Grain yield and nitrogen use efficiency of an ultrashort-duration variety grown under different nitrogen and seeding rates in direct-seeded and double-season rice in central China

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Abstract Nitrogen (N) and seeding rates are important factors affecting grain yield and N use efficiency (NUE) of direct-seeded rice. However, these factors have not been adequately investigated on direct-seeded and double-season rice (DDR) in central China. The objective of this study was to evaluate the effects of N and seeding rates on the grain yield and NUE of an ultrashort-duration variety grown under DDR. Field experiments were conducted in 2018 in Wuxue County and 2019 in Qichun County, Hubei Province, China with four N rates and three seeding rates. Results showed the grain yield of the ultrashort-duration variety ranged from 6.32 to 8.23 t ha^{-1} with total growth duration of 85 to 97 days across all treatments with N application. Grain yield was increased significantly by N application in most cases, but seeding rate had an inconsistent effect on grain yield. Furthermore, the response of grain yield to the N rates was much higher than that to seeding rates. The moderate N rates of 100-150 and 70-120 kg N ha^{-1} in the early and late seasons, respectively, could fully express the yield potential of the ultrashort-duration variety grown under DDR. Remarkably higher N response and agronomic NUE were achieved in the early season compared with that of the late-season rice due to the difference in indigenous soil N supply capacity (INS) between the two seasons. Seasonal differences in INS and N response should be considered when crop management practices are optimized for achieving high grain yield and NUE of ultrashort-duration varieties grown under DDR.

Keywords: direct-seed and double-season rice, grain yield, nitrogen rate, nitrogen use efficiency, seeding rate[1]

1. Introduction

Ongoing population and economic growth would exacerbate the supply-demand imbalance of food crops. It will be an urgent task to dramatically improve rice productivity in the coming decades (Huang and Zou 2018). Rice production in China has tripled primarily due to increased grain yield rather than expanded planting area in the past half-century, but yield stagnation has been observed in recent years (Peng *et al.* 2009). Multiple rice cropping, harvesting more than once on the same field per year, is now the most feasible way to improve existing farmland use efficiency and increase rice production (Ray and Foley 2013). Double-season rice is a major intensive cropping system in China. Maintaining the area of double-season rice is important for achieving self-sufficient in rice production (Deng *et al.* 2019; Chen *et al.* 2020). However, the planting area of early- and late-season rice is 36.8 and 37.3% lower in 2018 than those in 1999, respectively (NBS 2020). The substantial reduction in planting area of

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double-season rice is mainly due to high labor input and low economic return (Peng 2014). Technological innovations in double-season rice, such as simplified and reduced-input practice, could stabilize its planting area (Chen *et al.* 2020; Peng 2014).

In recent years, direct-seeded and double-season rice (DDR), a method to reduce labor and resource inputs, has obtained more attention (Wang *et al.* 2021; Xu *et al.* 2022). Due to the omittance of seedbed periods for both seasons in DDR, the early- and late-season rice in central China needs varieties with approximately 95 days of total growth duration so that both crops could reach maturity (Xu *et al.* 2018). It is widely accepted that short-duration varieties might produce lower yields compared to those with medium or long growth durations (Vergara *et al.* 1966; Peng 2014; Xu *et al.* 2018; Huang and Zou 2020). However, the previous study has confirmed that the annual yield of DDR could be up to 15.0 t ha^{-1} under optimum crop management (Wang and Peng 2018). This yield level is similar to that of double-season rice with medium-duration varieties grown under machine-transplanted conditions (Huang *et al.* 2018), and higher than that of middle-season rice with long-duration varieties grown under manual-transplanted conditions (Wei *et al.* 2020).

Crop management plays an important role in increasing both grain yield and nitrogen use efficiency (NUE) (Peng 2008). Nitrogen (N) application and planting density (or seeding rate) are regarded as two major crop management practices. In general, farmers prefer to increase N application rate rather than planting density under manual-transplanted conditions in order to save labor during transplanting (Peng *et al.* 2009). However, excessive application of N fertilizer not only causes seriously environmental degradation such as soil acidification and water eutrophication (Ju *et al.* 2009; Guo *et al.* 2010), but also reduces NUE resulted from ammonia volatilization and surface runoff (Peng *et al.* 2002, 2009). Therefore, many researchers have attempted to partially substitute N fertilizer with high planting density and confirmed that increasing planting density with reduced N application rate could increase grain yield and/or NUE under transplanted conditions (Huang *et al.* 2018; Fu *et al.* 2021). High planting density can be easily achieved by changing crop establishment from transplanting to direct seeding. In fact, to achieve a uniform crop stand, farmers often apply higher amount of seeds than the minimum required for direct-seeded rice (Farooq *et al.* 2011). However, limited information is available on the grain yield and NUE of the ultrashort-duration variety grown under different N and seeding rates in DDR. In addition, there is a large difference in temperature and solar radiation between early- and late-season rice, and it is not clear whether these differences could affect the responses of grain yield and NUE to N and seeding rates in DDR. To fulfill these knowledge gaps, this study was conducted to (1) determine the effects of N and seeding rates on grain yield and NUE, and (2) compare the responses of grain yield and NUE to N and seeding rates between early- and late-season rice in DDR.

2. Materials and methods

2.1. Experimental sites

Field experiments were conducted in Wuxue County in 2018 (29°51′N, 115°33′E) and Qichun County in 2019 (30°23′N, 115°43′E), Hubei Province, China. In these sites, early-season rice was grown from April to July, while late-season rice was grown from July to November. The fields were fallow before experimentation in both seasons. The soil test was based on samples taken from the upper 20 cm layer before the application of basal fertilizer in the early and late seasons of both years. Details of soil properties at Wuxue and Qichun were listed in Table 1. The climate parameters were obtained from a

weather station (AWS 800, Campbell Scientific, Inc., USA) located near the experimental sites. The daily mean air temperature and solar radiation were shown in Fig. 1.

