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Crop rotation-dependent yield responses to fertilization in winter oilseed rape (*Brassica napus* L.)

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ABSTRACT

Differences in soil physical, chemical and biological properties between paddy–upland and continuous upland rotations will influence nutrient relations and crop growth. With the aim of estimating rapeseed yield performance in response to fertilization in rice–rapeseed (RR) and cotton–rapeseed (CR) rotations, on-farm experiments were conducted at 70 sites across Hubei province, central China. The economically optimal fertilizer rates of winter oilseed rape in different rotations were determined. Field experiments showed that previous crops significantly influenced seed yields. Without N fertilization, seed yields were significantly lower for the RR rotation than for the CR rotation. The average yield increase ratio and agronomic efficiency associated with nitrogen (N) fertilization in the RR rotation were 96.6% and 6.56 kg kg^{-1}, significantly higher than those in the CR rotation. No seed yield differences were detected between the two rotations under phosphorus (P) and potassium (K) fertilization. In contrast to the CR rotation, N fertilizer played a more vital role in maintaining high seed yields in the RR rotation owing to the lower indigenous soil N supply. Compared with local N fertilizer recommendation rates for the RR rotation, on average an additional 18 kg N ha^{-1} was recommended according to the economically optimal N fertilizer rate (EONFR). In contrast, the EONFR was 14 kg N ha^{-1} lower than the locally recommended N fertilizer rate for the CR rotation. There were no differences between the two rotations for the average economically optimal P and K fertilization rates. Consequently, the average EONFR of winter oilseed rape could be reduced if cotton rather than rice preceded the winter oilseed rape.

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1. Introduction

Oilseed rape (*Brassica napus* L.) is used to produce important edible oil for human consumption and is also a promising biodiesel crop. Increasing demand for edible oil and fuel with limited arable land and expanding population will require greater oilseed rape production worldwide [1]. Reliance on the use of mineral fertilizer has resulted in high oilseed rape production [2–5], even under unpredictable environmental conditions [6]. However, imperfect fertilizer management has always resulted in the inconsistent and inappropriate application of fertilizer in agricultural production, with consequent environment risks [7]. Managing agricultural nutrients to provide a safe and secure food supply and protect the environment remains one of the great challenges of the 21st century [8].

Crop nutrient uptake and crop yield are the primary factors determining optimal fertilization practices [9]. However, seed yields are highly variable in winter oilseed rape production, depending on the crop rotations [3,10]. Rapeseed yields following cereal crops are considerably lower than those following peas, possibly owing to higher residual soil nitrogen (N) content and greater net soil N mineralization under cultivation in rotation with a legume [4,11]. A lower rapeseed yield response to mineral N fertilizer was observed in a pea than in a barley–winter oilseed rape rotation [12]. Optimal N fertilizer rate could be reduced if peas or fallow rather than winter wheat preceded the rape crop [3].

Differently from oilseed rape rotations in Europe, paddy-oilseed rape is the predominant oilseed rape rotation in Asia. Repeated transitions from flooding to drying affect soil physical, chemical, and biological properties [13,14]. Paddy–upland rotations showed a larger potential for carbon (C) sequestration, owing to the perennially flooded conditions [15,16]. Moreover, a rice-based crop rotation could enhance native arbuscular mycorrhizal (AM) activity and improve the phosphorus (P) nutrition of subsequent crops [17]. Thus, changes in soil physical, chemical, and biological features in paddy–upland rotation will influence nutrient relations and crop growth. Besides paddy-oilseed rape rotation, upland–oilseed rape rotations such as cotton–, peanut–, and spring maize–oilseed rape rotations are important oilseed rape rotations in Asia. So the question arises whether rapeseed yields and yield responses to mineral fertilization for paddy–upland rotations and continuous upland rotations are different. If there are differences between these two rotations, the recommended fertilizer rates of winter oilseed rape should be adapted to the respective previous crop, a critical measure for improving fertilizer use efficiency.

Winter oilseed rape followed by rice or cotton is the dominant oilseed rape rotation in the Yangtze River basin, where 91% of the total oilseed rape in China is produced [18]. From September 2009 to May 2010, on-farm experiments were conducted at 70 sites across Hubei province, central China to study the influences of different mineral fertilizer application rates on winter oilseed rape yield with the aim of providing guidance for reasonable winter oilseed rape fertilization. At 35 sites the previous crops were cotton, whereas the other 35 on-farm winter oilseed rape crops followed rice. The results from these experiments allowed the estimation of (1) the winter oilseed rape yield response differences to mineral fertilization between the RR and CR, and (2) the economically optimal rate of fertilization for winter oilseed rape in these two different rotations. These estimates will be helpful for improving fertilizer advisories for different rotations and for achieving sustainable oilseed rape production.

