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Effect of Different Form of *N* Fertilization on Yield Sustainability and Soil Quality in Double Cropped Rice System in a Long-Term Experiment

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Abstract

Purpose: Nitrogen fertilizer plays a crucial role in increasing crop yield. However, it is still unclear how long-term application of different forms of *N* fertilizer affect sustainable rice production and soil fertility. Methods: A ten-year field experiment was conducted to investigate the influence of four *N* fertilizer products on yield sustainability and soil factors in a double cropping rice system. Four types of *N* fertilizer were common urea with split applications (Urea), one-off application of polymer coating of sulfur-coated urea (PSCU), urea with nitrification inhibitor (UNI), and urea formaldehyde (UF). The same amount of 180 kg N ha^{-1} per rice season was applied for each *N* fertilized treatments. Rice grain yield, a total of eighteen soil parameters, and soil quality index (SQI) were determined. Results: The UNI had significantly greater rice grain production in 4/10 years in early rice and 5/10 years in late rice, while equivalent to Urea in the other years. The UF produced 5.4% higher averaged late rice grain yield compared to Urea. The UNI had significantly higher yield stability than PSCU in early rice. In addition, the UNI resulted in significantly higher soil pH (0.3 unit), nitrate reductase activity (24.6%), exchangeable K^+ (96.3%), and Ca^{2+} (41.6%) contents than PSCU in 0–10 cm depth. A significantly higher SQI value was observed in UNI than PSCU in 0–10 cm using the minimum data set method. Conclusions: Long-term application of various *N* fertilizer products would have distinct influences on rice grain production and soil parameters.

Keywords Controlled/Slow released urea · Double cropped rice · Soil fertility · Urea with nitrification inhibitor · Yield stability

1 Introduction

Rice (*Oryza sativa* L.), one of the most important food crops, accounts for 25% of total cultivated area and 31% of grain production in China (Xu et al. 2013; Mi et al. 2023). Nitrogen (*N*) is the greatest growth-limiting nutrient for rice (Grant et al. 2012). Traditionally, farmers are accustomed to split applications of urea to increase rice yield (Yang et al. 2011). However, this fertilization method requires high labor intensity and often needs to apply *N* fertilizer for 3–4 times during the entire rice growth season (Zhang 2008). Alternatively, slow/controlled released *N* fertilizers, such as coated urea (Shoji and Kanno 1994), urea formaldehyde (UF) (Mi et al. 2019), and urea with nitrification inhibitor (UNI) (Nikolajsen et al. 2020) are effective *N* management strategies that can minimize labor intensity while increasing crop yield. For example, single application of polymer-coated urea or UF respectively increased rice grain yield by 37.3% and 37.9% while sulfur-coated urea

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decreased rice grain yield by 17.4% compared to common urea with split applications (Wu et al. 2021). According to a meta-analysis, enhanced efficiency N fertilizers (EENF) products (i.e. N-(n-butyl) phosphoric triamide and dicyandiamide) improved rice yield by 5.7% on average (Linquist et al. 2013). However, previous studies have reported only the grain yield benefits of a specific type of slow/controlled released N product (Guo et al. 2017; Ziadi et al. 2011), and rarely compared the impacts of various N fertilizer products on rice grain production. On the other hand, the field experiment in most published studies often lasted for two or three years (Wang et al. 2015; Guo et al. 2016). More information about long-term effect of slow/controlled released N fertilizers on rice production are needed. The sustainable yield index (SYI) is calculated using actual yields over time, and a higher SYI implies a better management technique capable of producing acceptable yields through the years (Das et al. 2014). Thus, the SYI could be adopted to evaluate the rice grain yield performance with applications of different N fertilizer products.

Fertilization not only influenced crop yield, but also altered soil parameters (Zhao et al. 2021). Our study (Mi et al. 2019) found that soil pH significantly decreased after seven consecutive years of application of polymer coating sulfur-coated urea (PSCU) in comparison to the traditional split urea applications. Geng et al. (2015) reported after seven years of applying controlled-release N fertilizer led to 10.7% higher total nitrogen content in the 20–40 cm depth and 11.7% soil organic matter content in the 0–20 cm depth compared to the common urea. However, these prior studies only reported the changes of one or several soil chemical indicators caused by the application of slow/controlled released N fertilizers, lacking attention to soil physical and biological parameters. In addition, the response of individual soil parameters to N fertilizer might be different, thus confusing the evaluation of soil fertility. It is necessary to use a comprehensive indicator to evaluate the influences of certain N fertilizer products on soil fertility. Soil quality index (SQI) was a valuable tool for combining several soil metrics into a format that increases understanding of soil process and function (Obade and Lal 2016). To date, the responses of SQI to long-term application of different types of N fertilizers were not well understood.

Thus, our aims were to (1) examine the long-term impacts of various N fertilizer product types on sustainable rice production as well as soil quality in rice-rice cropping system; (2) identify the importance of soil organic carbon, nutrients, and pH factors affecting rice grain production. We hypothesized that (1) the multiple N fertilizer products would have distinct influences on rice grain production and soil parameters; (2) long-term application of different types of nitrogen fertilizers might impact rice yield by altering soil nutrients or pH.

