Research Article

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Impacts of nitrogen practices on yield, grain quality, and nitrogen-use efficiency of crops and soil fertility in three paddy-upland cropping systems

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Abstract

BACKGROUND: Global food security faces a number of challenges due to increasing population, climate change, and urbanization, while excessive use of nitrogen fertilizers has become a major challenge for sustainable, intensive agriculture. Assessing the impact of agronomic management practices on seed yield, grain quality, and soil fertility is a critical step in understanding nutrientuse efficiency.

RESULT: The comprehensive evaluation index had good fitness to that of single attribute (i.e. seed yield, crop quality and soil fertility), indicating that the comprehensive evaluation index was reliable. Applying controlled-release urea (rice in wheat and oilseed rape field: 150 kg N ha^{-1}, other crops: 120 kg N ha^{-1}) plus common urea (30 kg N ha^{-1}) incorporating straw from the previous season across the growing season for cereal and oilseed crops showed a slight improvement in seed productivity and Nuse efficiency among three cropping systems in the traditional evaluation method. Compared with local farm practice (applying common urea of 150 kg N ha^{-1}), applying these practices in combination based on the outcome of the comprehensive evaluation index method decreased the seed yield by −1.27 ~ 29.8% but improved quality and soil fertility for the paddy-upland cropping system, respectively.

CONCLUSION: Properly managing N application by applying partial and fully controlled release of urea with or without straw incorporation for a specific crop system has the potential to provide a better compromise among yield, grain quality, and soil fertility in southern China.

Supporting information may be found in the online version of this article.

Keywords: comprehensive evaluation index; cropping system; seed yield; crop quality; soil fertility

INTRODUCTION

Achieving global food security is a complex problem arising from a number of challenges such as increasing population, climate change, and urbanization.[1–3] To maintain or increase crop yields, chemical fertilizers have historically been mismanaged, resulting in environmental pollution and decreased nutrient-use efficiency.[4–6] Excessive use of N fertilizers has become a major challenge for sustainable intensive agriculture in China,[7,8] causing high greenhouse-gas emissions, nitrate-N content in groundwater and drinking water and residual N in soil.[9,10] Liu *et al*.[11] reported that nitrogen (N) fertilizer application rates ranged from 200 to 400 kg ha^{-1} over a rice (*Oryza sativa* L.) season in a rice winter wheat (*Triticum aestivum* L.) cropping system in China. Moreover, over-fertilization may result in yield reduction and poor seed quality.[12,13]

Nitrogen fertilizer is the most critical nutrient associated with crop productivity in an intensive cropping system. Supplementation with an appropriate quantity of N fertilizer can increase crop productivity as it increases leaf development and maintenance as well as the rate of photosynthesis.[14,15] For example, N fertilizer has been estimated to have contributed around a 40% increase in per capita food production in the past 50 years.[16] Moderate N application rates also increase enzyme activity related to lignin synthesis, thus improving mechanical strength in winter wheat culms and achieving high seed yields.[17,18] In addition, proper N fertilizer

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application is essential in improving grain quality because of an increase of N uptake and its remobilization to economic organ over the reproductive stage, thus increasing seed yield and economic benefits.[19,20] However, previous studies have shown that conventional N management practices producing increased seed yield tend to achieve lower grain quality and decrease soil fertility.[21,22] In recent years, focus has shifted towards considering the relationship with seed quality and soil fertility while maintaining high seed yield and economic benefits delivered by properly management N application. This has occurred in line with the improvement in China's economy and standard of living.[23] Thus, the definition of optimized N application for each cereal or oilseed crop should require consideration of seed yield, grain quality, and soil fertility, and should not compromise on any of these factors.

Principal component analysis (PCA) is a multi-index comprehensive evaluation method developed to identify patterns in data, and express data in a way that highlights their similarities and differences. It is a powerful tool for analyzing the major elements and structures in the original data, removing noise and redundancy, reducing dimensions, and revealing hidden elements behind simple structures with no parameter restrictions.[24] The PCA method is also simple and the result is easy to understand. It has been used to solve complicated decision-making problems in recent years.[24,25] Compared with other techniques (e.g. the analytic hierarchy process and the technique for order of preference by similarity to ideal solution), PCA decreases subjective judgement from analyzers in evaluating or ranking multiple attributes.[26] The multi-index comprehensive evaluation method that PCA therefore means that it is an appropriate tool for comprehensive assessment of the impacts of various fertilizer practices on yield, quality of crop seeds, and soil fertility.[27]

Three field experiments were conducted with different N management practices in wheat-rice, oilseed rape-rice and early rice-late rice cropping systems in the Yangtze River basin of China. The objectives of the study were (i) to compare the implications of N management practices on grain yield, crude protein, and N use efficiency; (ii) to determine the comprehensive evaluation index (EI) for different treatments, and (iii) to propose better N scheduling considering the components of yield, seed quality, and soil fertility in the area that was studied.

