore with no price scenario was designed (e.g. SU and SDU). The blue shade demonstrates the uncertainty associated with the response ratio due to the uncertainty in crop yield. Only the uncertainty for the price scenario closest to the dashed line is shown in the figure. QZ and LS are the abbreviation of Quzhou and Lishu sites. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

increase farmer profit by 6–10% even at the highest price scenario. However, SDU decreased profits and SDCAN hardly increase profit even in lower price scenarios (Fig. 6b). In Lishu spring maize, all TMPs' cost have to be reduced by 1%–9% to avoid profit loss without grain yield changes (Fig. 6c). In this study, enhanced efficiency fertilizers were generally not profitable when their prices exceed 2 times the price of urea.

3.2. The optimal TMP

Considering the three primary targets for sustainable agriculture, namely yield, NUE and profitability, only a few TMPs can achieve all three targets together (Table 3). For Quzhou summer maize, SDCAN achieved all three targets, while the other TMPs failed to increase NUE to 0.60 level. Among those TMPs, PCF nearly reached the NUE target with an average NUE of 0.59 over 2 years, and could increase farmer profit if the price of polymer-coated fertilizer is under 2.5 times that of urea. For Quzhou winter wheat, there were three TMPs achieved the three sustainable targets: PCF, SUI and SDCAN, but SDCAN only increases farmer profit when the price is under 1.5 times that of urea. For Lishu spring maize, PCF, UI, NI and SDCAN satisfied the requirements but profits decreased for each of them in most price scenarios.

Considering TMPs' performance in all six indicators, the optimal TMP was identified for each cropping system according to TOPSIS analysis (Fig. 7). For Quzhou summer maize, SDCAN has the lowest d_{PIN} values (i.e., best performance) among TMPs. For Quzhou winter wheat SUI was the best with greater effectiveness on increasing NUE and profit. For Lishu spring maize, both NI and SDCAN were the best options among TMPs. They greatly improved the environmental benefit and slightly increased productivity, but their economic benefit can be achieved only when the price is under 2 or 1.5 times of urea respectively (Fig. 6c). In addition, all TMPs in Lishu exceeded 0.90 NUE level and increased the "soil mining" risk. Therefore, adjustment of SDCAN and NI (e.g., slightly increasing fertilizer input and/or recycling straw) or developing new TMPs are needed to avoid soil degradation.

Overall, the two-year experimental results demonstrated that the production, environment, and economy targets can be achieved when suitable TMPs that integrate 4R principles were adopted. The efficacy of a given TMP can vary widely among different sites and cropping systems, e.g., UI are effective in increasing NUE on alkaline

Table 3
The specific targets fulfillment of each TMP at two sites.

	Yield (80% attainable yield potential)	NUE 0.6	Profit (increase or same as usual)
Quzhou summer maize			
PCF	✓	×	✓(price <2.5 urea)
SU	✓	×	×
SUI	✓	×	✓(price <2 urea)
SDU	✓	×	✓
SDCAN	✓	✓	✓
Quzhou winter wheat			
PCF	✓	✓	✓
SU	✓	×	✓
SUI	✓	✓	✓
SDU	×	×	×
SDCAN	✓	✓	✓(Price<1.5 urea)
Lishu spring maize			
PCF	✓	✓	✓(Price<2.5 urea)
UI	✓	✓	✓(Price<1.2 urea)
NI	✓	✓	✓(Price<2 urea)
SDU_1	✓	✓	×
SDU_2	✓	✓	×
SDCAN	✓	✓	✓(Price<1.5 urea)

