International Journal of Plant Production (2020) 14:77–92
https://doi.org/10.1007/s42106-019-00069-1

RESEARCH

Differential Responses of Seed Yield and Yield Components to Nutrient Deficiency Between Direct Sown and Transplanted Winter Oilseed Rape

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Received: 23 April 2019 / Accepted: 5 September 2019 / Published online: 16 September 2019

Abstract
Both transplanting and direct-sowing are the dominated methods for establishing winter oilseed rape in China. It is important to understand crop performances and responses to nutrient deficiency between transplanted oilseed rape (TOR) and direct sown oilseed rape (DOR). We estimated the effects of establishment methods (transplanting and direct-sowing) and nutrient deficiency (N, P, and K) on rapeseed yield, yield components, and nutrient uptake from 32 site-years field experiments. We found that DOR plants produced lower seed yield, dry matter, and harvest index than TOR plants. The population density in DOR was higher with poor individual growth as reflected by significantly reduced branches, pods, and seeds pod^{-1}. Thus, DOR plants were more sensitive to nutrient deficiency and would lose more yield under nutrient omission conditions. TOR and DOR yields significantly correlated with all yield components except for 1000-seed weight. Pod number plant^{-1} showed the strongest direct effect on TOR yield. However, population density and pod number plant^{-1} exhibited highest direct effect on DOR yield. The uptakes and harvest indexes of N and P were higher for TOR, while the DOR plots received higher K uptake and harvest index of K. DOR was more sensitive to nutrient deficiency and its nutrient management should be paid more attention.

Keywords Oilseed rape · Establishment method · Nutrient efficiency · Yield components · Nutrient uptake

Abbreviations

DOR	Direct sown winter oilseed rape
TOR	Transplanted winter oilseed rape
DHI	Dry matter harvest index
YRB	Yangtze River Basin

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Introduction

Oilseed rape (*Brassica napus* L.) planting areas are expanding very fast, especially in regions with moderate climatic conditions. The total production has been almost doubled in the world over the last 15 years and nowadays it has reached approximately 69 million Mg (FAO 2017). This oil crop is primarily grown because of both, high quality oil that meets the criteria of the most demanding nutritionists, and protein that is used as a feed pellet for livestock species. In addition, rapeseed is also used to produce biodiesel, oleochemical and other industrial products since recently (Lu 2010). In China, oilseed rape is grown on 8.0 million hectares and 15.3 million Mg rapeseed were obtained in 2016, accounting for approximately 23% of global planting areas and 22% of the rapeseed production (FAO 2017). However, about 60% of rapeseed oil have to be imported from other countries (CAY 2013). This gives China substantial influence on the global production and consumption of rapeseed. Hence, it is important to improve oilseed rape production in China for increasing edible oil supply and ensuring food security.

Yangtze River Basin (YRB) is a major winter oilseed rape cultivation belt in China, contributing over 85% of China's rapeseed production (CAY 2013). Presently, transplanted rapeseed is generally planted in Hilly and mountainous areas and/or at higher altitudes, while direct-seeded rapeseed is planted in large areas in the plain due to the shortage of labor. In the transplanting method, oilseed rape seedlings are firstly raised in the seedbed and subsequently selected for establishing in the main-field about 35 days later. This method was originally used to reduce the crop growth duration in main-field, which allows implementing multiple cropping systems (two or three crops per year) on the limited cropland to increase total crop production (Wang et al. 2011). Moreover, it is conducive to effectively use the solar and hot resources during the shifts of rotation, breed strong seedlings in a well-tended seedbed, and therefore produce a high and stable yield (Wang et al. 2011; Xin and Tong 1986). However, transplantation is a labor-intensive cultivation practice that requires a significant amount of agricultural labor. Hence, transplanted oilseed rape (TOR) is not often cost-effective for growers (Zhang et al. 2010). Compared with transplantation, direct-sowing method avoids the concentration of labor use in breeding and pulling seedlings in the seedbed, encourages timely and easy planting with limited labor, and greatly reduces total input costs. Direct sown oilseed rape (DOR) has been widely adopted throughout South China in recent years, especially in regions with double cropping systems due to its longer main-field duration, in which oilseed rape is always grown with rice (*Oryza sativa* L.) or cotton (*Gossypium hirsutum* L.) in 1 year (Li et al. 2012; Wang et al. 2013). The sowing dates of DOR are determined by the harvest time of previous crop, which generally resulting in a shorter growth duration than TOR (Wang et al. 2011). In addition, seasonal drought and low temperature often occur during the winter season in YRB, causing negative influences on the growth of late-sowing oilseed rape. To mitigate the environmental stresses and ensure an enough population density at maturity for high yield, a large amount of rapeseeds were generally sown by growers when planting DOR (Zhang et al. 2018). The sowing rate of DOR is usually set at 3.5–5 kg ha^{-1} (i.e., 100–140 seeds m^{-2}), while the planting density of TOR is quite low (e.g., 10–13 plants m^{-2}) due to the high cost of labor (Wang et al. 2011).

Our previous studies have indicated that the contrasting crop structure and individual plant morphology between TOR and DOR, because of the altered growth duration and plant density (Zou et al., 2008; Wang et al. 2011, 2012a, b). TOR plants show robust individual growth with more branches and pods, greater resistance to environmental stress, and higher yield level compared with DOR plants. However, the differences in yield components between TOR and DOR are still poorly understood, and their respective critical factors that affect yield are also not clear. Presently, similarly to winter oilseed rape in China, transplanting and direct-sowing methods also coexist simultaneously in many regions and countries for establishing crops such as rice (Liu et al. 2014; Farooq et al. 2011; Singh et al. 2011), maize (*Zea mays* L.) (Biswas et al. 2009; Fanadzo et al. 2009), and cotton (Dong et al. 2005; Rajakumar et al. 2010). Nevertheless, most studies mainly focused on comparing crop yield, agronomic performance, weed control, water management, and economic returns between transplanting and direct-sowing methods in these crops production (Farooq et al. 2011; Singh et al. 2011; Rajakumar et al. 2010; Fanadzo et al. 2009). It appears that the fertilizer application response and nutrient management received less attention when considering and comparing the crop establishment methods. Some researchers have reported that both growth duration and plant density affect nutrient uptake of crop plants (Ciampitti et al. 2013; Hocking and Stapper 2001). It is speculated that crop nutrient uptake and corresponding nutrient management strategy might be different between transplanting and direct-sowing methods. Nitrogen (N), phosphorus (P), and potassium (K) are the three essential macronutrients for oilseed rape, playing important roles in plants growth and yield formation (Lu 2010; Wang et al. 2013; Zou et al. 2009). Therefore, it is necessary to compare the crop responses to N, P, and K deficiencies between TOR and DOR for understanding the differences in their nutrient management practices.

The objectives of this study were (i) to compare crop performances and their responses to nutrient deficiency between TOR and DOR, including seed yield, yield components, dry matter production, nutrient uptake, and nutrient efficiency, (ii) to investigate the effects of yield components on seed yield between TOR and DOR by using correlation and path analysis, and (iii) to estimate the requirements of N, P, and K between TOR and DOR based on the relationships between seed yield and nutrients uptake. These results could give suggestions for increasing TOR and DOR yields through improving their critical yield components, and also provide the basis for their respective nutrient management strategies.

Materials and Methods

Description of the Study Area

On-farm experiments were conducted at 18 sites that located in six provinces (Anhui, Hubei, Hunan, Jiangsu, Jiangxi, and Zhejiang) of the YRB (Fig. 1), during three winter oilseed rape cropping seasons between 2009 and 2012. The oilseed rape cultivation area is 4.10 million ha and rapeseed production is 7.31 million Mg in these six provinces, accounting for 55.9% and 54.4% of the total cultivation area and production in China, respectively (CAY