2.2. Experimental design and crop management

The experiments were arranged in a completely randomized block design with four replications in 2018. Six treatments were zero N with low seeding rate (N0LS), zero N with medium seeding rate (N0MS), zero N with high seeding rate (N0HS), low N rate with high seeding rate (LNHS), medium N rate with medium seeding rate (MNMS, a conventional practice) and high N rate with low seeding rate (HNLS), and the details of these treatments were showed in Table 2. To separate the effects of N and seeding rates on grain yield and its related traits, experiments were arranged in a split-plot design with N rate as the main plot, and seeding rate as the subplot with four replications in 2019. Main-plot treatments were four N rates: N0, LN, MN, and HN. Subplot treatments were three seeding rates: LS, MS, and HS. The higher N and seeding rates were used in the early than in the late season because temperature after seeding was lower in the early than in the late season. The plot size was 20 m^2 (4 m×5 m). To prevent potential N runoff and seepage between adjacent plots, each plot was separated by 30 cm wide ridges covered with a plastic film. Xiangzaoxian 6, an inbred *indica* rice variety, was used as the experimental material in both seasons. This variety has been used in DDR because of its ultrashort growth duration and relatively high yield potential (Xu *et al.* 2018).

Seeding was done on 10 April in 2018 and 11 April in 2019 for early-season rice and on 18 July in 2018 and 19 July in 2019 for late-season rice by broadcasting manually. Early- and late-season rice were grown in two adjacent fields in order to avoid residual effect of N rates between the two seasons. Nitrogen (as urea) was split-applied: 40% at basal, 30% at mid-tillering (28 days after seeding in the early season; 24 days after seeding in the late season), 30% at panicle initiation. Phosphorus (31 kg P ha^{-1}, as single superphosphate) was applied as a part of the basal fertilizer. Potassium (93 kg K ha^{-1}, as potassium chloride) was split equally and applied at the basal and panicle initiation stages. The basal fertilizer was incorporated into the soil 1 day before seeding. The soil was kept saturated before the three-leaf stage. The field was flooded after the three-leaf stage and the floodwater depth of 3-5 cm was maintained until the maximum tillering stage, and then the field remained non-flooded for about 7 days to reduce unproductive tillers. After this, the field was intermittently irrigated until a week before maturity. Weeds were controlled by chemicals one time before the five-leaf stage. Then, weeds were removed by hand 1-2 times before heading stage. Insects and diseases were intensively controlled by chemicals to avoid yield loss.

2.3. Sampling and measurements

At maturity, about 70 hills were sampled diagonally from a 5-m^2 area in each plot to determine yield attributes. After recording the number of panicles, the plants were separated into leaves, stems, and panicles. The panicles were hand threshed, and then all spikelets were submerged into tap water to separate the filled spikelets from the unfilled spikelets. The empty spikelets were separated from the partially filled spikelets by winnowing. The fresh weight of total filled spikelets was recorded, and then three sub-samples with 30 g filled spikelets and all partially and empty spikelets were taken to determine the number of spikelets. The dry weights of leaves, stems, rachis, and the filled, partially filled and empty spikelets were measured after oven-drying at 75℃ to constant weight. The grain yield was determined from a 5-m^2 in the center of each plot (70 hills plus the rest hills) and was adjusted to 14%

moisture content. The grain moisture content was measured with a digital moisture tester (DMC-700, Seedburo, Chicago, IL, USA). The sampling area of the 70 hills (grain yield of 70 hills×5 m^2/grain yield of 5 m^2) was calculated. Panicle m^{-2} (panicles number/sampling area), spikelets m^{-2} (spikelets number/sampling area), spikelets per panicle (spikelets m^{-2}/panicle m^{-2}), grain filling percentage (100×filled spikelets m^{-2}/spikelets m^{-2}), total dry weight at maturity (TDW, sum of dry weights of each part/sampling area), and harvest index (HI, 100×filled spikelets weight/TDW) were calculated.

Canopy light interception was measured between 1100 and 1300 h with an interval of 7-15 days using a line ceptometer (AccuPAR LP-80, Decagon Devices Inc., Pullman, WA, USA). The light bar was placed 5-10 cm above the canopy and 5-10 cm above the water surface to measure light intensity above and inside the canopy with four replications in each plot, respectively. Canopy light interception percent each period [100×(incoming light intensive-light intensive inside canopy)/incoming light intensity], intercepted radiation during each period (the average of the canopy light interceptions at the beginning and end of this growth period×accumulated incoming radiation during this growth period), intercepted radiation (iRAD, the summation of intercepted radiation during each growth period) during the entire growing season, and radiation use efficiency (RUE, the ratio of TDW to iRAD), seasonal canopy light interception percent (LI, the ratio of iRAD to incoming light intensity during the entire growing season) were calculated according to Zhang *et al.* (2009).

The N concentration at maturity was measured by Elementar vario MAX CNS/CN (Elementar Trading Co., Ltd, Germany). The total N uptake (TN, kg ha^{-1}) was calculated as the sum of N contents (the product of N concentration and dry weight) for each part. Nitrogen-related use efficiencies were calculated according to Peng *et al.* (2006). Internal N use efficiency (IE_N, kg kg^{-1}) was calculated as the ratio of grain yield to TN. Agronomic N use efficiency (AE_N, kg kg^{-1}) was calculated as the increase in grain yield per unit of applied N. Nitrogen recovery efficiency (RE_N, %) was calculated as the ratio of the increase in plant N accumulation that resulted from N fertilizer application to the fertilizer-N rate.

2.4. Data analysis

Data were analyzed following analysis of variance (Statistix 9.0, Analytical Software, Tallahassee, FL, USA) and means of treatments were compared based on the least significant difference (LSD) at the 0.05 probability level.

3. Results

3.1. Weather conditions and crop growth duration

The daily mean temperature showed increased and decreased trends over the early and late seasons, respectively, while the daily solar radiation showed an inconsistent seasonal pattern in both years (Fig. 1). Average across two years, the daily mean temperatures and daily solar radiations were 9.5 and 13.6% lower in the early than in the late season, respectively. Seasonal and annual (the early plus the late seasons) growth duration ranged from 85 to 97 days and from 176 to 193 days, respectively, across all experiments (Table 3). As the N rate increased, the growth duration tended to increase, while the seeding rate did not affect the growth duration.