MATERIALS AND METHODS

Experimental sites

The field experiments were conducted at two sites in the Yangtze River basin of China from 2015 to 2018: Wangcheng County, Hunan province (28.37° N, 112.80 °E) and Qujialing County, Hubei province (30.90° N, 112.81° E) (Fig. 1). Mean monthly air temperature over the experimental years at the Qujialing site ranged from 4.7 °C in January to 28.7 °C in August and mean annual precipitation was 1064 mm, which mainly occurred between March and September. The averages of monthly minimum and maximum air temperature, and annual precipitation are 3.6 °C (January) 32.8 °C (August) and 1448 mm at the Wangcheng site. Daily minimum and maximum temperatures and rainfall for the Changsha and Jingmen sites are shown in Fig. S1. Three dominant rotations in the basin were used in this study: early – late rice (R–R), winter wheat – rice (W–R) and oilseed rape – rice (O–R). The R–R rotation was only included in the experiment at Wangcheng from 2016 to 2018, and the others were conducted at Qujialing from 2015 to 2018.

Experimental design and operation

Treatments were arranged in a randomized complete block design. The plot size for R–R was 4 m × 5 m, and 5 m × 8 m for W–R, and O–R. There were eight fertilizer treatments: no N fertilizer application (CK), controlled release urea at 150 kg N ha^{-1} (CR1), controlled release urea at 120 kg N ha^{-1} plus common urea at 30 kg N ha^{-1} (CR2), CR2 plus all straw return-to-field in previous season (CR2SR), common urea at 120 kg N ha^{-1} (N1), common urea at 150 kg N ha^{-1} (N2, farm conventional practice), N2 plus straw return-to-field in previous season (N2SR), and common urea at 180 kg N ha^{-1} (N3). Each treatment was replicated three times. In the W–R and O–R systems, an extra amount of 30 kg N ha^{-1} was applied to rice for all the treatments except CK. Seventy percent of applied N was basal fertilizer and the rest was top dressing applied at tillering. All the treatments received the same amount of calcium superphosphate (75 P_2O_5 kg ha^{-1}) and potassium chloride (120 K_2O kg ha^{-1}) as basal fertilizer for each crop. The total straw weight of the previous crop at harvest was returned to each plot, which was incorporated with soil ploughing (depth: 15 cm). Local crop cultivars were used and local field management practices including conventional tillage, weed, and pest control were adopted. The conventional N application rate in the area is 150 kg N ha^{-1} in the form of urea for each crop season, with the exception of 180 kg N ha^{-1} applied to following rice season in the W–R and O–R cropping system. Plots were tilled before sowing or transplanting with a field cultivator to a depth of 10–15 cm. The crop management schedule is shown in Table 1.

Crop and soil measurements

At harvest, seed yield was determined from all plants in each plot using hand harvest and machine threshing. Plant samples were collected from 1 m^2 per plot, divided into straw and grain components. All plant samples were oven dried at 60 °C to a constant weight, then weighed and analyzed for seed N concentration using H_2SO_4-H_2O_2 digestion and a continuous-flow injection analyzer (AA3, Bran and Luebbe, Norderstedt, Germany).[28] Then crude protein content of seed was calculated based on its N content multiplied by a conversion efficient (5.83, 5.95, and 5.53 for wheat, rice, and oilseed rape, respectively – https://std.smar.gov.cn).

Before the experiments started, soils at a depth of 0–20 cm were collected using a 2 cm diameter stainless steel sample auger with an S-shaped pattern in the field and were mixed to measure soil chemical properties as a baseline (Table 2). At harvest, soils were collected using the same method. After removing stone and visible roots by hand, the soil samples were air-dried and then sieved with a 0.25 mm to analyze soil pH, organic matter (OM), available N (AN), and total soil N content (TN). Soil pH was measured with a ratio of 1:1 soil to water. Organic matter content was determined using the dichromate-sulfuric acid ($K_2C_rO_7$-H_2SO_4) oxidation method, AN was quantified by the Alkali N proliferation method, and TN was determined using the Kjeldahl digestion-distillation method.[29,30]

Data analysis

Nitrogen use efficiency (NUE) is expressed as in Eqn (1):[31]

$$\text{NUE}=\frac{A_n-A_0}{F_n}\times 100 \tag{1}$$

where F_n is the rate of applied N for a fertilized treatment, A_n is N content in seed for the treatment, and A_0 is N content in seed from CK.

