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Agronomic performance of inbred and hybrid rice cultivars under simplified and reduced-input practices

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A B S T R A C T

Hybrid rice has higher yield potential than inbred rice under optimum growing conditions when large amount of resources are provided. However, little attention has been paid to the performance of inbred and hybrid rice cultivars under simplified and reduced-input practices (SRIP). Field experiments were conducted to evaluate the performance of widely grown inbred (Huanghuazhan, HHZ) and hybrid (Yangliangyou 6, YLY6) rice cultivars across farmers' practice (FP) and SRIP treatments in central China in 2014 and 2015. Compared with FP, reducing N input by 50.0% ($SRIP_N$) caused maximum yield reduction of 12.8%, while reducing planting density by 33.3% ($SRIP_D$) did not affect grain yield as much as $SRIP_N$. The large reduction in resource inputs did not cause substantial yield losses because of compensation among yield components. The average yield of YLY6 was 1.38 t ha^{-1} higher than that of HHZ. Higher yield of YLY6 was mainly resulted from longer total growth duration, and higher total dry weight, leaf area index, and 1000-grain weight than HHZ. More importantly, the yield advantage of YLY6 over HHZ was greater in SRIP than in FP, which implies that YLY6 was less sensitive to reduced inputs than HHZ. Overall, the yield stability of YLY6 was significantly higher than that of HHZ across the crop management treatments and years. These results suggest that hybrid rice is more suitable to simplified crop management practices with reduced inputs than inbred rice.

1. Introduction

China is the largest rice producer and consumer in the world (Cheng and Li, 2007). Rice yield in China has increased by more than two times over the last five decades (FAO, 2017), which has contributed significantly to the nation's food security. The increase in rice yield was primarily attributed to crop genetic improvement, increased agronomic input, and improved crop management practices (Cassman, 1999). In the past, the main focus of rice research in breeding and crop management was high yielding without much consideration of inputs of labor and other resources in China. Achieving super high yields was also advocated in rice production with ample supply of labor, water, and agro-chemicals. In recent three years, however, Chinese government has issued several key policy documents which emphasized on the increases of crop production efficiency with reduction in various inputs (MOA, 2015; Fang et al., 2016). As a consequence, rice production is in the unprecedented period of transition in China (Peng, 2014).

A serious labor shortage has occurred recently in the rural areas of China with the development of urbanization and the acceleration of industrialization (Fang, 2007). As result, rural labor cost has increased by 4.27 times from 2003 to 2013 (Zhong, 2016). In addition, the increase in the prices of agro-chemicals and seeds was substantial over the same period. Overall, the cost of rice production in China has increased from 10,829 CNY ha^{-1} in 2004 to 17,648 CNY ha^{-1} in 2014 (NDRC, 2015). This has resulted in a large decline in the profit of rice production and farmers' willingness to grow rice (Xu et al., 2010). More importantly, high agro-chemical inputs have put great burdens on the environment in recent years (Zhang et al., 2013). Clearly, it is vital to increase resource use efficiency with simplified and reduced-input practices (SRIP) in rice production.

Inputs of N fertilizer and seeds represent a major proportion of rice production costs, second to labor input. Rice crop in China uses about 36% of the total N fertilizer used for rice production in the world, although its planting area accounts only for 19% of the world total rice planting area (Peng et al., 2002). The average N application rate per unit area for rice production in China is 75% greater than in other countries (Peng et al., 2010). High N input leads to low N use efficiency (NUE) due to rapid N losses (Peng et al., 2006), which may further induce soil acidification (Guo et al., 2010), water pollution (Diaz and Rosenberg, 2008), and increased emissions of greenhouse gas (Cassman

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et al., 2003). Acidified soil can lead to high heavy metal concentration in rice grains (Zhao et al., 2015). The over use of N fertilizer may decrease yield and economic benefit because rice planted in excessive N condition is more susceptible to lodging, pests, and diseases (Cu et al., 1996). Several studies have demonstrated that there is room to reduce total N input in rice production without sacrifice in yield (Peng et al., 2010; Fan et al., 2011).