3.2. Grain yield and its components

Treatment significantly affected grain yield in both seasons of 2018 (Table 4). There were small differences in grain yield among seeding rates at N0 in the two seasons. Significant differences in grain yield among the three treatments with N application were observed only in the early season. Compared with HNLS, LNHS and MNMS reduced grain yield by 15.3 and 2.3%, respectively. In 2019, N rate, seeding rate, and their interaction significantly affected grain yield in the early season, but not in the late season (Table 5). High seeding rate increased grain yield by 8.0 and 6.4% compared with LS at LN and MN, respectively. At N0 and HN, however, the seeding rate did not affect grain yield.

Nitrogen application significantly increased grain yield compared with N0 except for the late-season rice in 2019. The grain yield increases from applied N (i.e., N response) ranged from 2.05 to 3.36 t ha^{-1} and 0.14 to 0.97 t ha^{-1} in the early and late seasons, respectively. Regardless of the seeding rate, there was a parabolic curvilinear relationship between grain yield and N rate in the early season in both years (Fig. 2). The grain yield increased as the N rate increased, but grain yield did not increase dramatically even displayed a slight decrease when the N rate was more than 150 kg ha^{-1} in the early season. In the late season, the response of grain yield to the N rate disappeared when the N rate was more than 70 kg ha^{-1}.

Nitrogen application significantly increased TDW compared with N0 in all experiments (Tables 4 and 5). The TDW tended to increase as the N rate increased from 100 to 200 kg ha^{-1} in the early season, but not in the late season. The seeding rate significantly affected TDW only at LN in the early season of 2019. Insignificant differences in HI were observed across all experiments except for the early season in 2019. The differences in grain yield among treatments were mainly due to the differences in TDW rather than HI. Among yield components, spikelets m^{-2} explained most of the yield variation across all treatments in the early season, and the variation of spikelets m^{-2} was attributed to panicles m^{-2} or spikelets $panicle^{-1}$, or both (Tables 6 and 7). For late-season rice, although there were significant differences in most of the yield components among treatments, yields of different treatments were similar due to compensation among yield components.

3.3. Radiation use efficiency and its related parameters

Treatment significantly affected LI and iRAD but did not affect RUE in both seasons of 2018 (Table 8). Increasing N and seeding rates significantly increased LI and iRAD but decreased RUE in both seasons of 2019 (Table 9). In the early season, the effect of N rate on LI and iRAD was greater than that of seeding rate, whereas the two treatments had similar effect on LI and iRAD in the late season in both years (Tables 8 and 9). Averaged across two years, N application increased LI and iRAD by 76.3 and 81.4% in the early season and 3.7 and 6.0% in the late season, respectively. Overall, N and seeding rates had much smaller effect on RUE than on LI and iRAD.

3.4. N uptake and use efficiency

Nitrogen rate had a significant effect on TN but it was not affected significantly by seeding rate (Tables 10 and 11). Total N uptake tended to increase as the N rate increased. The interaction between N and seeding rates on TN was significant only in the early season of 2019. Likewise, N rate had much greater effect on IE_N than seeding rate. There was a rapid decrease in IE_N as the N rate increased. There was no consistent difference in RE_N among treatments across seasons and years. Seeding rate

also had no consistent effect on AE_N. However, AE_N tended to decrease as the N rates increased although the difference in AE_N among N rates was not always significant. The late season had higher TN but lower AE_N than the early season, which meant that the former had a higher N uptake from soil. The average TN at N0 (i.e., indigenous soil N supply capacity, INS) and AE_N across treatments and years were 68.1 kg ha^{-1} and 20.2 kg kg^{-1} in the early season and 98.8 kg ha^{-1} and 3.9 kg kg^{-1} in the late season, respectively. Moreover, there was no consistent difference in IE_N and RE_N between the two seasons.

4. Discussion

When N was applied, grain yields of an ultrashort-duration variety, Xiangzaoxian6, ranged from 6.32 to 8.23 t ha^{-1} with a total growth duration of 85 to 97 days across seasons and years. Such yield level was similar or even better than that of double-season rice grown under transplanted conditions using medium-duration varieties (Wu *et al.* 2013; Huang *et al.* 2018; Zhou *et al.* 2018). Nitrogen application significantly increased grain yield compare with N0 in three out of four season and year combinations, but further increase in the N rate from 100 to 200 kg ha^{-1} in the early season and from 70 to 170 kg ha^{-1} in the late season did not result in additional yield. These results suggested that the moderate N rates of 100-150 kg N ha^{-1} in the early season and 70-120 kg N ha^{-1} in the late season could fully express the yield potential of the ultrashort-duration variety grown under DDR. Similar results were reported for transplanted double- and single-season rice (Yao *et al.* 2012; Wu *et al.* 2013). Furthermore, these N application rates were much lower than the famers' N practices and researchers' recommendation for transplanting double-season rice using medium-duration varieties in central China (Peng *et al.* 2006; Wang *et al.* 2017). This suggests that the N requirement of DDR using ultrashort-duration varieties could be lower than ordinary double-season rice grown under transplanted conditions with medium-duration varieties in central China.

There was a large difference in N response between the early and late seasons. Yield increase from N application was significantly greater in the early than in the late season. The difference in N response between two seasons was mainly due to the difference in grain yield of N0. Grain yield of N0 was 2.30 t ha^{-1} higher in the late than in the early season averaged across years and seeding rates, which was mainly attributed to the differences in total spikelet number m^{-2} and TDW between the two seasons. It was also reported that the grain yield of N0 was higher in the late than in the early season in previous studies (Wang *et al.* 2017; Xu *et al.* 2022). In the early-season rice, low temperature during the early vegetative growth period might limit plant growth and biomass accumulation, and consequently result in low grain yield when N was not applied (Wu *et al.* 2013). Applying N fertilizer could promote N uptake and plant growth during the early vegetative stage under low temperature, and thus mitigate the negative effects of low temperature on grain yield (Wang *et al.* 2017; Zhou *et al.* 2018). Therefore, N application played a more important role in improving grain yield of early-season rice than late-season rice under DDR.