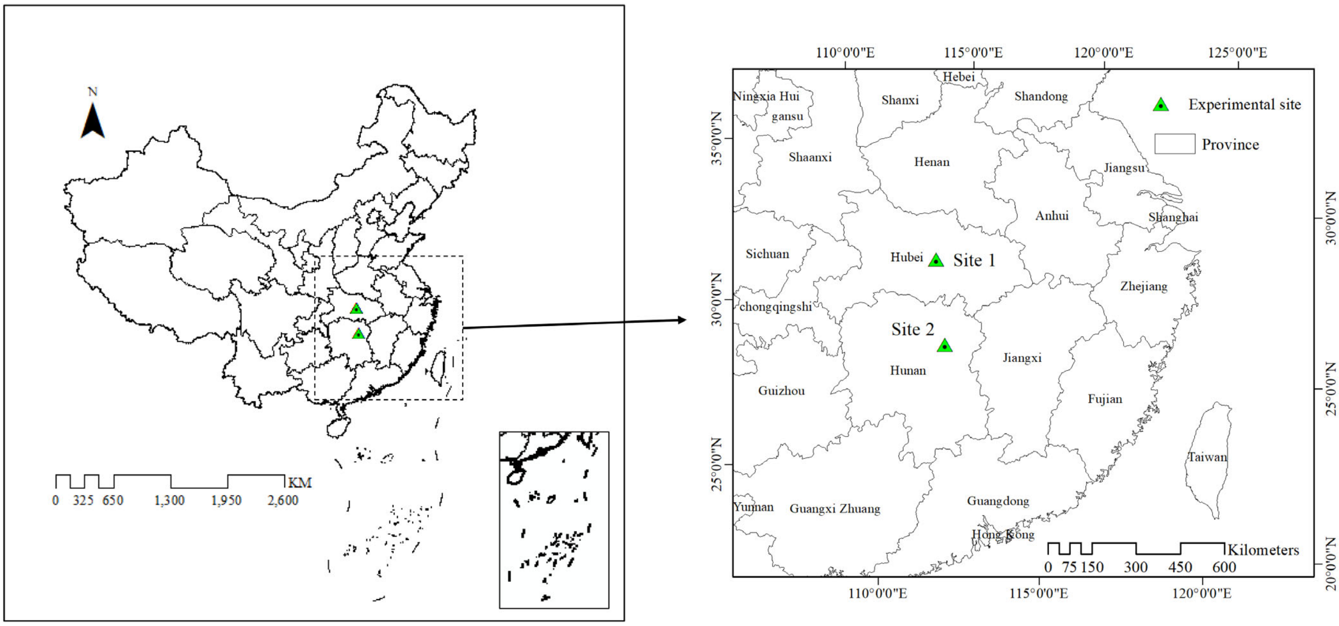

Figure 1. Location of the experimental sites. Site 1 included the cropping systems of wheat–rice and oilseed rape–rice, and site 2 included the early–late rice cropping system.

Table 1. Sowing or transplanting and harvest date, and cultivar for each crop

Cropping system	Crop	Sowing date	Harvest date	Cultivars
Rice – rice	Early rice	Late April	Mid-July	Fengyuanyou 272
	Late rice	Late July	Mid-October	Shenyou 9586
Wheat – Rice	Wheat	Late October	Late May	E'mai 596
	Rice	Mid-July	Late September	Huanghuazhan
Oilseed rape – rice	Oilseed rape	Mid-October	Early May	Zhongshuang 12
	Rice	Mid-July	Late September	Huanghuazhan

Table 2. Baseline soil properties at Wangcheng and Qujialing sites in the Yangtze River basin

Sites	pH	Available nitrogen mg kg^{-1}	Available phosphorus mg kg^{-1}	Available potassium mg kg^{-1}	Total soil nitrogen g kg^{-1}	Soil organic matter g kg^{-1}
Wangcheng	6.6	118.65	10.19	107.03	2.32	36.33
Qujiangling	5.99	187.00	5.66	195.40	1.99	27.03

In the present study, the PCA method was applied to evaluate the effects of N management on yield (grain yield (GY), kernel grain weight (KGW), effective panicles per plant (EEP), seed quality (crude protein content, CP), and soil fertility (AN, TN, and OM, respectively). A step-by-step procedure for computation was described by Zheng *et al*. in 2012,[32] including the original variable matrix establishment and standardization, the correlation coefficient matrix calculation, the eigenvector matrix calculation, and main component matrix calculation. The PCA was conducted using the IBM SPSS Statistics 19 analysis software. Principal components were determined by accumulated contribution rate of eigenvector contribution rate that was not less than 85%.[32]

In this study, when the eigenvector contribution rate of the first three principal components accumulated to 94%, these three components were chosen to be principal component values. The product of each selected variable and its eigenvector was summed as the value of a principal component. Then the total principal component value (F) was calculated as in Eqn (2):

$$F = \sum_{i=1}^{3} PV_i \times PCV_i \quad (2)$$

where PV_i is the proportion (%) of variance for component *i* and PCV_i is the value of principal component *i*.

A comprehensive evaluation index (EI) that considers the contribution of yield, grain quality, and soil fertility was used to determine the optimum N application strategy for each crop as in Eqn (3):[23]

$$EI = F_y + F_q + F_s \quad (3)$$

where F_y, F_q, and F_s are the F values for yield, grain quality, and soil fertility, respectively. A low EI value indicates that the N application practice would be superior among all the treatments for each crop.