2. Materials and methods

2.1. Site characteristics

Hubei province (29°25′ N–33°20′ N, 108°21′ E–116°07′ E) is located in the middle of the Yangtze River basin in central China. The climate in this region is subtropical, with an average annual temperature of 15–17 °C, 750–1600 mm of precipitation, and a mean frost-free period of 230–300 days. Rice–rapeseed (RR) and cotton–rapeseed (CR) are the dominant winter oilseed rape rotations in the province. Rice is typically transplanted at the end of May and harvested at the end of September. Winter oilseed rape plants are usually transplanted after the rice harvest to improve land use efficiency, to lessen erratic winter weather-related adverse impacts on seedlings, and to achieve high yields. Farmers sow the seeds in nursery beds in the middle of September and then manually transplant 30- to 40-day-old oilseed rape seedlings with 4–5 leaves at a density of 105,000 plants ha^{-1}. The cotton growing period is longer than that of rice, with cotton being usually transplanted at the end of May and harvested in early November. Approximately one week after the cotton harvest, 30- to 40-day-old winter oilseed rape seedlings are transplanted to the field. The double-low rapeseed cultivars, including Huashuang (HS), Huayouza (HYZ), Zhongshuang (ZS), and Zhongyouza (ZYZ), are widely grown and have average seed yields of 1.75 t ha^{-1}, varying from 0.96 to 2.44 t ha^{-1} [18].

On-farm experiments at 70 sites across Hubei were conducted from September 2009 to May 2010. In 2009–2010

Table 1 – General soil properties of 70 winter oilseed rape fields from different rotations in Hubei province, central China.

Soil property	CR (*n* = 35)				RR (*n* = 35)			
	Mean	Min.	Max.	CV (%)	Mean	Min.	Max.	CV (%)
SOM (g kg^{-1})	22.7	11.0	38.8	29.0	25.6	11.3	44.0	33.3
Available N (mg kg^{-1})	123	49.0	204.0	34.4	118.0	33.0	248	39.4
Olsen-P (mg kg^{-1})	15.8	2.5	48.2	65.7	12.1	3.1	27.4	46.1
NH_4OAc–K (mg kg^{-1})	110.0	25.0	250.0	46.7	96.0	44.0	246.0	40.6
pH	7.1	4.0	8.4	14.8	6.1	4.7	8.1	12.8

1) CR: cotton–oilseed rape rotation; RR: rice–oilseed rape rotation.
2) Available N is alkaline hydrolyzable N.
3) CV: coefficient of variation.

the climate conditions during rapeseed production were similar as the past 10 years and no disastrous weather occurred. The soil chemical properties of the total 70 winter oilseed rape fields with different rotations are shown in Table 1.

2.2. On-farm experiments

The following treatments, including four rates of nitrogen (N), phosphorus (P), and potassium (K) fertilizer applications, were applied at each experimental site: $N_0P_2K_2$, $N_1P_2K_2$, $N_2P_2K_2$, $N_3P_2K_2$, $N_2P_0K_2$, $N_2P_1K_2$, $N_2P_3K_2$, $N_2P_2K_0$, $N_2P_2K_1$, and $N_2P_2K_3$. The numbers represent the fertilizer application rates of winter oilseed rape, where 0 indicates no fertilizer application; 2 indicates the locally recommended fertilizer rate; 1 is equivalent to half the recommended fertilizer rate; and 3 indicates 1.5 times the recommended fertilizer rate. The locally recommended fertilizer rates were determined by local technicians, based on site-specific target yields and soil fertility levels that varied by field irrespective of crop rotation. The average locally recommended fertilizer rates of winter oilseed rape across the two rotations were 179 kg N ha^{-1}, 32 kg P ha^{-1}, and 82 kg K ha^{-1}. Differentiated according to crop rotation, the recommended average fertilizer rates were 185 kg N ha^{-1}, 32 kg P ha^{-1}, and 76 kg K ha^{-1} for CR rotations and 174 kg N ha^{-1}, 32 kg P ha^{-1} and 87 kg K ha^{-1} for RR rotations (Table 2). More N was recommended in the CR rotations than in the RR rotations and the recommended K fertilizer application rate was higher in the RR rotations. In addition, in our study the average mineral fertilizer inputs in the preceding crops were 280 kg N ha^{-1} (range 120–350 kg ha^{-1}), 90 kg P ha^{-1} (range 54–135 kg ha^{-1}), and 117 kg K ha^{-1} (range 56–175 kg ha^{-1}) for cotton and 178 kg N ha^{-1} (range 141–315 kg ha^{-1}), 69 kg P ha^{-1} (range 36–120 kg ha^{-1}), and 65 kg K ha^{-1} (range 0–120 kg ha^{-1}) for rice. More mineral fertilizers were applied in the cotton season.

