



Analysis of Gaps Yield and Resource use Efficiency of Cold-Region Japonica Rice

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Abstract

Rice is the primary staple food for more than 50% of the world's population. Narrowing the gap between the maximum potential food crop yield and actual yield is critical for improving the current yield, resource use efficiency, and global food security. Here, we examined the fertilizer use efficiency (FUE), radiation use efficiency (RUE), and temperature production efficiency (TPE) of four management treatments (super high yield [SH], high yield and high efficiency [HH], farmer level [FP], and basic production level [CK]). SH and HH treatments significantly reduced the yield gap by 22.4 and 9.5%, respectively. The large yield gap between HH and FP was mainly attributed to high specific leaf weight at the jointing stage (7.5–7.7 mg·cm⁻²), and the high leaf area maintained during tillering–jointing stages (35.4–37.6 m²·m⁻²·per day). Compared with FP, HH increased the specific leaf weight in the heading stage (8.2–8.4 mg·cm⁻²), relative crop growth rate, net assimilation rate (NAR), and mean leaf area index (> 2.6). Moreover, compared with FP, HH significantly increased partial factor productivity (PFP) of nitrogen, FUE, TPE, and RUE owing to greater yield and NAR after the full heading stage. Although the HH yield was 93.32% that of SH, HH increased PFP of fertilizer (12.5%), fertilizer nitrogen (9.07%), and fertilizer K₂O (36.34%), and required 26% less fertilizer than SH. The findings of this study could facilitate high-efficiency rice production and bridging of yield gaps.

Keywords Rice · Yield · Photosynthetic production · Radiation and temperature production efficiency · Gap

Introduction

Rice (*Oryza sativa* L.) is a staple food for more than 50% of the world's population (Iizumi et al., 2017; Zhang et al., 2016) and is the dominant cereal crop in China (Khush, 2013). Over the past 20 years, the annual increase in rice

yields has dropped below 1% worldwide; however, rice yields must continue to increase by 1.2–1.5% per year to meet the expected demand of the increasing population and economic development in the next decade (Alam et al., 2013). Narrowing the gap between the maximum potential food crop yield and actual yield is critical (Yuan et al., 2021), especially as crop yields must continue to increase at an annual rate of 2% to ensure national food security in China (Fan et al., 2012).

China is the source of 28% of the global rice supply (Deng et al., 2019) and possesses 36% of the global area under rice cultivation (Wang et al., 2020). As the largest production base for japonica rice, Northeast China contributes 53% of the national japonica rice supply, with Heilongjiang Province being the largest producer in China (National Bureau of Statistics of China, 2016). Therefore, bridging the gap in japonica rice yield in Northeast China could enhance food security in China as well as globally (Wang et al., 2018).

Extreme temperatures negatively influence rice growth, and in turn, rice yield in China (Jia et al., 2019, 2022; Wang

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et al., 2019). This is especially true in Northeast China, which has experienced frequent cold waves in the past (Jia et al., 2019; Shimono et al., 2007; Sun et al., 2017; Zhang et al., 2017). Numerous studies have demonstrated that Northeast China has a great potential to increase its rice yield (Chen et al., 2017; Wang et al., 2020; Zhang et al., 2014a, 2014b). Therefore, to enhance average farm yields and reduce the yield gap (Peng et al., 2008; Zhang et al., 2009), it is necessary to develop countrywide adaptation strategies based on spatial rice production patterns (Zhang et al., 2014a, 2014b, 2017).

Investigation of cold-region *japonica* rice production in Heilongjiang province has revealed large yield gaps and resource use efficiency. The average yield gap is used to estimate the gaps between current farm yields and the potential yield (Van Ittersum et al., 2013). To improve crop yields, the following aspects are critical: understanding the yield potentials and yield gaps of major cereal crops, reducing yield and resource use efficiency gaps, and improving average farm yields (Liu et al., 2016). Yield gaps are caused by limiting factors that can be roughly categorized into climatic, soil, and social factors, varieties and cultivation measures, and other aspects (Deng et al., 2019). Among these, light and temperature affect biomass production by modulating the environment for crop growth (Ramankutty et al., 2002). Temperature fluctuations, increases in temperature (≥ 10 °C), and solar radiations are key factors that limit potential yield (Wang et al., 2020); the contribution of meteorological factors to the yield gap is approximately 8% (Liu et al., 2016). Currently, the actual crop radiation use efficiency (RUE) is only 1–2% worldwide, which is far lower than the maximum theoretical crop RUE of 5–6% (Loomis & Williams, 1963).

Increasing biomass and improving crop RUE are potential key strategies of increasing crop yield (Zhang et al., 2009). Furthermore, to reduce gaps in both yield and efficiency, high-efficiency populations can be grown by breeding hardy varieties, determining reasonable densities, optimizing fertilization (Foley et al., 2011), and eliminating nutrient overuse (Mueller et al., 2013). There are considerable opportunities for reducing the environmental impact of agriculture by eliminating nutrient overuse while still allowing an approximate 30% increase in the production

of major cereal crops such as rice. For instance, breeding new rice varieties can lead to a 12% increase in yields (Zhang et al., 2009). However, in practice, 45–70% of the potential for increased production remains untapped (Mueller et al., 2013).

Few studies have identified the yield gaps and efficiency between different yield levels in Northeast China, and to date, systematic analysis has not been employed to estimate the rice yield and efficiency gaps across this region. Bridging of these gaps is necessary to improve yield and use efficiencies that are based on resources. It is difficult to draw concrete conclusions based on the quantification of yield gaps and efficiency between different yield levels of *japonica* rice in the cold regions of Heilongjiang Province; therefore, elucidating the relationship would facilitate the development of strategies to address the gaps.

To highlight the relationship between yield gap and resource use efficiency, we examined the resource use efficiency and production efficiency of four management treatments for 2 years. Using an integrative analysis of radiation-temperature production potential and crop yield performance, we explored factors affecting yield and efficiency. The aims of this study were to: (1) identify the key factors contributing to the high grain yield and yield gaps, (2) discover the mechanism underlying high-efficiency rice production, and (3) explore the potential options for bridging the yield gaps and increasing efficiency. The results of the present study could facilitate high-efficiency rice production and help bridge yield gaps.

Materials and Methods

Plant Material and Growth Conditions

The study was conducted in the Acheng District in Harbin, Heilongjiang Province, China (longitude, 127°04' E; latitude, 45°52' N). The soils in the paddy fields were classified as Black soil. Basic soil fertility (0–20 cm) was analyzed before starting the experiment in 2017 and 2018 (Table 1). The *Oryza sativa* L. subsp. *japonica* variety DN427 was used.

Table 1 Soil fertility (0–20 cm) of the experimental fields at the beginning of the experiment

Year	Organic matter g·kg ⁻¹	Nitrogen content g·kg ⁻¹	Phosphorus content g·kg ⁻¹	Slow-acting available potassium content mg·kg ⁻¹	Available nitrogen content mg·kg ⁻¹	Available phosphorus content mg·kg ⁻¹	Available potassium content mg·kg ⁻¹	Soil bulk density g·cm ⁻³	Soil pH
2017	22.1	1.20	0.39	704.8	125.3	18.0	97.6	1.31	6.56
2018	22.0	1.18	0.38	704.1	124.8	17.9	97.1	1.30	6.61

Experimental Design

Field experiments were carried out in a randomized complete block design in triplicates of four treatments, namely: (1) basic production management (control, CK), without NPK application; (2) farmer management (following the local farmers' fertilizer practice, FP), with total N, P₂O₅, and K₂O application rates of 150, 60, and 45 kg·ha⁻¹, respectively; (3) high yield and high efficiency (HH), with total N, P₂O₅, and K₂O application rates of 150, 60, and 45 kg·ha⁻¹, respectively; and (4) super high yield (SH), with total N, P₂O₅, and K₂O application rates of 200, 60, and 45, respectively. The HH treatment employed alternate irrigation, whereas all other treatments used submerged irrigation, which involves a continuous water layer of 1–3 cm from transplanting until approximately 10 days before rice harvest. Alternation irrigation consists of the following: maintaining a 2 cm water layer for 7–9 d after transplanting, with a soil water potential of –10 kPa (measured by the WET-2Soil Moisture Meter; Cambridge, UK) before the booting stage; re-watering at the booting stage with a water layer of 1–3 cm; irrigating to achieve a saturated state; and drying naturally until a soil water potential of –20 kPa from the heading stage to maturity stage was achieved (Sun et al., 2012). Approximately 35-day-old seedlings were transplanted at three seedlings per hill with a spacing of 13.3 cm (hill space) by 30 cm (row space) for each yield level. Each plot area measured 300 m², with three replicates. Urea (containing 46% N) was used as nitrogen fertilizer, diammonium phosphate (containing 18% N and 46% P₂O₅) was used as phosphate fertilizer, and potassium (containing 50% K₂O) sulfate was used as potassium fertilizer (Table 2).