Transplanting is a major establishment method in most rice producing areas in China. The labor shortage and high seed costs have caused the desirability of reducing planting density in recent years. Farmers transplant rice at a wide spacing to reduce seed and labor inputs. Such practice do not necessarily cause yield losses because the reduced hills m^{-2} are compensated by increased tillering and growth of individual plants (Li et al., 2013). In fact, high planting density could result in a yield loss due to excessive tiller number and leaf area, increased unproductive tiller percentage, and high spikelet sterility (Kabir et al., 2008). Furthermore, the dense canopy and less ventilation around the plants at high density can create favorable conditions for diseases and make plants more prone to lodging (Islam et al., 2008). Therefore, reduction in planting density can be a potential option for SRIP to reduce rice production costs without yield penalty.

Rice grain yield potential has been greatly improved due to the development of semi-dwarf cultivars in the 1950s, hybrid rice in 1970s, and super hybrid rice in 1996 (Peng et al., 2009; Zhang et al., 2009). It is well documented that hybrid rice has 15–20% higher yield potential than inbred cultivars (Yuan et al., 1994; Peng et al., 1999). Peng et al. (2008) reported that super hybrid rice has further improved rice yield potential over ordinary hybrid rice cultivars. The high yields of hybrid and super hybrid cultivars are often achieved under optimum growing conditions when large amount of resources are provided, which lead to a perception that hybrid and super hybrid rice performed better than inbred rice only under high-input conditions (Islam et al., 2007; Katsura et al., 2007; Zhang et al., 2009). There are limited information on the performance of inbred and hybrid rice cultivars under SRIP. In this study, we grew inbred and hybrid rice cultivars under reduced N rate and planting density. The objectives were to (1) determine the effects of SRIP on the yield and yield attributes of inbred and hybrid rice cultivars, and (2) compare the suitability of inbred and hybrid rice cultivars for simplified crop management practices with reduced inputs.

2. Materials and methods

2.1. Site description

Experiments were conducted in farmer's fields during the middle growing season from May to October in 2014 and 2015 at Dajin Township, Wuxue County, Hubei Province, China (29°51′N, 115°33′E, 23 m altitude). Wuxue County is located in central China in the basin of the Yangtze River and it represents a typical agricultural region of central China where agricultural production is highly intensive. Prior to the experiment, soil samples from upper 20 cm layer were collected for analysis of soil properties. Soil had a clay loam texture with pH of 5.29 and 5.27, organic matter of 23.02 and 19.93 g kg^{-1}, total N of 1.79 and 1.83 g kg^{-1}, available P of 12.01 and 49.66 mg kg^{-1}, and available K of 123.3 and 167.5 mg kg^{-1} in 2014 and 2015, respectively. In both years, climate data (daily minimum temperature, maximum temperature, and solar radiation) were collected during the growing season from a weather station located near the experimental site, and are shown in Fig. 1.

2.2. Experimental design

Experiments were laid out in a split-plot design with crop management treatments as main plot and cultivars as subplot and with four replications in both years. For crop management treatments, farmers' practice (FP) was compared with simplified and reduced-input practices (SRIP) including reduced N input ($SRIP_N$) and reduced planting density ($SRIP_D$). The detailed information of three treatments is shown in Table 1. Two widely grown rice cultivars in central China, Huanghuazhan (HHZ) and Yangliangyou 6 (YLY6), were used as the experimental materials. HHZ is an indica inbred cultivar developed in 2006 with Huangxinzhan as the female parent and Fenghuazhan as the male parent (CRDC, 2016). YLY6 is an indica hybrid cultivar developed by two-line system in 2001 with Guangzhan63–4 s as the female parent and Yangdao 6 as the male parent.