All P and K fertilizers and 60% of N fertilizers were applied to the field one or two days before transplanting. The remaining N fertilizer was topdressed during the stem elongation period. The N, P, and K fertilizers consisted of urea (46% N), superphosphate (5% P), and potassium chloride (50% K), respectively. In addition, 7.5 kg borax (11% B) ha^{-1} was applied to all plots to ensure a sufficient boron supply. Based on the local multipoint distribution experimental method, replicates were not established at each site. Each site was considered to be a replication, and a randomized design was used for statistical analysis [19]. The individual plot area was 20 m^2, with length 4 m and width 5 m. Farmers followed common methods of water management and pest control for all plots.

2.3. Plant and soil sampling and sample analysis

Initial soil samples were collected from 0 to 20 cm depth at each experimental site before basic fertilizer was applied. Fresh soil was taken to the lab, mixed thoroughly to produce a composite sample, sieved, air-dried, and analyzed for soil chemical properties, including soil organic matter, alkaline hydrolyzable N, Olsen-P, NH_4OAC–K, and soil pH [20].

Plants were sampled by the same protocol at all experimental sites. All of the plants in each experimental plot were harvested for seed yield estimation. The seeds were cleaned by hand, oven-dried at 60 °C, and weighed. Ten oilseed rape plants from each plot were collected at harvest for measurement of harvest indexes and nutrient concentrations in plant tissue. Straw yields were estimated on the basis of oven-dried seed yields from all of the plots and the seed-to-straw ratio of ten-plant samples. Sub-plant samples were digested with H_2SO_4–H_2O_2 following the method of Thomas et al. [21], after which they were analyzed for N and P concentrations using a flow injection analyzer (FIAstar 5000, FOSS, Denmark). The K concentration was analyzed with a flame photometer. Nutrient uptake was calculated as the product of dry matter content and nutrient concentration in the different plant parts. Total plant N accumulation at maturity in $N_0P_2K_2$ (0–N) plots, total plant P accumulation in $N_2P_0K_2$ (0–P) plots, and total plant K accumulation in $N_2P_2K_0$ (0–K) plots were defined as indigenous N, P, and K supplies, respectively [22].

2.4. Calculations and statistical analysis

Four treatments from each site, including $N_0P_2K_2$ (0–N), $N_2P_0K_2$ (0–P), $N_2P_2K_0$ (0–K), and $N_2P_2K_2$ (NPK), were selected to estimate basic seed yields, yield increase ratio, fertilizer contributions to yield, and fertilizer use efficiencies under local fertilizer recommendations.

The yield increase ratio (YIR) and fertilizer contribution to yield (FCY) were calculated as follows:

$$YIR_{N/P/K} = \frac{Y_{N_2P_2K_2} - Y_0}{Y_0} \times 100 \quad (1)$$

$$FCY_{N/P/K} = \frac{Y_{N_2P_2K_2} - Y_0}{Y_{N_2P_2K_2}} \times 100 \quad (2)$$

where YIR_N, YIR_P, and YIR_K represent the yield increase ratio associated with locally recommended N, P, and K fertilizer

Table 2 – Recommended fertilizer rates for winter oilseed rape in oilseed rape–cotton and oilseed rape–rice rotations determined in 2009/2010 by local technicians at 70 different sites in Hubei province, central China.

Recommended fertilizer rates ($kg\ ha^{-1}$)	CR (n = 35)				RR (n = 35)				All (n = 70)			
	Mean	Min.	Max.	CV (%)	Mean	Min.	Max.	CV (%)	Mean	Min.	Max.	CV (%)
N	185	135	315	21.2	174	138	225	9.5	179	135	315	17
P	32	17	62	31.9	32	18	52	25.7	32	17	62	28.8
K	76	38	156	39.9	87	38	150	33.8	82	38	156	37

1) CR: cotton–oilseed rape rotation; RR: rice–oilseed rape rotation.
2) Recommended fertilizer rates were determined by local technicians, based on site-specific target yields and soil fertility levels.

applications; FCY_N, FCY_P, and FCY_K represent the contributions of N, P, and K fertilizers to seed yield, respectively; Y_{N2P2K2} is the seed yield of the $N_2P_2K_2$ treatment; and Y_0 represents the seed yields of the $N_0P_2K_2$, $N_2P_0K_2$ and $N_2P_2K_0$ treatments when calculating the parameters for N, P, and K, respectively. $YIR_{N/P/K}$, $FCY_{N/P/K}$, and Y_{NPK} are expressed as %, %, and t ha^{-1}.