Field Sampling and Lab Analyses

A field climate meter (RR-9100; Hangzhou, Zhejiang, China) was used to measure the field temperature and light

radiation. The total radiation from sunshine hours was calculated using the Ångström-PreScott method (Ångström, 1924).

For each replication, ten hills with the same crop growth were selected at tillering, jointing, full heading, and maturity stages, and three replications were performed. Then, the samples were divided into roots, stems, leaves, and panicles. After the samples had been fixed at 105 °C for 30 min, they were oven dried at 80 °C to a constant weight before the calculation of the accumulated biomass.

The leaf area was monitored from the tillering to the maturing stage. The standing leaf area of the stand was calculated using every leaf of selected plants. The specific leaf weight (Saengwilai et al., 2020), leaf area duration, crop growth rate (Bowsher et al., 2016), relative crop growth rate (Li et al., 2016), and net assimilation rate (NAR; Hirose, 1984) were used to evaluate the production capacity of photosynthetic products. They were calculated as follows:

$$\text{Specific leaf weight (mg} \cdot \text{cm}^{-2}) = \frac{\text{Dry weight of leaf}}{\text{Leaf area}}$$

$$\text{Leaf area duration (m}^2 \cdot \text{m}^{-2} \cdot \text{per day)} = \frac{\text{PLA}_1 + \text{PLA}_2}{2(t_2 - t_1)}$$

$$\text{Crop growth rate (g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}) = \frac{\text{Wt}_2 - \text{Wt}_1}{t_2 - t_1}$$

$$\text{Relative crop growth rate (g} \cdot \text{g}^{-1} \cdot \text{d}^{-1}) = \frac{\text{Ln}(\text{Wt}_2) - \text{Ln}(\text{Wt}_1)}{t_2 - t_1}$$

$$\begin{aligned} \text{Net assimilation rate (g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}) \\ = \frac{(\text{Wt}_2 - \text{Wt}_1) \times (\text{lnPLA}_2 - \text{lnPLA}_1)}{(\text{PLA}_2 - \text{PLA}_1) \times t} \end{aligned}$$

where, PLA₁ and PLA₂ are the leaf areas at times t₁ and t₂, respectively, Wt₁ and Wt₂, represent the total plant dry

Table 2 Experimental treatments adopted in 2017 and 2018

Treatment	Fertilizer (P-K-N) kg·ha ⁻¹	K splits (B-MT) kg·ha ⁻¹	N splits (B-MT-PI-FL) kg·ha ⁻¹	Management	
				Spacing (hill × row, cm) of hills m ²	Water management
CK	0–0–0	0–0	0–0–0–0	13.3 × 30 (25/m ²)	Continuous flooding
FP	60–45–150	45–0	110–40–0–0	13.3 × 30 (25/m ²)	Continuous flooding
HH	60–45–150	22.5–22.5	90–45–15–0	13.3 × 30 (25/m ²)	Continuous flooding: shallow wetting and drying
SH	60–45–200	22.5–22.5	100–60–20–20	13.3 × 30 (25/m ²)	Continuous flooding

CK basic production level, FP farmer level, HH high yield and high efficiency, SH super high yield, B basal, MT maximum tillering, PI panicle initiation stage, FL, just before flowering

matter accumulation at t_1 and t_2 , respectively, and it is the number of days between two measurements.

For each yield level, three replicates in a 5 m² area were randomly selected at the mature stage to determine the actual yield. Representative plants from 10 hills were selected in triplicate for each yield level to measure effective panicles (EP), grains per panicle, 1000-grain weight (GW), and seed setting rate. The yield gaps (GY) between CK and FP, FP and HH, and HH and SH were defined as GY1, GY2, and GY3, respectively. Light temperature yield potential productivity (YPT) was calculated using a method described by Lai et al. (2014), using the equation $YPT = Y_p \times f(T)$; where, Y_p is the photosynthetic production potential and $f(T)$ is the temperature correction factor. The $f(T)$ of thermophilic crops was calculated as follows:

$$f(T) = \begin{cases} 0.02T - 0.1626^\circ\text{C} \leq T < 21^\circ\text{C} \\ 0.086T - 1.4121^\circ\text{C} \leq T < 28^\circ\text{C} \\ 128^\circ\text{C} \leq T < 32^\circ\text{C} \\ -0.083T + 3.6732^\circ\text{C} \leq T < 44^\circ\text{C} \\ 0T < 6^\circ\text{C} \text{ or } T \geq 44^\circ\text{C} \end{cases}$$

where T is the daily average temperature. Y_p was calculated as follows:

$$Y_p = \frac{C \times S \times \epsilon \times \varphi \times (1 - \alpha) \times (1 - \beta) \times (1 - \rho) \times (1 - \gamma) \times (1 - \omega) \times f(L) \times E \times \sum Qi}{q \times (1 - \eta) \times (1 - \xi)}$$

where Y_p (kg·hm⁻²) is the photosynthetic potential productivity per unit area, C is the conversion factor with a value of 666.7, and $\sum Qi$ (MJ·m⁻²) is the total radiation in each month of the growing season. The other parameters are described in Table 3.

The partial factor productivity of fertilizer (PFP) was calculated as follows: $PFP (\text{kg} \cdot \text{kg}^{-1}) = \text{yield} (\text{kg} \cdot \text{ha}^{-1}) / \text{fertilization amount} (\text{kg} \cdot \text{ha}^{-1})$. Fertilizer use efficiency (FUE) was calculated as follows: $FUE (\text{kg} \cdot \text{kg}^{-1}) = [\text{yield in the fertilized area} (\text{kg} \cdot \text{ha}^{-1}) - \text{yield in non-fertilized area} (\text{kg} \cdot \text{ha}^{-1})] / \text{fertilization amount} (\text{kg} \cdot \text{ha}^{-1})$. The PFP gaps between FP and HH and between HH and SH were defined as GPF1 and GPF2, respectively. The FUE gaps between FP and HH, and HH and SH were defined as GFUE1 and GFUE2, respectively.

RUE was calculated as follows: $RUE (\text{g} \cdot \text{MJ}^{-1}) = \text{above-ground biomass during the growth period} (\text{g} \cdot \text{m}^{-2}) / \text{total intercepted solar radiation per unit area} (\text{MJ} \cdot \text{m}^{-2})$. Temperature production efficiency (TPE) was calculated as follows: $TPE (\text{g} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1} \cdot \text{d}^{-1}) = \text{aboveground biomass during the growth period} (\text{g} \cdot \text{m}^{-2}) / \text{effective accumulated temperature during the growth period} (^\circ\text{C})$. Gaps in RUE between CK and FP, FP and HH, and HH and SH were defined as GRUE1, GRUE2, and GRUE3, respectively; gaps in TPE between CK and FP, FP and HH, and HH and SH were defined as GTPE1, GTPE2, and GTPE3, respectively.

Three representative samples were obtained for each growth stage: tillering, jointing, full heading, and maturity. The yield performance parameters were calculated as previously described by Zhang et al. (2007):

$$MLAI \times D \times MNAR \times HI = EP \times GN \times GW$$

where MLAI is the mean leaf area index, D is the total days in the growth period, MNAR is the mean NAR, HI is the harvest index, EP is the effective panicles, GN is the filled grain number per panicle, and GW is the 1000-grain weight.

Table 3 Parameters for calculating photosynthesis potential productivity of rice

Parameter	Definition	Value
S	Proportion of CO ₂ photosynthetic fixation	0.90
ε	Photosynthetic radiation accounting for total radiation proportion	0.49
φ	Quantum efficiency of photosynthesis	0.22
α	Population reflectivity	0.06
β	Population transmittance	0.08
ρ	Non-photosynthetic organ interception: radiation proportion	0.10
γ	More than light saturation point: light proportion	0.05
ω	Respiratory consumption accounting for photosynthate proportion	0.33
f(L)	Revised value of crop leaf area dynamic	0.56
E	Crop economic coefficient	0.45
q	Dry matter contains calories (MJ/kg)	16.90
η	Moisture content of mature grains	0.14
ξ	Plant inorganic ash content ratio	0.08

Statistical Analysis

Data analyses were performed using SPSS 21.0 software (IBM, Armonk, NY, USA). Analysis of variance (ANOVA) was used to evaluate the effects of the different yield levels on yield, yield components, yield performance parameters, RUE, and TPE. The statistical model included variation due to year, treatment, and year × treatment interactions. The results are reported as the mean values of triplicates. Standard deviation (SD) was calculated directly from the crude data from at least three different replicates in each experiment. Microsoft Excel 2016 was used for mapping and calculating the standard errors of the mean, which are shown in the graphs as error bars. Multiple stepwise regression was used to analyze the relationship between FUE and yield gap.