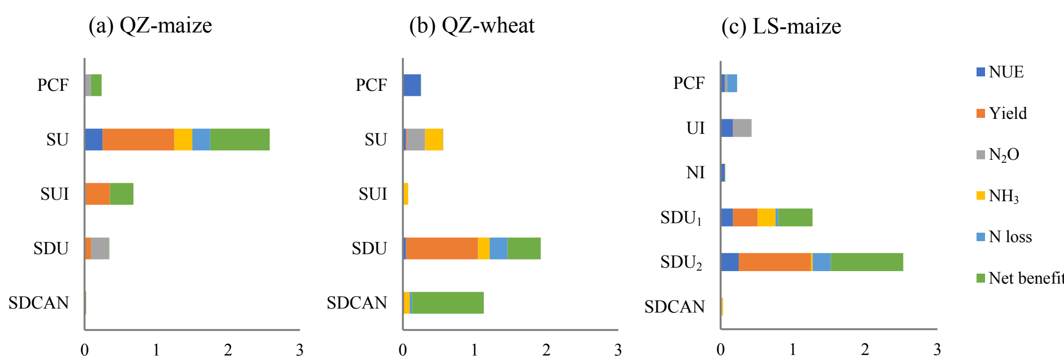

Fig. 7. Integrated evaluation of different technonlogies and practices (TMPs) with 6 indicators. The length of bars means the sum of distance from the Positive Ideal Solution (d_{PIN}) for each indicator. The bigger the d_{PIN} value is, the further the TMP is from the most positive impact. Different color represents different indicators. The calculation of net benefit was using the average price of 4 scenarios. QZ and LS are the abbreviation of Quzhou and Lishu sites. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

soils at Quzhou but less effective on acid soils at Lishu; SDCAN is the most effective option in increasing NUE in the maize cropping system, while less efficient in the wheat cropping system. Therefore, the selection of optimal TMPs should be based on the local biophysical and socioeconomic conditions.

4. Discussion

Implementing the “4R” principles of right rate, right source, right time and right place in intensive production systems in China is still very challenging. First of all, site-specific biophysical information for guiding “4R” implementation is still very limited, and the current technologies extension system is incomplete, hindering the “4R” adoption by smallholder farmers (Gao et al., 2010; Hu et al., 2009). Secondly, competing interests exist among food security, environmental protection, and economic objectives (Chen, 2007; Lu et al., 2015), and the implementation of “4R” need to be accompanied with multiple benefits for productivity, environment, and farmers' profit. To tackle these challenges, this study used field experiments and integrated analysis to provide potential guidelines to design TMPs following “4R” principles, considering biophysical factors and interactions between different “R”s to facilitate the identification and recommendation of optimal measures in China (Fig. 8).

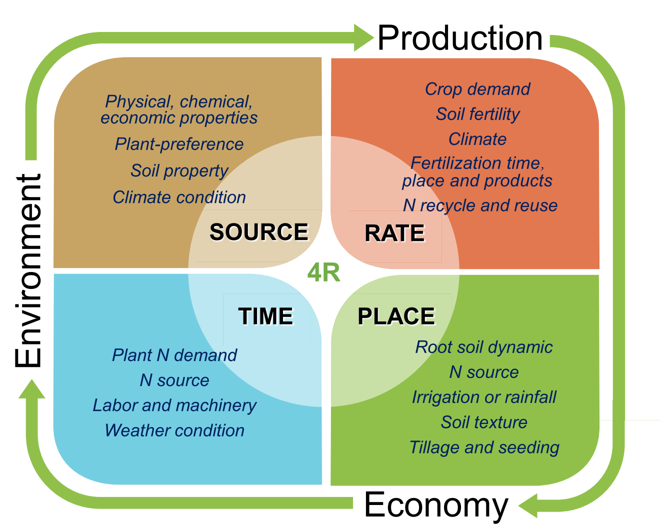

Fig. 8. The principles and methods for “4R” determination in specific sites.

4.1. Design TMPs at a specific site following "4R" principles

Among "4R" principles, the ***"Right rate"*** is the fundamental component and directly affects yield, NUE, N loss, and profit. N fertilizer rate is mainly determined by crop demand, soil fertility and weather situation and is affected by other "Rs" (time, place and source; Fig. 8). The precision of fertilizer application rate recommendation largely depends on the management tools, including soil nutrient testing and crop growth simulation model etc. However, for small farmers with limited farm size, these test-based recommendation services are often inaccessible or insufficient under the inadequate agricultural extension system in China. Therefore, balancing fertilizer input with crop aboveground N uptake is a simple approach that could apply to these smallholders at the current stage (Ju and Christie, 2011; Rajkovich et al., 2015). Other nitrogen sources like stover residues, manure, deposition and bio-fixation are also important. It has been reported that the fertilizer application could be reduced by more than 30% if the stover and manure recycling rate increased to 80% (Niu and Ju, 2017). While the balance approach currently does not account for these N sources, they could be taken into consideration if the practice becomes widespread.