2 Materials and Methods

2.1 Study Site

The 10-year experiment was established in 2011 in Xinzhu village (29°01′N, 119°27′E), Zhejiang province, China, with a double rice cropped system, which is a typical cropping system in this region. Double cropped rice included the consecutive cultivation of two seasons of rice in a year, namely early rice (from late April to late July) and late rice (from late July to early November). The site has a typical subtropical climate. The mean maximum and minimum temperature were respectively 29.1 °C and 20.4 °C for early rice, 26.6 °C and 18.6 °C for late rice, and the mean precipitation during the rice growth season was 836 mm for early rice and 429 mm for late rice, respectively. The topsoil (0–15 cm) at the experiment location is a yellow clayey paddy soil, which is classified as Ultisols according to USDA Soil Taxonomy. Before the experiment began, the topsoil properties were as follows: organic carbon (C) 15.2 g kg^{-1}, total nitrogen (TN) 1.96 g kg^{-1}, alkali-hydrolyzable nitrogen (AN) 132 mg kg^{-1}, available Bray-phosphorus (P), 4.4 mg kg^{-1}, NH_4OAc-extractable potassium (K) 79 mg kg^{-1}, pH (soil to water ratio 1:2.5) 5.24.

2.2 Experimental Design

Five treatments were selected, including (1) without N fertilizer application as the control (no-N); (2) common prilled urea (46% N) with split applications (Urea); (3) polymer coating of sulfur-coated urea (34% N) with one-off application (PSCU, application with only once); (4) one-off application of prilled urea with nitrification inhibitor (2-chloro, 6-trichloromethyl pyridine, 0.25%, UNI); (5) one-off application of urea formaldehyde (38% N, UF). The PSCU was provided by Shandong Kingenta Ecological Engineering Co., Ltd, China. Urea with nitrification inhibitor was provided by Zhejiang Aofutuo Chemical Co., Ltd., China. The UF was provided by Shandong Meigao International Chemical CO., Ltd, China. Each treatment had three replicates in a randomized block design. Each plot was 12.5 m^2. Plots were isolated by ridges (30 cm wide and 30 cm high), which was sealed off with plastic films to prevent water and fertilizer to seepage to the adjacent plots. In each rice season, the same rate of 180 kg N ha^{-1} was applied to all N applied treatments. For the treatment 2 (split application of N fertilizer), 40% N was applied prior to rice seedling transplanting. The leftover N was surface applied in equal parts at

the rice tillering and booting stages in early rice season. In late rice season, common urea was surface applied in two splits at ratio of 4:6 (basal: tillering). For treatments 3–5, a complete dose of N fertilizer was used with one-off application prior to transplantation of rice seedling in each rice season. All P and K fertilizers, in the form of super phosphate and potassium chloride, were used as a base rate of 90 kg P ha^{-1} and 120 kg K ha^{-1} per rice season. The K application rate was increased to 200 kg ha^{-1} from 2015. The early rice and late rice cultivars were "Jinzao 09" and "Yueyou 9113", respectively. Pre-germinated seeds were sown in a seeding field in March for early rice and early July for late rice each year. The seeding rates for early rice and late rice were 36 and 12 kg ha^{-1}, respectively. Rice seedlings were transplanted at a density of 31 hills per square meter for early rice in late-April. For late rice, the transplantation was conducted at a density of 26 hills per square meter in late-July. Alternate Wetting and Drying water management was employed throughout most of the growing season for each rice crops (Mi et al. 2017). Weeds in each plot were manually removed during the rice growing season. Insecticides (Imidacloprid) were sprayed after the rice jointing stage to prevent and control pests and diseases.

2.3 Sampling and Analytical Methods

Rice in each whole plot was harvested manually and the yield was given on 14% moisture content basis. Soil samples were obtained at random from six cores in the two soil depths (0–10 cm and 10–20 cm) of each plot by using an auger in November, 2020 (at the completion of 10th year of cropping system). One fraction of soil sample was air-dried and powdered to pass < 2 mm sieve for determining the pH (1:2.5 soil to water suspensions) and alkali-hydrolyzable N (AN) (Xiong et al. 2008). Soil available P content was determined colorimetrically after extraction with ammonium fluoride and hydrochloric acid (Bray and Kurtz 1945). Soil exchangeable cations including K, calcium (Ca), sodium (Na), and magnesium (Mg) were extracted by 1 M ammonium acetate and measured using atomic absorption spectrophotometry technique (PE-2100, Perkin-Elmer, U.S.A.). Soil available iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn) were determined by atomic absorption spectrophotometry (PE-2100, Perkin-Elmer, U.S.A.) after extraction with 5 mmol L^{-1} DTPA (pH = 7.3). Soil samples passing through a 0.15 mm sieve were analyzed for total organic C (TOC) and TN using a Vario EL Cube elemental analyzer (Elementar Corp., Germany). The other portion of soil samples were kept in refrigerator at 4 °C for NH_4^+ and NO_3^- analyses (Pansu and Gautheyrou 2006).