Results

Yield Gap and Yield Components of Cold-Region Japonica Rice Under Different Management Treatments

The YPT of rice in Heilongjiang Province was 16,163.74 kg·ha⁻¹ (16,372.04 kg·ha⁻¹ in 2017 and 15,955.43 kg·ha⁻¹ in 2018). The SH, HH, FP, and CK management treatments achieved 65.7, 52.8, 43.3, and 28.1% of the YPT, respectively. The yield gap between CK and YPT was 11,625.7 kg·ha⁻¹ (71.9% of the YPT). Compared with CK treatment, HH and SH displayed an increase in yield of 15.7 and 43.9%, respectively. The GY1, GY2, and GY3 of cold-region japonica rice were 2462.0, 1534.0, and 2074.7 kg·ha⁻¹, respectively (Fig. 1).

Significant differences were observed in the number of EP under different management treatments, but there were no differences in the seed setting rate and GW. The values of the number of EP, grain number per panicle, and yield under the CK treatment were lower than those under the FP

treatment. Compared with those under FP, the number of EP significantly increased under HH, and the number of EP and grain number per panicle significantly increased under SH (Table 4).

Yield Performance Parameters of Cold-Region Japonica Rice Under Different Management Treatments

As the yield level increased, the MLAI and EP significantly increased, the MNAR gradually increased, and the 1000-GW decreased or remained unchanged. MLAI, MNAR, and EP reached their maximum values under SH and were significantly higher than those under the other management treatments. The HI was significantly higher under HH than under FP and SH. The extent of changes in MLAI and GW reflected the inconsistencies between groups and individuals, and changes in HI and MNAR reflected source-sink coordination differences (Table 5). Compared with those under FP, the MLAI (13.9%, on average), HI (3.9%, on average), and EP (22.5%, on average) under HH were significantly higher, indicating that the population size of cold-region japonica rice is more manageable and that the source-sink coordination is better in the case of HH. Under SH, the MLAI (27.3%, on average), MNAR (12.9%, on average), and EP (38.3%, on average) were significantly higher (compared with FP), whereas HI (2.9%, on average) was significantly lower ($P < 0.05$), indicating that the source-sink relationship is not coordinated, and that the translocation efficiency of dry matter is reduced.

Fertilizer PFP and FUE of Cold-Region Japonica Rice Under Different Management Treatments

The PFPn and PFP of cold-region japonica rice were significantly different among different yield levels. Compared with FP, HH displayed a significant increase (8.13%, on average) in PFP, whereas SH displayed a significant decrease (3.61%,

Fig. 1 Grain yield under different yield levels of cold-region japonica rice. Error bars indicate the mean ± SD (n=3); different lowercase letters indicate significant difference ($P < 0.05$). SH super high yield, HH high yield and high efficiency, FP farmer level, CK basic production level

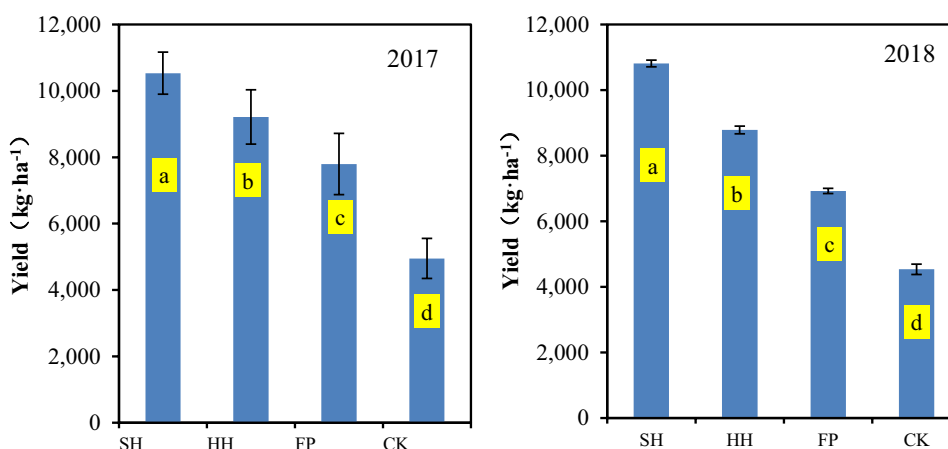


Table 4 Differences in yield components of cold-region japonica rice under different management treatments

Year	Treatment	Effective panicles	Grain number per panicle	Seed setting	1000-grain weight
		m ²		%	g
2017	CK	286.0 ^d	77.9 ^c	85.1 ^a	27.5 ^a
	FP	369.6 ^c	88.9 ^{ab}	85.9 ^a	26.2 ^b
	HH	489.0 ^b	85.9 ^b	83.1 ^a	26.2 ^b
	SH	551.1 ^a	91.1 ^a	83.5 ^a	26.4 ^b
2018	CK	303.2 ^d	70.2 ^c	90.3 ^a	27.2 ^a
	FP	381.6 ^c	82.0 ^b	93.4 ^a	27.5 ^a
	HH	431.1 ^b	85.9 ^{ab}	94.2 ^a	27.5 ^a
	SH	488.1 ^a	89.6 ^a	94.4 ^a	27.7 ^a
<i>F</i> value	Treatment (T)	90.58 ^{**}	17.62 ^{**}	0.15	0.54
	Year (Y)	0.38	2.28	56.27 ^{**}	5.55 [*]
	T×Y	38.98 ^{**}	3.02	2.56	3.22

CK basic production level, FP farmer level, HH high yield and high efficiency, SH super high yield. Data are presented as the mean (n=3). Different superscript letters indicate significant difference (P < 0.05)

*P < 0.05

**P < 0.01

Table 5 Differences in photosynthetic performance parameters of cold-region japonica rice under different management treatments

Year	Treatment	Photosynthetic performance parameters				Yield composition parameters		
		MLAI	MNAR	D	HI	EN	GN	GW
2017	CK	1.574 ^d	4.433 ^b	136 ^c	0.52 ^b	286.0 ^d	66.3 ^b	27.5 ^a
	FP	2.488 ^c	4.428 ^b	139 ^b	0.53 ^b	369.6 ^c	76.4 ^a	26.2 ^b
	HH	2.859 ^b	4.252 ^b	143 ^a	0.55 ^a	489.0 ^b	71.4 ^{ab}	26.2 ^b
	SH	3.210 ^a	4.936 ^a	143 ^a	0.51 ^b	551.1 ^a	76.1 ^a	26.4 ^b
2018	CK	1.755 ^b	4.588 ^b	137 ^c	0.48 ^b	303.2 ^d	70.2 ^c	28.7 ^a
	FP	2.524 ^b	5.032 ^b	139 ^b	0.49 ^b	381.6 ^c	82.0 ^b	27.5 ^a
	HH	2.851 ^b	5.093 ^b	143 ^a	0.51 ^a	431.1 ^b	85.9 ^{ab}	27.5 ^a
	SH	3.169 ^a	5.746 ^a	143 ^a	0.48 ^b	488.1 ^a	89.6 ^a	27.7 ^a

CK basic production level, FP farmer level, HH high yield and high efficiency, SH super high yield, MLAI mean leaf area index, MNAR mean net assimilation rate, D total days in the growth period, HI harvest index, EP effective panicles, GN filled grain number per panicle; GW, 1000-grain weight. Data are presented as the mean (n=3). Different superscript letters indicate significant difference (P < 0.05)

on average), but the change was not significant. Values for GPP2 and GPP3 were 2.6 and 3.8 kg·kg⁻¹, respectively. FUE and PFPn were improved significantly under the HH treatment (53.13% higher than that under FP, on average) and SH treatment (18.09% higher than that under FP, on average). The FUE gaps between FP and HH and between HH and SH were defined as GFUE1 and GFUE2, respectively. GFUE1 and GFUE2 were 3.9 and 1.7 kg·kg⁻¹, respectively, and GPPn1 and GPPn2 were 9.1 and 4.9 kg·kg⁻¹ N, respectively (Table 6).

According to multiple stepwise regression analysis results, PFPn was the main factor influencing the production of GY2 and GY3 (Table 7). The amount of nitrogen fertilizer used was the same in both HH and FP treatments. However, the irrigation methods and N application strategies,

which are conducive to the accumulation and transportation of photosynthetic compounds, differed and represented the key factors influencing the GY2 value. In addition, the incremental application of N fertilizer was responsible for the GY3 value (Table 7).