The ***"Right source"*** implies that N is plant-available and soil-suitable, or N release is better synchronized with crop uptake to reduce loss (e.g., enhanced-efficiency fertilizers; IFA, 2009). The selection of N fertilizer products must consider whether the N form is available and preferable for the crop and not harmful for the environment. The soil and climate conditions greatly influence the efficacy of fertilizers and should also be taken into consideration (Rodgers et al., 1985; Shaviv, 2005), Fig. 8. Among the N products, urea as a dominant N fertilizer product has a competitive price advantage and is widely used in China, but it has low efficiency and high emissions risk especially in arid regions with high temperature. As an alternative, urease inhibitors can effectively control NH_3 loss and should be used at sites with high NH_3 emissions, (e.g. alkaline soils at the Quzhou site), areas sensitive to ammonia emissions (e.g., natural habitat) or fields where machinery cannot be operated to deep apply fertilizers (e.g., paddy crops). Nitrification inhibitors have been reported to increase NH_3 loss in many previous studies (Li et al., 2018; Qiao et al., 2015), however, for acid soils such as those at the Lishu site, nitrification inhibitors may significantly reduce N_2O emissions and enhance NUE, while marginally affecting NH_3. Based on our study and previous research (Zhang et al., 2018), nitrification inhibitors can be a good management strategy for crops that prefer NH_4^+-N, in acidic soil with a modest rate of nitrification. Calcium ammonium nitrate, with N as both NH_4^+ and NO_3^- could be the optimal source both for Quzhou and Lishu maize, where it achieved higher yield and lowered environmental risk. Previous studies have also indicated that the utilization of mixtures of NH_4^+ and NO_3^- can result in an improvement in maize growth and higher yields compared to using either form alone (Wang et al., 2009; Absalan et al., 2011; Ma et al., 2015). However, the limited adoption of mixture of NH_4^+ and NO_3^- type fertilizers in China indicates that the "Right" product has been neglected by industries and farmers. This could be due to insufficient understanding of its agricultural advantages or other factors, e.g., the influence of security policies (NH_4NO_3 as one of explosive).

The ***"Right place"*** determination should consider the factors of plant root distribution and N source (Fig. 8). In this study deep placement of urea reduced N loss by 60% in Quzhou summer maize but was less effective in winter wheat, suggesting that different crops prefer different nutrient placements. This finding is consistent with previous research (Ju et al., 2007), they found that the nitrate recovery rate by maize at deeper soil depth was still very high in a ^{15}N tracer study. In addition, different N products require different placement. For example, urea amended with urease inhibitors could be applied on soil surface, while urea alone and other products should be incorporated to avoid NH_3 or runoff loss. Finally, soil texture, irrigation and rainfall condition may also influence the impacts of fertilizer placement (Nash et al., 2012; Vlek et al., 1980).

The ***"Right timing"*** was mainly determined by plant N demand patterns. This study found that other factors, such as N source and climate, are also important. For example, PCF can slow the release of nutrients and synchronize the release with crop uptake, therefore it only requires one-time application (Trenkel, 2010). According to the results from two sites, the PCF treatment showed similar or even better performance on enhancing NUE, reducing loss and increasing profit compared to split treatments. PCF was the second-best option in both Quzhou and Lishu sties. This result indicated that PCF can be a good strategy to improve NUE and save labor at the same time. However, the integrated efficacy of PCF needs to be confirmed before its wide implementation, especially in dryland systems where low soil water content would limit the nutrient release, reduce nutrient availability to crops and affect the growth (Li et al., 2018). For split application, weather conditions are important in determining the "Right timing", especially in rain-fed cropland. For example, continuous drought events delayed urea hydrolysis and affected crop N uptake (Lishu spring maize). For this reason, fertilizers are usually applied before an expected rainfall event to insure sufficient water and nutrient supply. In addition, socio-economic factors like labor and machinery availability are important considerations when determining application time (Fig. 8).

4.2. Customizing optimal TMPs for a specific region

TMPs designed following "4R" principles can still have variable impacts on crop productivity and environmental performances (e.g., N_2O and NH_3 emission), due to the inter-annual and spatial variability of biophysical conditions. For example, urease inhibitors could significantly increase NUE on alkaline soils at Quzhou site but had no such positive effect on acid soils at Lishu. In addition, deep placement treatments increased Quzhou winter wheat grain yield in the first year but failed in the second year, and N loss mitigation potential among most TMPs also varied significantly between two years in Quzhou rotation (Tables S8 and S10). Therefore, regional long-term experiments are necessary to understand the long-term effects of TMPs for a specific region.