Pre-germinated seeds were sown in a seedbed with the sowing date of 10 May in 2014 and 11 May in 2015. Twenty five-day old seedlings were transplanted on 4 June 2014 and 5 June 2015. Seedlings were transplanted at a hill spacing of 13.3 × 30.0 cm in FP and $SRIP_N$, and of 20.0 × 30.0 cm in $SRIP_D$, with two seedlings per hill. Phosphorus (40 kg P ha^{-1}, calcium superphosphate) and zinc (5 kg Zn ha^{-1}, zinc sulfate heptahydrate) were manually broadcasted and incorporated in all plots 1 d before transplanting for basal application. Potassium (100 kg K ha^{-1}, potassium chloride) was split equally and applied at basal and panicle initiation. Nitrogen fertilizers for $SRIP_N$ (90 kg ha^{-1}, basal: panicle initiation = 6:4) and other treatments (180 kg ha^{-1}, basal: mid-tillering: panicle initiation = 4:3:3) were applied in the form of urea in both years. To minimize seepage between plots, all bunds were covered with plastic film and the plastic film was installed to a depth of 20 cm below soil surface. Water depth of 5–10 cm was maintained in the whole period except for the period when mid-season drainage was carried out. Mid-season drainage lasted for 10 days starting at 20 and 15 days after transplanting in 2014 and 2015, respectively. Weeds, pests, and diseases were intensively controlled by chemicals to avoid yield loss.

2.3. Sampling and measurements

Twelve hills were sampled from each subplot at mid-tillering, panicle initiation, heading, and maturity. Panicle and stem (main stems plus tillers) numbers were recorded at maturity and other stages, respectively. Plant samples were separated into leaf, stem (culm plus sheath), and panicle. The green leaf area was measured using a leaf area meter (LI-3100, LI-COR, Lincoln, NE, USA) and was expressed as leaf area index (LAI) at mid-tillering, panicle initiation, and heading. The maximum stems m^{-2} and maximum LAI was defined as the highest values across all stages. Dry weights of leaf, stem, and panicle were determined after oven-dried at 80 °C to constant weight. Panicles at maturity were hand-threshed and filled spikelets were separated from unfilled spikelets by submerging them in tap water. Empty spikelets were separated from partially filled spikelets by winnowing. Three subsamples with each of 30 g filled spikelets and 2 g empty spikelets were taken to determine the numbers of filled and empty spikelets, whereas the entire sample was counted to determine the number of partially filled spikelets. The numbers of filled, partially filled, and empty spikelets were added to determine total spikelets m^{-2}. Dry weights of rachis, filled, partially filled, and empty spikelets were determined after oven-dried at 80 °C to constant weight. Total dry weight was the summation of the dry weights of leaf, stem, rachis, filled, partially filled, and empty spikelets. Productive tiller percentage was defined as the percent of productive tillers (total panicles m^{-2}–main stems m^{-2}) to maximum tillers m^{-2}. Spikelets per panicle (spikelets m^{-2}/panicles m^{-2}), grain filling percentage (100 × filled spikelets m^{-2}/total spikelets m^{-2}), harvest index (100 × yield/total dry weight), and crop growth rate (total dry weight/growth duration in the main field) were calculated. Yield was determined from a 5-m^2 area at maturity in each subplot and adjusted to the standard moisture content of 0.14 g H_2O g^{-1} fresh weight. Grain moisture content was measured with a digital moisture tester (DMC-700, Seedburo, Chicago, IL, USA).

Plant N concentration was determined by an elemental analyzer (Elementar vario MAX CNS/CN, Elementar Trading Co., Ltd, Germany). Plant N accumulation was the summation of N content of each