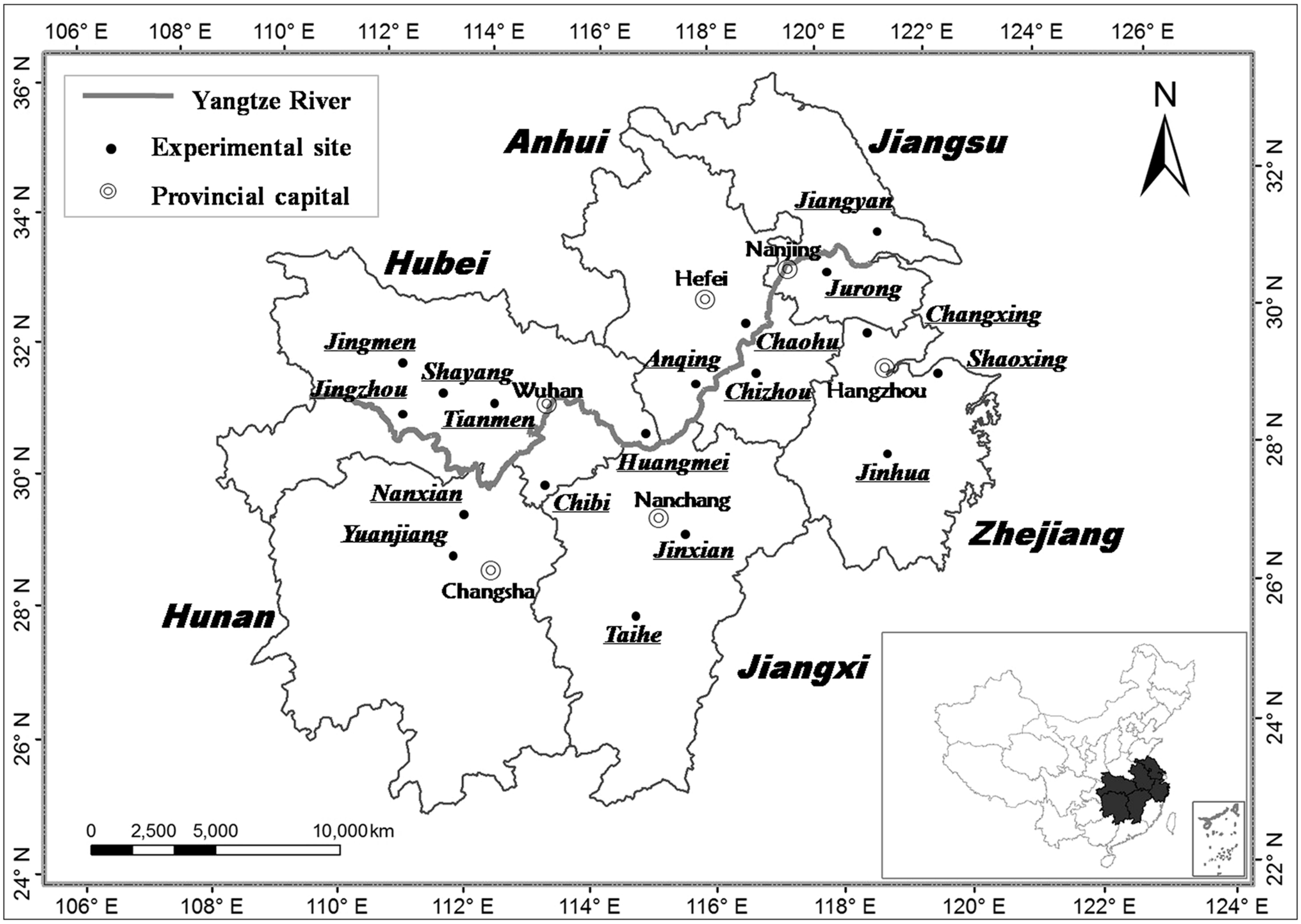

Fig. 1 Locations of 18 experimental sites for testing seed yield and yield components responses to nutrient deficiency between direct sown and transplanted winter oilseed rape in the Yangtze River Basin from 2009 to 2012

2013). The climate is subtropical in the study region, with a mean annual temperature of 14.3–17.5 °C, mean annual precipitation of 1160–1750 mm (25–40% of the precipitation occur during the oilseed rape cropping season), mean annual sunshine hours of 1100–2050 h. The precipitation and temperature during the winter oilseed rape seasons at Wuhan, Hubei are shown in Fig. 2. The temperatures during the three seasons were similar and close to the 30-year average, except for significantly lower temperature in January 2011. The precipitation was relatively less in 2010/2011 and in the early stages of 2011/2012. The experimental years and initial soil properties (0–20 cm soil layer) of the 18 experimental sites are shown in Table 1. The harvest time was close between DOR and TOR at the same site. Thus, the growth durations of DOR plants were generally shorter in this study.

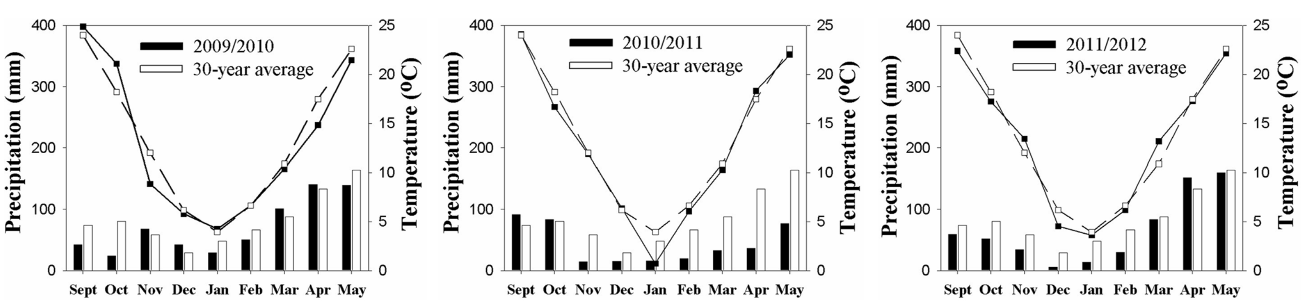

Fig. 2 Monthly precipitation and monthly mean temperature during the winter oilseed rape growing season in 2009/2010, 2010/2011, and 2011/2012 at Wuhan, Hubei, compared with the 30-year average (1980–2010)

Table 1 Experimental years and initial soil properties (0–20 cm soil layer) of the 18 experimental sites in the Yangtze River Basin from 2009 to 2012

Province	Site	Year	Soil texture	pH	Organic C (g kg^{-1})	Total N (g kg^{-1})	Olsen-P (mg kg^{-1})	NH_4OAc-K (mg kg^{-1})	Hotwater-soluble B (mg kg^{-1})
Anhui	Chaohu	2009/2010	Loam	7.00	24.7	1.86	26.26	209.31	0.62
	Chizhou	2009/2010	Loam	5.96	9.2	1.33	6.60	44.83	0.28
	Anqing	2010/2011	Silt loam	5.45	15.3	1.14	13.93	29.88	0.19
Hubei	Jingmen	2009/2010	Loam	6.43	14.2	1.29	19.66	144.52	0.44
	Jingzhou	2009/2010	Loam	6.12	14.4	1.24	8.03	62.68	0.49
	Chibi	2010/2011	Loam	6.15	13.7	1.18	17.72	94.04	0.69
	Tianmen	2010/2011	Loam	6.17	11.9	0.88	8.49	100.31	0.23
	Huangmei	2011/2012	Sand	4.82	21.0	2.29	13.24	59.78	0.66
	Shayang	2011/2012	Loam	5.92	13.7	1.39	11.49	136.28	0.74
Hunan	Nanxian	2009/2010	Silt loam	7.74	26.7	2.26	25.92	75.22	0.31
	Yuanjiang	2009/2010	Loam	7.60	27.1	2.72	15.32	74.74	0.18
Jiangsu	Jiangyan	2009/2010	Silt loam	8.03	7.2	0.81	9.83	39.85	0.39
	Jurong	2010/2011	Loam	6.37	15.1	1.61	7.17	94.67	0.49
Jiangxi	Taihe	2009/2010	Clay loam	4.90	17.7	1.32	16.63	89.69	0.26
	Jinxian	2010/2011	Clay loam	4.69	24.1	2.36	30.73	49.82	0.23
Zhejiang	Changxing	2009/2010	Loam	5.69	22.0	2.21	10.03	54.80	0.60
	Jinhua	2009/2010	Loam	5.86	18.8	0.82	56.77	189.38	0.47
	Shaoxing	2010/2011	Loam	5.60	16.9	1.64	23.38	76.27	0.87
Mean ± SD				6.1 ± 1.0	17.4 ± 5.8	1.6 ± 0.6	17.8 ± 12.1	90.3 ± 50.1	0.45 ± 0.21

Experimental Details

At each site in this study, the experiment was a split-plot factorial design using a randomized complete block arrangement with three replicates. Each plot size was 30 m^2. The main plots were the two establishment methods, i.e., direct sowing and transplanting. The split plots were the five fertilization treatments, i.e. control (CK), balanced NPK fertilizers application (NPK), N omission (−N), P omission (−P), and K omission (−K). Each plot size was 30 m^2. In the NPK plot, 180 kg N, 39.3 kg P, 100 kg K, and 1.8 kg B per ha were applied during the oilseed rape growing season according to the recommended balanced fertilization practices for winter oilseed rape in YRB. In the nutrient omission plots, i.e., −N, −P, and −K treatments, the corresponding major element was omitted based on the NPK treatment.