Population Quality of Cold-Region Japonica Rice Under Different Management Treatments

Growth Period

Compared with those under FP, the tillering stage of cold-region japonica rice occurred two days later, and the jointing stage to maturity stage occurred 2–3 days earlier under

Table 6 Differences in fertilizer partial factor productivity and use efficiency of cold-region *japonica* rice under different management treatments

Year	Treatment	Fertilizer use efficiency kg.kg ⁻¹	Partial factor productivity of total fertilizer kg.kg ⁻¹	N partial factor productivity kg.kg ⁻¹ N
2017	FP	10.6 ^c	29.5 ^{ab}	47.2 ^c
	HH	13.9 ^b	30.7 ^a	55.2 ^a
	SH	16.1 ^a	28.9 ^b	52.0 ^b
2018	FP	10.3 ^b	32.8 ^b	52.5 ^c
	HH	14.8 ^a	36.8 ^a	62.6 ^a
	SH	15.9 ^a	31.1 ^b	56.0 ^b
<i>F</i> value	Treatment (T)	32.96 ^{**}	2.98	4.31 [*]
	Year (Y)	0.01	12.17 ^{**}	4.17
	T × Y	0.38	2.27	0.19

CK basic production level, FP farmer level, HH high yield and high efficiency, SH super high yield. Data are presented as the mean (n=3). Different superscript letters indicate significant difference (P < 0.05)

*P < 0.05

**P < 0.01

Table 7 Stepwise regression analysis of the yield, PFP and PFPn gaps

Dependent variable (Y)	Stepwise regression	Correlation coefficient (r)	R ²
<i>Y</i> _{GY2}	<i>Y</i> _{GY2} = - 0.317 + 0.204x	0.875	0.765*
<i>Y</i> _{GY3}	<i>Y</i> _{GY3} = 2.233 + 0.032x	0.895	0.802*

x: PFPn partial factor productivity of fertilizer nitrogen

*P < 0.05

CK, whereas the booting stage to maturity stage occurred 2–4 days later under HH and SH (Table 8).

Biomass Accumulation and Transport

The biomass of stems and leaves at the full heading stage and the biomass of panicles were significantly higher under

HH and SH than that under FP or CK. The translocation rate of the vegetative dry matter of cold-region *japonica* rice was significantly lower under CK than under other treatments, and was also significantly lower under HH and SH than under FP. Additionally, the translocation contribution rate was significantly higher under CK than under other management treatments and significantly lower under HH and SH than under FP management. The above results indicate that dry matter transport is correlated with yield level; the higher the yield level, the greater the mass that is assimilated in the vegetative organs and the higher the contribution rate of photosynthetic contraction to spike development after the full heading stage (Table 9).

Crop Growth Rate and Relative Crop Growth Rate

The crop growth rate of cold-region *japonica* rice at each growth stage was significantly lower under FP than under

Table 8 Growth process of cold-region *japonica* rice under different management treatments

Year	Treatment	Tillering stage	Jointing stage	Booting stage	Heading stage	Full heading stage	Maturity stage
2017	CK	6–1	7–11	7–26	8–3	8–6	9–11
	FP	5–30	7–13	7–28	8–5	8–8	9–14
	HH	5–30	7–13	7–30	8–7	8–10	9–18
	SH	5–30	7–13	7–30	8–7	8–10	9–18
2018	CK	6–1	7–7	7–22	7–31	8–2	9–8
	FP	5–30	7–9	7–22	8–1	8–4	9–10
	HH	5–30	7–9	7–26	8–3	8–6	9–14
	SH	5–30	7–9	7–26	8–3	8–6	9–14

CK basic production level, FP farmer level, HH high yield and high efficiency, SH super high yield. The numbers in the table represent month-day

Table 9 Differences in biomass accumulation and transport of cold-region *japonica* rice under different management treatments

Year	Treatment	Full heading stage g/hill		Maturity stage g/hill		Translocation g/hill	Translocation rate%	Translocation contribution rate%
		Stems and leaves	Spike	Stems and leaves	Spike			
2017	CK	22.03 ^d	3.19 ^c	15.33 ^d	19.01 ^d	6.70 ^b	30.41 ^a	42.35 ^a
	FP	35.43 ^c	4.01 ^b	25.63 ^c	30.43 ^c	9.80 ^a	27.66 ^b	37.09 ^b
	HH	40.65 ^b	5.77 ^a	31.25 ^b	34.14 ^b	9.40 ^a	23.12 ^c	33.13 ^c
	SH	45.63 ^a	5.60 ^a	36.25 ^a	41.14 ^a	9.37 ^a	20.53 ^d	26.36 ^d
2018	CK	24.09 ^d	3.30 ^c	16.37 ^d	20.23 ^d	7.72 ^b	32.04 ^a	45.61 ^a
	FP	34.15 ^c	4.05 ^b	23.59 ^c	31.48 ^c	10.56 ^a	30.92 ^b	38.50 ^b
	HH	39.14 ^b	5.62 ^a	28.59 ^b	35.89 ^b	10.55 ^a	26.95 ^c	34.84 ^c
	SH	46.29 ^a	6.02 ^a	36.02 ^a	43.69 ^a	10.27 ^a	22.18 ^d	27.25 ^d
F value	Treatment (T)	519.97 ^{**}	406.85 ^{**}	376.08 ^{**}	428.73 ^{**}	37.85 ^{**}	45.19 ^{**}	211.98 ^{**}
	Year (Y)	0.01	0.05	0.09	0.22	3.37	2.51	0.37
	T×Y	7.73 ^{**}	8.88 ^{**}	13.75 ^{**}	1.53	1.16	1.46	2.94

CK basic production level, FP farmer level, HH high yield and high efficiency, SH super high yield. Data are presented as the mean (n=3). Different superscript letters indicate significant difference (P<0.05)

*P<0.05

**P<0.01

other management treatments. Compared with FP, HH was not associated with significant difference in growth rate from full heading stage to maturity stage, but this growth rate significantly increased under other management treatments. The relative growth rate (RGR) after the full heading stage was significantly higher under SH than that under the other management treatments. Compared with that under FP, the RGR of cold-region *japonica* rice increased by 16.9% under SH. The above results indicate that increasing the growth rate and RGR after the full heading stage is conducive to yield improvement (Fig. 2).

Leaf Area Duration and NAR

The leaf area duration under SH treatment was the highest, and the leaf area duration gap between different management treatments increased gradually as growth progressed. With a progression in growth, the NAR of cold-region *japonica* rice showed a downward trend. During the tillering stage–jointing stage and full heading stage–maturity stage, the NAR of *japonica* rice was the highest under SH (Fig. 3). Furthermore, the specific leaf weight under CK showed an upward trend with the growth period but was significantly lower than under other management treatments. The specific leaf weight in both tillering and heading stages under HH and TS–HS under SH significantly increased compared with those under HH (Fig. 3).

Resource use Efficiency and the Efficiency Gap of Cold-Region *Japonica* Rice Under Different Management Treatments

The average potential RUE of cold-region *japonica* rice was 1.62 g·MJ⁻¹. RUE significantly differed between treatments (SH>HH>FP>CK), with the SH, HH, FP, and CK treatments achieving 80.9, 68.8, 61.1, and 38.3% of the potential RUE, respectively. GRUE1 of tillering stage–jointing stage, jointing stage–full heading stage, full heading stage–maturity stage, and the full growth period of cold-region *japonica* rice were 0.62, 0.36, 0.29, and 0.37 g·MJ⁻¹, respectively; in the cases of GRUE2 and GRUE3, the values were 0.22, 0.13, 0.12, and 0.13 g·MJ⁻¹, respectively, and 0.24, 0.24, 0.37, and 0.20 g·MJ⁻¹, respectively. The maximum RUE gaps for the tillering stage–jointing stage and jointing stage–full heading stage occurred in GRUE1, with values of 0.62 g·MJ⁻¹ and 0.36 g·MJ⁻¹, respectively. The full heading stage–maturity stage had the highest GRUE3 values (0.37 g·MJ⁻¹). The findings show that by using the HH treatment, RUE may be significantly enhanced from full heading stage to maturity stage (Table 10).

