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Effects of Different Fertilization Strategies on Soil Nutrients, Runoff Losses, Crop Nutrient and Yield in Rice-Wheat Rotation

Jinling Zhao, Lingling Liu, Yan Fang, Jie Wang, Qi Hong and Linsheng Huang*
National Engineering Research Center for Analysis and Application of Agro-Ecological Big Data, Anhui University, Hefei, 230601, China
*For correspondence: linsheng0808@163.com; zhaojl@ahu.edu.cn
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Abstract

This study examined the effects of different fertilization treatments on soil nutrient, runoff nutrient loss, plant nutrient and yield in a rice-wheat rotation system. The treatments included were non-N-fertilised control (CK), conventional N management (CON), optimised N management (OPT), 30% reduced N (OPT-N), 50% reduced P (OPT-P) and straw with chemical fertilizer (OPT-NP+S). Results showed that the soil organic matter improved after fertilisation. The soil nitrate nitrogen (N) content for wheat and the available phosphorus (AP) content in rice did not differ between treatments. Conversely, the other nutrients showed significant differences. Only the total phosphorus content of wheat significantly differed among the treatments, and the maximum plant yield was 5154.87 kg/ha under the OPT-P. The mean total potassium content of rice plant did not significantly differ and the maximum plant yield was 9532.68 kg/ha under the OPT. Corresponding results can provide a reference for variable fertilization in rice-wheat rotation. © 2020 Friends Science Publishers

Keywords: Rice-wheat rotation; Soil nutrients; Nutrient runoff losses; Plant nutrient; Crop yield

Introduction

As important grain crops, wheat and rice have been widely planted around the world and have played an important role in human lives and industrial production. For example, wheat is a cereal plant extensively grown worldwide and used as one of the staple foods of human being. Wheat flour is generally used for producing bread, taro, biscuits, noodles, etc. It can be also fermented into beer, alcohol, liquor (*e.g.*, vodka) or biomass fuel (Green *et al*. 2015; Das *et al*. 2016). As a staple food planted in Northeast and South China, the domestic cultivation area of conventional rice is 245 million mu, and 200 million mu of hybrid rice. In addition to being edible, it can be used for producing wine, sugar and industrial raw materials. Rice husks and rice straw can be also utilized as livestock feed (Matsumura *et al*. 2005; Kafle and Chen 2016).

Applying chemical fertilizers is an important measurement for ensuring high grain yields. According to Food and Agriculture Organization (FAO) of the United Nations, it showed that fertilizer application accounts for 60−67% of crop yield (Bouwman *et al*. 2005). Soil fertility monitoring in China showed that fertilizer application contributes 57.8% to grain production (Wang *et al*. 2011; Teng *et al*. 2014). In the 1980s, a large area of cultivated land in China was deficient in main soil nutrients or deficient in some soils. A total of 78% of China's total cultivated land areas are low- and medium-yielding fields (Wu *et al*. 2003; Zhang *et al*. 2016). Excessive fertilisation can result in soil nutrient loss (Doan *et al*. 2015). For example, land surface runoff is one of the main pathways for the nitrogen (N) and phosphorus (P) nutrient loss in farmland and third largest pollution source in rivers and lakes in the United States (Beusen *et al*. 2016). At present, considerable attentions have been paid to the studies on the losses of land surface runoff of agricultural compounds (N, P, K).

The absolute amount of nutrients absorbed by rice and wheat in a growth cycle is positively correlated with the amount of fertilizer applied within a certain range. At low fertilisation level, the amount of N and K absorbed by the crop increases with the amount of applied fertilizer (Niu *et al.* 2013). Balanced application of N, P, K fertilizers is crucial for the crop growth, but the amount of N in rice and wheat plants was higher than other fertilizers (Aggarwal *et al*. 2006). The reason may be due to the fact that the coordination of nutrient between two or more nutrients is various in different cropping systems. For example, the P, N, and N, K showed the positive interactions, which promotes the absorption and utilization of nutrients by rice and wheat. The K can promote the absorption, transportation and accumulation of N, thereby increasing the utilization of N (Landeweert *et al*. 2001).