The methods of crop establishment and fertilizers application followed the current recommended practices in the YRB (Lu 2010; Wang et al. 2011). The established methods and N fertilizer application splits were different between DOR and TOR. For the DOR plots, 4.5 kg ha^{-1} rapeseeds were broadcast sown uniformly on the surface of tilled fields in early or middle October across all the experimental sites and years. Nitrogen fertilizer was applied in four splits, i.e., 40% prior to sowing, 30% at the seedling stage, 15% at the over-wintering stage, and 15% at the initiation of stem elongation. In case of the TOR plots, rapeseeds were first sown in the prepared seedbeds from late September to early October across the different experimental sites and years. The soils with high fertility were used in seedbeds, 20 kg N and 5 kg P ha^{-1} were applied as foundational fertilizer supply. During the seedbed preparation, weed, pest, and disease were well controlled to produce strong seedlings. Seedlings, approximately 35 days old with 5–6 leaves, were transplanted into the tilled field with a unified density of 11.3 plants m^{-2}. Nitrogen fertilizer was applied in three splits during the main-field duration: 60% prior to transplanting, 20% at the over-wintering stage, and 20% at the initiation of stem elongation. The seedlings have accumulated some dry matter (c. 2–4 g $plant^{-1}$) and nutrient (c. 100–170 mg N, 7.5–13.0 mg P, and 85–150 mg K per plant) before transplanting across the sites and years. In YRB, the seedlings in 1 ha of seedbed are usually used for 5–6 ha of main-field. Moreover, a portion of the foundational fertilizer nutrient in seedbed cannot be brought into the main-field with transplanted seedlings, because of the soil residual or the unpredictable loss. Thus, the foundational nutrient supply during the seedbed preparation was not included in the total nutrient input for TOR in this study.

All the P, K, and B fertilizers were applied as the basal fertilizers. The fertilizer sources were urea (46.4% N), single superphosphate (5% P), muriate of potash (50% K), and borax (12% B). The Huayouza 9, a predominant hybrid oilseed rape variety with a high yield and extensive adaptability, was used in all the experiments. At each site, the experimental field was separated from the farmers' lands by a 1-m-wide plant-free border, and the sub-plot was separated from the adjacent plots by a 0.5-m-wide border. Paddy rice was the preceding crop across all the experimental sites. Field managements such as irrigation, herbicide application, pest control, and disease control were performed following local methods. No obvious weed, pest, and disease stress were observed during oilseed rape cropping season across the sites and years.

Sampling and Measurement

Initial soil samples were obtained at depths of 0–20 cm at 15 random points as a mixed sample when each experiment was established. All these soils were air-dried at room temperature and ground to pass through a 2 mm sieve for the measurements of pH (1:2.5 soil/water), organic C (dichromate oxidation method), total N (Kjeldahl acid-digestion method), Olsen-P, NH_4OAc-K, and hotwater-soluble B (Sparks et al. 1996).

Seed yield was determined from a 12 m^2 harvest area in the center of each plot with a moisture content of 8 to 12% across all the sites and years, and the yields were expressed on a dry matter basis. The yield components were measured in each experiment before harvesting, including plant density, branch number $plant^{-1}$, pod number $plant^{-1}$, pod number on main raceme, seed number pod^{-1}, and 1000-seed weight. In addition, a detailed investigation of individual yield components on a branch-by-branch basis was conducted at Huangmei because of its central location in the study area and the typical oilseed rape responses to establishment methods and nutrient deficiency. At Huangmei site, 20 plants were selected from each plot before harvesting and air dried in an unheated greenhouse. These plants were later dissected on a branch-by-branch basis from top to bottom, e.g., Main raceme (MR), Branch 1 (B1), Branch 2 (B2)… Branch n (Bn) (Islam and Evans 1994). The pods in each branch were counted, crushed by hand, and cleaned in an aspirator to separate the seeds, which were then counted and weighed.

When the winter oilseed rape was mature, the aboveground portions of six winter oilseed rape plants were randomly selected as the samples for each treatment. The plants were separated into seed and shoot (i.e., aboveground biomass, except for the seed) to analyze the N, P and K uptake of the oilseed rape. The plant samples were oven dried at 65 °C, ground to pass a 1 mm sieve, and digested separately with H_2SO_4–H_2O_2. The content of N, P, and K were measured using the Kjeldahl method (Horwitz and Latimer Jr 1970), vanadium molybdate yellow colorimetric method and flame emission method (Walinga et al. 1995), respectively. Nutrient harvest index (NHI) was defined as the percentage of seed nutrient uptake (kg ha^{-1}) account for total shoot nutrient uptake (kg ha^{-1}) at maturity.

Data analysis

In each experiment, agronomy efficiency (AE, kg kg^{-1}), partial factor productivity (PFP, kg kg^{-1}), fertilizer contribution rate (FCR), fertilizer recovery efficiency (RE, %) were calculated as (taking N for example)

$$AE_N\left(kg\,kg^{-1}\right) = \left(Y_{NPK} - Y_{-N}\right)/F_N \quad (1)$$

$$PFP_N\left(kg\,kg^{-1}\right) = Y_{NPK}/F_N \quad (2)$$

$$FCR_N(\%) = \left(Y_{NPK} - Y_{-N}\right) \times 100/Y_{NPK} \quad (3)$$

$$RE_N(\%) = \left(U_{NPK} - U_{-N}\right) \times 100/F_N \quad (4)$$

where Y_{-N} is the seed yield of the -N plot (kg ha^{-1}), Y_{NPK} is the seed yield of the NPK plot (kg ha^{-1}), U_{-N} is the N uptake of the -N plot (kg N ha^{-1}), U_{NPK} is the N uptake of the NPK plot (kg N ha^{-1}), and F_N is the N fertilizer application rate (kg N ha^{-1}).

Statistical analysis focused on the effects of establishment method, fertilization treatment, and their interactions on seed yield and yield components. Thus, we used experimental sites as replicates in this study (Cui et al. 2008). All the data were subjected to a two-way analysis of variance (ANOVA) after testing the normality and homogeneity. Multiple comparisons among treatments were performed using Duncan's multiple range test at 0.05 probability level. Descriptive statistical analysis was performed for initial soil properties and yield components parameters to evaluate the range of variability and standard deviation (S.D.) across all the experimental sites and years. Simple correlation analysis and path analysis were used to estimate the relationships between seed yield and yield components. All these analyses were performed by using SPSS 17.0 software (SPSS, Chicago, IL, USA).

Results

Rapeseed Yield

The ANOVA results (Fig. 3) showed that both establishment methods and fertilization treatments had significant effects ($P < 0.01$) on seed yields across all the experimental sites and years. However, there was no significant interaction effects between the establishment methods and fertilization. The TOR plants produced significantly the higher seed yields than DOR plants. In DOR plots, on average, seed yield was 768 kg ha^{-1} (range 56–1587 kg ha^{-1}) in CK treatment, 2208 kg ha^{-1} (range

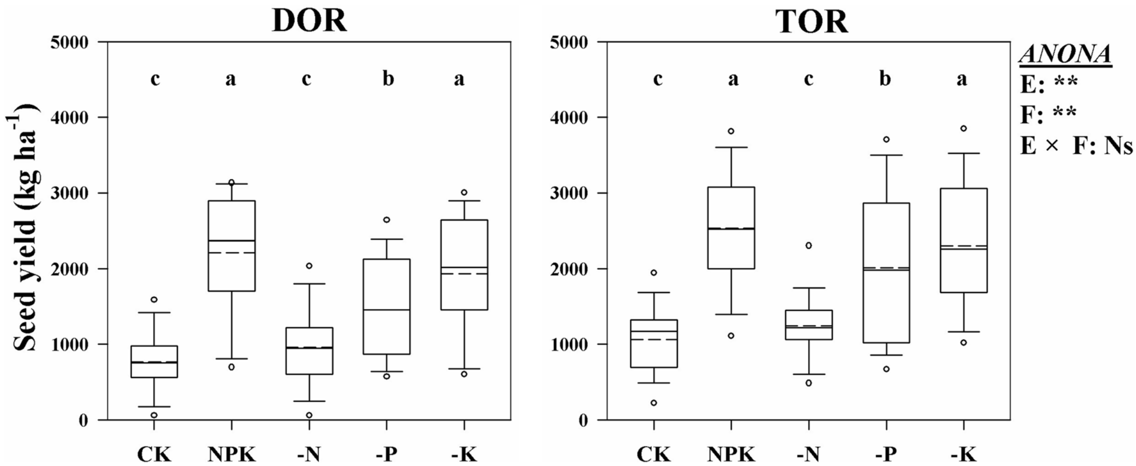

Fig. 3 Seed yields as affected by NPK fertilization between direct sown (DOR) and transplanted winter oilseed rape (TOR) across the 18 experimental sites in the Yangtze River Basin from 2009 to 2012. The upper and lower whisker caps outside each box indicate 10th and 90th percentiles, the upper and lower limits of each box represent 25th and 75th percentiles, and the horizontal solid and dashed lines inside the box indicate the median and mean values, respectively. *E* Establishment method, *F* fertilization treatment, *Ns* non-significant; $**P \leq 0.01$. Boxes with different letters indicate the differences are significant among treatments ($P \leq 0.05$). The same as below

Table 2 Yield components as affected by N, P, and K fertilizers application between direct sown (DOR) and transplanted winter oilseed rape (TOR) across the 18 experimental sites in the Yangtze River Basin from 2009 to 2012