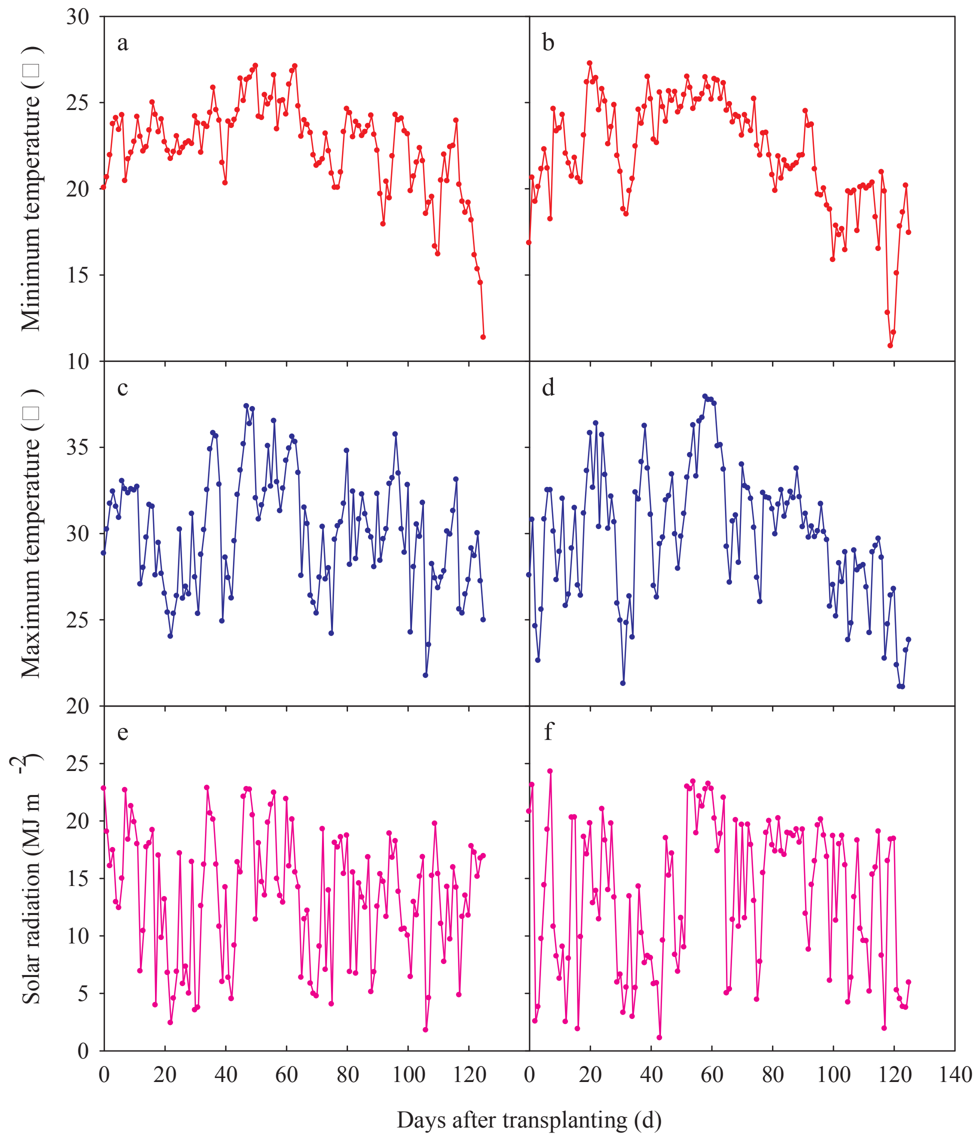

Fig. 1. Daily minimum temperature (a and b), maximum temperature (c and d), and solar radiation (e and f) during rice growing season from transplanting to maturity at Wuxue County, Hubei Province, China in 2014 (a, c, and e) and 2015 (b, d, and f).

Table 1
Detailed information of different treatments at Wuxue County, Hubei Province, China in 2014 and 2015.

Treatment	Nitrogen management		Planting
	Rate (kg ha^{-1})	Timing	density (cm)
FP	180	Basal: MT: PI = 4:3:3	13.3 × 30.0
$SRIP_N$	90	Basal: MT = 6:4	13.3 × 30.0
$SRIP_D$	180	Basal: MT: PI = 4:3:3	20.0 × 30.0

FP, farmers' practice; $SRIP_N$, reduced nitrogen input; $SRIP_D$, reduced planting density. MT, mid-tillering; PI, panicle initiation.

component. N use efficiency for grain production was calculated as the ratio of yield to plant N accumulation. N harvest index was calculated as the percentage of accumulated N in grain to plant N accumulation (Peng et al., 2002). Partial factor productivity of applied N fertilizer was defined as the yield per unit N application rate.