To test the difference between N fertilizer treatments, we performed a one-way analysis of variance (ANOVA) and calculated the least significant differences (LSDs, $P < 0.05$). The analyses were conducted in SPSS 20.0 (SPSS, Inc., 2011, Chicago IL, USA).

RESULTS

Crop yields

The seed yield of each crop significantly increased with fertilizer application, compared with that in CK (Fig. 2). There was no significant effect of N application rate on yields of rice and oilseed rape (Fig. 2(a) and (c)). However, wheat yield was significantly affected by N management with the highest (3942 kg ha^{-1}) in the CR2 treatment (Fig. 2(b)). Rice yields with the N2SR treatment reached their highest in the R–R cropping system. Rice yields with the CR2SR treatment reached their highest in the W–R cropping system. Rice yields with the CR2 treatment reached their highest in the O–R cropping system. Oilseed rape field yield was the highest with the CR2SR treatment.

Crude protein

The average crude protein content in seeds over three cropping seasons for each crop in different cropping systems is shown in Fig. 3. The addition of nitrogen significantly increased the crude protein content in seeds. The content also increased with the N rate until 150 kg N ha^{-1} (180 kg N ha^{-1} of rice in wheat and oilseed rape field), while further increases of N input failed to improve seed crude protein. Among the N management treatments, the highest crude protein concentrations for early rice and late rice were observed under CR2 (85 g kg^{-1} DM) and CR2SR (88 g kg^{-1} DM), respectively, which were significantly higher than N2 (74 g kg^{-1} DM) (Fig. 3(a)). Similarly, CR2 and CR2SR had the highest seed crude protein in the W–R cropping system compared with other treatments. Compared with local farmer custom fertilization (N2), the crude protein under CR2 and CR2SR for wheat and rice (wheat field) were significantly increased by an average of 127 g kg^{-1} DM and 120 g kg^{-1} DM, respectively (Fig. 3(b)). For the O–R cropping system, the crude protein content was highest with CR2 in oilseed rape and with CR1 in rice (oilseed rape field). There was a significant difference between optimum N management (oilseed rape and rice, CR2 and CR1) and N2 in O–R cropping system (Fig. 3(c)).

Nitrogen use efficiency

Crop NUE tended to be higher with partial or full substitution of common urea by CR urea than in the treatments amended with common urea only, and the lowest NUE was observed in the N2SR treatment for all the crops in three cropping systems except early rice (Fig. 4). Mean NUE for each crop, except early rice in the N2SR treatment, tended to be significantly lower than in other treatments. Nitrogen-use efficiency decreased with an increase in the N rate, but the significance of the difference between treatments was inconsistent among the crops. Mean NUE for late rice under CR1 (70%) was significantly higher than that in the N2 treatment (54%) (Fig. 4(a)). In general, the practice for CR2 treatment was superior to enhance NUE for all the crops in the W–R and O–R cropping systems compared with other treatments, although rice NUE (62% and 70% in W–R and O–R, respectively) for the treatment was slightly lower than that in N1 (65% and 75% in W–R and O–R, respectively, Fig. 4(b) and (c)).

Comprehensive evaluation

Comprehensive evaluation indices suggested that partial or full substitution of common urea by CR urea was superior in each crop in three cropping systems (Tables 3, S1 and S2). Among the N treatments in the R–R rotation, the lowest EIs for early rice and late rice were observed under CR2SR (−0.51) and CR1 (−0.34),