The indophenol-blue colorimetry method was used to measure soil urease activity (Guo et al. 2012). Soil nitrate reductase activity was measured using KNO_3 as a substrate with α-naphthylaminesulfanilic acid, and soil slurry incubated at 25 °C in a gyratory shaker (Abdelmagid and Tabatabai 1987).

To assess the soil quality, the soil quality index (SQI) based on minimum data set (MDS) method was adopted (Liu et al. 2014). First, the minimum dataset of indicators was selected by principal component analysis. A total of 8 indicators were selected in the 0–10 cm soil layer, including K, TOC, NH_4^+, Na, P, nitrate reductase activity, percentage of macroaggregate, and Zn. A total of 5 indicators were selected in the 10–20 cm soil layer, including K, Na, Ca, NH_4^+, TN, and pH. Then the indicator values were transformed into scores (0–1).

The following equation (Doran and Parkin 1994) was used to compute the SQI value:

$$SQI = \sum_{i=1}^{n} Wi \times Si$$

where n represented the number of variables, Si represented the indicator score, and Wi represented the weight of each indicator. The weight value of each indicator was assigned by the communality value through factor analysis (Table S1).

Sustainable yield index (SYI) was used to evaluate the crop production sustainability. The equation (Singh et al. 1990) was as follows:

$$SYI = \frac{Ymean - \sigma}{Ymax}$$

Where Y_{mean} represented the mean yield of a treatment, Y_{max} was the greatest yield for each treatment over time, and σ was the standard deviation.

Yield stability of various cropping systems was measured using the reciprocal of the coefficient of variation (Smith et al. 2007; Knapp and van der Heijden 2018; Chen et al. 2022):

$$ST_i = \frac{Mean_i}{SDi}$$

Where $Mean_i$ and SD_i respectively represented the mean yield and standard deviation of each season of rice from year 2011 to 2020. The higher value indicated the higher the yield stability.

2.4 Statistical Analysis

Rice grain yield, TOC and soil nutrients were examined by a two-way analysis of variance (ANOVA) followed

by Tukey's tests at a probability level of 0.05. One-way ANOVA was used to evaluate the impact of different forms of *N* fertilizer on yield stability, soil enzyme activities, and soil quality index. Random Forest model (RFM) analysis was employed to evaluate the relative importance of various soil parameters on rice grain yield using the 'randomForest' package. The 'rfpermute' package in R version 4.1.2 was used to further evaluate the significance of each predictor. Annual double cropped rice grain yield and soil parameters after rice harvest in Year 2013, 2017 and 2020 were used in the RFM model and stepwise regression analysis. The least squares regression was conducted to evaluate relative yield (PSCU/Urea, UNI/Urea, and UF/Urea) over time in early rice, late rice, and annual double cropped rice.

3 Results

3.1 Rice Grain Yield

Fertilizer types (F) and year (Y) and their interaction had significant impacts on the yields of early rice, late rice and double cropping rice (Fig. 1). Over ten years, the UNI improved rice grain production by 6.3%, 13.3% and 7.4% for early rice, 6.5%, 2.4% and 1.1% for late rice, 6.4%, 6.8% and 3.7% for annual, respectively, compared to the Urea, PSCU, and UF treatments (Table S2; Fig. 1). When compared to the split applications of ordinary prilled urea, the UNI treatment produced obviously greater rice grain yield in 4/10 years for early rice and 5/10 years for late rice, with no apparent difference in the other years. In contrast, yield performance of PSCU and UF treatments varied with the rice growth seasons. The 10-year averaged late rice grain yield were 4.0% and 5.4% higher in the PSCU and UF than the Urea treatment (Table S2). However, average early rice yield reduction of 6.6% and 1.1% were recorded in the PSCU and UF treatments compared to the Urea (Table S2).

The regression of relative early rice yield of PSCU, UNI and UF against time revealed that the yield declined relative to that of Urea throughout the years (PSCU/Urea: y=–0.02x+1.04, R^2=0.36, n=30, P<0.01; UNI/Urea: y=–0.01x+1.14, R^2=0.23, n=30, P<0.01; UF/Urea: y=–0.02x+1.09, R^2=0.40, n=30, P<0.01) (Table S3), suggesting the rice production advantage of UNI relative to common urea gradually diminished over time. There was no increase (or decrease) trend for late rice yield of these treatments relative to that of Urea. Overall, a significant downward trend of relative double cropped rice yield was observed in the PSCU/Urea (y=–0.01x+1.04, R^2=0.17, n=30, P<0.05) and UNI/Urea (y=–0.01x+1.13, R^2=0.18, n=30, P<0.05) (Table S3).