Fertilizer use efficiencies were calculated as follows:

$$AE_{N/P/K} = \frac{Y_{N_2P_2K_2} - Y_0}{F_{N_2P_2K_2}} \quad (3)$$

$$RE_{N/P/K} = \frac{N_{N_2P_2K_2} - N_0}{F_{N_2P_2K_2}} \times 100 \quad (4)$$

where AE_N, AE_P, and AE_K and RE_N, RE_P, and RE_K represent the agronomic efficiencies (AE) and fertilizer recovery efficiencies (RE) for N, P and K fertilizers, respectively; $F_{N_2P_2K_2}$ is the N, P, and K fertilizer application rates for the $N_2P_2K_2$ treatment; N_{N2P2K2} is the nutrient uptake for the $N_2P_2K_2$ treatment; and N_0 represents the N, P and K uptakes of the $N_0P_2K_2$, $N_2P_0K_2$, and $N_2P_2K_0$ treatments when calculating RE_N, RE_P, and RE_K, respectively. AE, RE, and N_{NPK} are expressed in kg kg^{-1}, %, and kg ha^{-1}, respectively.

Two response models, including quadratic and linear models with plateaus, were employed to estimate the seed yield response curves to different fertilizer application rates at each site [23]. The criterion for selecting the better model was the smaller residual sum of squares (SS) [24]. The economically optimal rates of N, P, and K fertilization were calculated from the selected model at a price of 5.2 yuan kg^{-1} N, 2.5 yuan kg^{-1} P, 5.6 yuan kg^{-1} K, and 4.6 yuan kg^{-1} of rapeseed. The price was chosen to represent the regional average during the study period.

All on-farm data were analyzed with OriginPro 8.5 software (OriginLab, Northampton, MA, USA). Descriptive statistical analyses were performed for the parameters measured at each site to evaluate the range of variation and coefficient of variation (CV) for each parameter. The yield data in the different rotations were pooled for all experiments at each site to compare treatments, and two-way ANOVA was performed according to the factorial randomized block design. Means were compared using the least significant difference test (LSD) at a 5% level of probability. Yield increase ratio and fertilizer use efficiencies associated with mineral fertilization in different rotations were analyzed by *t*-test ($P < 0.05$).

Table 3 – Oilseed rape seed yields under different NPK fertilizer treatments in two different winter oilseed rape rotations.

Treatment	Winter oilseed rape yield (t ha^{-1})		$P > \lvert T \rvert$
	CR	RR	
0–N ($N_0P_2K_2$)	1.68 ± 0.50 c	1.40 ± 0.48 c	0.0199
0–P ($N_2P_0K_2$)	2.04 ± 0.53 b	2.03 ± 0.49 b	0.945
0–K ($N_2P_2K_0$)	2.12 ± 0.48 b	2.19 ± 0.54 b	0.615
NPK ($N_2P_2K_2$)	2.61 ± 0.59 a	2.55 ± 0.51 a	0.652
ANOVA			
Treatment (T)			$P < 0.001$
Rotation (R)			$P = 0.246$
T × R			$P = 0.233$

1) N_0 and N_2 represent no N fertilizer and the locally recommended N fertilizer rate; P_0 and P_2 represent no P fertilizer and the locally recommended P fertilizer rate; and K_0 and K_2 represent no K fertilizer and the locally recommended K fertilizer rate.
2) CR: cotton–oilseed rape rotation; RR: rice–oilseed rape rotation.
3) Seed yields of treatments followed by the same letter did not differ significantly ($P < 0.05$, LSD test).
4) $P > |T|$, probability of a significant mean difference from the same treatment between rotations.

3. Results

3.1. *Seed yield and fertilizer use efficiency under locally recommended fertilization*

Oilseed rape yields varied between 1.4 and 2.6 t ha^{-1} depending on fertilization and crop rotation. Mineral fertilizer application successfully improved oilseed rape seed yields. The seed yields of the NPK ($N_2P_2K_2$) treatment were the highest (Table 3). However, the contributions of mineral fertilizer to seed yields were different. Seed yields of the 0–N treatment were significantly lower than those of the 0–P and 0–K treatments, revealing that N was the most restrictive element for seed yields. The previous crop also influenced yield response to fertilization. With optimized fertilization, there were no differences in seed yield between the two rotations. However, without N fertilizer application, the average rapeseed yields following rice cultivation were 1.40 t ha^{-1}, significantly lower than those after cotton with 1.68 t ha^{-1}. The average seed yield increase ratio and agronomic efficiencies associated with N fertilization were 96.6% and 6.56 kg seed kg^{-1} N in the RR rotation, significantly higher than those in the CR rotation (Table 4). N fertilizer contributed much more to RR rotation seed yields; the average N fertilizer contribution to seed yield was 45.0%, much higher than that in the CR rotation (34.5%), whereas no differences between the two rotations in yield response to P or K fertilization were observed. The higher agronomic efficiency of K fertilizer in the CR rotation is possibly due to the lower K fertilizer recommendation rates.