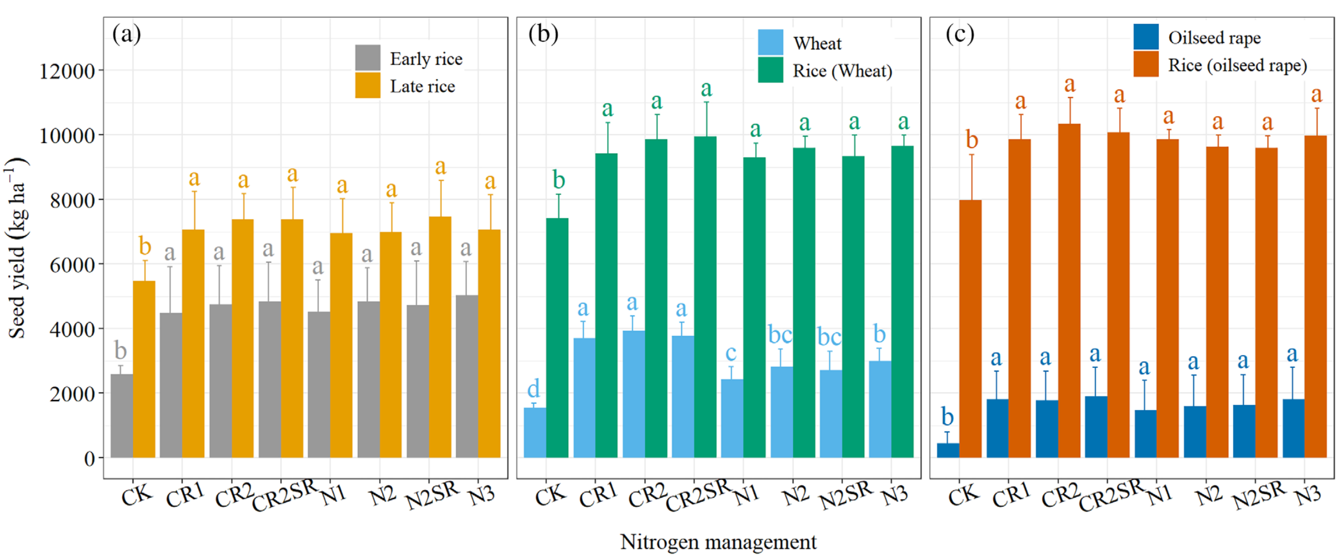

Figure 2. Average yield of rice, wheat, and oilseed rape in each treatment between 2015 and 2018. Different lowercase letters represent significant differences ($P < 0.05$, LSD) under different N treatments in each individual crop. The bar represents standard deviation of yield in each N treatment.

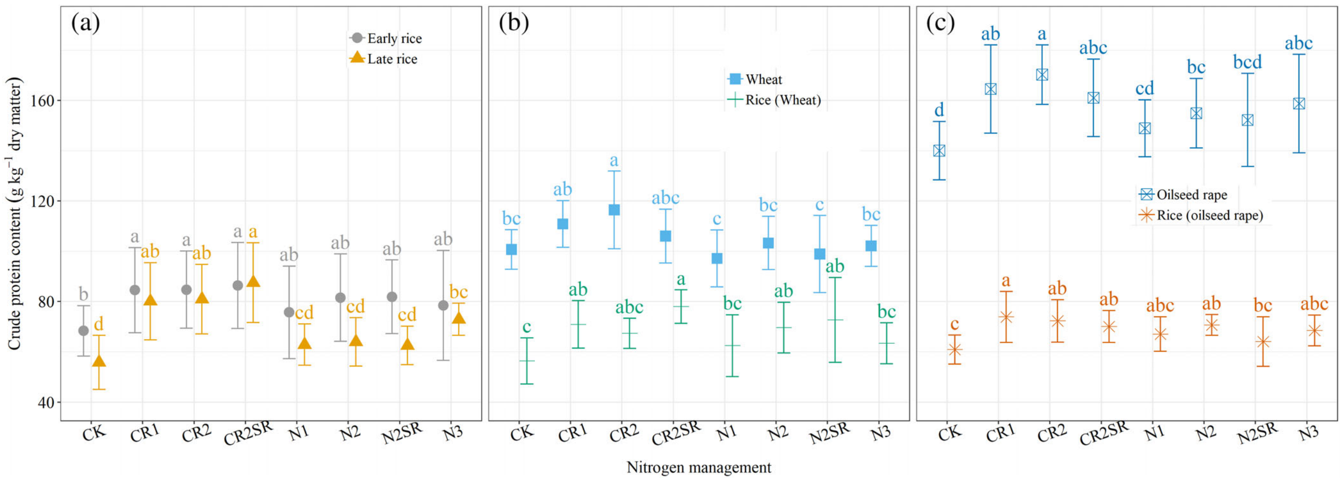

Figure 3. Average crude protein content of rice, wheat, and oilseed rape in each treatment from 2015 to 2018. Different lowercase letters represent significant differences ($P < 0.05$, LSD) under different N treatments in each individual crop. The bar represents standard deviation of crude protein content in each N treatment.