To identify optimal TMPs for a specific region, regional priorities could be considered in addition to biophysical conditions. The distance measurement-based TOPSIS approach was implemented in this study to determine the TMP closest to the ideal, without prioritizing specific indicators. However, different regions may have different management priorities. For example, a county closer to metropolitan areas may prioritize mitigating air pollutants (e.g., NH_3) above greenhouse gas emission mitigation (Reche et al., 2012), while for regions with very low productivity, TMPs improving soil fertility and achieving higher yield might be prioritized (Mwangi, 1996; Pypers et al., 2011). In addition to regional priorities, optimal TMPs could vary based on the economic incentives for implementation.

Finally, the optimal TMPs recommended for a specific region should not be cast in stone, rather they should be updated regularly according to changes in soil and climate conditions, as well as technology advancement. Soil N dynamics, N sources and soil fertility need to be considered in updating TMPs. Both this and previous studies found high variation in seasonal soil N residual in intensive production systems (Figs. S2–S3; Zhou et al., 2016). The high accumulation of soil mineral N increases the risk of nitrate leaching and gas emissions, and the N input should be adjusted accordingly to maintain the synchrony between crop demand and soil supply. It is clear that fertilizer inputs could be considerably reduced by improving application time, place, and products in China's intensive cropping systems. However, the NUE level from most TMPs (Quzhou) is still less than the national target or current level in other countries (e.g., 0.68 in the U.S.), where N fertilizer input is less than N uptake due to high biological N fixation, manure substitution, high soil fertility, and full consideration of environmental N sources like deposition (Liu et al., 2010; Vitousek et al., 2009). Therefore, further improvement on NUE in China requires careful consideration of soil fertility improvement and other nitrogen sources, including biological N fixation, manure substitution, and deposition.

In this study, the efficacy of nitrification inhibitors could not be tested at the Quzhou site. This lack of information reduced the robustness in recommendations guiding nitrification and urease inhibitors application on alkaline soils, although they were all tested on acid soils at Lishu site with clear conclusions. Other fertilizer innovations such as liquid products, organic fertilizers or advanced fertilizer application technologies (e.g., fertigation) were not incorporated in the design of TMPs. In addition, TMPs should be tested at additional sites, as the two tested sites are insufficient for guiding maize-wheat production nationally.

5. Conclusion

China's three sustainability targets-enhanced crop productivity, environmental performance, and economic benefit can only be achieved simultaneously by implementing combinations of the "4R" principles of right rate, place, time and source together. By evaluating each TMP according to a range of criteria, optimal TMPs were identified for each site and crop. For summer maize in Quzhou, the optimal TMP used basal formula fertilizer followed by application of calcium ammonium nitrate. For winter wheat at the same site, split application of basal formula fertilizer and urease inhibitors provided the best results. For spring maize in Lishu, split application of basal formula fertilizer and calcium ammonium nitrate, and one-time application of nitrification inhibitors performed similarly and were the best options tested.

Optimal TMPs must be carefully designed to fit site-specific biophysical contexts in different regions, while considering the interaction among the rate, time, source and placement of nitrogen. This work provided some basic guidelines for determining each "R": The *"Right rate"* can be determined by balancing with crop aboveground N uptake for global grain cropping systems that without other N source input like biological fixation of nitrogen, which reduces the difficulties of soil testing; while timing, source, and placement were varied in order to match crop nutrient demand, as well as local soil and climate conditions. The *"Right timing"* must consider the fertilizer products used and local climatic features. Split application is not always better than one-time application if using enhanced efficiency fertilizers. For the *"Right source"*, the selection of enhanced efficiency fertilizers like urease and nitrification inhibitors should take soil properties (especially soil pH) into consideration. The *"Right place"* needs to be designed according to characteristics of crop root distribution, and it is possible to substitute urea deep placement with broadcasting urease inhibitors when machinery is unavailable.