3.2. *Indigenous soil nutrient supply*

Among the 70 winter oilseed rape fields, the average indigenous soil nutrient supplies were 47.8 kg N ha^{-1}, 14.5 kg P ha^{-1}, and 97.6 kg K ha^{-1} for the RR rotations and 74.6 kg N ha^{-1}, 16.2 kg P ha^{-1}, and 94.8 kg K ha^{-1} for the CR rotations (Fig. 1). The indigenous soil N supply in the winter oilseed rape field was significantly lower in the RR than in the CR rotation and no differences in the indigenous soil P and K supplies between the two rotations were found. The increased seed yield of the $N_2P_2K_2$ plot was associated with an increase in the indigenous soil nutrient supply (Fig. 2), whereas the relationships between indigenous soil nutrient supply and yield increase ratio associated with mineral fertilization were negative. The yield increase ratio decreased gradually with an increase in the indigenous soil nutrient supply.

Table 4 – Yield increase ratio, fertilizer recovery efficiency, and agronomic efficiency associated with mineral fertilization in different winter oilseed rape rotations.

Nutrient	Rotation	Yield increase ratio (%)	Fertilizer contribution to yield (%)	Recovery efficiency (%)	Agronomic efficiency (kg kg^{-1})
N	CR	64.8 ± 49.5 b	34.5 ± 17.8 b	36.8 ± 19.7 a	5.12 ± 3.12 b
	RR	96.6 ± 57.5 a	45.0 ± 15.3 a	35.7 ± 11.1 a	6.56 ± 2.41 a
P	CR	31.3 ± 26.4 a	21.2 ± 13.6 a	11.5 ± 8.5 a	8.57 ± 6.40 a
	RR	29.7 ± 30.2 a	19.9 ± 14.2 a	13.2 ± 4.8 a	7.12 ± 5.37 a
K	CR	23.6 ± 16.2 a	17.8 ± 10.0 a	37.8 ± 23.2 a	6.24 ± 4.88 a
	RR	18.7 ± 15.1 a	14.5 ± 9.8 a	46.1 ± 19.1 a	3.97 ± 3.18 b

1) CR: cotton–rapeseed rotation; RR: rice–rapeseed rotation.
2) The parameters of rotations assigned the same letter did not differ significantly ($P < 0.05$, *t*-test).

3.3. Economically optimal rate of fertilization

According to the seed yield response curves to different fertilizer application rates at each site, the average economically optimal rates for the fertilization of winter oilseed rape were 171 kg N ha^{-1}, 29 kg P ha^{-1}, and 67 kg K ha^{-1} for the CR rotations and 192 kg N ha^{-1}, 29 kg P ha^{-1}, and 63 kg K ha^{-1} for the RR rotations (Fig. 3). The average economically optimal N fertilizer rates (EONFRs) were close to the locally recommended N fertilizer rate. However, compared with the locally recommended N fertilizer rate of 174 kg ha^{-1} in the RR rotation, on average an additional 18 kg N ha^{-1} was recommended according to the EONFR. In contrast, the EONFR was about 14 kg N ha^{-1} lower than the locally recommended N fertilizer rate of 185 kg N ha^{-1} in the CR rotation. There were no differences between these two rotations for the average economically optimal P and K fertilizer rates (EOPFR and EOKFR). The EOPFR was similar to the locally recommended P fertilizer rate and the EOKFRs were 9 and 24 kg K ha^{-1} lower than the recommended K fertilizer rates for the CR and RR rotations, respectively.

4. Discussion

4.1. Seed yield and yield responses to fertilizer applications

Under recommended fertilization, rapeseed yields were comparable between the CR and RR rotations, but without N fertilization, the oilseed rape seed yields following rice cultivation were significantly lower than those following cotton, a result similar to those reported for other crops [25–27]. Although rapeseed yields varied with different environmental variables [28], there was only one season's result, the experiments were located in different counties, and the weather conditions at the specific sites were different. Indeed, further pairing experiments depending on soil characters and weather conditions should also be performed to study the critical processes of soil nutrient supply in different rotations.

Mineral fertilizer plays an important role in sustaining high yields during winter oilseed rape production. N is the most critical limiting element in seed yield and the positive