The average potential TPE of cold-region *japonica* rice was 2.61 g·m⁻²·°C⁻¹·d⁻¹, with the SH, HH, FP, and CK treatments achieving 77.6, 64.4, 56.1, and 36.8% of the potential TPE, respectively. The TPE also differed significantly between yield levels (SH>HH>FP>CK) and increased under HH (14.8%) and SH (38.4%) than under

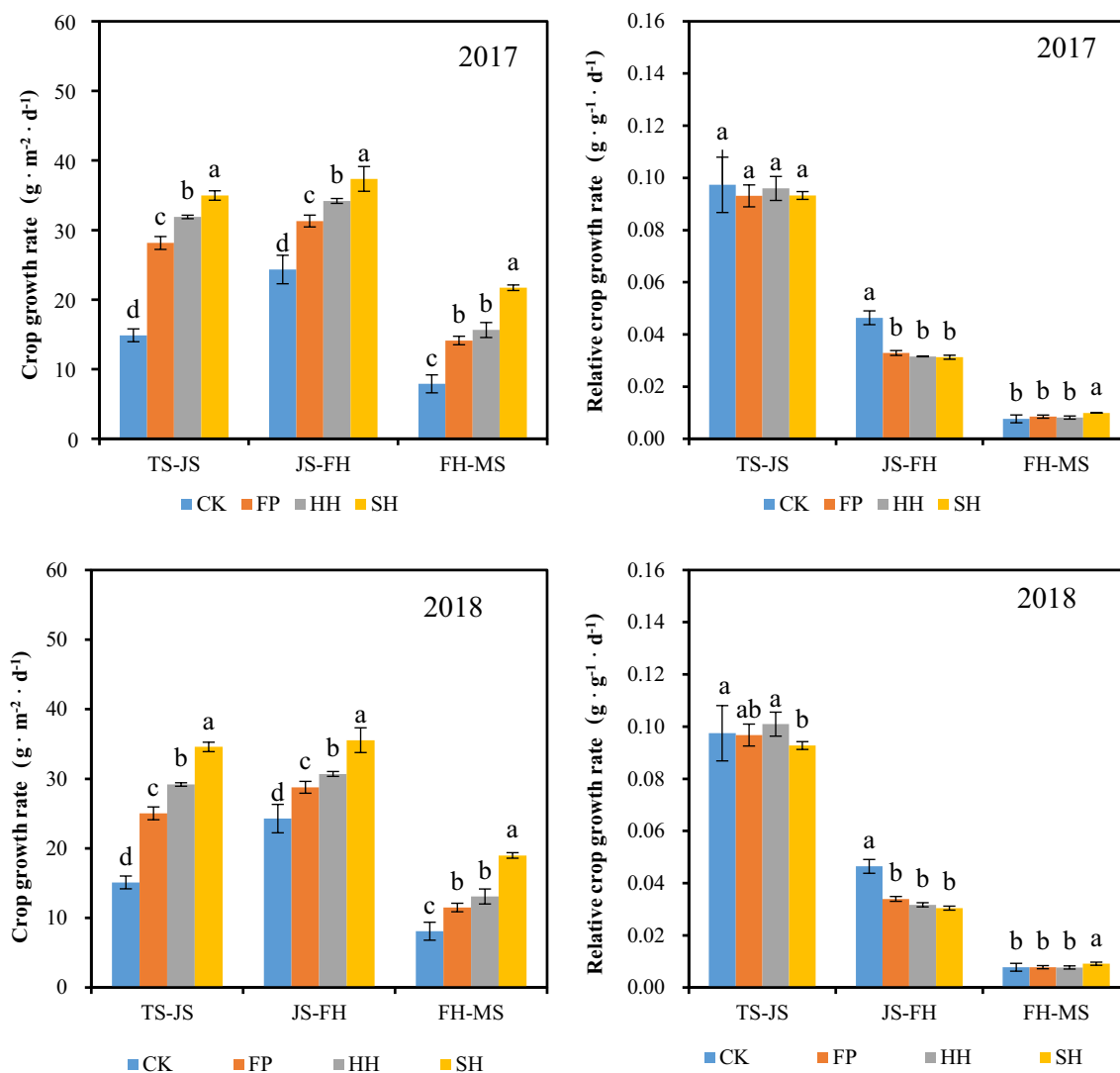


Fig. 2 Crop growth rate and relative crop growth rate of cold-region japonica rice under the four different yield levels. Error bars indicate the mean ± SD (n=3); different lowercase letters indicate significant difference (P<0.05). CK basic production level, FP farmer level, HH

high yield and high efficiency, SH super high yield, TS tillering stage, JS jointing stage, BS booting stage, HS heading stage, FH full heading stage, MS maturity stage

FP. The GTPE1, GTPE2, and GTPE3 values were 0.50, 0.22, and 0.35 g·m⁻²·°C⁻¹·d⁻¹, respectively (Fig. 4).

Relationship Between RUE, TPE, and Population Quality of Cold-Region Japonica Rice Under Different Management Treatments

RUE of the whole growth period showed a significant positive correlation with the leaf area duration from the tillering stage–jointing stage (R²=0.96), while the leaf area duration of TS–JS showed a significant positive correlation with the specific leaf weight of the heading stage (R²=0.97) and the highest correlation coefficient (Fig. 5a). With an increase in leaf area duration in the

tillering stage–jointing stage, the specific leaf weight of the heading stage under each yield treatment increased, and the RUE of the whole growth period increased (Fig. 5c). When the leaf area duration of the tillering stage–jointing stage was 35.4–37.6 m²·m⁻²·per day and the specific leaf weight under HS was in the range of 8.2–8.4 mg·cm⁻², the RUE of the whole growth period (1.44–1.24 g·MJ⁻¹) was higher compared to that observed under CK and FP (Fig. 5c). Specific leaf weight at the jointing stage showed a significant positive correlation with the leaf area duration of the tillering stage–jointing stage (R²=0.96; Fig. 5a) and was in the range of 7.5–7.7 mg·cm⁻², while the leaf area duration of tillering stage–jointing stage was higher than observed under CK

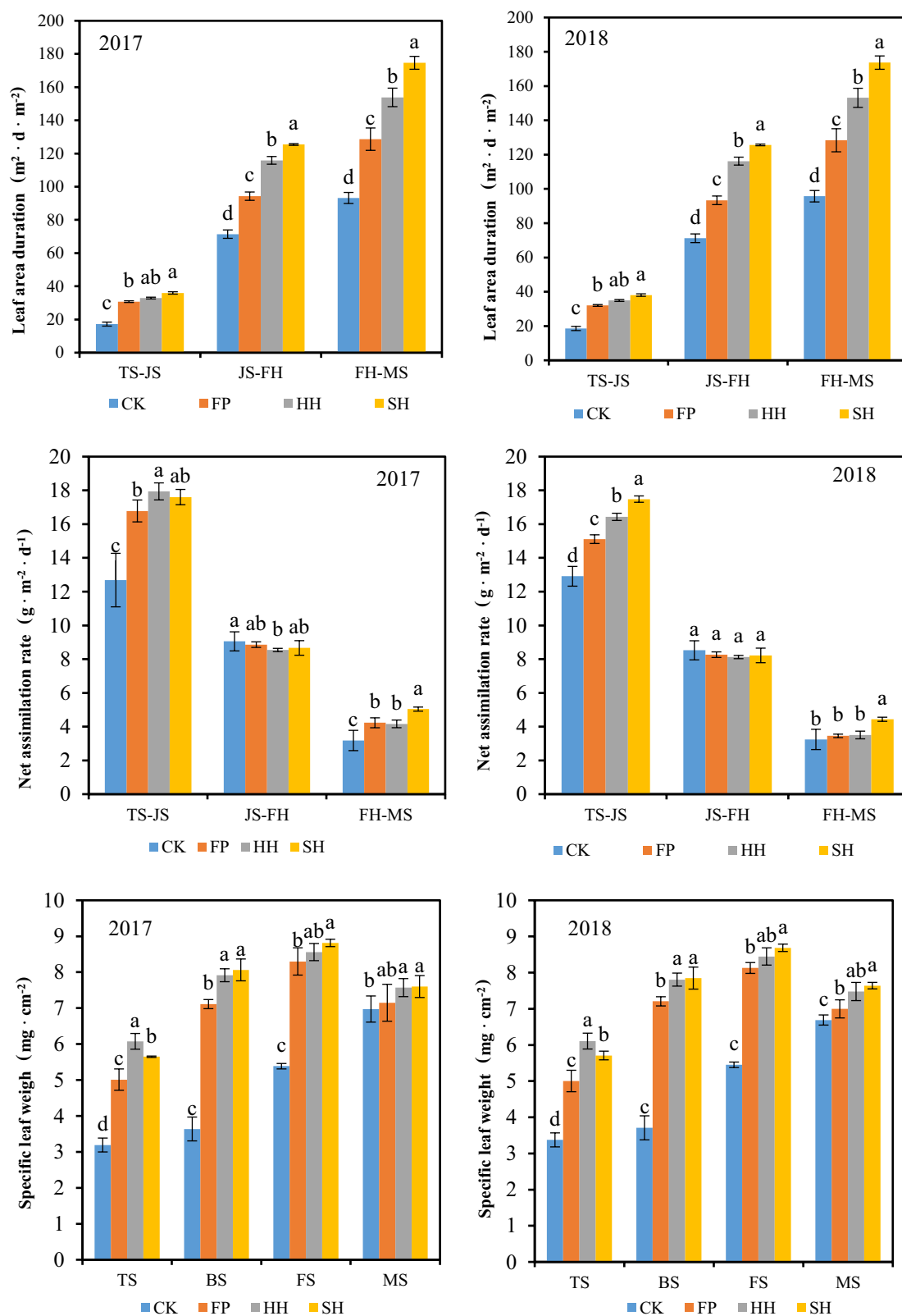


Fig. 3 Leaf area duration, net assimilation rate, and specific leaf weight of cold-region *japonica* rice under four different yield levels. Error bars indicate the mean \pm SD ($n=3$); different lowercase letters indicate significant difference ($P<0.05$). CK basic production level,