The response of grain yield to seeding rate varied with N rate and rice growing season, which was consistent with the result of Chen *et al.* (2021). Moderate seeding rate was optimum for grain yield only when N was applied at moderate rate in the early-season rice. For the late-season rice, the seeding rate had no effect on grain yield across all N treatments. Therefore, seeding rate had a greater effect on grain yield in the early- than late-season rice. The lack of response of grain yield to seeding rates in the late season might be attributed to the high soil N supply, which ensured high biomass accumulation

regardless of N and seeding rates. Overall, the response of grain yield to seeding rates was much smaller than that to N rates, especially in the early season.

The increase in grain yields from applied N was mainly explained by TDW rather than HI in three out of four season and year combinations. However, Huang *et al.* (2015) reported that increasing HI is the feasible way to increase the potential yield of short-duration rice. The discrepancy was due to the fact that HI of Xiangzaoxian 6 generally exceeded 0.50 in the present study, and the scope for further increase is limited (Evans and Fischer 1999). Total dry weight is generally regarded as the product of iRAD and RUE, and the former is determined by LI and incident solar radiation (Katsura *et al.* 2008). The differences in TDW among treatments in both years were mainly explained by LI, which might be related to leaf area index before pre-canopy closure (Wang *et al.* 2017; Wei *et al.* 2020). Although RUE did not explain the variation in TDW and grain yield among treatments as much as LI and iRAD in present study, improving RUE should be considered for enhancing TDW and grain yield of ultrashort-duration varieties due to their limitation in total growth duration (Huang and Zou 2018).

Nitrogen uptake generally increased with the increase of N rate, while NUE tended to decrease as the N rate increased in the present study, which was similar to most of the previous studies conducted under different conditions (Peng *et al.* 2006; Bhuiyan *et al.* 2017; Tian *et al.* 2017). There were obvious differences in TN between the two seasons, which was lower in the early than in the late season although the N rate was higher in the early than in the late season. Differences in AE_N between the two seasons were more obvious, and higher average AE_N across treatments and years was observed in the early season (20.2 kg kg^{-1}) than in the late season (3.9 kg kg^{-1}), which was consistent with the results of Wu *et al.* (2013) and Wang *et al.* (2017). Lower $\mathrm{AE_N}$ of the late season was resulted from higher yields without added N compared with the early season but similar yields in the two seasons when N was applied. This suggested that the late-season rice could utilize indigenous soil N more efficiently to produce grain yield than the early-season rice in DDR. Temperature was the key factor explaining the differences in INS between the two seasons (Yang *et al.* 2019). Optimization of N management for DRR should consider the difference in INS between the two seasons to achieve high grain yield and NUE in both seasons. Similarly, Liu *et al.* (2019) reported that optimal N management of direct-seeded rice varied across dry and wet seasons in the tropical environment.

5. Conclusion

When N was applied, grain yield of 6.32 to 8.23 t ha^{-1} was produced in Xiangzaoxian 6 with a total growth duration of 85 to 97 days in DDR. Grain yield was increased significantly by N application, and N rate had greater effect on grain yield than seeding rate. Optimum N rates was 100-150 kg N ha^{-1} in the early season and 70-120 kg N ha^{-1} in the late season for the ultrashort-duration variety grown under DDR. Remarkably higher N response and AE_N were achieved in the early season compared with that of the late-season rice due to the difference in INS between the two seasons. Seasonal differences in INS and N response should be considered when crop management practices are optimized for achieving high grain yield and NUE in both seasons in DDR.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (31971845, 32101819), the earmarked fund for China Agriculture Research System (CARS-01-20), the China Postdoctoral

Science Foundation (2021M691179).

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Table 1 Soil chemical properties of the upper 20 cm layer in four experimental fields at Wuxue County in 2018 and Qichun County in 2019, Hubei Province, China.

Soil property	2018 (Wuxue) [1)]		2019 (Qichun) [1)]	
	ES	LS	ES	LS
pH	4.9	5.0	5.1	5.3
Organic matter (g kg^{-1})	31.4	24.7	27.8	25.7
Total N (g kg^{-1})	0.21	0.18	0.18	0.19
Olsen P (mg kg^{-1})	45.0	38.5	14.6	17.2
Exchangeable K (mg kg^{-1})	126.8	100.2	194.7	162.5

[1)] ES, early season; LS, late season.

Table 2 Description of nitrogen and seeding rates

Season	Nitrogen rate (kg N ha^{-1})[1)]				Seeding rate (g m^{-2})[2)]		
	N0	LN	MN	HN	LS	MS	HS

Early	0	100	150	200	6	9	12
Late	0	70	120	170	4	7	10

1) N0, zero N; LN, low N rate; MN, medium N rate; HN, high N rate.

2) LS, low seeding rate; MS, medium seeding rate; HS, high seeding rate.

Table 3 Growth duration (days) from seeding to maturity of an ultrashort-duration variety grown under different nitrogen and seeding rates in direct-seeded and double-season rice in 2018 and 2019

Nitrogen1)	Seeding2)	2018 (Wuxue)			2019 (Qichun)		
		Early	Late	Annual	Early	Late	Annual
N0	LS	92	91	183	91	85	176
	MS	92	91	183	91	85	176
	HS	92	91	183	91	85	176
LN	LS	-	-	-	93	85	178
	MS	-	-	-	93	85	178
	HS	95	93	188	93	85	178
MN	LS	-	-	-	94	86	180
	MS	95	93	188	94	86	180
	HS	-	-	-	94	86	180
HN	LS	97	96	193	94	86	180
	MS	-	-	-	94	86	180
	HS	-	-	-	94	86	180

1) N0, zero N; LN, low N rate; MN, medium N rate; HN, high N rate.

2) LS, low seeding rate; MS, medium seeding rate; HS, high seeding rate.