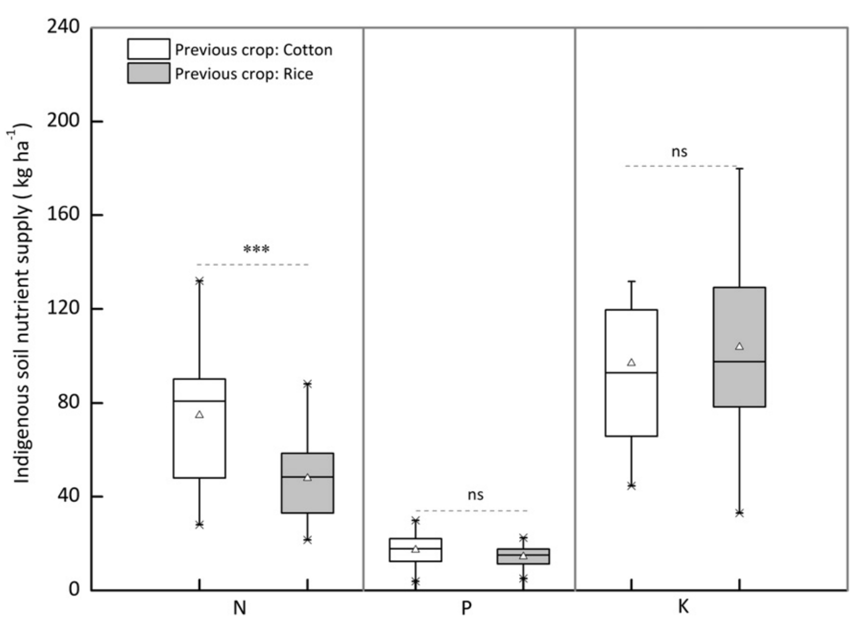

Fig. 1 – Soil indigenous nutrient supply in the different winter oilseed rape rotations (*n* = 35). The upper and lower limits of each box represent the 25th and 75th percentiles of the soil indigenous nutrient supply. The horizontal line in the center of the box indicates the median. The triangle in the box indicates the average soil indigenous nutrient supply. ***indicates a significant difference at the 0.001 probability level; ns indicates no significant difference.

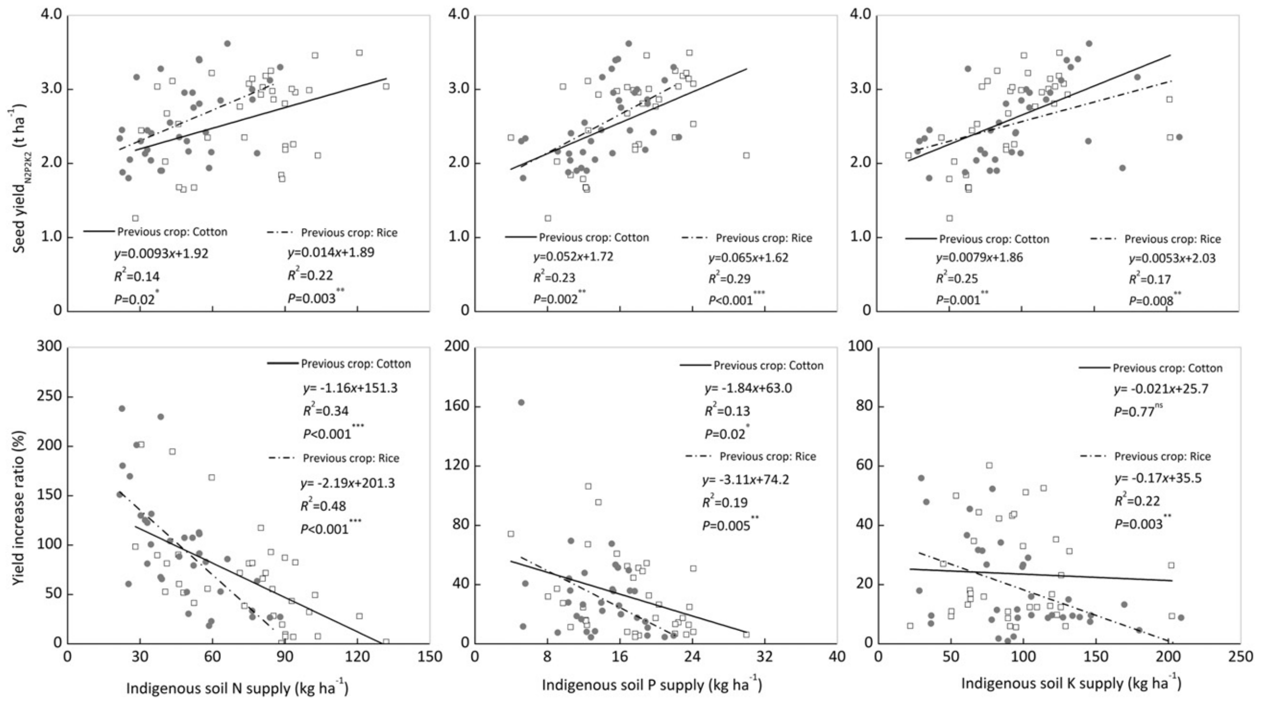

Fig. 2 – The relationships between indigenous soil nutrient supply (n = 35), seed yield of the $N_2P_2K_2$ treatment, and yield increase ratio associated with mineral fertilization in different winter oilseed rape rotations.