Consequently, it is extremely important to investigate the relationship between fertilisation application, soil nutrient and crop yield in a rice-wheat rotation system (Sun *et al*. 2018). In this study, rational fertilisation was achieved for improving crop yield and economic benefits in a typical rice-wheat cropping system. Additionally, the differences in soil nutrients, nutrient runoff losses, crop nutrient and yield were also observed.

Materials and Methods

Experimental material

The rice-wheat rotation system was adopted in the experimental area. The specific fertilizers were carbamide, potassium chloride, calcium superphosphate and other binary or three-nutrient compound fertilizers. The wheat variety Yangmai 13 and the rice variety Wandao 158 were grown.

Experimental location and climate

The study area is located in Jianhua Village, Zhonghan Town, Juchao District, Chaohu City (117°47′35", 31°38′45") at a distance of 2 km from Chaohu Lake and 17 m above sea level. It has a subtropical humid monsoon climate. The annual precipitation is 996.0 mm and the annual average temperature is 16°C. The hottest month is July with monthly average temperature of 28.7°C and the coldest month is January with monthly average temperature of 2.7°C. The annual frost-free period is 247 d and the sunshine hours are 2106 h. The soil type for the field experiment site is the subspecies of gleyed paddy soil. The soil nutrients for the 0–20 cm soil layer in the study area are: pH of 6.99, organic matter (OA) of 34.07 g/kg, total nitrogen (TN) of 1.58 g/kg, total phosphorus (TP) of 0.78 g/kg, available potassium (AK) of 136.31 mg/kg, available phosphorus (AP) of 25.97 mg/kg and alkali-hydrolyzale nitrogen (Alkeline-N) of 168.54 mg/kg.

Experimental design

Six treatments included were non-N-fertilised control (CK), conventional N management (CON) based on local custom, optimised N management (OPT), 30% reduced N (OPT-N) compared to OPT, 50% reduced P (OPT-P) on the basis of OPT and straw with chemical fertilizer (OPT-NP+S) @200 kg of wheat straw per acre on the basis of OPT-N and OPT-P. Each treatment had three repetitions on the experimental plot with an area of 30 m^2 (Fig. 1).

Data collection

The experimental soil nutrients, nutrient runoff losses and crop nutrient and yield were collected during the years of 2015–2017. Data were compiled by the Microsoft Excel (Office 2016) software. Data analysis was performed by applying the analysis of variance (ANOVA, $P < 0.05$) in SPSS 23.0 software (SPSS® Inc., Chicago, IL, USA). Least significant difference (LSD) test was used for multiple comparisons.

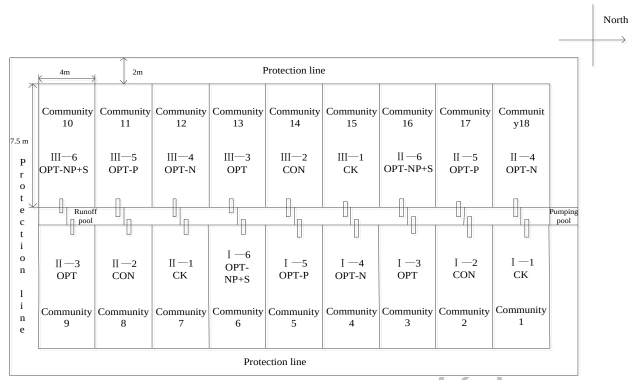

Fig. 1: Schematic plot of the experimental design

ANOVA

Factor A is set with different levels of k denoted as A_1, A_2, …, A_k. The n_i (i=1, 2, …, k) test is repeated at each level and the indicators can be obtained. The overall sample size is required to investigate whether the change in single factor A has a significant effect on test indicator y of N=sum(n_i) (Chakraborty and Chowdhury 2016). The u_i is set to represent the true average of the test indicator y at the level of A_i. The results of each experiment should exhibit random fluctuations around the true average. Then, under the A_i, the result of each test A_{ij} should show random fluctuation around the true average. This random fluctuation is recorded as ε_{ij}. The ANOVA model is $y_{i\,j} = u_i + \varepsilon_{ij}$ (i=1, 2, …, k, j=1, 2, …, n_i) where $\varepsilon_{ij} \sim N(0, \sigma^2)$ are independent and u_i and σ^2 are unknown. The significance of influence of factors is shown by whether k totals have the same average. The test hypothesis is H_0: $u_i = u_i = \ldots = u_k$.