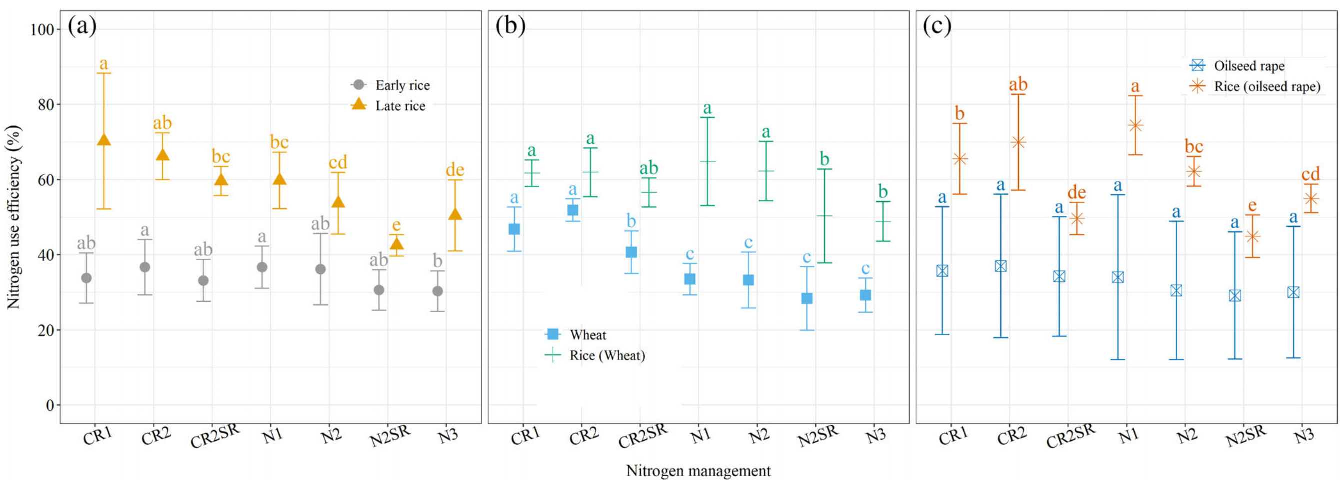

Figure 4. Average N use efficiency of rice, wheat, and oilseed rape in each treatment from 2015 to 2018. Different lowercase letters represent significant differences ($P < 0.05$, LSD) under different N treatments in each individual crop. The bar represents standard deviation of N use efficiency in each N treatment.

respectively, followed by N2 (−0.47 and −0.30). In the W–R system, the lowest EI was found in CR2 for wheat and CR1 for rice, respectively. Similarly in the O-R system, CR2SR and CR1 had the lowest comprehensive EI for oilseed rape and rice among the treatments, respectively, and N application rates decreased 35.3% and 33.7%, respectively, compared with local practice (N2). Among the rotation systems, the lowest total EIs were observed under straw with synthetic fertilizer incorporated in the O–R rotation (−1.52), followed by the W–R (−0.90) and R – R (−0.80).

DISCUSSIONS

Effects of nitrogen management on seed yield and nitrogen use efficiency

The CR urea plus straw incorporation or the combination of CR urea products and common urea outperformed common urea in increasing N use efficiency and in seed yield, which is in agreement with previous studies.[33,34] These two practices are well suited to the N requirements of cereal crops, which enhanced grain yield, NUE, and economic benefit, as well as reducing the leaching of inorganic N around the plant root.[33] In our study, the yield of each single crop in mixture treatments (CR2 and CR2SR) increased 34.0–39.9%, 0.1–7.3% and 11.3–18.2% for winter wheat, rice, and oilseed rape, respectively, compared with the yield with common urea at the same N rate, due to slow release of CR urea, which increased the late-season N availability and crop growth (Fig. 2).[35] Moreover, the mineralization of straw incorporation had a direct nutritional effect on improving soil characteristics across various pedo-climatic environments under field conditions, which indirectly enhanced grain yields.[36–38]

In this study, partial or full substitution of common urea by CR urea tended to improve plant growth and N availability compared with farm conventional practice (Fig. 4). The NUE values obtained with CR1 and CR2 for late rice and rice (wheat field) were 4.1–27.8% and 5.1–23.5% higher than those with the other treatments, respectively (Fig. 4(a) and (b)). Similar results were described by Wang *et al.*[35] who reported that NUE from the

Table 3. Evaluation indices for different crops with various treatments

Rotation	Treatment	Crop	F_y	F_q	F_s	EI	Crop	F_y	F_q	F_s	EI	Total EI
Rice - rice	CR1	Early rice	−0.49	−0.28	0.29	−0.48	Late rice	**−0.28**	−0.32	0.26	**−0.34**	−0.82
	CR2		−0.49	−0.29	030	−0.49		−0.28	−0.32	0.26	−0.33	−0.82
	CR2SR		−0.48	**−0.32**	0.29	**−0.51**		−0.27	**−0.33**	0.26	−0.34	**−0.84**
	N1		−0.49	−0.28	0.29	−0.48		−0.22	−0.29	**0.25**	−0.26	−0.74
	N2		−0.46	−0.28	0.28	−0.47		−0.26	−0.30	0.26	−0.30	−0.76
	N2SR		**−0.50**	−0.29	**0.23**	−0.48		−0.25	−0.29	0.27	−0.27	−0.75
	N3		−0.49	−0.28	0.31	−0.46		−0.27	−0.31	0.27	−0.31	−0.77
Wheat - rice	CR1	Wheat	−0.42	−0.51	**0.20**	−0.73	Rice	−0.10	−0.27	0.20	**−0.16**	−0.89
	CR2		−0.45	**−0.52**	0.22	−0.76		−0.04	−0.26	0.20	−0.10	−0.86
	CR2SR		−0.44	−0.51	0.22	−0.73		**−0.08**	**−0.29**	0.21	−0.16	−0.89
	N1		−0.46	−0.48	0.21	−0.73		−0.04	−0.24	**0.19**	−0.09	−0.82
	N2		−0.45	−0.50	0.21	−0.75		−0.06	−0.26	0.21	−0.12	−0.86
	N2SR		**−0.50**	−0.50	0.23	**−0.77**		−0.07	−0.26	0.20	−0.13	**−0.90**
	N3		−0.49	−0.51	0.23	−0.77		−0.06	−0.26	0.20	−0.12	−0.89
Oilseed rape - rice	CR1	Oilseed rape	−1.26	−0.28	0.21	−1.33	Rice	−0.00	**−0.29**	0.18	**−0.11**	−1.44
	CR2		−1.17	**−0.29**	0.19	−1.26		**−0.03**	−0.27	0.20	−0.10	−1.36
	CR2SR		**−1.35**	−0.28	**0.19**	**−1.43**		−0.01	−0.27	0.19	−0.09	**−1.52**
	N1		−0.87	−0.26	0.19	−0.93		−0.03	−0.27	0.19	−0.10	−1.04
	N2		−0.98	−0.27	0.19	−1.06		−0.00	−0.26	**0.17**	−0.08	−1.14
	N2SR		−1.14	−0.26	0.20	−1.21		−0.02	−0.26	0.19	−0.10	−1.30
	N3		−1.13	−0.27	0.20	−1.21		−0.02	−0.27	0.17	−0.08	−1.29