Consequently, to provide ongoing guidance on appropriate nitrogen management practices throughout China and other regions, we argue that a national network of long-term agricultural research should be established, and more case studies that explore the performance of different TMPs following "4R" principles are needed. Going forward, more attention should be paid to updating TMPs, including the use of information systems and crop growth simulation models to recommend N rate, and other improved technologies on fertilizer innovation and sound soil conservation practices. The framework used in this study could be applied to design and assess TMPs in other regions.

Acknowledgements

This work was supported by National Key Technologies R&D Program (Grant 2016YFD0201303) and Department of Agriculture Project (Grant 101721301122441007). And it was also supported by National Science Foundation CNS-1739823, and National Socio-Environmental Synthesis Center (SESYNC) under funding received from the National Science Foundation DBI-1639145.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.118295.

References

Absalan, A.A., Armin, M., Asghripour, M.R., Karimi-Yazdi, S., 2011. Effects of different forms of nitrogen application on yield response of corn under saline conditions. Adv. Environ. Biol. 5, 719–724.

Baky, I.A., Abo-Sinna, M.A., 2013. TOPSIS for bi-level MODM problems. Appl. Math. Model. 37, 1004–1015. https://doi.org/10.1016/j.apm.2012.03.002.

Brentrup, F., Küsters, J., Kuhlmann, H., Lammel, J., 2001. Application of the Life Cycle Assessment methodology to agricultural production: an example of sugar beet production with different forms of nitrogen fertilisers. Eur. J. Agron. 14, 221–233. https://doi.org/10.1016/S1161-0301(00)00098-8.

Brouwer, R., Van Ek, R., 2004. Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands. Ecol. Econ. 50, 1–21. https://doi.org/10.1016/j.ecolecon.2004.01.020.

Chen, J., 2007. Rapid urbanization in China: a real challenge to soil protection and food security. Catena 69, 1–15. https://doi.org/10.1016/j.catena.2006.04.019.

Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X., Yang, J., Deng, X., Gao, Q., Zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Wang, Z., Huang, J., Tang, Q., Sun, Y., Peng, X., Zhang, J., He, M., Zhu, Y., Xue, J., Wang, G., Wu, L., An, N., Wu, L., Ma, L., Zhang, W., Zhang, F., 2014. Producing more grain with lower environmental costs. Nature 514, 486–489. https://doi.org/10.1038/nature13609.

Coleman, R., 2012. Using response-ratios for tests of physiological hypotheses in field experiments. J. Exp. Mar. Biol. Ecol. 428, 1–4. https://doi.org/10.1016/j.jembe.2012.06.001.

Conant, R.T., Berdanier, A.B., Grace, P.R., 2013. Patterns and trends in nitrogen use and nitrogen recovery efficiency in world agriculture. Glob. Biogeochem. Cycles 27, 558–566. https://doi.org/10.1002/gbc.20053.

Cui, Z., Chen, X., Zhang, F., 2010. Current nitrogen management status and measures to improve the intensive wheat-maize system in China. Ambio 39, 376–384. https://doi.org/10.1007/s13280-010-0076-6.

Davidson, E.A., Suddick, E.C., Rice, C.W., Prokopy, L.S., 2015. More food, low pollution (mo fo lo Po): a grand challenge for the 21st century. J. Environ. Qual. 44, 305–311. https://doi.org/10.2134/jeq2015.02.0078.

Davidson, E.A., Nifong, R.L., Ferguson, R.B., Palm, C., Osmond, D.L., Baron, J.S., 2016. Nutrients in the nexus. J. Environ. Stud. Sci. 6, 25–38. https://doi.org/10.1007/s13412-016-0364-y.

Engel, R., Liang, D.L., Wallander, R., Bembenek, A., 2010. Influence of urea fertilizer placement on nitrous oxide production from a silt loam soil. J. Environ. Qual. 39, 115–125. https://doi.org/10.2134/jeq2009.0130.

EU Nitrogen Expert Panel, 2015. Nitrogen Use Efficiency (NUE) an Indicator for the Utilization of Nitrogen in Food Systems. Wageningen University, Alterra, Wageningen, Netherlands.

Forrestal, P.J., Harty, M.A., Carolan, R., Watson, C.J., Lanigan, G.J., Wall, D.P., Hennessy, D., Richards, K.G., 2017. Can the agronomic performance of urea equal calcium ammonium nitrate across nitrogen rates in temperate grassland? Soil Use Manag. 33, 243–251. https://doi:10.1111/sum.12341.