No differences in SYI were observed in the four *N* applied treatments in early rice, late rice and annual double cropped rice (Table 1). The UNI resulted in significantly higher yield stability than PSCU in early rice. However, no differences in rice yield stability among four *N* applied treatments were recorded in late rice and annual double cropped rice (Table 1).

3.2 Soil Quality Variables

There were no significant differences in soil organic carbon and total nitrogen contents among four *N* fertilizer management treatments in both soil layers (0–10 and 10–20 cm) but they decreased significantly with increasing soil depth (Table 2). In the surface soil layer (0–10 cm), UNI had significantly 11.9% higher AN and 56.6% higher NO_3^- contents than the UF treatment (Table 2). No obvious differences in AN and NO_3^- contents were observed in the deeper soil layer (Table 2).

Significant responses (P<0.01) of soil available P to *N* fertilizer type and soil depth as well as their interaction were observed (Table 2). Split application of common urea had significantly 26.4–74.9% higher soil available P content in the 0–10 cm soil depth than the other *N* fertilized treatments (Table 2). In the 10–20 cm soil layer, the UNI treatment had the highest soil available P content than the other treatments (Table 2). For soil available K, the PSCU resulted in significantly lower soil available K content than in the UNI in both soil layers. In addition, soil pH values were both significantly lower in the PSCU than in the UNI and UF in 0–10 cm and 10–20 cm soil depths (Table 2). Across all *N* management treatments, soil pH increased significantly with increasing soil depth. Likewise, soil available Fe and Mn contents in the deeper soil depth (10–20 cm) were significantly greater than in the surface soil (Table S4). However, the contents of soil available Na, Mg, Cu, and Zn decreased significantly with increasing soil depth (Tables S4 and S5). The UF treatment had the greatest urease activity, which were significantly 36.5% higher than the PSCU (Fig. 2). For the activities of soil nitrate reductase, 23.5–24.6% higher were observed in the UNI and UF than in the PU and PSCU treatments (Fig. 2).

3.3 Soil Quality Index

The UNI treatment resulted in the highest SQI value (0.89) at 0–10 cm depth, increased by 14.7% higher compared to the PSCU treatment (Fig. 3). There were no differences in SQI among four *N* applied treatments in the 10–20 cm depth. A significant positive correlation between SQI (0–10 cm) and rice grain yield of the last five years for early rice (y=4.7x+1.7, R^2=0.45, n=12, P=0.01)
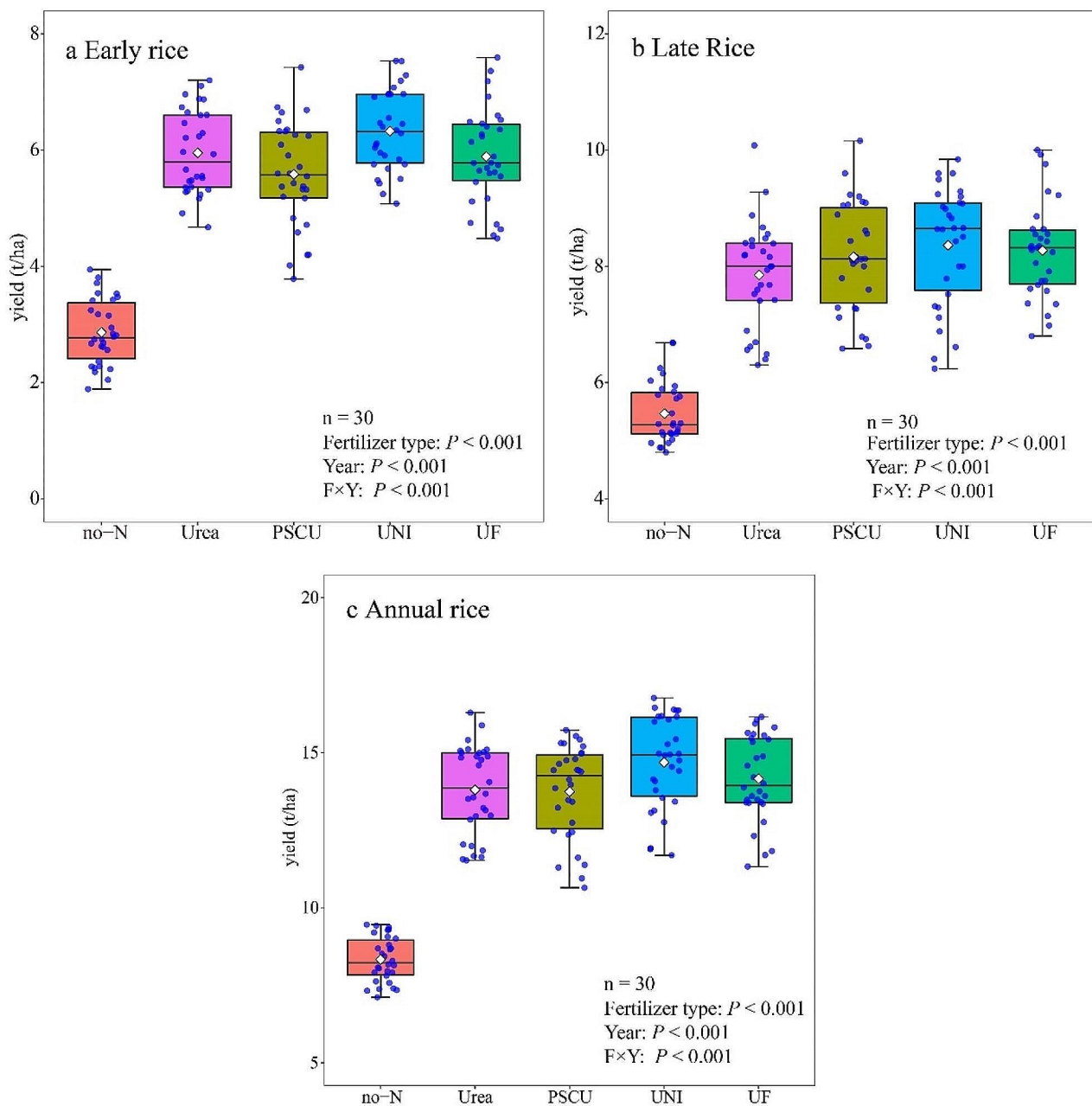
Fig. 1 Rice grain yield of early rice **(a)**, late rice **(b)**, and annual rice **(c)** with different *N* managements during year 2011–2020. Note: no-*N*, without *N* input; Urea, split applications of prilled urea; PSCU, one-off application of polymer coated sulfur-coated urea; UNI, one-off application of urea with nitrification inhibitor; UF, one-off application of urea formaldehyde