Table 4 Grain yield, total dry weight (TDW), and harvest index (HI) of an ultrashort-duration variety grown under different nitrogen and seeding rates in direct-seeded and double-season rice in 2018

Treatment1)	Early season			Late season		
	Grain yield (t ha-1)	TDW (g m-2)	HI (%)	Grain yield (t ha-1)	TDW (g m-2)	HI (%)
N0LS	4.10 c	691 c	50.9 a	6.77 bc	1101 cd	53.3 a
N0MS	4.76 c	773 c	52.7 a	6.58 c	1040 d	54.4 a
N0HS	4.27 c	721 c	50.9 a	6.99 b	1105 bcd	54.4 a
LNHS	6.32 b	1044 b	52.0 a	7.46 a	1213 ab	52.9 a
MNMS	7.29 a	1164 a	53.9 a	7.55 a	1268 a	51.2 a
HNLS	7.46 a	1190 a	53.9 a	7.45 a	1190 abc	53.8 a
ANOVA						
Treatment	**	**	ns	**	**	ns

1) N0, zero N; LN, low N rate; MN, medium N rate; HN, high N rate; LS, low seeding rate; MS, medium seeding rate; HS, high seeding rate.

Within a column for each treatment, means followed by different letters are significantly different according to LSD (0.05). ns, not significant at the 0.05 probability level; * and **, significant at the 0.05 and 0.01 probability levels, respectively.

Table 5 Grain yield, total dry weight (TDW), and harvest index (HI) of an ultrashort-duration variety grown under different nitrogen and seeding rates in direct-seeded and double-season rice in 2019

Nitrogen1)	Seeding	Early season Grain yield (t ha^{-1})	Early season TDW (g m^{-2})	Early season HI (%)	Late season Grain yield (t ha^{-1})	Late season TDW (g m^{-2})	Late season HI (%)
N0	LS	4.67 a	750 a	53.3 a	6.83 a	1134 a	51.8 a
	MS	4.93 a	789 a	53.7 a	7.02 a	1219 a	49.7 a
	HS	4.79 a	776 a	53.0 a	7.17 a	1197 a	51.6 a
LN	LS	7.25 b	1132 b	55.1 a	7.30 a	1278 a	49.1 a
	MS	8.23 a	1279 a	55.4 a	7.22 a	1266 a	49.3 a
	HS	7.83 a	1246 a	54.1 a	7.54 a	1303 a	49.7 a
MN	LS	7.46 b	1252 a	51.3 a	7.34 a	1237 a	51.1 a
	MS	7.73 ab	1271 a	52.3 a	7.21 a	1240 a	50.2 a
	HS	7.94 a	1288 a	53.0 a	7.31 a	1234 a	50.9 a
HN	LS	7.48 a	1320 a	48.7 a	7.28 a	1238 a	50.7 a
	MS	7.48 a	1287 a	50.0 a	7.41 a	1255 a	50.9 a
	HS	7.50 a	1297 a	49.7 a	7.42 a	1249 a	51.1 a
Nitrogen	N0	4.80 B	772 C	53.4 AB	7.01 A	1183 B	51.0 A
	LN	7.77 A	1219 B	54.9 A	7.35 A	1283 A	49.4 A
	MN	7.71 A	1271 AB	52.2 B	7.29 A	1237 A	50.7 A
	HN	7.48 A	1301 A	49.5 C	7.37 A	1247 A	50.9 A
Seeding	LS	6.71 B	1114 B	52.1 A	7.19 A	1222 A	50.7 A
	MS	7.09 A	1157 A	52.8 A	7.22 A	1245 A	50.0 A
	HS	7.01 A	1152 A	52.5 A	7.36 A	1246 A	50.8 A
ANOVA							
Nitrogen (N)		**	**	**	ns	*	ns
Seeding (S)		**	*	ns	ns	ns	ns
N*S		*	**	ns	ns	ns	ns

1) N0, zero N; LN, low N rate; MN, medium N rate; HN, high N rate.

2) LS, low seeding rate; MS, medium seeding rate; HS, high seeding rate.

Within a column for each treatment, means followed by different letters are significantly different according to LSD (0.05). Lower-case letters indicate comparisons among the three seeding rates within each N rate. Upper-case letters indicate comparisons among the four N rates or among the three seeding rates. ns, not significant at the 0.05 probability level; * and **, significant at the 0.05 and 0.01 probability levels, respectively.

Table 6 Yield components in direct-seeded and double-season rice using an ultrashort-duration variety under different nitrogen and seeding rates in 2018

Treatment1)	Early season Panicles m^{-2}	Early season Spikelets Panicles^{-1}	Early season Spikelets m^{-2} (×10^3)	Early season Grain filling (%)	Early season Grain weight (mg)	Late season Panicles m^{-2}	Late season Spikelets Panicles^{-1}	Late season Spikelets m^{-2} (×10^3)	Late season Grain filling (%)	Late season Grain weight (mg)
N0LS	278.6 d	65.8 b	18.4 c	92.1 a	20.9 bc	421.4 a	77.4 ab	31.5 c	91.0 b	20.4 c
N0MS	344.2 c	60.8 b	20.9 c	93.1 a	21.1 abc	462.6 a	61.7 c	28.6 d	95.2 a	20.9 a
N0HS	455.1 a	41.7 c	18.5 c	94.1 a	21.1 ab	469.3 a	65.3 c	30.5 cd	94.3 a	20.9 a

LNHS	409.8 ab	65.9 b	26.9 b	94.2 a	21.5 a	511.3 a	66.0 bc	33.7 b	91.9 b	20.8 ab
MNMS	413.5 ab	79.7 a	32.6 a	91.4 a	21.1 ab	493.3 a	72.8 abc	35.8 a	88.6 c	20.5 bc
HNLS	377.0 bc	89.7 a	33.8 a	91.7 a	20.7 c	449.2 a	82.0 a	36.6 a	88.4 c	19.9 d
ANOVA										
Treatment	**	**	**	ns	*	ns	*	**	**	**

1) N0, zero N; LN, low N rate; MN, medium N rate; HN, high N rate; LS, low seeding rate; MS, medium seeding rate; HS, high seeding rate.
Within a column for each treatment, means followed by different letters are significantly different according to LSD (0.05). ns, not significant at the 0.05 probability level; * and **, significant at the 0.05 and 0.01 probability levels, respectively.