FP farmer level, HH high yield and high efficiency, SH super high yield, TS tillering stage, JS jointing stage, BS booting stage, HS, heading stage, FH full heading stage, MS maturity stage

Table 10 Radiation use efficiency (RUE) at different stages of cold-region *japonica* rice under different management treatments ($\text{g}\cdot\text{MJ}^{-1}$)

Year	Treatment	TS–JS	JS–FH	FH–MS	Full growth period
2017	CK	0.68 ^d	1.26 ^d	0.44 ^d	0.57 ^d
	FP	1.29 ^c	1.69 ^c	0.79 ^c	0.91 ^c
	HH	1.46 ^b	1.83 ^b	0.92 ^b	1.03 ^b
	SH	1.60 ^a	2.00 ^a	1.28 ^a	1.21 ^a
2018	CK	0.94 ^d	1.51 ^c	0.49 ^d	0.67 ^d
	FP	1.56 ^c	1.80 ^b	0.72 ^c	1.07 ^c
	HH	1.82 ^b	1.92 ^b	0.82 ^b	1.20 ^b
	SH	2.16 ^a	2.22 ^a	1.19 ^a	1.41 ^a
<i>F</i> value	Treatment (T)	28.34 ^{**}	50.53 ^{**}	281.46 ^{**}	61.89 ^{**}
	Year (Y)	4.46 [*]	2.18	0.20	2.13
	T×Y	31.43 ^{**}	7.14 ^{**}	23.07 ^{**}	5.94 ^{**}

CK basic production level, FP farmer level, HH high yield and high efficiency, SH super high yield, TS tillering stage, JS jointing stage, FH full heading stage, MS maturity stage. Data are presented as the mean ($n=3$). Different superscript letters indicate significant difference ($P<0.05$)

^{*} $P<0.05$

^{**} $P<0.01$

and FP (Fig. 5b). TPE and MLAI, as well as the MLAI and growth rate of the full heading stage, were significantly positively correlated and showed the highest correlation coefficient (Fig. 5a). When the MLAI value

exceeded 2.6, TPE under HH and SH was higher than under the other yield treatments (Fig. 5d).

Relationship Between the Yield and Efficiency Gaps of Cold-Region *japonica* Rice

The relationships between the yield, TPE, and RUE gaps of cold-region *japonica* rice at different yield levels were significantly positive ($R^2=0.9297$ or 0.9273). As the yield gap shrank, the TPE and RUE gaps were also reduced (Fig. 6).

Coupling Effect of Irrigation, N and K Application on Rice Grain Yield

Irrigation, topdressing N and K application were independent variables. Grain yield was response variables. Based on the least square method, and binary quadratic regression equations were established to calculate the amounts of irrigation, topdressing N and K needed to maximize the above parameters (Table 11). The results showed that the influence of irrigation, N and K input on the dependent variables reached significant level ($P<0.01$). The amounts of irrigation and topdressing N and K fertilizer corresponding to the maximum value were shown in Table 11. The maximum grain yield of was obtained when $10,187.7\text{--}10,562.9\text{ m}^3\text{ ha}^{-1}$ of irrigation water, 76.047 kg ha^{-1} of topdressing N fertilizer and 26.733 kg ha^{-1} of topdressing K fertilizer were applied (Fig. 7).

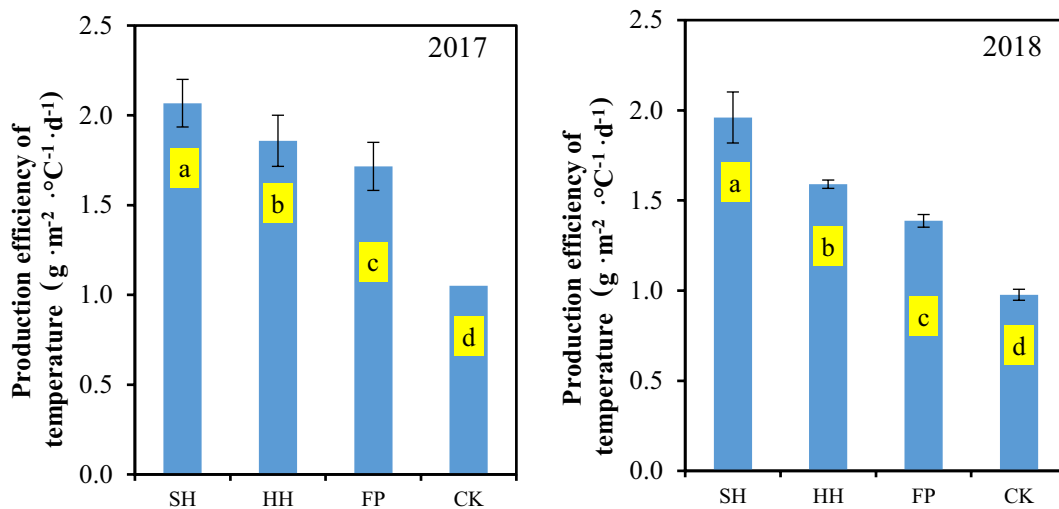


Fig. 4 Production efficiency of temperature of cold-region *japonica* rice under four different yield levels. Error bars indicate the mean \pm SD ($n=3$); different lowercase letters indicate significant dif-

ference ($P<0.05$). SH super high yield, HH high yield and high efficiency, FP farmer level, CK basic production level