Galloway, J., Aber, J., Erisman, J., Seitzinger, S., Howarth, R., Cowling, E., Cosby, B., 2003. The nitrogen cascade. Bioscience 53, 341–356. CO;2. https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A., 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 320, 889–892. https://doi.org/10.1126/science.1136674.

Gao, Q., Feng, G., Wang, Z., 2010. Present situation of fertilizer application on spring maize in Northeast China. Chin. Agric. Sci. B. 26, 229–231.

Gu, B., Ge, Y., Chang, S., Luo, W., Chang, J., 2013. Nitrate in groundwater of China: sources and driving forces. Glob. Environ. Chang. 23, 1112–1121. https://doi.org/10.1016/j.gloenvcha.2013.05.004.

Guo, J., Liu, X., Zhang, Y., Shen, J., Han, W., Zhang, W., Christie, P., Goulding, K.W.T., Vitousek, P.M., Zhang, F., 2010. Significant acidification in major Chinese croplands. Science 327, 1008–1010. https://doi.org/10.1126/science.1182570.
Guo, J., Wang, Y., Fan, T., Chen, X., Cui, Z., 2016. Designing corn management strategies for high yield and high nitrogen use efficiency. Agron. J. 108, 922–929. https://doi.org/10.2134/agronj2015.0435.
Hartmann, T., Yue, S., Schulz, R., He, X., Chen, X., Zhang, F., Müller, T., 2015. Yield and N use efficiency of a maize-wheat cropping system as affected by different fertilizer management strategies in a farmer's field of the North China Plain. Field Crop. Res. 174, 30–39. https://doi.org/10.1016/j.fcr.2015.01.006.
Hu, R., Yang, Z., Kelly, P., Huang, J., 2009. Agricultural extension system reform and agent time allocation in China. China Econ. Rev. 20, 303–315. https://doi.org/10.1016/j.chieco.2008.10.009.
Hu, X., Su, F., Ju, X., Gao, B., Oenema, O., Christie, P., Huang, B., Jiang, R., Zhang, F., 2013. Greenhouse gas emissions from a wheat-maize double cropping system with different nitrogen fertilization regimes. Environ. Pollut. 176, 198–207.
IFA, 2009. The Global "4R" Nutrient Stewardship Framework. Developing Fertilizer Best Management Practices for Delivering Economic, Social, and Environmental Benefits. IFA Task Force on Fertilizer Best Management Practices. International Fertilizer Industry Association (IFA) Paris, France.
Ju, X., Christie, P., 2011. Calculation of theoretical nitrogen rate for simple nitrogen recommendations in intensive cropping systems: a case study on the North China Plain. Field Crop. Res. 124, 450–458. https://doi.org/10.1016/j.fcr.2011.08.002.
Ju, X., Gu, B., 2017. Indexes of nitrogen management. Acta Pedol. Sin. 54, 281–296. https://doi.org/10.11766/trxb201609150320.
Ju, X., Gao, Q., Christie, P., Christie, P., Zhang, F.S., 2007. Interception of residual nitrate from a calcareous alluvial soil profile on the north China plain by deep-rooted crops: a 15n tracer study. Environ. Pollut. 146, 534–542. https://doi.org/10.1016/j.envpol.2006.07.014.
Ju, X., Xing, G., Chen, X., Zhang, S., Zhang, L., Liu, X., Cui, Z., Bin, Y., Christie, P., Zhu, Z., Zhang, F., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proc. Natl. Acad. Sci. U.S.A. 106, 3041–3046. https://doi.org/10.1073/pnas.0813417106.
Lai, Y., Liu, T., Hwang, C., 1994. Topsis for MODM. Eur. J. Oper. Res. 76, 486–500. https://doi.org/10.1016/j.apm.2012.03.002.
Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 9, 105011. https://doi.org/10.1088/1748-9326/9/10/105011.
Li, Q., Yang, A., Wang, Z., Roelcke, M., Chen, X., Zhang, F., Pasda, G., Zerulla, W., Wissemeier, A.H., Liu, X., 2015. Effect of a new urease inhibitor on ammonia volatilization and nitrogen utilization in wheat in north and northwest China Field. Crop Res. 175, 96–105. https://doi.org/10.1016/j.fcr.2015.02.005.