Table 7 Yield components of an ultrashort-duration variety grown under different nitrogen and seeding rates in direct-seeded and double-season rice in 2019

		Early season					Late season				
Nitrogen[1)]	Seeding[2)]	Panicles m^{-2}	Spikelets Panicles s^{-1}	Spikelets m^{-2} ($\times 10^3$)	Grain filling (%)	Grain weight (mg)	Panicles m^{-2}	Spikelets Panicles s^{-1}	Spikelets m^{-2} ($\times 10^3$)	Grain filling (%)	Grain weight (mg)
N0	LS	325.2 c	67.0 a	21.9 a	88.7 a	20.7 a	424.6 b	88.3 a	37.1 a	78.2 b	20.3 a
	MS	408.0 b	55.9 b	22.7 a	90.4 a	20.6 a	532.3 a	72.1 b	38.4 a	77.9 b	20.4 a
	HS	514.4 a	43.4 c	22.2 a	90.4 a	20.5 a	538.2 a	67.8 b	36.5 a	82.8 a	20.5 a
LN	LS	396.0 b	91.3 a	36.2 b	83.0 a	20.8 a	484.6 c	89.0 a	43.1 a	71.8 b	20.3 a
	MS	452.6 b	90.4 a	40.8 a	83.7 a	20.8 a	543.1 b	73.2 b	39.8 b	77.2 ab	20.4 a
	HS	539.7 a	74.3 b	39.8 a	82.1 a	20.7 a	590.1 a	68.1 c	40.2 ab	78.8 a	20.5 a
MN	LS	437.7 b	95.3 a	41.7 a	75.7 a	20.5 a	474.8 b	86.9 a	41.2 a	76.5 a	20.1 b
	MS	466.8 ab	87.0 b	40.5 a	79.4 a	20.7 a	505.3 b	80.4 b	40.7 a	75.7 a	20.3 b
	HS	492.0 a	83.8 c	41.2 a	80.8 a	20.5 a	546.9 a	69.8 c	38.2 b	80.0 a	20.6 a
HN	LS	494.8 b	91.5 a	45.2 a	70.6 a	20.1 a	485.2 a	89.6 a	43.4 a	72.4 b	20.0 b
	MS	467.2	91.4 a	42.7 b	74.	20.3	511.9	78.4 b	40.1	79.	20.1

		b			2 a	a	a		ab	3 a	ab
	HS	528.0 a	81.7 b	43.0 b	73.9 a	20.3 a	543.5 a	72.6 c	39.3 b	80.0 a	20.3 a
Nitrogen	N0	415.9 B	55.4 B	22.3 C	89.9 A	20.6 A	498.4 B	76.0 A	37.3 B	79.6 A	20.4 A
	LN	462.7 A	85.3 A	38.9 B	83.0 B	20.8 A	539.3 A	76.8 A	41.0 A	75.9 A	20.4 A
	MN	465.5 A	88.7 A	41.1 B	78.6 B	20.6 AB	509.0 B	79.0 A	40.0 A	77.4 A	20.3 A
	HN	496.7 A	88.2 A	43.6 A	72.9 C	20.2 B	513.5 AB	80.2 A	41.0 A	77.2 A	20.1 B
Seeding	LS	413.4 C	86.3 A	36.2 A	79.5 B	20.5 A	467.3 C	88.4 A	41.2 A	74.7 C	20.2 B
	MS	448.6 B	81.2 B	36.7 A	81.9 A	20.6 A	523.1 B	76.0 B	39.7 B	77.5 B	20.3 B
	HS	518.5 A	70.8 C	36.5 A	81.8 A	20.5 A	554.7 A	69.6 C	38.5 B	80.4 A	20.5 A
ANOVA											
Nitrogen (N)		*	**	**	**	*	*	ns	*	ns	**
Seeding (S)		**	**	ns	*	ns	**	**	**	**	**
N*S		**	*	**	ns	ns	ns	*	ns	*	ns

1) N0, zero N; LN, low N rate; MN, medium N rate; HN, high N rate.

2) LS, low seeding rate; MS, medium seeding rate; HS, high seeding rate.

Within a column for each treatment, means followed by different letters are significantly different according to LSD (0.05). Lower-case letters indicate comparisons among the three seeding rates within each N rate. Upper-case letters indicate comparisons among the four N rates or among the three seeding rates. ns, not significant at the 0.05 probability level; * and **, significant at the 0.05 and 0.01 probability levels, respectively.

Table 8 Canopy light interception (LI), intercepted radiation (iRAD), and radiation use efficiency (RUE) of an ultrashort-duration variety grown under different nitrogen and seeding rates in direct-seeded and double-season rice in 2018

Treatment[1)]	Early season			Late season		
	LI (%)	iRAD (MJ m^{-2})	RUE (g MJ^{-1})	LI (%)	iRAD (MJ m^{-2})	RUE (g MJ^{-1})
N0LS	34.0 c	434.2 c	1.60 a	62.8 d	889.9 d	1.24 a
N0MS	38.4 b	489.9 b	1.58 a	67.9 c	961.4 c	1.08 a
N0HS	36.5 bc	465.8 bc	1.55 a	69.2 abc	980.8 bc	1.13 a
LNHS	58.8 a	781.4 a	1.34 a	72.6 ab	1041.4 ab	1.17 a
MNMS	61.0 a	810.6 a	1.44 a	73.0 a	1046.9 a	1.21 a
HNLS	59.5 a	815.2 a	1.46 a	68.5 bc	988.7 abc	1.21 a
ANOVA						
Treatment	**	**	ns	**	**	ns

[1)] N0, zero N; LN, low N rate; MN, medium N rate; HN, high N rate; LS, low seeding rate; MS, medium seeding rate; HS, high seeding rate.