The sum of the squared deviations of all the data is shown as follows:

$$SS_{\mathrm{T}} = \sum_{i=1}^{k} \sum_{j=1}^{n_i} (y_{ij} - \bar{y})^2 \quad (1)$$

The total sum of squares is the sum of squares between groups and within groups:

$$SS_{\mathrm{T}} = SS_{\mathrm{B}} + SS_{\mathrm{W}} + \sum_{i=1}^{k} n_i (\bar{y}_i - \bar{y})^2 + \sum_{i=1}^{k} \sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2 \quad (2)$$

The sum of squares between groups is attributed to a change in A and reflects the difference between the overall average, and the sum of squares within the group is caused by random factors. Theoretically, the degree of freedom for

SS_T, SS_B and SS_W are respectively n-1, k-1 and n-k. Under the assumption of normal distribution, if the groups of means are equal as the originally assumed, then the statistical parameter F obeys an F-distribution, which has a degree of freedom k-1 and n-k.

$$F = \frac{MS_B}{MS_W} = \frac{SS_B/(k-1)}{SS_W/(n-k)} \quad (3)$$

SS_T for a given sample is determined. If the original assumption keeps true, SS_B is extremely small and SS_W is extremely large by decomposition. Thus, F is extremely small. Conversely, if F is extremely large, SS_B is extremely large in the case where SS_T is determined, and SS_W is small by decomposition. The original hypothesis is valid. Therefore, the F can be used in determining whether the original hypothesis is true. The P-value (sig. = p) can be calculated on the basis of F-distribution. When P < alpha (the default value is 0.05), the original hypothesis is rejected. This result shows that the factor A has a significant effect on the test indicators. The $P < 0.01$ is indicative of a highly significant effect.

Statistical analysis

The LSD test was introduced and T-test was performed for pairwise comparison between groups due to its high sensitivity. Slight differences in the mean between levels may be also tested (Sun *et al*. 2014).

If the data for each group are n, the standard error (SE) of the LSD is:

$$\sqrt{\frac{2\text{MSE}}{n}} \quad (4)$$

Or,

$$\sqrt{\text{MSE}\left(\frac{1}{n_i}+\frac{1}{n_j}\right)} \quad (2)$$

Where MSE is the mean square error and n is the number of data for each level of A factor. If A has the k levels and the total data are N, then

$$n = \frac{N}{k} \quad (3)$$

Results

Soil nutrients under rice-wheat rotation system after harvest

The mean of soil nitrate N content did not significantly differ among treatments (Table 1). The ammonium N content followed the order of OPT-N > CK > OPT-P > OPT-NP+S > CON > OPT. The OA had an increasing trend for different fertilization treatments. The average value of AP was significantly different among treatments of CON, OPT, OPT-N, CK, OPT-P and OPT-NP+S. The maximum average content of AP was obtained under the OPT-N. The mean content of AK followed the order of OPT-N > OPT-NP+S > OPT > OPT-P > CK > CON and it reached 180.0 mg/kg for the OPT-N. The pH value also decreased after six treatment methods.

The soil nutrients after rice harvest showed that only the AP content did not significantly differ during the treatments. The maximum nitrate N content was 7.978 mg/kg under the OPT-P, while the minimum was 2.623 mg/kg under the CON. The content of ammonium N and OA had been improved after different fertilization treatments. The highest AK content was 206.667 mg/kg under the OPT-N, and the minimum value was 90.0 mg/kg under the CON. The pH decreased after six treatment methods (Table 2).