Table 1 Sustainable yield index and yield stability under different *N* management treatments in double cropped rice system

|	Sustainable yield index			Yield stability		
	Early rice	Late rice	Annual rice	Early rice	Late rice	Annual rice
Urea	0.73	0.74	0.78	8.03ab	8.66	9.32
PSCU	0.67	0.75	0.79	6.05b	8.59	8.91
UNI	0.76	0.75	0.80	8.98a	7.92	9.55
UF	0.68	0.75	0.79	6.96ab	9.99	10.1

Note: Different lowercase letters in the same column indicated significant difference at $P < 0.05$. Urea, split applications of prilled urea; PSCU, one-off application of polymer coated sulfur-coated urea; UNI, one-off application of urea with nitrification inhibitor; UF, one-off application of urea formaldehyde

Table 2 Soil total organic carbon, pH and soil nutrients contents in 0–10 cm and 10–20 cm under different N managements at the end of 10th year of cropping

Soil Depth	Treatment	TOC	TN	AN	NH$_4^+$	NO$_3^-$	P	K	pH
		g kg^{-1}		mg kg^{-1}					
0–10 cm									
	no-N	19.0b	2.1	150c	9.2	4.6	39ab	194a	4.9a
	Urea	22a	2.2	176ab	9.3	5.5	43.4a	77.9bc	4.9a
	PSCU	22.6a	2.2	169ab	10.3	4.3	24.8d	44.3c	4.6b
	UNI	23a	2.2	183a	9.7	6.7	34.4bc	87b	4.9a
	UF	21.9ab	2.1	163bc	10.6	5.6	27 cd	71.3bc	5.0a
	Mean	21.9 A	2.1 A	168 A	9.8	5.3	33.7	94.9 A	4.9B
10–20 cm									
	no-N	17b	1.5b	110b	8.5	5.2	3.58b	180a	5.1a
	Urea	19ab	1.9a	136ab	9.1	4.3	4.09b	65.7bc	5.0ab
	PSCU	19.6a	1.9a	147a	10.2	5.7	3.39b	49.3c	4.9b
	UNI	20.2a	2.0a	149a	11.5	5.5	8.22a	84.3b	5.1a
	UF	18.8ab	1.8a	140a	9.3	5.0	3.4b	60bc	5.1a
	Mean	18.9B	1.8B	137B	9.7	5.1	4.5	87.8 A	5.1 A
Source of Variation									
N fertilizer management (N)		**	**	***	ns	ns	***	***	**
Soil depth (S)		***	***	***	ns	ns	***	ns	**
$N×S$		ns	ns	ns	ns	ns	***	ns	ns

Note: Different lower-case letters in the same soil depth indicated significant difference at $P < 0.05$. Different upper-case letters for both soil depths indicated significant difference at $P < 0.05$. ** and *** indicated significant difference at $P < 0.01$ and $P < 0.001$, respectively. ns indicated no significant difference. TOC, total soil organic carbon; TN, total nitrogen; AN, soil alkali-hydrolyzable N. no-N, without N input; Urea, split applications of prilled urea; PSCU, one-off application of polymer coated sulfur-coated urea; UNI, one-off application of urea with nitrification inhibitor; UF, one-off application of urea formaldehyde