F_y, F_q and F_s are the total principal component values for yield, grain quality, and soil fertility, respectively. EI and total EI indicated the evaluation indices in each crop and rotation.

farmer's fertilizer practice with 150 kg N ha^{-1} as split urea application was 6–11% lower than that for sole CR urea basal application. Li *et al.*[34] found that the NUE values from CR urea at a rate of 165 kg N ha^{-1} ranged from 41% to 71%, which was higher than that from common urea application over the rice growing season. Applying CR urea for improving NUE could be because the N release of the CR urea closely matched the N demands of the rice plants and enhanced the activities of N remobilization-related enzymes in leaves and stems over the reproductive stage, such as nitrate reductase and glutamine synthetase.[39] Delayed N release under coated fertilizer or incorporated straw also coincided with high temperature and humidity in southern China (Fig. S1) leading to a high N mineralization rate, which enhanced leaf photosynthesis and biomass accumulation at late growth stage.[40] These results showed that CR urea application with urea or straw incorporation could greatly increase both seed yield and NUE in the cropping system.

Seed quality response to nitrogen management

Nitrogen is a major structural component of protein, and N addition could result in increasing protein content or improving seed quality.[41] Properly managing N application is essential in N transformation and remobilization between vegetative and economic organs in plants over the grain filling process, which is beneficial for obtaining good appearance and seed quality.[22] The CR urea significantly enhanced seed quality and improved the appearance and taste quality, which is beneficial for performance in the agricultural market.[42] This is because applied slow-release fertilizers with 'peak cutting for valley filling' characteristics supplied sufficient N for the plants over the reproductive period, which improved seed quality by increasing the stability of the grain-filling process.[43] Similarly, urea with the urease inhibitor *N*-(*n*-butyl) thiophosphoric triamide can reduce seed chlorophyll and glucosinolates, and thus enhance seed quality in oilseed rape.[41] This may be because seed quality benefits from straw incorporation in anaerobic environments such as paddy soil where plant N uptake relies on N mineralized from crop residues or straw. The breakdown of incorporated straw (by environmental factors weather, soil, water and microbial activity) also resulted in increased nutrient release.[38] This may be because seed quality benefits from straw incorporation in anaerobic environments, such as paddy soil, where plant N uptake relies on N mineralized from crop residues or straw.[38] Thus, with a proper N source, CR urea plus straw could have the potential to improve seed quality and economic benefits.

A previous study reported that crude protein content is an appropriate measure for seed quality for cereals and oilseeds.[44] In this study, therefore, we focused on crude protein as a proxy for crop quality, due to the focus on N use efficiency. A number of further crop quality indicators, such as cooking and eating quality, and further nutritional factors such as starch, could be important in determining the final quality of a crop. To acquire reliable effects of N management on crop quality in cereal and oilseed crop, it would therefore be advantageous to consider further indicators in future work where there is a wider nutritional focus.

Nitrogen scheduling with the compromise among yield, seed quality and soil fertility

Properly managed N application has the opportunity to offer increased economic benefit by improving seed yield and quality and also by maintaining soil fertility.[45–47] However, there is often an imbalance between these factors.[45] Nitrogen scheduling should take into consideration the effects of N on the yield and seed quality as well as sustainability of soil fertility. A focus on only high-yielding production could deplete fertilizer resources and reduce the N use efficiency.[48] In this study, applying high N rates for wheat (180 kg N ha^{-1}), oilseed rape (180 kg N ha^{-1}), and rice (210 kg N ha^{-1}) over the growing period had a slight improvement in grain yield and its components and yet significantly decreased NUE compared with other N treatments (Figs 2 and 4, Table S3).