Factor	Plant density (plant m^{-2})	Branch number (plant^{-1})	Total pod number (plant^{-1})	Pod number on main raceme (plant^{-1})	Seed number (pod^{-1})	1000-seed weight (g)
Establishment method (E)						
DOR	28.1 ± 6.7	2.7 ± 1.6	83 ± 30	51.8 ± 12.9 b	19.6 ± 2.0 b	3.09 ± 0.30
TOR	11.1 ± 0.2	7.6 ± 3.3	263 ± 105	85.5 ± 13.9 a	21.2 ± 2.1 a	3.01 ± 0.30
Fertilization treatment (F)						
CK	16.7 ± 6.7	3.0 ± 2.2	110 ± 68	58.4 ± 21.2 c	19.5 ± 2.2 b	3.07 ± 0.31 ab
NPK	22.3 ± 12.0	7.2 ± 3.7	230 ± 135	77.7 ± 20.5 a	21.4 ± 2.1 a	3.06 ± 0.29 ab
-N	17.8 ± 7.8	3.5 ± 2.3	127 ± 75	63.1 ± 20.7 c	19.6 ± 2.0 b	3.12 ± 0.30 a
-P	19.6 ± 9.4	5.6 ± 3.7	185 ± 124	70.0 ± 19.9 b	20.6 ± 2.2 a	2.97 ± 0.31 c
-K	21.6 ± 11.2	6.6 ± 3.6	211 ± 130	74.3 ± 20.1 ab	21.0 ± 2.1 a	3.05 ± 0.29 b
Establishment method × Fertilization treatment (E × F)						
DOR CK	22.4 ± 4.8 c	1.4 ± 0.8 f	55 ± 20 f	41.8 ± 13.0	18.7 ± 1.9	3.11 ± 0.31
DOR NPK	33.4 ± 5.8 a	4.1 ± 1.3 d	108 ± 20 d	59.7 ± 7.4	20.6 ± 1.9	3.10 ± 0.30
DOR -N	24.5 ± 5.3 c	1.7 ± 1.0 f	64 ± 23 f	47.1 ± 15.4	18.9 ± 1.9	3.16 ± 0.30
DOR -P	28.0 ± 5.6 b	3.0 ± 1.5 e	87 ± 24 e	53.2 ± 8.4	19.7 ± 1.8	3.01 ± 0.31
DOR -K	31.9 ± 5.4 a	3.6 ± 1.4 de	99 ± 23 de	57.2 ± 8.2	20.1 ± 1.9	3.08 ± 0.30
TOR CK	11.0 ± 0.3 d	4.6 ± 1.8 cd	166 ± 52 c	74.9 ± 13.4	20.4 ± 2.1	3.02 ± 0.31
TOR NPK	11.2 ± 0.1 d	10.3 ± 2.4 a	351 ± 77 a	95.7 ± 11.3	22.1 ± 2.0	3.01 ± 0.28
TOR -N	11.0 ± 0.2 d	5.3 ± 1.8 c	190 ± 50 c	79.0 ± 10.3	20.3 ± 2.0	3.07 ± 0.30
TOR -P	11.1 ± 0.2 d	8.2 ± 3.3 b	282 ± 104 b	86.7 ± 12.2	21.5 ± 2.1	2.94 ± 0.31
TOR -K	11.2 ± 0.1 d	9.5 ± 2.6 a	324 ± 87 a	91.4 ± 12.0	21.8 ± 2.1	3.03 ± 0.30
Analysis of variance (ANOVA)						
E	**	**	**	**	**	Ns
F	**	**	**	**	**	*
E × F	**	**	**	Ns	Ns	Ns

Different letters indicate a significant difference ($P \leq 0.05$) among different treatments

Ns non-significant

$*P \leq 0.05$; $**P \leq 0.01$. The same as below

697–3133 kg ha^{-1}) in NPK treatment, 959 kg ha^{-1} (range 56–2033 kg ha^{-1}) in –N treatment, 1455 kg ha^{-1} (range 570–2640 kg ha^{-1}) in –P treatment, and 1934 kg ha^{-1} (range 601–3003 kg ha^{-1}) in –K treatment. In TOR plots, the mean seed yields in these fertilization treatments were 1065 kg ha^{-1} (range 222–1944 kg ha^{-1}), 2531 kg ha^{-1} (range 1107–3816 kg ha^{-1}), 1241 kg ha^{-1} (range 485–2305 kg ha^{-1}), 2012 kg ha^{-1} (range 670–3707 kg ha^{-1}), 2305 kg ha^{-1} (range 1022–3849 kg ha^{-1}), respectively. The yield gaps between DOR and TOR plots were 297–557 kg ha^{-1} for the fertilization treatments, with a mean value of 366 kg ha^{-1}.

Yield Components

Establishment methods significantly affected all the yield components except for 1000-seed weight, whilst each yield component parameter varied among different fertilization treatments (Table 2). Significant establishment method × nutrient interactions were observed on plant density, branch number, and total pod number, but not on pod number on the main raceme, seed number pod^{-1}, and 1000-seed weight. In each fertilization treatment, population density of DOR plants was significantly higher than that of TOR plants. Across the five fertilization treatments, the mean density was 28.1 plants m^{-2} in the DOR plots, which was almost 2.5 times of that in the TOR plots (11.1 plants m^{-2}). However, individual yield components were significantly poor for DOR plants compared with TOR plants. Across all the fertilization treatments, on average, an individual plant in the DOR plots produced 4.8 branches, 180 pods, and 1.6 seeds pod^{-1} fewer than that in the TOR plots. The yield components performance of individual DOR plant in the NPK treatment was even worse than that of TOR plant in the CK or –N treatments. The mean contribution rate of pod on the main raceme to the total pod number was 66.7% for DOR plants across all the fertilization treatments, which was considerably higher than that of TOR plants (36.5%). Both in DOR and TOR plots, the best individual yield components were observed in the NPK treatment, and followed by –K treatment. Compared with the balanced NPK fertilization, N deficiency significantly limited all the yield components except for 1000-seed weight, while P deficiency showed significant negative effects on

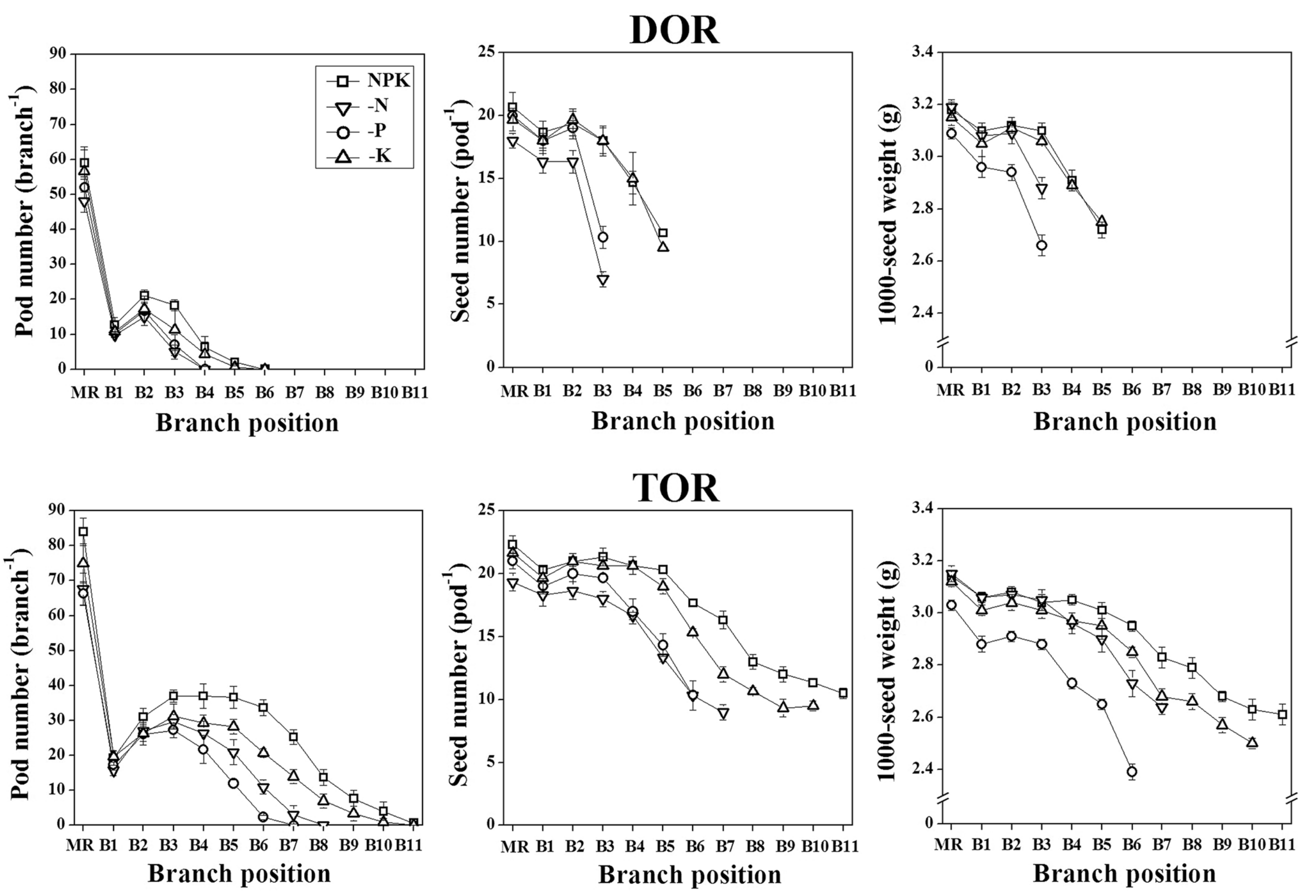

Fig. 4 Individual yield components on a branch-by-branch basis as affected by NPK fertilization between direct sown (DOR) and transplanted winter oilseed rape (TOR) at Huangmei in 2011–2012. *MR* main raceme, *B* lateral branch. Error bars show ± SE of the mean