Li, P., Dong, H., Liu, A., Liu, J., Sun, M., Li, Y., Liu, S., Zhao, X., Mao, S., 2017. Effects of nitrogen rate and split application ratio on nitrogen use and soil nitrogen balance in cotton field. Pedosphere 27, 769–777. https://doi.org/10.1016/S1002-0160(17)60303-5.
Li, T., Zhang, W., Yin, J., Chadwick, D., Norse, D., Lu, Y., Liu, X., Chen, X., Zhang, F., Powlson, D., Dou, Z., 2018. Enhanced-efficiency fertilizers are not a panacea for resolving the nitrogen problem. Glob. Chang. Biol. 24, e511–e521. https://doi.org/10.1111/gcb.13918.
Liu, J., You, L., Amini, M., Obers teiner, M., Herrero, M., Zehnder, A., Yang, H., 2010. A high-resolution assessment on global nitrogen flows in cropland. Proc. Natl. Acad. Sci. U.S.A. 107, 8035–8040. https://doi.org/10.1073/pnas.0913658107.
Lu, Y., Jenkins, A., Ferrier, R.C., Bailey, M., Gordon, I.J., Song, S., Huang, J., Jia, S., Zhang, F., Liu, X., 2015. Addressing China's grand challenge of achieving food security while ensuring environmental sustainability. Sci. Adv. 1, e1400039. https://doi.org/10.1126/sciadv.1400039.
Ma, Q., Wang, X., Li, H., Li, H., Zhang, F., Rengel, Z., Shen, J., 2015. Comparing localized application of different N fertilizer species on maize grain yield and agronomic N-use efficiency on a calcareous soil. Field Crop. Res. 180, 72–79. https://doi.org/10.1016/j.fcr.2015.05.011.
Maharjan, B., Venterea, R.T., 2013. Nitrite intensity explains N management effects on N_2O emissions in maize. Soil Biol. Biochem. 66, 229–238. https://doi.org/10.1016/j.soilbio.2013.07.015.
Mwangi, W.M., 1996. Low use of fertilizers and low productivity in sub-Saharan Africa. Nutrient Cycl. Agroecosyst. 47, 135–147. https://doi.org/10.1007/BF01991545.
Nash, P., Motavalli, P., Nelson, K., 2012. Nitrous oxide emissions from claypan soils due to nitrogen fertilizer source and tillage/fertilizer placement practices. Soil Sci. Soc. Am. J. 76, 983–993. https://doi.org/10.2136/sssaj2011.0296.
Niu, X., Ju, X., 2017. Organic fertilizer resources and utilization in China. J. Plant Nutr. Fert. Sci. 23, 1462–1479. https://doi.org/10.11674/zwyf.17430.
Pypers, P., Sanginga, J.M., Kasereka, B., Walangululu, M., Vanlauwe, B., 2011. Increased productivity through integrated soil fertility management in cassava–legume intercropping systems in the highlands of Sud-Kivu, DR Congo. Field Crop. Res. 120, 76–85. https://doi.org/10.1016/j.fcr.2010.09.004.
Qiao, C., Liu, L., Hu, S., Compton, J., Greaver, T., Li, Q., 2015. How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. Glob. Chang. Biol. 21, 1249–1257. https://doi.org/10.1111/gcb.12802.
Rajkovich, S., Crozier, C., Smyth, T., Crouse, D., Osmond, D., 2015. Updating North Carolina corn yields and nitrogen recommendations to match current production practices and new hybrids. Crop Forage Turfgrass Manag. 1. https://doi.org/10.2134/cftm2014.0085.
Reche, C., Viana, M., Pandolfi, M., Alastuey, A., Moreno, T., Amato, F., Ripoll, A., Querol, X., 2012. Urban NH_3 levels and sources in a Mediterranean environment. Atmos. Environ. 57, 153–164. https://doi.org/10.1016/j.atmosenv.2012.04.021.
Rodgers, G., Wickramasinghe, K., Jenkinson, D., 1985. Mineralization of dicyandiamide, labelled with 15N, in acid soils. Soil Biol. Biochem. 17, 253–254. https://doi.org/10.1016/0038-0717(85)90124-5.