Fig. 2 Soil urease **(a)** and nitrate reductase activities **(b)** in 0–10 cm soil depth under five N management treatments at the end of 10th year of rice cropping. Different lower-case letters indicated significant difference at $P < 0.05$. Error bars indicated the standard deviation of the mean. no-N, without N input; Urea, split applications of prilled urea; PSCU, one-off application of polymer coated sulfur-coated urea; UNI, one-off application of urea with nitrification inhibitor; UF, one-off application of urea formaldehyde
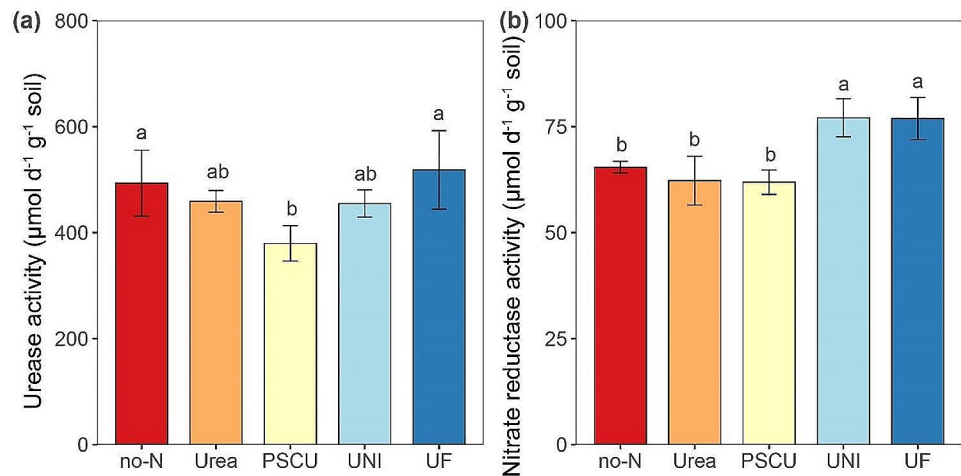

and annual double cropped rice (y = 5.5x + 8.9, R^2 = 0.42, $n = 12$, $P = 0.014$).

3.4 Relationships Between Soil Properties and Rice Grain Yield

Random Forest model (RFM) revealed that soil available nutrients and soil pH could significantly explain the response of double cropped rice grain yield to N fertilizer addition (Fig. 4). Soil exchangeable K had the strongest explanatory effect, followed by soil pH, soil available P, and soil available N related parameters (Fig. 4).

The stepwise regression analysis also showed that soil pH, soil inorganic nitrogen (NH$_4^+$ and NO$_3^-$) were the most important factors influenced double cropped rice grain yield (Y = 3.3×$_1$ + 0.33×$_2$ – 0.23×$_3$ – 2.9, $P < 0.01$, R^2 = 77.5%, $n = 36$, X$_1$: pH, X$_2$: NO$_3^-$, X$_3$: NH$_4^+$). In addition, rice grain yield decreased significantly with decreasing soil pH (y = 5.6x – 14.1, $P < 0.01$, R^2 = 40.9%, $n = 96$).
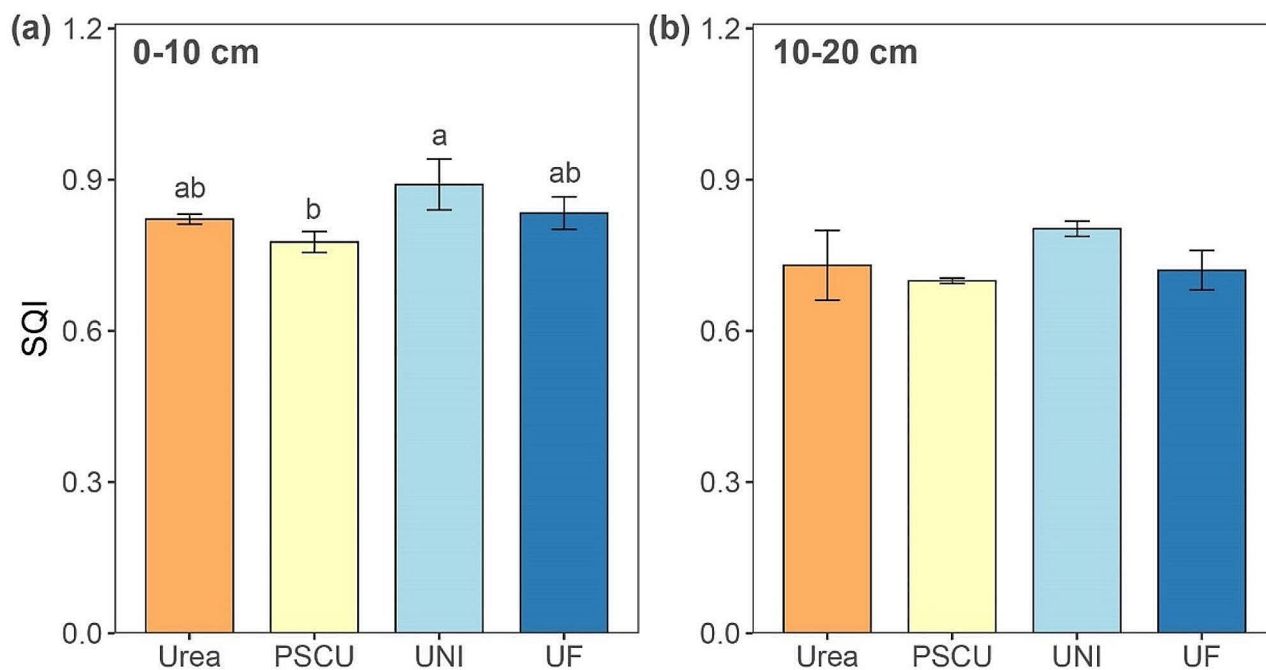
Fig. 3 Soil quality index (SQI) at different soil depths with different N management treatments. Different lower-case letters indicated significant difference at $P < 0.05$. Error bars indicated the standard of the deviation. Urea, split applications of prilled urea; PSCU, one-off application of polymer coated sulfur-coated urea; UNI, one-off application of urea with nitrification inhibitor; UF, one-off application of urea formaldehyde