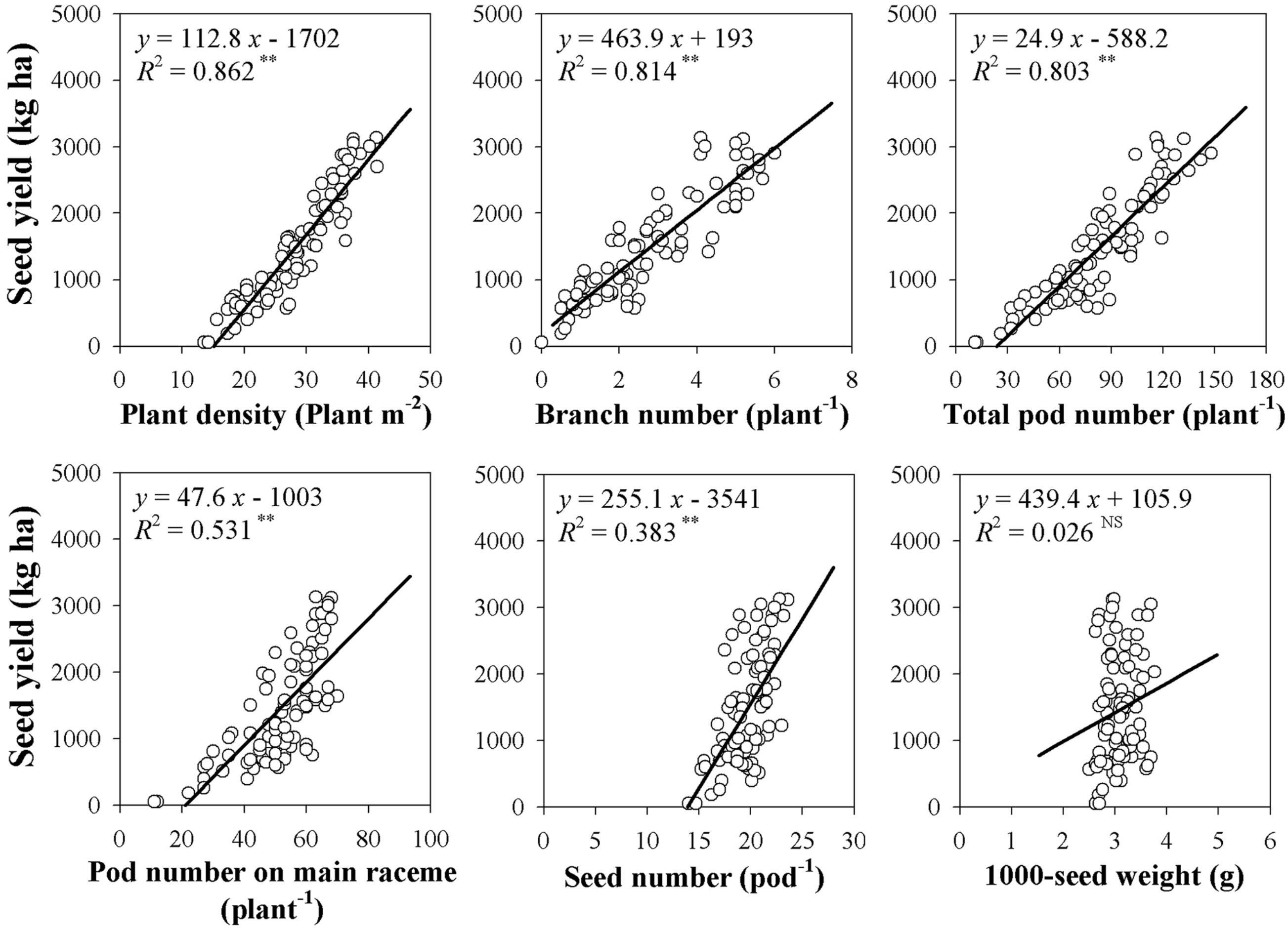

Fig. 5 Correlations between seed yield and yield components for direct sown winter oilseed rape as affected by NPK fertilization across the 18 experimental sites in the Yangtze River Basin from 2009 to 2012. NS, non-significant; $^{**}P \leq 0.01$

all the yield components but not on seed number pod^{-1}. In the TOR plots, no difference was observed in plant density among the fertilization treatments. By contrast, in the DOR plots, plant density varied significantly in different fertilization treatments. Compared with the NPK treatment, the largest density reductions were observed in the CK and –N treatments, followed by –P treatment. These results indicated that DOR plants had contrasting yield components compared with TOR plants, its limited individual growth and reduced plant density together resulted in the significantly decreased yields under the nutrient deficiency treatments.

Yield Components on a Branch-by-Branch Basis

Individual yield components analysis on a branch-by-branch basis between TOR and DOR are shown in Fig. 4. The distribution trends of pod number, seed number pod^{-1}, and 1000-seed weight with branch positions were similar among different establishment methods and fertilization treatments. Main raceme had considerably more pods and seeds pod^{-1} than lateral branches, and its seed weight was also relatively higher. The pod number, seed number pod^{-1}, and seed weight on the lower order branches were shorter than those on the high and middle order branches, and they showed obviously decreased trends with the increasing branch positions. Compared with TOR plant, an individual DOR plant produced obviously fewer branches, and pods number and seeds number pod^{-1} on the same branch position were also relatively lower. Regarding 1000-seed weight, it was comparable on the same branch position between TOR and DOR plants. Compared with NPK treatment, nutrient deficiency reduced pods number, seeds number pod^{-1}, and seed weight on almost all the branches for the DOR and TOR plots. The responses of yield components to N, P, and K deficiencies on a branch-by-branch basis were consistent with those on a plant basis. Moreover, it was clear that nutrient deficiency showed greater negative influences on lateral branches than main raceme, especially on the lower order branches. The branch-wise analysis results indicated that the poor individual yield components in the DOR plots were not only