Nutrient runoff loss under wheat and rice rotation

For the nutrient runoff under the wheat cultivation, the TN and nitrate N considerably varied, while the TP, ammonium N and total soluble phosphorus (TSP) showed the minimal changes. The proportion of lost nitrate N to total nitrogen were respectively 38.49, 57.30, 52.09, 55.05, 53.36 and 42.00% under the six treatments (Table 3). The TN, TP, nitrate N and TSP did not significantly differ during among treatments, while the ammonium N loss under the OPT-NP+S and OPT were significantly different. The highest mean of nutrient loss was 0.39 mg/L under the OPT-NP+S, and the lowest value was 0.23 mg/L under the OPT. The ratios between ammonium N loss and TN among treatment methods were 5.33, 4.30, 3.70, 4.95, 4.24 and 7.09%, respectively. The ratios between lost TSP under various treatments and TP were 50.66, 54.10, 62.16, 53.075, 43.18 and 41.35%, respectively.

For the nutrient runoff under the rice cultivation, the highest TN, TP, nitrate N, ammonium N and TSP were observed under the CON. Only the average value of TN did not significantly differ during the treatments. The proportions of lost nitrate N to TN under various treatments were respectively 35.18, 32.11, 31.97, 17.10, 20.67 and 30.99%. The ratios between ammonium N loss and TN under treatment methods were respectively 10.42, 8.64, 8.21, 8.50, 7.00 and 8.39%. The highest average loss was 0.216 mg/L under the CON and the lowest loss was 0.116 mg/L under the OPT-P. The ratios between lost TSP and TP under various treatments were 72.34, 81.2, 83.67, 63.18, 73.89 and 79.41% (Table 4).

Nutrient contents and yields of wheat and rice plants

The mean values of TN and total potassium (TK) in wheat plants did not significantly vary among treatments, while that of TP and crop yield significantly differed among the six treatments. The TP content followed the order of CK

Table 1: Significance test for soil nutrients among six treatments under wheat cultivation

	Nitrate N (mg/kg)	Ammonium N (mg/kg)	OA (mg/kg)	AP (mg/kg)	AK (mg/kg)	pH
CK	3.80	1.62a	27.70b	4.62b	103.33c	6.84a
CON	3.62	0.94b	38.15a	20.25a	101.33c	6.70b
OPT	3.58	0.68b	38.94a	20.37a	160.00ab	6.61c
OPT-N	3.70	2.12a	36.27a	22.42a	180.00a	6.58cd
OPT-P	3.10	1.45ab	38.16a	6.77b	140.00b	6.63bc
OPT-NP+S	3.15	1.28b	40.68a	7.08b	163.33a	6.53d

Note: There are no significance for the values with the same letter in each row ($P < 0.05$). OA, AP and AK denote organic matter, available phosphorus and available potassium, respectively; CK, CON, OPT, OPT-N, OPT-P and OPT-NP+S denote non-N-fertilised control, conventional N management based on local custom, optimised N management, 30% reduced N compared to OPT, 50% reduced P on the basis of OPT and straw with chemical fertilizer @200 kg of wheat straw per acre on the basis of OPT-N and OPT-P

Table 2: Significance test for soil nutrients among six treatments under rice cultivation

	Nitrate N (mg/kg)	Ammonium N (mg/kg)	OA (mg/kg)	AP (mg/kg)	AK (mg/kg)	pH
CK	5.42b	1.36c	21.55b	15.51	103.33d	7.10a
CON	2.62c	2.67b	28.21a	15.92	90.00d	6.72b
OPT	5.97b	2.61b	26.33ab	20.64	163.33bc	7.06ab
OPT-N	6.04b	2.29b	30.89a	15.55	206.67a	6.80b
OPT-P	7.98a	2.06b	26.52ab	16.43	180.00b	6.87b
OPT-NP+S	4.18b	5.48a	31.22a	15.01	150.00c	6.89ab