Within a column for each treatment, means followed by different letters are significantly different according to LSD (0.05). ns, not significant at the 0.05 probability level; * and **, significant at the 0.05 and 0.01 probability levels, respectively.

Table 9 Canopy light interception (LI), intercepted radiation (iRAD), and radiation use efficiency (RUE) of an ultrashort-duration variety grown under different nitrogen and seeding rates in direct-seeded and double-season rice in 2019

Nitrogen[1)]	Seeding[2)]	Early season			Late season		
		LI (%)	iRAD (MJ m^{-2})	RUE (g MJ^{-1})	LI (%)	iRAD (MJ m^{-2})	RUE (g MJ^{-1})
N0	LS	34.2 a	442.6 a	1.69 ab	56.0 b	846.4 b	1.34 a
	MS	34.7 a	449.6 a	1.76 a	59.5 a	899.0 a	1.36 a
	HS	36.8 a	475.3 a	1.64 b	60.0 a	906.4 a	1.32 a
LN	LS	58.0 b	758.0 b	1.49 b	60.1 b	908.0 b	1.41 a
	MS	61.4 ab	801.6 ab	1.60 a	63.2 a	955.0 a	1.33 a
	HS	62.8 a	819.8 a	1.52 b	63.8 a	964.9 a	1.35 a
MN	LS	63.1 b	823.9 b	1.52 a	59.9 c	909.3 c	1.36 a
	MS	64.0 ab	836.7 ab	1.52 a	62.1 b	942.0 b	1.32 a
	HS	65.7 a	858.5 a	1.50 a	65.2 a	989.0 a	1.25 b
HN	LS	65.7 b	873.4 b	1.51 a	61.1 b	927.4 b	1.34 a
	MS	68.0 a	904.7 a	1.42 b	63.5 ab	963.9 ab	1.30 a
	HS	69.4 a	922.3 a	1.41 b	65.2 a	989.0 a	1.26 a
Nitrogen	N0	35.2 D	455.8 D	1.69 A	58.5 B	883.9 B	1.34 AB
	LN	60.7 C	793.1 C	1.54 B	62.4 A	942.6 A	1.36 A
	MN	64.3 B	839.7 B	1.51 B	62.4 A	946.8 A	1.31 B
	HN	67.7 A	900.1 A	1.45 B	63.3 A	960.1 A	1.30 B
Seeding	LS	55.3 C	724.4 C	1.55 A	59.3 C	897.8 C	1.36 A
	MS	57.0 B	748.1 B	1.58 A	62.1 B	940.0 B	1.32 AB
	HS	58.6 A	769.0 A	1.52 B	63.5 A	962.3 A	1.30 B
ANOVA							
Nitrogen (N)		**	**	**	*	*	*
Seeding (S)		**	**	**	**	**	*
N*S		ns	ns	**	ns	ns	ns

[1)] N0, zero N; LN, low N rate; MN, medium N rate; HN, high N rate.

[2)] LS, low seeding rate; MS, medium seeding rate; HS, high seeding rate.

Within a column for each treatment, means followed by different letters are significantly different according to LSD (0.05). Lower-case letters indicate comparisons among the three seeding rates within each N rate. Upper-case letters indicate comparisons among the four N rates or among the three seeding rates. ns, not significant at the 0.05 probability level; * and **, significant at the 0.05 and 0.01 probability levels, respectively.

Table 10 Total N uptake at maturity (TN), internal N use efficiency (IE_N), N recovery efficiency (RE_N), and agronomic N use efficiency (AE_N) of an ultrashort-duration variety grown under different nitrogen and seeding rates in direct-seeded and double-season rice in 2018

Treatment[1)]	Early season				Late season			
	TN (kg ha^{-1})	IE_N (kg kg^{-1})	RE_N (%)	AE_N (kg kg^{-1})	TN (kg ha^{-1})	IE_N (kg kg^{-1})	RE_N (%)	AE_N (kg kg^{-1})
N0LS	69.9 c	50.4 b	-	-	101.2 c	58.5 b	-	-
N0MS	79.7 c	51.1 b	-	-	87.9 c	64.5 a	-	-
N0HS	69.7 c	52.7 ab	-	-	95.4 c	63.1 ab	-	-
LNHS	99.7 b	54.5 a	29.9 b	20.5 a	131.2 b	49.0 c	51.1 b	6.8 a
MNMS	138.7 a	45.3 c	39.3 a	16.9 a	164.1 a	39.7 d	63.5 a	8.1 a
HNLS	149.7 a	42.8 c	39.9 a	16.8 a	167.7 a	38.3 d	39.2 b	4.0 b
ANOVA								
Treatment	**	**	*	ns	**	**	**	*

1) N0, zero N; LN, low N rate; MN, medium N rate; HN, high N rate; LS, low seeding rate; MS, medium seeding rate; HS, high seeding rate.

Within a column for each treatment, means followed by different letters are significantly different according to LSD (0.05). ns, not significant at the 0.05 probability level; * and **, significant at the 0.05 and 0.01 probability levels, respectively.

Table 11 Total N uptake at maturity (TN), internal N use efficiency (IE_N), N recovery efficiency (RE_N), and agronomic N use efficiency (AE_N) of an ultrashort-duration variety grown under different nitrogen and seeding rates in direct-seeded and double-season rice in 2019