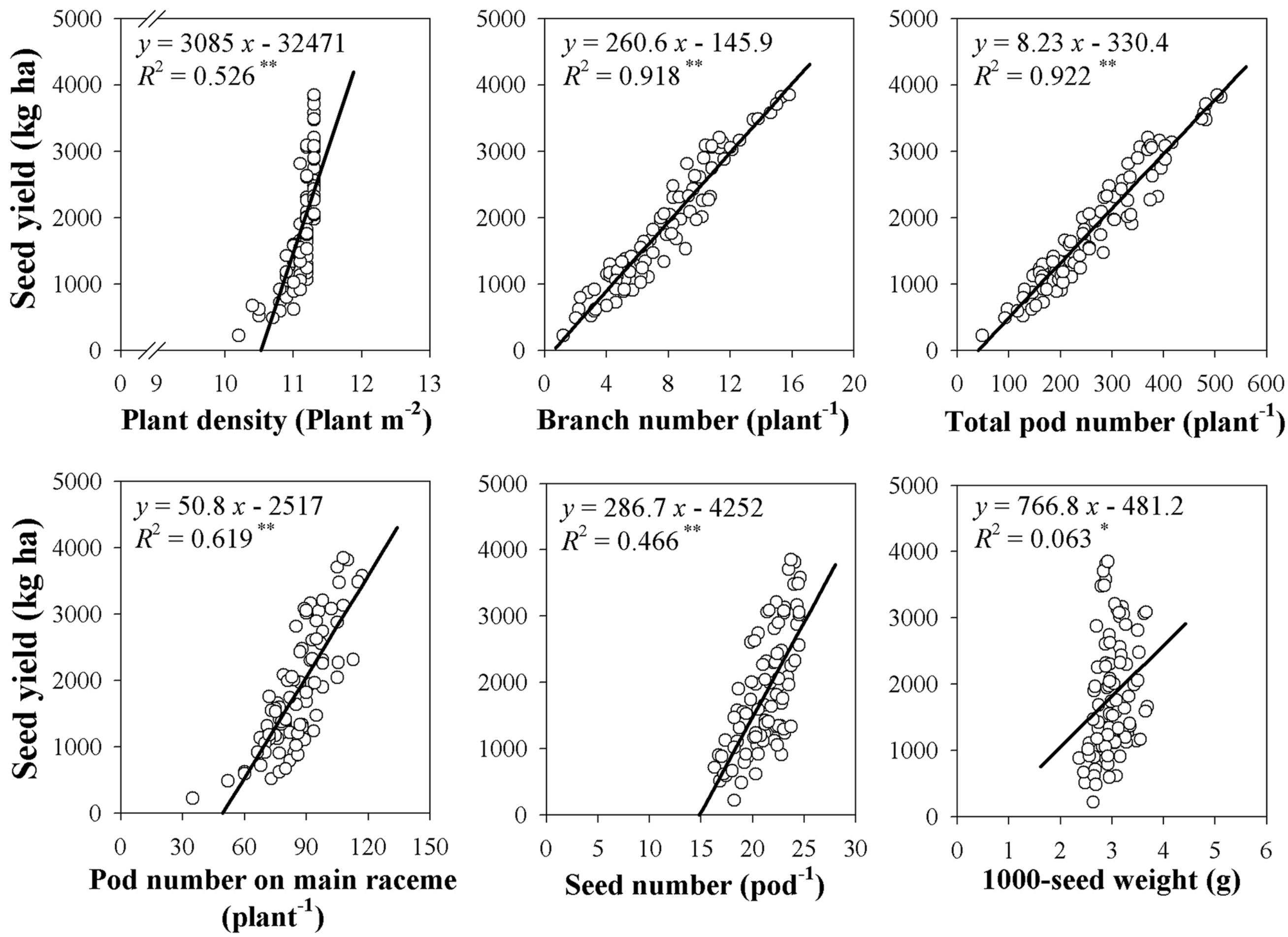

Fig. 6 Correlations between seed yield and yield components for transplanted winter oilseed rape as affected by NPK fertilization across the 18 experimental sites in the Yangtze River Basin from 2009 to 2012. $*P \leq 0.05$; $**P \leq 0.01$

caused by the fewer branches, but also by the limited pod growth on each branch.

Correlations Between Seed Yield and Yield Components

Across the fertilization treatments and experimental sites, positive and significant correlations were observed between seed yield and all the yield components except for 1000-seed weight in the DOR plots (Fig. 5). The strongest correlation was found between DOR yield and plant density, and then followed by branch number and total pod number. The correlations were relatively weaker between DOR yield and pod number on main raceme and seed number pod^{-1}. In the TOR plots, seed yield showed positive and significant correlations with all the yield components across the fertilization treatments and experimental sites (Fig. 6). The strongest correlations were determined between TOR yields and total pod number and branch number, whilst moderate and weak correlations were found between TOR yields and pod number on main raceme, plant density, and seed number pod^{-1}. The correlation between TOR yields and 1000-seed weight was very low. Our results indicated that the correlations between seed yield and yield components varied greatly under the different establishment methods.

Path Analysis Between Seed Yield and Yield Components

Path analysis was used to estimate the direct and indirect effects of yield components on seed yield between TOR and DOR plants (Table 3). The determination coefficients of path analysis exceeded 0.95 in TOR and DOR plots, suggesting that yield component parameters involved in this study have essentially explained the variability in seed yield. In the TOR plots, total pod number showed the strongest positive direct effect on seed yield, while its indirect effects through other parameters were slight. The direct effects of branch number, seed number pod^{-1}, and 1000-seed weight on TOR yields were positive but relatively low, while the direct

Table 3 Path analysis between seed yield and yield components for direct sown (DOR) and transplanted winter oilseed rape (TOR) across the 18 experimental sites in the Yangtze River Basin from 2009 to 2012

Parameter	Direct effect	Indirect effect via					
		Plant density	Branch number	Total pod number	Pod number on main raceme	Seed number	1000-seed weight
DOR[a]							
Plant density	0.4530		0.0654	0.4074	– 0.0640	0.0523	0.0145
Branch number	0.0825	0.3594		0.5027	– 0.0763	0.0314	0.0026
Total pod number	0.5327	0.3465	0.0778		– 0.0939	0.0345	– 0.0016
Pod number on main raceme	– 0.1062	0.2729	0.0593	0.4710		0.0307	0.0013
Seed number	0.0776	0.3052	0.0334	0.2373	– 0.0421		0.0081
1000-seed weight	0.0728	0.0900	0.0030	– 0.0114	– 0.0019	0.0086	
TOR							
Plant density	– 0.1087		0.0990	0.5775	– 0.0302	0.1081	0.0800
Branch number	0.1409	– 0.0763		0.8156	– 0.0353	0.0993	0.0139
Total pod number	0.8352	– 0.0751	0.1376		– 0.0375	0.0901	0.0098
Pod number on main raceme	– 0.0444	– 0.0741	0.1121	0.7056		0.0902	– 0.0022
Seed number	0.1620	– 0.0725	0.0864	0.4646	– 0.0247		0.0674
1000-seed weight	0.1833	– 0.0475	0.0107	0.0448	0.0005	0.0596	

[a]Determination coefficient: $R^2=0.951$ for DOR plants, $R^2=0.978$ for TOR plants

effects of plant density and pod number on main raceme were negative. In could be found that all the indirect effects through plant density on TOR yields were negative, while the indirect effects of plant density, branch number, pod number on main raceme, and seed number pod^{-1} through total pod number were positive and relatively strong. In the DOR plots, both total pod number and plant density showed positive and strong direct effects on seed yield, while the direct effects of other parameters were relatively weak. All the indirect effects of other parameters on DOR yields were positive and/or moderate through the total pod number and plant density. The results indicated that, besides total pod number, plant density was also an important factor for determining DOR yield. Hence, increasing TOR yield required to breed stronger individual plant with more pods, while increasing TOR yield needed to increase total pods number based on a higher population density.

Nutrients Content and Uptake

Nitrogen, phosphorus and potassium fertilizer application significantly affected nutrients content of different parts of winter rapeseed (Table 4). There were also differences in nutrient contents in different parts of winter rape plants between the two planting methods. The N content in the stem of DOR winter rape was generally lower than that of TOR winter rape. As compared with TOR, DOR had lower P content in the pod wall but higher P content in seed. In addition, the K content in seeds of DOR was significantly higher than that of TOR plants in all fertilization treatments. The results of variance analysis showed that there was no significant interaction between fertilization and planting methods on N, P and K contents in different parts of winter rape plants.

Nutrient uptake in winter rapeseed was significantly affected by fertilization and planting methods. However, the interaction between fertilization and planting methods was not significant (Fig. 7). Under the two planting methods, NPK treatment had the highest nutrient uptake in winter rape at maturity stage. Nutrients uptake in NPK treatment of DOR were 108.1 kg N ha^{-1} (range 29.4–184.0 kg N ha^{-1}), 20.3 kg P ha^{-1} (range 7.7–37.4 kg P ha^{-1}) and 153.9 kg K ha^{-1} (range 36.9–240.4 kg K ha^{-1}), respectively. For the TOR plants, averaged nutrient uptake under NPK treatment was 119.3 kg N ha^{-1} (range 22.4–275.8 kg N ha^{-1}), 20.9 kg P ha^{-1} (range 4.5–47.9 kg P ha^{-1}) and 158.0 kg K ha^{-1} (range 34.0–349.5 kg K ha^{-1}). Nutrient uptake of DOR was lower than that of TOR plants. Among different fertilization treatments, nutrient uptake gaps were 11.0–21.0 kg N ha^{-1}, 0.6–2.2 kg P ha^{-1}, and 2.4–17.5 kg K ha^{-1} between the DOR and TOR plants.