Note: There are no significance for the values with the same letter in each row ($P < 0.05$). OA, AP and AK denote organic matter, available phosphorus and available potassium, respectively; CK, CON, OPT, OPT-N, OPT-P and OPT-NP+S denote non-N-fertilised control, conventional N management based on local custom, optimised N management, 30% reduced N compared to OPT, 50% reduced P on the basis of OPT and straw with chemical fertilizer @200 kg of wheat straw per acre on the basis of OPT-N and OPT-P

Table 3: Significance test for the wheat runoff losses among six treatments (unit: mg/L)

	TN	TP	Nitrate N	Ammonium N	TSP
CK	5.82	0.30	2.24	0.31ab	0.15
CON	6.51	0.27	3.73	0.28ab	0.15
OPT	6.22	0.26	3.24	0.23b	0.16
OPT-N	5.45	0.23	3.00	0.27ab	0.12
OPT-P	6.84	0.26	3.65	0.29ab	0.11
OPT-NP+S	5.50	0.27	2.31	0.39a	0.11

Note: There are no significance for the values with the same letter in each row ($P < 0.05$). TN, TP and TSP denote total nitrogen, total phosphorus and total soluble phosphorus, respectively; CK, CON, OPT, OPT-N, OPT-P and OPT-NP+S denote non-N-fertilised control, conventional N management based on local custom, optimised N management, 30% reduced N compared to OPT, 50% reduced P on the basis of OPT and straw with chemical fertilizer @200 kg of wheat straw per acre on the basis of OPT-N and OPT-P, respectively

Table 4: Significance test for the rice runoff losses among six treatments (unit: mg/L)

	TN	TP	Nitrate N	Ammonium N	TSP
CK	3.13	0.19ab	1.12ab	0.33ab	0.14b
CON	4.64	0.27a	1.49a	0.40a	0.22a
OPT	3.91	0.20ab	1.25ab	0.32ab	0.16ab
OPT-N	3.86	0.24ab	0.66b	0.33ab	0.15ab
OPT-P	3.87	0.16b	0.80ab	0.27b	0.12b
OPT-NP+S	3.55	0.17b	1.10ab	0.30ab	0.14b

Note: There are no significance for the values with the same letter in each row ($P < 0.05$). TN, TP and TSP denote total nitrogen, total phosphorus and total soluble phosphorus, respectively; CK, CON, OPT, OPT-N, OPT-P and OPT-NP+S denote non-N-fertilised control, conventional N management based on local custom, optimised N management, 30% reduced N compared to OPT, 50% reduced P on the basis of OPT and straw with chemical fertilizer @200 kg of wheat straw per acre on the basis of OPT-N and OPT-P, respectively

> CON > OPT-NP+S > OPT-N > OPT > OPT-P. The LSD test revealed that wheat yield followed the order of OPT-P > OPT-N > OPT > OPT-NP+S > CON > CK (Table 5).

Only the TK content did not significantly differ for the six treatments. The TN content decreased after fertilization treatments. There were significant differences for the other five treatments except the CK. The TP content significantly differed between the six treatment methods and followed the order of CON > CK > OPT > OPT-N >OPT-NP+S>OPT-P. The rice yield followed the order of OPT > OPT-NP+S > OPT-P > OPT-N > CON > CK (Table 6).

Table 5: Significance test for the wheat nutrients and yield among six treatments

	TN (%)	TP (%)	TK (%)	Yield (kg/ha)
CK	1.19	0.29a	0.91	3684.41b
CON	0.84	0.17ab	1.16	4567.77a
OPT	0.86	0.13b	0.96	4925.04a
OPT-N	0.94	0.13b	0.89	5087.41a
OPT-P	0.85	0.13b	0.79	5154.87a
OPT-NP+S	0.84	0.14b	1.08	4817.54a