Shaviv, A., 2005. Controlled Release Fertilizers IFA International Workshop on Enhanced-Efficiency Fertilizers, Frankfurt. International Fertilizer Industry Association, Paris, France.
Snyder, C., Davidson, E., Smith, P., Venterea, R., 2014. Agriculture: sustainable crop and animal production to help mitigate nitrous oxide emissions. Curr. Opin. Environ. Sust. 9–10, 46–54. https://doi.org/10.1016/j.cosust.2014.07.005.
Sommer, S.G., Schjoerring, J.K., Denmead, O.T., 2004. Ammonia emission from mineral fertilizers and fertilized crops. Adv. Agron. 82, 557–622. https://doi.org/10.1016/S0065-2113(03)82008-4.
Sun, H., Zhang, H., Powlson, D., Min, J., Shi, W., 2015. Rice production, nitrous oxide emission and ammonia volatilization as impacted by the nitrification inhibitor 2-chloro-6-(trichloromethyl)-pyridine. Field Crop. Res. 173, 1–7. https://doi.org/10.1016/j.fcr.2014.12.012.
Trenkel, M.E., 2010. Slow-and Controlled-Release and Stabilized Fertilizers: an Option for Enhancing Nutrient Use Efficiency in Agriculture. IFA, International Fertilizer Industry Association, Paris, France.
Venterea, R.T., Coulter, J.A., Dolan, M.S., 2016. Evaluation of intensive "4R" strategies for decreasing nitrous oxide emissions and nitrogen surplus in rainfed corn. J. Environ. Qual. 45, 1186–1195. https://doi.org/10.2134/jeq2016.01.0024.
Vitousek, P.M., Naylor, R., Crews, T., David, M.B., Drinkwater, L.E., Holland, E., Johnes, P.J., Katzenberger, J., Martinelli, L.A., Matson, P.A., Nziguheba, G., Ojima, D., Palm, C.A., Robertson, G.P., Sanchez, P.A., Townsend, A.R., Zhang, F.S., 2009. Nutrient imbalances in agricultural development. Science 324, 1519–1520. https://doi.org/10.1126/science.1170261.
Vlek, P., Byrnes, B., Craswell, E., 1980. Effect of urea placement on leaching losses of nitrogen from flooded rice soils. Plant Soil 54, 441–449. https://doi.org/10.1007/bf02181836.
Wang, M., Yang, J., Xu, W., Wang, H., Sun, J., 2009. Influence of nitrogen rates with split application on N use efficiency and its eco-economic suitable amount analysis in rice. J. Zhejiang Univ. (Agric. Life Sci.) 35, 71–76.
Yan, X., Hosen, Y., Yagi, K., 2001. Nitrous oxide and nitric oxide emissions from maize field plots as affected by N fertilizer type and application method. Biol. Fertil. Soils 34, 297–303. https://doi.org/10.1007/s003740100401.
Zhang, X., 2017. A plan for efficient use of nitrogen fertilizers. Nature 543, 322–323. https://doi.org/10.1038/543322a.
Zhang, X., Davidson, E., Mauzerall, D., Searchinger, T., Dumas, P., Shen, Y., 2015a. Managing nitrogen for sustainable development. Nature 528, 51–59. https://doi.org/10.1038/nature15743.
Zhang, X., Mauzerall, D.L., Davidson, E.A., Kanter, D.R., Cai, R., 2015b. The economic and environmental consequences of implementing nitrogen-efficient technologies and management practices in agriculture. J. Environ. Qual. 44, 312–324. https://doi.org/10.2134/jeq2014.03.0129.
Zhang, W., Cao, G., Li, X., Zhang, H., Wang, C., Liu, Q., Chen, X., Cui, Z., Shen, J., Jiang, R., Mi, G., Miao, Y., Zhang, F., Dou, Z., 2016. Closing yield gaps in China by empowering smallholder farmers. Nature 537, 671–674. https://doi.org/10.1038/nature19368.
Zhang, J., Cai, Z., Müller, C., 2018. Terrestrial N cycling associated with climate and plant-specific n preferences: a review. Eur. J. Soil Sci. 69, 488–501. https://doi.org/10.1111/ejss.12533.
Zhou, J., Gu, B., Schlesinger, W., Ju, X., 2016. Significant accumulation of nitrate in Chinese semi-humid croplands. Sci. Rep. 6, 25088. https://doi.org/10.1038/srep25088.