Conventional evaluation methods can only assess the impact of N management practices on a single objective (i.e. seed yield or NUE) (Figs 2 and 4). Thus, a multiple indicator evaluation method could have potential in assessing the effects of various fertilizer practices on yield, quality of crop seeds, and soil fertility.[45] As for the comprehensive EI, which considers yield and its components (F_y), partial or full substitution of common urea by CR urea tend to reach the highest yield or NUE in each crop (Tables 3, S3 and Fig. 4). This may be because (i) a simple indicator such as NUE tends to increase with a decrease in the N application rate, which might not achieve the target yield,[31] and (ii) yield components such as effective panicles and 1000-grain weight were affected by the varieties and environmental changes.[49,50] For the comprehensive EI that considering high seed quality (F_q), applying partial or full substitution of common urea by CR urea (CR2 and CR1) could be a potential way to increase the crude protein content for oilseed rape and rice crops (Table 3). However, this may lead to a slightly decreasing seed yield due to the decline of N uptake in plant at an early growing stage, which is in agreement with a previous study (Fig. 2, Table S4).[51]

Soil organic matter, total N content, and available N are the main components of soil fertility, which plays a crucial role in regulating soil carbon and N cycling, soil aeration, nutrient retention and use efficiency, gaseous emissions, plant growth and development.[52–54] In this study, therefore, soil N sources for plant uptake and utilization, such as STN, AN, and OM were considered as specific indicators of soil fertility for evaluating the effects of N management on crop productivity. For the comprehensive EI considering soil fertility (F_s), reduced N fertilization and straw return into soil could be effective in increasing soil organic carbon and decreasing N losses compared with single soil attributes (Tables 3 and S4).[55] This may be because incorporated straw is decomposed by microbial activities under appropriate environmental conditions such as soil temperature and moisture during the growing season, which increases crop N uptake while minimizing N leaching later.[56–58]

The lowest total EI was found in the O–R cropping system under CR2SR compared with other rotation under appropriate N management (CR2SR and N2SR for R – R and W–R, respectively) (Table 3). This may be because the optimization of N management strategy (i.e. CR2SR) could meet crop N requirement in time,[59] which is able to achieve better seed yield (the average of F_y: −0.44) and soil fertility (the average of F_s: 0.23) and maximize the crude protein (the average of F_q: −0.33) (Table 3). Additionally, the W–R and R–R rotations have higher nutrient utilization efficiency, harvest index, and leaf area index while emitting N losses to the environment through gaseous emission and leaching,[34,60] which could result in depleting more soil nutrients and posing a great threat in the sustainability of agricultural land use.[61,62]

For intensive agricultural systems in southern China, seed yield is reaching a plateau level with high-yielding cultivars and higher fertilizer application in recent decades.[63] However, crop quality and soil sustainability issues associated with agricultural management practices have not been fully explored because the main economic driver is seed yield. High seed quality is one of the measures for evaluating the nutritional value of food, which can result in greater economic benefits in a competitive market.[23] Maintaining soil fertility is also fundamental for building an input-based high agricultural production system, which has the potential to increase resilience of food demand to increasing population, climate change, and urbanization.[1,2,54]

Properly managing N application based on yield, seed quality, and soil fertility should be maximized.[23,47] However, higher fertilization rates are only required for maximizing yield, not for optimizing seed quality.[64] Seed yield for oilseed rape and early rice was maximized at N3, whereas optimum seed quality was recorded at the lower rates at CR2 and CR2SR due to the slower seed quality response to N (common urea) than yield (Fig. 2 and Table 3). If considering yield, seed quality and soil fertility, moderate N management for R–R, W–R and O–R cropping systems, respectively, would be the combinations of CR2SR-CR1, N2SR-N2SR, and CR2SR-CR2SR, in which the N practice had better quality and soil fertility. This is in agreement with a previous study, which showed that enhancing crop quality and maintaining soil fertility are usually at the expense of partial yield.[64,65] Thus, CR urea and straw incorporation may be a suitable N management practice for improving the seed quality and maintaining soil fertility, although with a slightly declining yield in the cropping systems.

CONCLUSION

Properly managing N application is vital for the improvement of crop yield, quality and N use efficiency, soil fertility, and ecological sustainability in agricultural systems. Application of controlled release urea at 120 kg N ha^{-1} (rice in wheat and oilseed rape field: 150 kg N ha^{-1}) and urea at 30 kg N ha^{-1}, with or without straw incorporation, achieved a considerably higher crop yield in three rotation systems but was not superior in grain quality and soil fertility. Based on the comprehensive evaluation indices, the combined practices of CR2SR-CR1 (in R–R), N2SR-N2SR (in W–R), and CR2SR-CR2SR (in O–R) for individual crops in the rotation system can achieve higher yield, better seed quality, and soil fertility. The suitable N management by partial and full controlled release urea, with or without straw incorporation, in a specific crop system has the potential to produce a better balance among yield, grain quality, and soil fertility in southern China.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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