Nitrogen[1)]	Seeding[2)]	Early season				Late season			
		TN (kg ha^{-1})	IE_N (kg kg^{-1})	RE_N (%)	AE_N (kg kg^{-1})	TN (kg ha^{-1})	IE_N (kg kg^{-1})	RE_N (%)	AE_N (kg kg^{-1})
N0	LS	64.4 a	62.8 b	-	-	101.4 a	58.4 a	-	-
	MS	63.0 a	67.5 a	-	-	106.7 a	58.3 a	-	-
	HS	61.7 a	67.0 ab	-	-	100.4 a	62.0 a	-	-
LN	LS	110.1 b	56.8 a	45.7 b	25.8 b	140.4 a	44.7 a	55.7 a	6.6 a
	MS	132.6 a	53.6 a	69.6 a	33.0 a	133.0 a	47.0 a	37.5 b	3.0 a
	HS	126.5 a	53.5 a	64.8 a	30.5 ab	138.7 a	46.9 a	54.7 a	5.3 a
MN	LS	143.8 a	45.0 a	52.9 a	18.6 b	154.5 a	41.1 a	44.3 a	4.2 a
	MS	143.4 a	46.4 a	53.6 a	18.6 b	153.7 a	41.0 a	39.2 a	1.7 a
	HS	148.8 a	45.9 a	58.1 a	21.0 a	153.7 a	41.2 a	44.4 a	1.1 a
HN	LS	170.0 a	37.9 b	52.8 a	14.0 a	172.9 a	36.4 a	42.1 a	2.6 a
	MS	155.9 b	41.3 a	46.5 b	12.8 a	178.1 a	36.1 a	42.0 a	2.4 a
	HS	162.5 ab	39.8 ab	50.4 ab	13.6 a	176.3 a	36.4 a	44.6 a	1.5 a
Nitrogen	N0	63.0 D	65.8 A	-	-	102.9 D	59.5 A	-	-
	LN	123.0 C	54.6 B	60.0 A	29.8 A	137.4 C	46.2 B	49.3 A	5.0 A

	MN	145.3 B	45.8 C	54.9 A	19.4 B	154.0 B	41.1 BC	42.6 A	2.3 A
	HN	162.8 A	39.6 D	49.9 A	13.4 C	175.8 A	36.3 C	42.9 A	2.2 A
Seeding	LS	122.1 A	50.6 A	50.5 B	19.5 B	142.3 A	45.1 A	47.3 A	4.5 A
	MS	123.7 A	52.2 A	56.6 A	21.5 A	142.9 A	45.6 A	39.5 B	2.3 A
	HS	124.9 A	51.6 A	57.8 A	21.7 A	142.3 A	46.6 A	47.9 A	2.6 A
ANOVA									
Nitrogen (N)		**	**	ns	**	**	**	ns	ns
Seeding (S)		ns	ns	**	*	ns	ns	*	ns
N*S		**	ns	**	**	ns	ns	ns	ns

1) N0, zero N; LN, low N rate; MN, medium N rate; HN, high N rate.

2) LS, low seeding rate; MS, medium seeding rate; HS, high seeding rate.

Within a column for each treatment, means followed by different letters are significantly different according to LSD (0.05). Lower-case letters indicate comparisons among the three seeding rates within each N rate. Upper-case letters indicate comparisons among the four N rates or among the three seeding rates. ns, not significant at the 0.05 probability level; * and **, significant at the 0.05 and 0.01 probability levels, respectively.

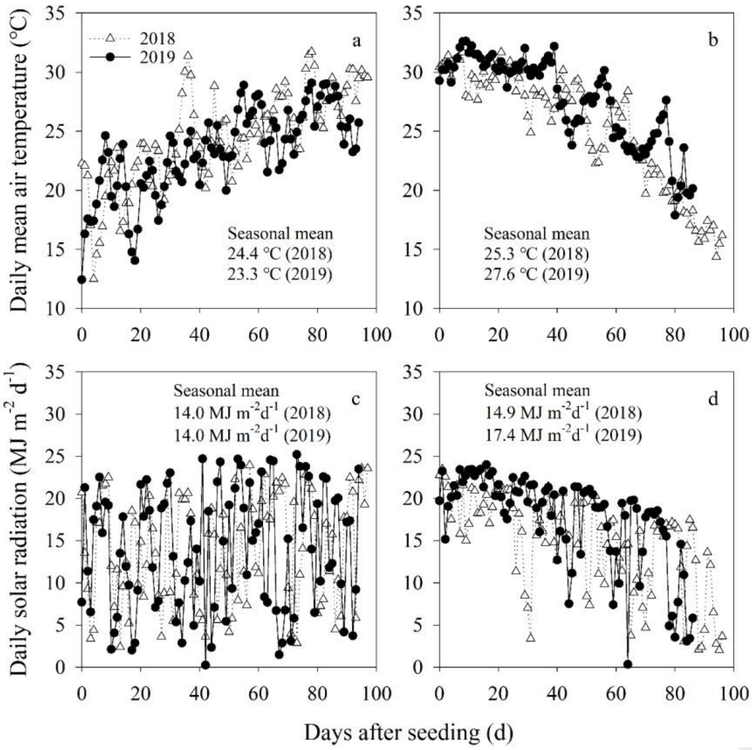

Fig. 1 The daily mean air temperature (A and B) and daily solar radiation (C and D) during early (A and C) and late seasons (B and D) in 2018 and 2019.

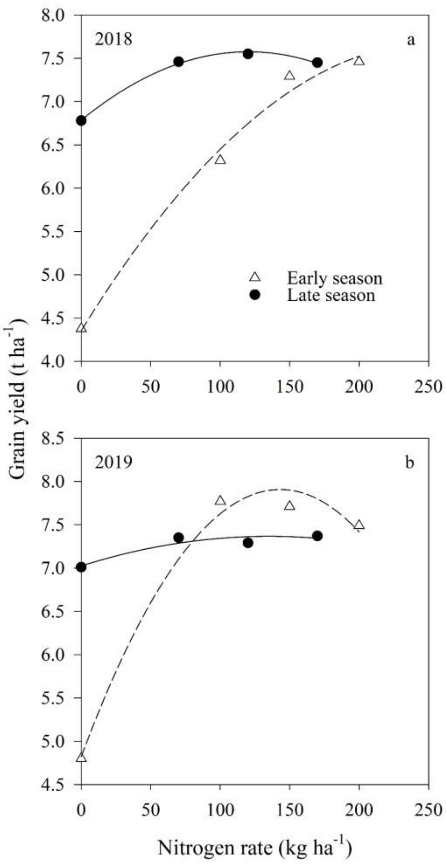

Fig. 2 Relationship between grain yield and nitrogen rate in the early and late seasons of 2018 (A) and 2019 (B).