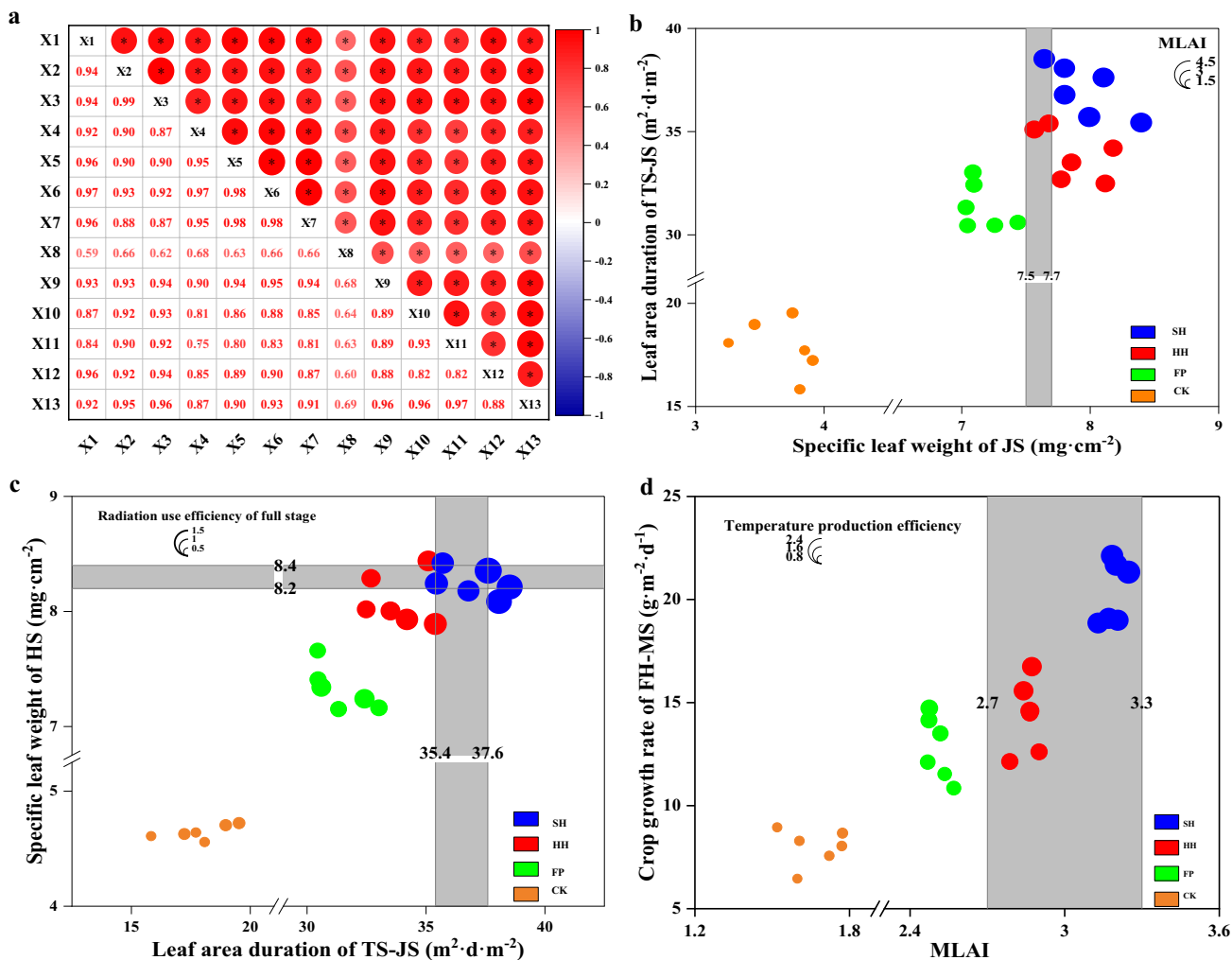


Fig. 5 The relationship between RUE, TPE, and population quality. X1, X2, and X3, leaf area duration of tillering stage (TS)–jointing stage (JS), JS–full heading stage (FH), and FH–maturity stage (MS), respectively; X4, X5, X6, X7, and X8, specific leaf weight of TS, JS, heading stage (HS), FH, and MS, respectively; X9, X10,

and X11, crop growth rate of TS–JS, JS–FH, and FH–MS, respectively; X12: RUE of full growth period; X13: TPE. CK basic production level, FP farmer level, HH high yield and high efficiency, SH super high yield, MLAI mean leaf area index. *P < 0.01

Therefore, it is necessary to further analyze the water and topdressing fertilizer input to determine the best coupling treatments. The coupling effects of irrigation and topdressing of N and K application on the rice grain yield in the two-year experiment exhibited a downward convex shape. The 95, 90, 85, and 80% grain yields were analyzed. The grain yield in the 90% acceptable regions could be achieved at the acceptable range of 90% simultaneously, and the ranges of the three indicators were similar (Fig. 7). Considering all factors of the two years comprehensively, the grain yield could achieve the optimal value at the irrigation water of 10,187.7–10,562.9 m³ ha⁻¹, and topdressing fertilizer of N and K of 50–80 kg ha⁻¹ and 20–40 kg ha⁻¹, respectively.

Discussion

Achieving High Yields of Cold-Region Japonica Rice in the First Accumulated Temperature Zone of Heilongjiang

Studies have found that a reasonable population structure is the key to ensuring yield, whereas simultaneously ensuring a balance in source-sink-translocation and efficient light use by the population is the key to increasing yield (Cao and Moss, 1989; Cook & Evans, 1983; Zelitch, 1982). Nevertheless, few studies have focused on group quality to identify the gaps in the yield between different

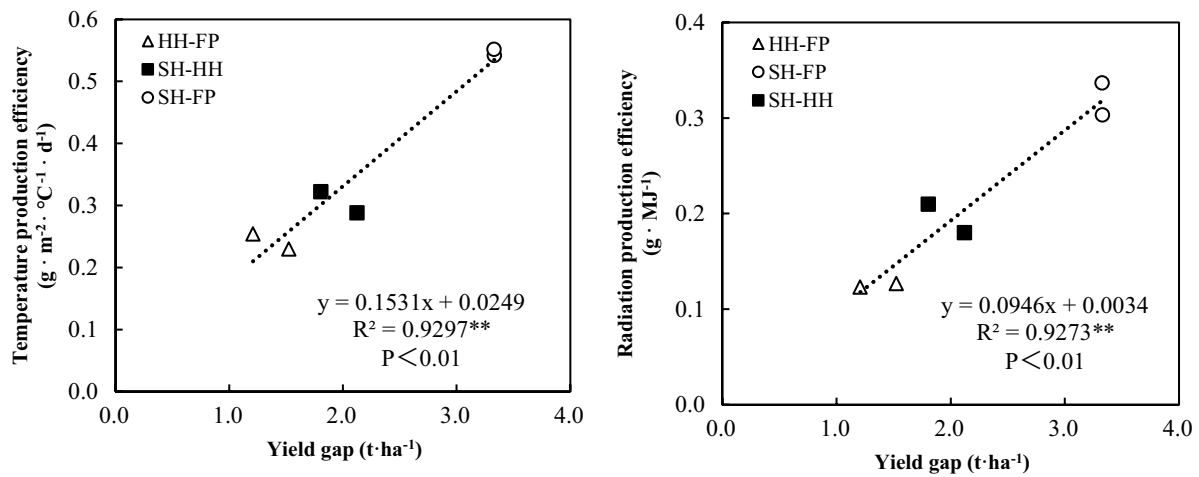


Fig. 6 Relationship between the yield and efficiency gaps of cold-region *japonica* rice in the first accumulated temperature zone of Heilongjiang. ** $P < 0.01$

Table 11 Regression equation between irrigation, topdressing fertilizer and GY. And the maximum GY with the amount of irrigation and topdressing fertilizer of N and K

Response variable Y	Regression equation	R ²	Y max (kg ha ⁻¹)	Irrigation (m ³ ha ⁻¹)	Topdressing fertilizer (kg ha ⁻¹)
GY/Y ₁ (kg ha ⁻¹)	$Y_1 = 15.307 N + 400.496 I - 0.00067 N^2 - 1.175 I^2 - 0.02177 N I - 82884.85$	0.691**	10,314.6	10,187.7	76.047
GY/Y ₂ (kg ha ⁻¹)	$Y_2 = 6.29326 K + 612.85339 I - 2.75813 \times 10^{-4} K^2 - 8.01502 I^2 - 0.01745 K I - 30889.99852$	0.827**	10,539.2	10,562.9	26.733

I is irrigation amount, *N* is topdressing N fertilizer, *K* is topdressing K fertilizer, respectively

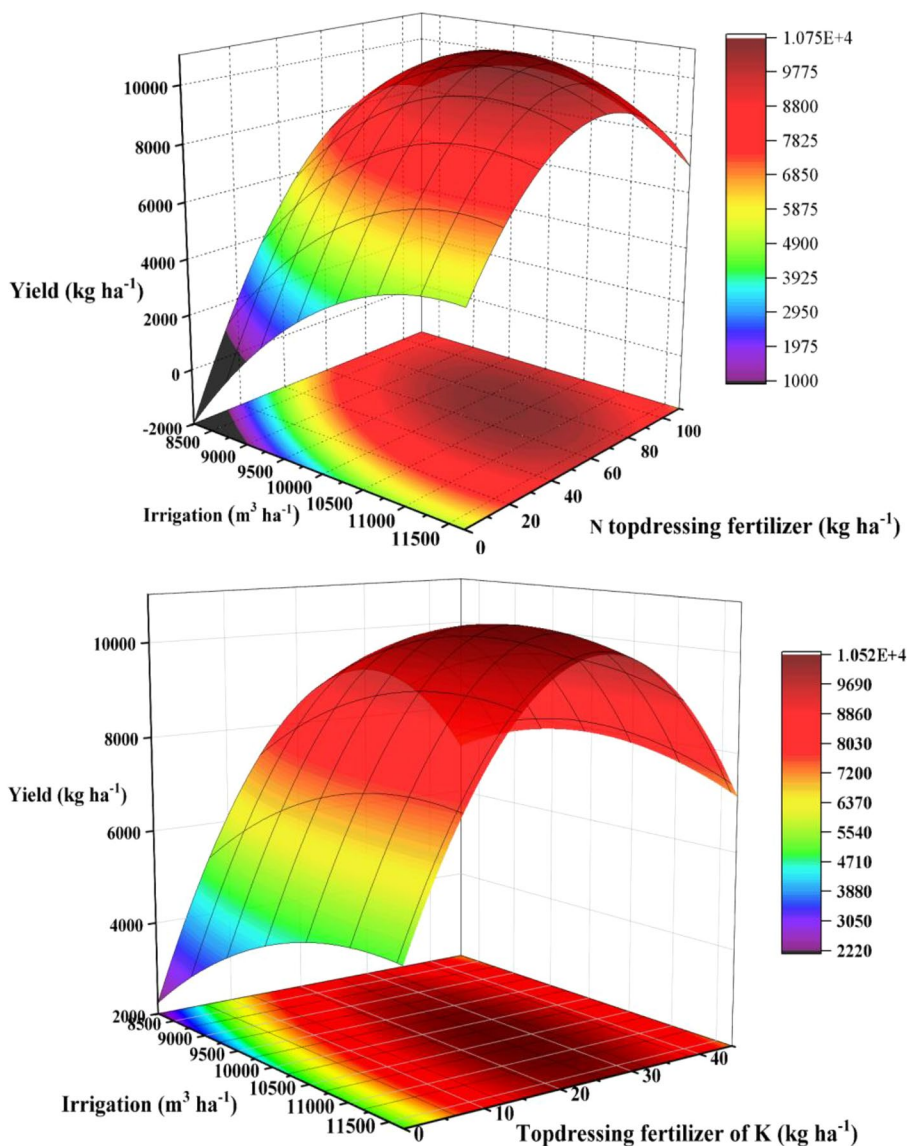
yield treatments in Northeast China. According to the results of the present study, two factors could explain the yield gap between FP and HH.