4 Discussion

The effectiveness of nitrification inhibitors on rice grain yield varies greatly with soil properties (Linquist et al. 2013) and climatic conditions (Rose et al. 2023). In this study, the UNI had notable average yield superiority of early rice compared to the other N fertilized treatments. This could be ascribed to that sufficient nitrogen supply during the whole growth period of early rice promoting yield formation (Mi et al. 2017). However, Liu et al. (2020) observed that application of nitrification inhibitor (3, 4-dimethylepyrazole phosphate, DMPP) did not improve rice yield in acidic soil due to the failure to effectively extend the NH_4^+ residence time. The differences in nitrification inhibitors performance might be related to the temperature (Menéndez et al. 2012) and the length of rice growth period. For late rice, the yield superiority diminished in the UNI, possibly due to that the higher temperature increased loss of fertilizer nitrogen (Chen et al. 2010). Kelliher et al. (2008) also found that increased soil temperature accelerated the degradation of dicyandiamide, thereby reducing its effectiveness. Likewise, rice yield performance of the PSCU varied with the seasons. Our previous study showed that delayed N release from the PSCU could not synchronize the N needs of rice (less 80% of total N released at rice harvest), which led to low yield of early rice (Mi et al. 2017). The decrease in N release was probably related to the lower temperature (Husby et al. 2003) in the early growth stage (the average temperature was 23.9 °C) of early rice. In contrast, using PSCU and UF had obvious yield advantage in late rice compared to the split applications of prilled urea, which had similar findings with Huang et al. (2019). We speculated that relatively higher temperatures accelerated the rapid release of nitrogen (Fan and Li 2010) at initial stage of late rice (the average temperature was 27.3 °C), which was conducive to rice tillering. Through 10-year field trial we found that the application of different types of nitrogen fertilizers did not change SYI in double cropped rice system.

Nevertheless, the application of different forms of nitrogen fertilizer could affect soil quality variables. For example, soil acidification could be slowed from application of controlled-release urea under rice-oilseed rape rotation system (Geng et al. 2015). However, our result showed that a significant decrease in soil pH in the PSCU. This was probably due to the oxidation of S element in PSCU to SO_4^{2-} and the release of H^+, thereby accelerating soil acidification (Turan et al. 2013). A significant positive correlation between soil pH and Ca^{2+} ($y = 277x–924$, $P < 0.01$, $R^2 = 51\%$, $n = 15$) implied that soil acidification might exacerbate the loss of certain base cations. The random forest model and stepwise regression analyses results showed that soil pH was the important factor related to rice grain