impact of N on the seed yield of winter oilseed rape and canola has been repeatedly reported [2,3,29]. Significant differences between RR and CR rotations in yield response to N fertilization were identified and the dependence of seed yield on N fertilizer was higher in the RR than in the CR rotation, a result that might be attributed to lower indigenous soil N supply in the RR rotations. In our study the average mineral N fertilizer input in the preceding crops was 280 kg N ha^{-1} for cotton and 178 kg N ha^{-1} for rice, and nutrient surpluses were higher in cotton than in rice fields (Table 5). Additionally, because of higher N losses from runoff and ammonia volatilization during the rice season [30], the flooded rice production soil contained significantly decreased accumulated mineral N after harvest [31]. We accordingly

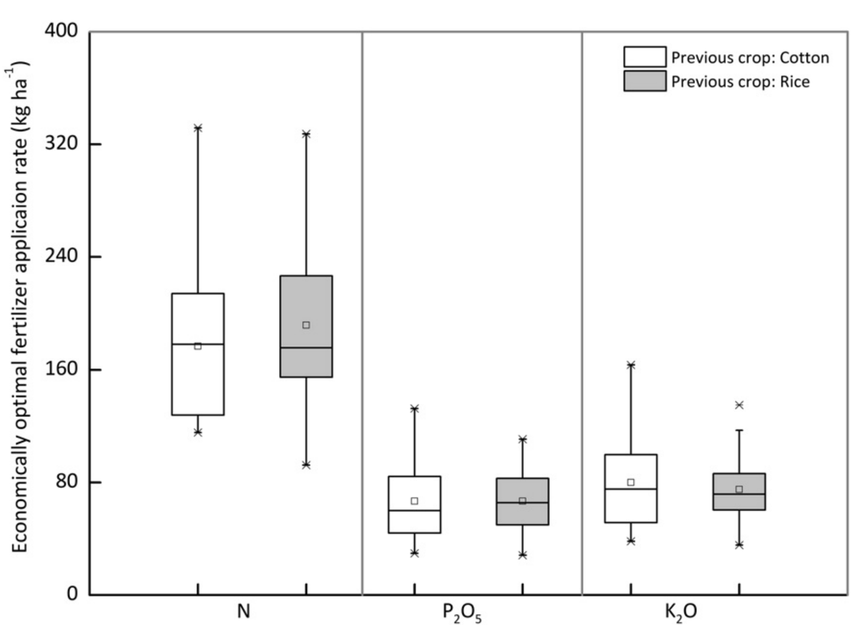

Fig. 3 – Economically optimal fertilizer application rates of winter oilseed rape in different rotations (n = 35). The upper and lower limits of each box represent the 25th and 75th percentiles for economic optimal fertilizer application rates. The horizontal line in the center of the box indicates the median. The square in the box indicates the mean.

Table 5 – Crop yield and nutrient balance for cotton and rice in Hubei province, central China.

Parameter		Cotton				Rice			
		Mean	Min.	Max.	CV (%)	Mean	Min.	Max.	CV (%)
Yield (t ha^{-1})		3.02	1.35	4.5	40.4	7.52	6	8.25	9.8
Fertilizer application rate (kg ha^{-1})	N	280	120	350	20.8	178	141	315	23.3
	P	90	54	135	28.9	69	36	120	33.4
	K	117	56	175	24.2	65	0	120	45
Nutrient uptake (kg ha^{-1})	N	235	105	351	40.4	147	117	161	9.8
	P	40	18	59	40.4	39	31	43	9.8
	K	180	81	269	40.4	179	143	196	9.8
Nutrient balance (kg ha^{-1})	N	45	−72	210	226.9	31	−20	169	141.2
	P	51	11	80	41.7	30	1	81	76.1
	K	−63	−176	39	115.5	−111	−196	−59	33.2

1) Nutrient uptakes were estimated as nutrient uptake per 100 kg yield [39].
2) Nutrient balance = fertilizer application rate − nutrient uptake.

speculated that the residual N in the soil profile was higher following the cotton than the rice harvest. Besides the soil residual-N after harvest of the previous crop, the differences in soil N mineralization in winter oilseed rape seasons between these two rotations might also represent one of the principal influences on indigenous soil N supply. Meelu et al. [25] found that more N applied to wheat following paddy was immobilized in the organic form than was immobilized when wheat followed maize. An increase in soil organic matter and soil labile organic matter fractions in paddy–upland rotations can affect soil N turnover and lead to reduced rates of net N mineralization [32,33]. In addition, dry–wet cycling influences N turnover and drought induces a reduction in gross N turnover [34]. Overall, the combined effects of these factors presumably triggered lower soil N supply in paddy soil than in upland soil, so that optimal N fertilization was crucial to ensure the highest seed yields in the paddy–upland rotation.