First, alternating irrigation and an appropriate basal ratio to tillering and panicle fertilizer can achieve high yields (Sun et al., 2012). Although HH and FP utilized comparable amounts of N fertilizer, the irrigation methods and N fertilizer management differed. Under HH, alternating irrigation and a basal to tillering to panicle fertilizer ratio of 6:3:1 enhanced the accumulation and transportation of photosynthetic compounds, supporting HH as the best management treatment. The large GY2 yield gap was mainly attributed to the high specific leaf weight in the jointing stage, maintaining the high leaf area duration of the tillering stage–jointing stage under HH, resulting in increased specific leaf weight in the heading stage that promoted greater MLAI, RGR, and NAR values when compared with those under FP. Secondly, compared with FP, HH significantly increased partial factor productivity (PFP) of nitrogen, FUE, TPE, and RUE owing to greater yield and NAR after the full heading stage. This indicates that under HH, the population size of cold-region *japonica*

rice is more reasonable, and the source-sink coordination is better than that under FP (Hirotsu et al., 2005).

RGR is a key variable in influential treatments of plant ecology, while the NAR is largely independent of RGR (Shipley, 2006). The grain yield depends mainly on photosynthates produced after full heading, which depends on NAR (Li et al., 2008). In the present study, the GY3 of cold-region *japonica* rice was 2074.7 kg·ha⁻¹. The NAR during tillering stage–jointing stage and full heading stage–maturity stage growth and the RGR after full heading stage growth of cold-region *japonica* rice were significantly higher under SH than under other treatments. This indicates that a reasonable tillering population structure ensured that the population maintained a high photosynthetic potential and NAR after full heading stage as well as a relatively high population growth rate; this is the key explanation for the GY3 value. However, compared with those under FP, the MLAI, MNAR, and EP values increased significantly, and HI decreased significantly under SH. This indicates that the source-sink relationship is uncoordinated, and that the biological yield conversion efficiency decreased under SH.

Fig. 7 Relationships among irrigation, N and K application and grain yield of *japonica* rice in the first accumulated temperature zone of Heilongjiang



Achieving High Efficiency of Cold-Region *Japonica* Rice in the First Accumulated Temperature Zone of Heilongjiang

The key strategies for increasing crop yield – when increasing the crop leaf area and harvest indices is not possible – include increasing the biomass and improving the crop RUE (Zhang et al., 2009). Compared to FP, HH was found to be effective at simultaneously increasing the yield and efficiency, as it reduced the yield gap by 9.5% and increased PFPn, FUE, PFP, TPE, and RUE.

Leaf photosynthetic rate also affects RUE (Sinclair & Horie, 1989), and a high RUE may increase the grain yield of rice (Zhang et al., 2009). The large RUE gap between HH and FP was mainly attributed to the high specific leaf weight of the jointing stage and leaf area duration of tillering

stage–jointing stage under HH that increased the specific leaf weight of the heading stage, promoting greater biomass accumulation than that observed under FP. The increased specific leaf weight of the jointing stage and leaf area duration of tillering stage–jointing stage due to increased MLAI were also major contributors to the improved TPE under HH. These are the key factors involved in the bridging of the gaps in RUE and TPE by HH. Although the HH yield was 93.32% of the SH yield, HH increased PFP and PFPn and required less fertilizer application compared to SH. Less fertilizer application may reduce the pressure on the environment and decrease production costs. Thus, HH is an effective production method where the yield and fertilizer use efficiency are improved synergistically (Sun et al., 2018).

The present study also demonstrated that the SH yield only reached 65.7% of the YPT, much lower than the

reported threshold value of 80% (Lobell et al., 2009). Moreover, the attainable yield was found accounted 80.9%–94.8% of the yield potential in Northeast China (Wang et al., 2018), which is 15.7%–29.1% higher than that reported in our study. There are two possible explanations for this discrepancy; first, the low production efficiency in utilizing radiation and temperature by crops has become an important limiting factor in reducing the yield gap (Chen et al., 2017; Deng et al., 2019; Liu et al., 2016; Zhang et al., 2016). Indeed, the relationships between yield gaps and RUE and TPE gaps of cold-region *japonica* rice with different yield levels were significantly positive, consistent with the findings of previous studies (Peng et al., 2004; Strock et al., 2018). The RUE and TPE of SH achieved 80.9% and 77.6% of the potential RUE and TPE, respectively, indicating that it is difficult to eliminate the yield gaps between the current yields reported by farmers and the simulated maximum yield in the short term. However, it is feasible to eliminate the yield gaps between reported yields and regional trials (Deng et al., 2019). Second, FUE requires improvement; although high-level fertilizer input increases yield production, it reduces resource use efficiency and increases environmental pressure (Sun et al., 2018). Compared with those under HH, the PFP and PFPn values did not significantly increase with the increased amount of fertilization used under SH, which also had an extremely low FUE. Moreover, PFP was higher under FP than under SH. Although the “one-time fertilization” method can effectively reduce labor costs in the case of FP, it increases the loss of fertilizer resources and lowers the yield and FUE. Overall, achieving high yields at low costs should be recognized as advantageous in rice production (Trachsel et al., 2013).

Challenges and Prospects for Bridging the Rice Yield Gap in Heilongjiang Province

Small holdings are the main agricultural treatments in China (Zhang et al., 2016), and the current agronomic yield levels of farmers is affected by culture and income level (Shen et al., 2013). In the present study, the FP yield was 7000.0 kg·ha⁻¹ on average in Heilongjiang, accounting for 43.3% of the YPT, which is far lower than the threshold value of 80% (Lobell et al., 2009). These results indicate a great opportunity for yield improvement in Heilongjiang Province in the future (Wang et al., 2020), as providing farmers with information on proper crop management strategies and breeding high-yield crop varieties may significantly improve the current yields (Stuart et al., 2016). Implementing nationwide macro-control and promoting agricultural technologies to improve the current crop management strategies could reduce GRUE2 (0.13 g·MJ⁻¹),

GTPE2 (0.22 m⁻²·°C⁻¹·d⁻¹), and GY2 (1534.00 kg·ha⁻¹). Furthermore, other aspects of rice production under HH, such as its economic benefits and environmental sustainability, should be examined.

Conclusion

To bridge yield gaps and boost efficiency in *japonica* rice production in Northeast China, the current study set out to discover the principles underpinning high-efficiency rice production and investigate viable solutions. The yield disparity was dramatically narrowed by SH and HH treatments by 22.4 and 9.5%, respectively. HH was an effective method to simultaneously increase yield, PFPn, TPE, and RUE. The large yield gap between HH and FP was mainly attributed to high specific leaf weight at the jointing stage (7.5–7.7 mg·cm⁻²), and high leaf area duration maintained during the tillering–jointing stages (35.4–37.6 m²·d·m⁻²). Compared with FP, HH increased the specific leaf weight of the heading stage (8.2–8.4 mg·cm⁻²), promoting a high mean leaf area index (> 2.6), relative crop growth rate, and NAR. Moreover, owing to the greater yield and NAR after the full heading stage, HH significantly increased PFPn, FUE, TPE, and RUE (compared with FP). Although HH yield was 93.32% of SH, HH increased the PFP of fertilizer (12.5%), fertilizer nitrogen (9.07%), and required less fertilizer application than SH. Reliance on imports for even a small fraction of China's rice supply is cause for concern, especially when Heilongjiang's cold stress causes a shortage of the grain. Compared to the FP management treatment, the HH management treatment is highly flexible and might make it easier to maintain yields and resource use efficiency. Indeed, it may be possible to achieve and maintain rice self-sufficiency in China, especially if the rate of increase in yield can be accelerated in Heilongjiang Province.

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Author Contributions HZ and DZ designed the experiments. YJ, HL, and YM wrote the manuscript. HZ, JW, and HZ conducted the metabolite analyses and analyzed the data. YJ carried out the experiments. HW and JW prepared the experimental materials. All authors read and approved the final manuscript.

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Data Availability The data shown in this article are public, but data files cannot be uploaded. The research data are confidential.

Declarations

Conflict of Interest The authors have no competing interests to declare that are relevant to the content of this article.

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