Fig. 4 Random Forest model analysis showed that importance (mean square error increase percentage) for edaphic factors for rice grain yield. * and ** indicated the significance of each predictor at $P < 0.05$ and $P < 0.01$, respectively. AN, alkali-hydrolyzable nitrogen; TN, total nitrogen; TOC, soil total organic carbon
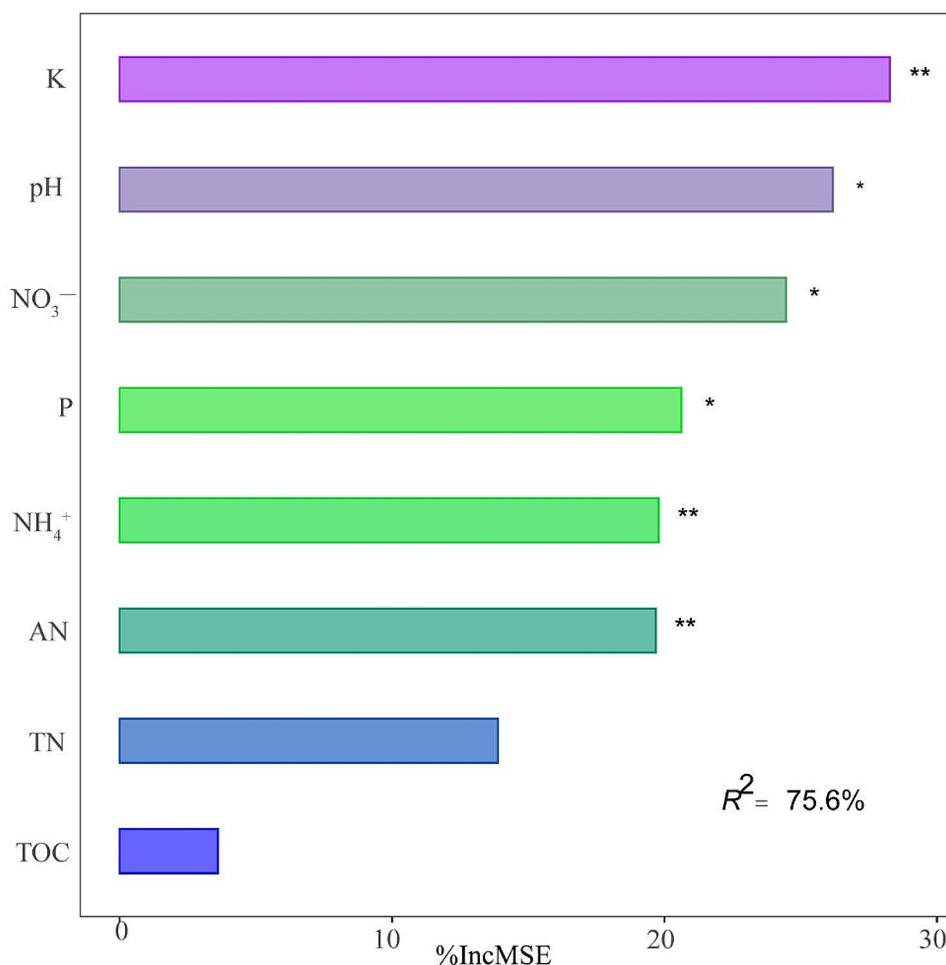
production. A significantly positive correlation between soil pH and yield (Fig. S1) suggested that soil acidification might cause the decrease in rice grain yield, which agreed with the findings of Linquist et al. (2013). In terms of soil exchangeable K, although we increased K input after year 2015, soil exchangeable K levels were lower than initial values in all N applied treatments after ten years. Considering the significant relationship between exchangeable K and rice yield (Fig. 3), this could be the reason for the lack of differences in annual yield among N applied treatments in the last four years (Table S2). Besides, soil N related parameters (including AN, NH_4^+, and NO_3^-) were the important factors affecting the yield response. Compared to the initial value, all N fertilized treatments increased soil available P content, particular in the surface soil layer (Table 2). This result suggested the phosphorus fertilizer input in each treatment exceeded the amount removed by rice crops. However, soil available P content decreased significantly along with soil depth, and its contents in all treatments were lower than 5 mg kg^{-1} except for the UNI treatment. Such low soil P content was not conducive to root growth. It is necessary to use deep plowing to increase the soil available P content of

the subsoil layer due to the random forest analysis showed that P could significantly affect rice yield. Soil total organic C was a crucial indicator of soil quality (Yang et al. 2019). Long-term nitrogen addition increased the content of TOC in both soil layers compared to treatments without nitrogen application (Table 2), indicating that imbalanced fertilization may hinder the accumulation of organic C. This was attributed that balanced NPK fertilization increased the biomass of rice in each season, thereby augmenting the annual input of residues and root derived carbon into the soil (Tian et al. 2017). Overall, long-term application of different types of nitrogen fertilizer changed soil quality. The lower SQI in the PSCU than UNI suggest that long-term application of PSCU could cause the risk of soil degradation.

The price was a critical factor for farmers in determining the choice of nitrogen fertilizer products. Despite UNI being priced higher than common urea (150 vs. 120 \$ ha^{-1} per season), the reduced labor costs and the augmented income from increased grain yield associated with UNI application still contribute considerable overall profits (Mi et al. 2019).

5 Conclusion

Long-term one-off application of urea with nitrification inhibitor (UNI) could achieve 6.4% higher 10-year averaged rice annual yield relative to split applications of common urea (Urea). However, there were no differences in sustainable yield index and rice yield stability between UNI and Urea. The polymer coating of sulfur-coated urea (PSCU) application could cause early rice yield reduction (6.6%), soil acidification (0.3 pH unit) and soil available K content decline (43.1%) compared to Urea. In addition, a significant downward trend of relative double cropped rice yield was observed in the PSCU/Urea. In contrast, urea formaldehyde (UF) with one-off application was superior to Urea in yield of late rice. Overall, the continuous application of the new types of N fertilizer products did not lead to an improvement in soil quality compared to common urea. To enhance soil quality and achieve sustainable rice production, organic fertilizers should be considered in the future.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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