Soil available P and K contents are important parameters for assessing yield response to fertilization. With an increase in soil available P and K contents, the yield increase ratio decreased gradually [35,36]. In our study the average soil Olsen-P and NH_4OAc–K contents averaged 12.1 and 96.1 mg kg^{-1} in the RR rotations and 15.8 and 110.3 mg kg^{-1} in the CR rotations. The absence of differences in soil available P and K contents between these two rotations in our study illustrated the similar seed yield performances for P and K fertilizations. In addition, soil indigenous P and K supplies were similar for these two rotations. It should be noted that the average fertilizer contributions to yield were 19.9% and 14.5% for the RR rotations and 21.2% and 17.8% for the CR rotations, indicating that optimal P and K fertilizations were still essential for achieving high seed yields from oilseed rape production, in agreement with the results of other studies [37,38]. Furthermore, soil P availability decreased when the soil was converted from flooding to drying, owing to the production of large amounts of amorphous iron [39]. More concern should be focused on P fertilizer management in the upland portion of the paddy–upland rotation [40].

4.2. Economically optimal fertilizer application rate

The average EONFRs of oilseed rape were 192 and 171 kg N ha^{-1} for the RR and CR rotations, respectively. These values were similar to the locally recommended N fertilizer rates (Table 2). They were also close to the regional mean optimal fertilizer application rate for winter oilseed rape in the Yangtze River basin [41]. However, unlike the locally recommended N fertilizer rates, the EONFR of winter oilseed rape was lower in the continual upland rotation than in the paddy–upland rotation. Considering the higher availability of soil residual N and the higher indigenous soil N supply following a cotton crop, the optimal N fertilizer recommendation rates should be reduced. Otherwise, excessive N recommendation will increase environmental risks. In contrast, owing to the lower residual N in the soil profile and indigenous N supply following rice, an increased N fertilizer input is needed to obtain a high seed yield in the rice–winter oilseed rape rotation.

The average EOPFR and EOKFR approached the locally recommended fertilizer rates. However, compared with the EOPFR and EOKFR of each site, approximately 42% and 56% of P and K fertilizer recommendations would be excessive if the local fertilizer recommendation rates were followed. This finding implies that optimal P and K fertilizer application rates should be refined according to the specific field conditions. Soil Olsen-P and NH_4OAc–K contents are usually employed to estimate soil P and K supplies and to guide reasonable fertilization [42,43]. According to Zou [44], the threshold values for soil available P and K contents in winter oilseed rape in the Yangtze River basin are 25 mg kg^{-1} Olsen-P and 135 mg kg^{-1} NH_4OAc–K, respectively. Soil Olsen-P content in approximately 50% of the sites in these two different rotations was at or above the “slightly deficient” level. Depending on seed yield and soil Olsen-P content, P fertilizer recommendation rates varied from 26 kg P ha^{-1} to 35 kg P ha^{-1}. At more than 80% of sites, soil available K content also was at or above the “slightly deficient” level; K fertilizer recommendation rates ranged from 33 to 75 kg K ha^{-1} [44]. These values approximated the EOPFR and EOKFR. Furthermore, it should be noted that K deficiency was more severe in the rice season than in the cotton season (Table 5). More K fertilizer needs to be applied in the rice season for the RR rotation. Although the P surplus was higher in the cotton than in the rice season, the P fertilizer recommendation of oilseed rape for the CR rotation could be reduced. Thus, the local fertilizer recommendations based upon crop rotations and soil available P and K contents at site specific conditions will be optimum for P and K applications. Following them will result in achieving high seed yields and high P and K fertilizer use efficiencies.

5. Conclusion

Previous crops significantly influenced ensuing seed yields and seed yield responses to fertilization. Differences in indigenous soil nutrient supply were the dominant reasons for different responses to fertilization. The average soil indigenous N supply from winter oilseed rape fields was 47.8 kg N ha^{-1} in the RR rotation, significantly lower than that in the CR rotation. The average economically optimal fertilization rates for winter oilseed rape were 171 kg N ha^{-1}, 29 kg P ha^{-1}, and 67 kg K ha^{-1} for the CR rotations and 192 kg N ha^{-1}, 29 kg P ha^{-1}, and 63 kg K ha^{-1} for the RR rotations. For CR rotations, local N fertilizer recommendation rates should be reduced to improve N use efficiency further. In contrast, they should be increased to maintain high seed yields for RR rotations. For P and K fertilizations, the local fertilizer recommendation rates were higher than the EOPFR and EOKFR for most sites during these two rotations. Establishment of optimal fertilizer management for winter oilseed rape in central China on the basis of crop rotations and soil nutrient levels will be key to further improving fertilizer use efficiency.

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