Table 4 Effects of N, P, and K fertilizers application on nutrients concentration at maturity for direct sown (DOR) and transplanted winter oilseed rape (TOR) across the 18 experimental sites in the Yangtze River Basin from 2009 to 2012

Establishment method	Fertilization treatment	N concentration (%)			P concentration (%)			K concentration (%)		
		Stem	Pod wall	Seed	Stem	Pod wall	Seed	Stem	Pod wall	Seed
Direct-sowing	CK	0.41 ± 0.23 c^{Ns}	0.61 ± 0.25 b^{Ns}	3.26 ± 0.68 b^{Ns}	0.06 ± 0.04 b^{Ns}	0.13 ± 0.06 b^{Ns}	0.68 ± 0.12 c^{Ns}	2.14 ± 0.41 b^{Ns}	2.59 ± 0.42 b^{Ns}	0.74 ± 0.23 b*
	NPK	0.49 ± 0.19 b*	0.78 ± 0.28 a^{Ns}	3.64 ± 0.57 a^{Ns}	0.07 ± 0.04 b^{Ns}	0.14 ± 0.08 b^{Ns}	0.76 ± 0.09 b**	2.41 ± 0.53 a^{Ns}	2.91 ± 0.25 a^{Ns}	0.84 ± 0.19 a**
	–N	0.34 ± 0.14 d^{Ns}	0.54 ± 0.21 c^{Ns}	3.12 ± 0.57 c^{Ns}	0.08 ± 0.02 a^{Ns}	0.17 ± 0.08 a*	0.81 ± 0.09 a**	2.39 ± 0.51 a^{Ns}	2.74 ± 0.42 a^{Ns}	0.80 ± 0.22 a**
	–P	0.58 ± 0.26 a*	0.81 ± 0.31 a^{Ns}	3.56 ± 0.64 a^{Ns}	0.05 ± 0.03 c^{Ns}	0.10 ± 0.06 c^{Ns}	0.65 ± 0.11 d*	2.32 ± 0.33 a^{Ns}	2.81 ± 0.45 a^{Ns}	0.77 ± 0.21 b**
	–K	0.53 ± 0.17 ab^{Ns}	0.76 ± 0.32 a^{Ns}	3.62 ± 0.61 a^{Ns}	0.07 ± 0.02 b^{Ns}	0.14 ± 0.07 b^{Ns}	0.76 ± 0.11 b**	1.81 ± 0.61 c^{Ns}	2.51 ± 0.48 b^{Ns}	0.78 ± 0.13 b**
Transplanting	CK	0.46 ± 0.21 c	0.55 ± 0.23 b	3.25 ± 0.51 b	0.06 ± 0.04 b	0.14 ± 0.08 b	0.66 ± 0.15 b	2.22 ± 0.50 b	2.69 ± 0.47 b	0.64 ± 0.12 bc
	NPK	0.57 ± 0.22 b	0.71 ± 0.23 a	3.63 ± 0.42 a	0.07 ± 0.05 ab	0.15 ± 0.02 b	0.66 ± 0.08 b	2.33 ± 0.52 ab	2.92 ± 0.48 a	0.68 ± 0.13 a
	–N	0.43 ± 0.14 d	0.56 ± 0.25 b	3.11 ± 0.46 c	0.07 ± 0.03 a	0.21 ± 0.10 a	0.73 ± 0.10 a	2.43 ± 0.34 a	2.76 ± 0.54 b	0.68 ± 0.15 a
	–P	0.62 ± 0.21 a	0.79 ± 0.31 a	3.69 ± 0.52 a	0.05 ± 0.04 c	0.09 ± 0.07 c	0.56 ± 0.13 c	2.22 ± 0.58 b	2.97 ± 0.54 a	0.63 ± 0.18 c
	–K	0.57 ± 0.25 b	0.76 ± 0.32 a	3.63 ± 0.52 a	0.06 ± 0.01 b	0.13 ± 0.08 b	0.66 ± 0.03 b	1.75 ± 0.72 c	2.61 ± 0.59 c	0.66 ± 0.14 ab
ANOVA	E	*	Ns	Ns	Ns	*	**	Ns	Ns	**
	F	**	**	**	**	**	**	**	**	*
	E×F	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns

Different letters indicate a significant difference ($P \leq 0.05$) among different fertilization treatments. Superscript * and ** indicate significant difference at $P \leq 0.05$ and $P \leq 0.01$ between the direct-sown and transplanted oilseed rape, respectively. The same as below

Ns, non-significant

*$P \leq 0.05$; **$P \leq 0.01$

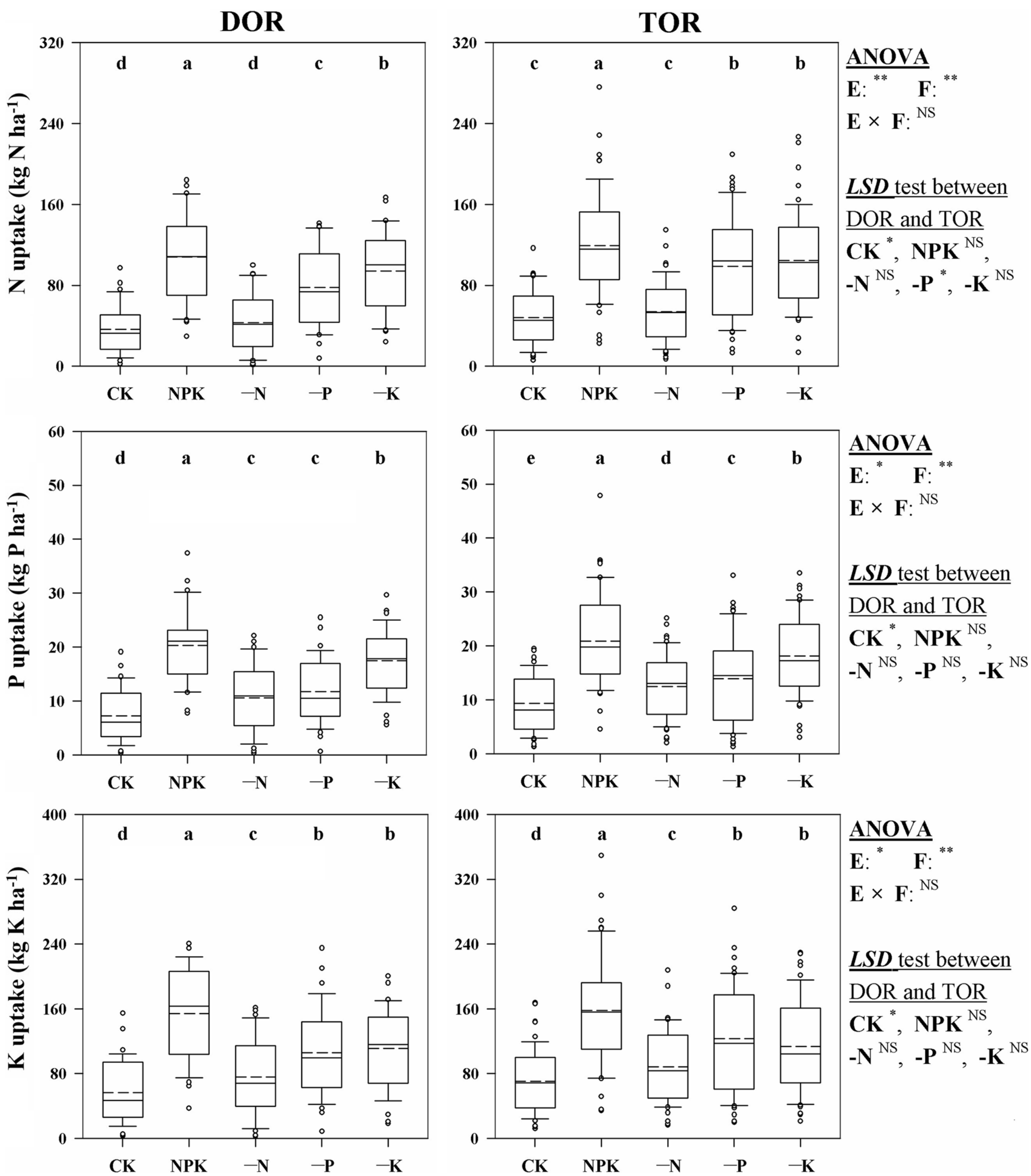

Fig. 7 Nutrients uptake between direct sown (DOR) and transplanted winter oilseed rape (TOR) across the 18 experimental sites in the Yangtze River Basin from 2009 to 2012. NS, non-significant; $*P \le 0.05$; $**P \le 0.01$

Nutrient Efficiencies

Table 5 showed that fertilization had significant effects on N, P and K nutrient harvest indices (i.e., NNHI, PNHI, and KNHI) of DOR and TOR winter rapeseed. Apparently, treatment with nutrient emission had the highest NHI among the treatments. Planting patterns significantly affected PNHI and KNHI, but had no effect on NNHI. Under all fertilization treatments, the PNHI and KNHI of DOR were higher than those of TOR plants. The results showed that the distribution of P and K in DOR was more than that in TOR.