Note: There are no significance for the values with the same letter in each row ($P < 0.05$). TN, TP and TK denote total nitrogen, total phosphorus and total potassium, respectively; CK, CON, OPT, OPT-N, OPT-P and OPT-NP+S denote non-N-fertilised control, conventional N management based on local custom, optimised N management, 30% reduced N compared to OPT, 50% reduced P on the basis of OPT and straw with chemical fertilizer @200 kg of wheat straw per acre on the basis of OPT-N and OPT-P, respectively

Table 6: Significance test for the rice nutrients and yield among six treatments

	TN (%)	TP (%)	TK (%)	Yield (kg/ha)
CK	2.16a	0.37ac	1.11	5434.78d
CON	1.64b	0.37ac	1.10	8248.43c
OPT	1.36b	0.34abc	1.14	9532.68a
OPT-N	1.50b	0.27abc	1.24	8503.30c
OPT-P	1.48b	0.20b	1.10	8783.06b
OPT-NP+S	1.64b	0.23b	1.26	9272.86ab

Note: There are no significance for the values with the same letter in each row ($P < 0.05$). TN, TP and TK denote total nitrogen, total phosphorus and total potassium, respectively; CK, CON, OPT, OPT-N, OPT-P and OPT-NP+S denote non-N-fertilised control, conventional N management based on local custom, optimised N management, 30% reduced N compared to OPT, 50% reduced P on the basis of OPT and straw with chemical fertilizer @200 kg of wheat straw per acre on the basis of OPT-N and OPT-P, respectively

Discussion

The results showed that fertilization can increase the soil OA content (Galantini and Rosell 2006) and the accumulation of OA can be significantly improved under the OPT-NP+S. Appropriate reduction of N, P fertilizer and straw with chemical fertilizer could increase ammonium N in rice soil. After chemical fertilizer application, the soil available nutrients increased significantly (Moharana *et al*. 2012; Joshi *et al*. 2015), while the soil pH decreased. It showed that rational fertilization can reduce the pH of soil (Li *et al*. 2007, 2017). The AK content of wheat and rice soils were the highest under the OPT-N and appropriate reduction of N fertilizer could increase the soil AK content.

Through the improvement of fertilization methods, the amount of N and P losses can be effectively reduced (Zhao *et al*. 2006). The rate of nitrate N loss in wheat under the CON was the largest and ammonium N loss under the OPT-NP+S was the largest. The loss rate of TSP was the largest under the OPT. The loss rate of nitrate N and ammonium N in rice soil were the largest under the CON and the TSP showed the same trend under the OPT. The runoff loss of N and P fertilizers has a certain relationship with the rainfall situation and farmland farming conditions. In addition, there are many other external factors, which will inevitably cause certain errors during the testing process (Li *et al*. 2017).

After fertilization, the TP nutrient in wheat and rice plants was the least under the OPT-P. Reducing the usage of P fertilizer will reduce the absorption of P in plants. The uptake of N in rice plants was reduced by fertilization. The absorption of nutrients by crops mainly comes from soil and fertilization (Fageria *et al*. 2016). In terms of absorption, more than two-thirds of the N, P and K at different growth stages are derived from the soil, and most of them are obtained from the soil than from the fertilizers (Smith 1976). Fertilization treatments can increase the crop yield, but yields vary with different fertilization treatments. The reason was that different fertilization treatments have certain effects on soil fertility and nutrient uptake by various plants (Mohammad *et al.* 2003).

Conclusion

The effects of different fertilisation treatments under a rice-wheat rotation system revealed imbalances in different soil nutrients. The order of TN loss in wheat among treatments was OPT-P > CON > OPT > OPT-NP+S > OPT-N and that of TP loss was CON>OPT-NP+S>OPT-P>OPT>OPT-N. For rice cultivation, the order of TN loss was CON> OPT> OPT-P> OPT-N> OPT-NP+S and TP loss was CON > OPT-N > OPT > OPT-NP+S> OPT-P. The absorption of N, P and K nutrients in rice was slightly higher than wheat. The wheat plant yield followed the order of OPT-P > OPT-N > OPT > OPT-NP+S > CON > CK and that for rice followed the order of OPT > OPT-NP+S > OPT-P > OPT-N > CON > CK.

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