The agronomy efficiency (AE), partial productivity (PFP), fertilizer contribution rate (FCR) and recovery efficiency (RE) of DOR and TOR winter rapeseed was presented in Table 6. The average AE of N, P and K fertilizers for DOR were 6.2 kg kg^{-1} N, 16.7 kg/kg P and 2.6 kg kg^{-1} K, and 6.1 kg kg^{-1} N, 12.0 kg kg^{-1} P and 2.7 kg kg^{-1} K for TOR, respectively. AE_P in DOR was significantly higher than TOR, which indicated that the application of P fertilizer had a better

Table 5 Effects of N, P, and K fertilizers application on nutrient harvest index at maturity for direct sown (DOR) and transplanted winter oilseed rape (TOR) across the 18 experimental sites in the Yangtze River Basin from 2009 to 2012

Establishment method	Fertilization treatment	Nutrient harvest index(%)		
		N	P	K
Direct-sowing	CK	72.1 ± 6.4 b^{Ns}	77.2 ± 10.1 b^{Ns}	11.2 ± 2.4 b*
	NPK	72.3 ± 6.2 ab^{Ns}	78.1 ± 9.1 ab*	11.6 ± 2.0 b*
	–N	73.8 ± 6.3 a^{Ns}	74.6 ± 9.7 c^{Ns}	10.7 ± 2.1 b*
	–P	70.2 ± 6.3 c^{Ns}	79.9 ± 9.2 a^{Ns}	10.8 ± 2.1 b^{Ns}
	–K	71.6 ± 5.2 b^{Ns}	78.3 ± 9.0 ab^{Ns}	13.7 ± 3.5 a^{Ns}
Transplanting	CK	73.2 ± 7.6 ab	75.8 ± 10.6 bc	9.8 ± 2.3 b
	NPK	71.6 ± 7.2 b	75.6 ± 9.4 c	10.2 ± 2.1 b
	–N	74.7 ± 6.8 a	72.5 ± 9.7 d	9.7 ± 2.4 b
	–P	69.6 ± 9.2 c	79.6 ± 7.4 a	10.1 ± 2.3 b
	–K	71.8 ± 7.4 b	77.4 ± 7.8 b	13.2 ± 3.7 a
ANOVA	E	Ns	*	**
	F	**	**	**
	E×F	Ns	Ns	Ns

Different letters indicate a significant difference ($P \leq 0.05$) among different fertilization treatments. Superscript * and ** indicate significant difference at $P \leq 0.05$ and $P \leq 0.01$ between the direct-sown and transplanted oilseed rape, respectively. The same as below

Ns, non-significant

*$P \leq 0.05$; **$P \leq 0.01$

effect on rapeseed yield improvement in DOR. The FCR values of N, P and K were 55.0%, 31.0% and 13.4% in DOR, and 47.1%, 22.8% and 12.4% in TOR, respectively. The higher FCR of N and P in DOR indicated that N and P fertilizer played a more important role in the rapeseed production. There was no significant difference in PFP and RE of N, P and K between the two planting modes.

Discussion

In this study, yield levels of oilseed rape were significantly affected by experimental sites, which mainly caused by different regional environments, soil properties, or management practices. They were also different between years due to the variability in climate. Direct-sowing winter rapeseed is vulnerable to external environmental impact during seedling emergence and seedling growth (Liu et al. 2019). The decline of light and heat resources under late-seeding conditions was not conducive to the seedling growth of direct-sowing winter rapeseed, resulting in weak early plant growth and affecting later flowering (Liu et al. 2018). In this case, DOR plants lacks fine seedbed management and nutrient accumulation in the early stage, and is more vulnerable to nutrient deficiency in field growth, thus limiting the production.

Despite all this, TOR showed generally higher seed yields than DOR. This corroborated the trends observed in our previous studies (Wang et al. 2011, 2013; Zou et al. 2009). TOR plants produced more dry matter during the longer growth

Table 6 Fertilizer efficiency for direct sown (DOR) and transplanted winter oilseed rape (TOR) across the 18 experimental sites in the Yangtze River Basin from 2009 to 2012

Establishment method	Fertilizer	AE (kg/kg)	PFP (kg/kg)	FCR (%)	RE (%)
Direct-sowing	N	6.2 ± 3.1 b^{Ns}	11.7 ± 4.0 c^{Ns}	55.0 ± 22.0 a*	36.2 ± 14.6 b^{Ns}
	P	16.7 ± 12.9 a*	53.8 ± 18.4 a^{Ns}	31.0 ± 20.8 b*	21.8 ± 12.2 c^{Ns}
	K	2.6 ± 1.7 c^{Ns}	21.1 ± 7.2 b^{Ns}	13.4 ± 8.6 c^{Ns}	42.9 ± 20.7 a^{Ns}
Transplanting	N	6.1 ± 3.1 b	12.9 ± 4.5 c	47.1 ± 17.1 a	36.3 ± 17.4 b
	P	12.0 ± 9.6 a	59.1 ± 20.7 a	22.8 ± 18.4 b	18.0 ± 14.4 c
	K	2.7 ± 2.0 c	23.2 ± 8.1 b	12.4 ± 8.4 c	45.0 ± 30.1 a

Different letters indicate a significant difference ($P \leq 0.05$) among different fertilization treatments. Superscript * indicate significant difference at $P \leq 0.05$ and $P \leq 0.01$ between the direct-sown and transplanted oilseed rape, respectively. The same as below

Ns, non-significant

*$P \leq 0.05$

duration, along with a higher HI, therefore obtained a better yield performance. Based on the perspectives of yield components, TOR showed stable population densities and a stronger individual growth with more branches plant^{-1}, pods plant^{-1}, and seeds pod^{-1}. In contrast, the high sowing rates in DOR plots lead to a weaker individual development (Wang et al. 2011, 2013), resulted in unstable population densities at maturity due to the plants loss during the growing season. Hence, DOR showed a generally lower seed yield, and its yield reduction was greater when nutrient was omitted. Our results revealed that DOR was more sensitive to nutrient deficiency, suggesting that its nutrient management deserves more attention and further improvement.

Several studies estimated the relationships between oilseed rape yield and yield components by comparing different cultivars. Ozer et al. (1999) found that seed yield was significantly and positively correlated to pod number plant^{-1} and 1000-seed weight. Ali et al. (2003) calculated a positive correlation between seed yield per plant and seed weight. Similarly, Marjanović-Jeromela et al. (2008) reported that seed yield per plant showed positive and significant relationships with branch number plant^{-1}, pod number plant^{-1}, and 1000-seed weight. In our study, based on the measured data in different fertilization treatments across 18 sites, significant and positive correlations were observed between seed yield and all the yield components except for 1000-seed weight in both TOR and DOR plots. This means that oilseed rape yield could be improved through altering nutrient management practices for optimizing yield components. Seed weight is an inherent characteristic that mainly governed by genotypes (Diepenbrock 2000), has less variability with fertilizer application, therefore showed a nonsignificant correlation with seed yield when an unified cultivar was used. The use of simple correlation analysis could not fully explain the relationships among yield characters (Marjanović-Jeromela et al. 2008). Thus, we performed path analysis to examine the impacts of each yield component on yield and to determine whether the critical factor for increasing yield was consistent between TOR and DOR. For TOR plants, pod number plant^{-1} showed the strongest direct effect on seed yield. However, the strongest direct effect on DOR yield was estimated for plant density and followed by pod number plant^{-1}. This suggested that different approaches should be adopted to improve seed yields of TOR and DOR.

Numerous researchers had investigated the responses of yield components to nutrient application for oilseed rape (Islam and Evans 1994; Ozer 2003; Liu et al. 2012; Hocking et al. 1997; Amanullah et al. 2011). However, the respective effects of different nutrients were still not well understood. Our results indicated that N, P, and K played different roles on yield components. Nitrogen showed the strongest effects on plant density, branch number plant^{-1}, pod number plant^{-1}, and seed number pod^{-1}; phosphorus not only affected above parameters but also has a significant influence on seed weight; and potassium only exhibited slight effects on the branch and pod numbers per plant. Furthermore, the branch-wise analysis pointed that nutrient deficiency limited the pod and seed development on each branch, and greater negative influences were observed on lateral branches than main raceme, especially for the lower order branches. Along with the results of correlation and path analysis, seed yield therefore could be increased by intentionally improving the critical yield components based on appropriate nutrient management practices. To increase TOR yield, it is important to breed a stronger plant with more pods. While the improvement in DOR yield required increasing pod number plant^{-1} based on a sufficient population density at maturity.

Conclusions

We investigated the effects of establishment methods (transplanting and direct-sowing) and nutrient deficiency (N, P, and K) on crop performances of winter oilseed rape. The results showed that TOR produced 16.6% higher seed yield than DOR due to the higher dry matter production. Significant relationships were found between seed yield and all the yield components except for 1000-seed weight in both TOR and DOR plots. Pod number plant^{-1} showed the strongest direct effect on TOR yield, while the strongest direct effects on DOR yield were estimated for plant density and followed by pod number plant^{-1}. TOR plants accumulated more N and P than DOR plants, while its K uptake was lower. DOR showed greater responses under nutrient omission conditions compared with TOR. Our results suggested that the nutrient requirement strategies should be altered between TOR and DOR, depending on their differential approaches for the increasing yield and nutrient requirement.

Acknowledgements This study was supported by National Key Research and Development Program of China (2018YFD0200908), the Earmarked Fund for China Agriculture Research System (CARS-12), the Fundamental Research Funds for the Central Universities (2662017JC010), and International Plant Nutrition Institute Co-operation Program (Hubei-35). We are grateful to Yanhong Lu, Yongchun Zhang, Lina Jiang, Fusheng Yuan, and Ji Wu for their excellent supports in conducting the on-farm experiments. There is no conflict of interest in the manuscript.

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