2.4. Data analysis

Analysis of variance (ANOVA) was performed using Statistix 8 (Analytical Software, FL, USA) and means between cultivars and among treatments within a cultivar were compared based on the least significant difference (LSD) test at the 0.05 probability level. Yield stability of the two cultivars was determined following the procedure of Finlay and Wilkinson (1963). Environmental mean was calculated as the mean yield of the two cultivars at each treatment and for each year. All figures were generated by SigmaPlot 10.0 (SPSS Inc., Point Richmond, CA, USA).

3. Results

The average daily solar radiation, minimum temperature, and maximum temperature during the crop growing season in main field (from transplanting to maturity) were 13.3 and 13.9 MJ m^{-2}, 22.8 and 22.5 °C, and 30.2 and 30.4 °C in 2014 and 2015, respectively (Fig. 1). Although the differences in seasonal mean climatic parameters were small between 2014 and 2015, there were relatively large differences in solar radiation and temperature between the two years for each growth stage (Table 2). Higher solar radiation was observed during vegetative period from transplanting to panicle initiation in 2014 than in 2015, but the opposite was true during ripening period from heading to maturity for both cultivars (YLY6 and HHZ). Temperature during vegetative period was higher in 2014 than in 2015 and it was reversed during reproductive period from panicle initiation to heading. During ripening period, minimum temperature was higher in 2014 than 2015. However,

Table 2
The average daily minimum temperature (Tmin, °C), maximum temperature (Tmax, °C), and solar radiation (Rad, MJ m^{-2}) for Huanghuazhan (HHZ) and Yangliangyou 6 (YLY6) in different growth stages at Wuxue County, Hubei Province, China in 2014 and 2015.

Cultivar	TP-PI			PI-HD			HD-PM		
	Tmin	Tmax	Rad	Tmin	Tmax	Rad	Tmin	Tmax	Rad
2014									
HHZ	23.0	29.9	13.6	24.9	32.5	15.8	22.6	30.2	12.4
YLY6	23.3	30.2	13.5	24.0	31.2	13.8	21.5	29.7	12.6
2015									
HHZ	22.2	29.1	11.8	25.2	33.1	15.0	22.1	30.7	15.6
YLY6	22.8	29.7	11.2	25.1	33.2	16.5	20.7	29.5	15.0

TP-PI, from transplanting to panicle initiation; PI-HD, from panicle initiation to heading; HD-PM, from heading to maturity.

Table 3
Analysis of variance (ANOVA) for yield and yield-related traits.

Traits	Year	Treat.	Cultivar	Y × T	Y × C	T × C	Y × T × C
Yield	**	**	**	**	**	ns	ns
Panicle m^{-2}	ns	**	**	**	**	**	ns
Spikelets per panicle	ns	**	**	ns	**	*	*
Spikelets m^{-2}	ns	**	**	**	ns	ns	ns
Grain filling	ns	**	**	*	*	**	**
1000-grain weight	**	**	**	**	**	**	**
Total dry weight	ns	**	**	*	**	ns	ns
Harvest index	ns	**	ns	**	**	**	*

Y × T, year × treatment; Y × C, year × cultivar; T × C, treatment × cultivar; Y × T × C, year × treatment × cultivar.
ns denotes non-significance at the 0.05.
*significant at P ≤ 0.05.
**significant at P ≤ 0.01.

Table 4
Yield for Huanghuazhan (HHZ) and Yangliangyou 6 (YLY6) in different treatments and the percentage of yield under simplified and reduced-input practices to farmers' practice at Wuxue County, Hubei Province, China in 2014 and 2015.

Cultivar	Treat.	Yield (t ha^{-1})		Compared to FP (%)	
		2014	2015	2014	2015
HHZ	FP	8.91 a	10.33 a	100.0	100.0
	$SRIP_N$	8.22 b	9.01 b	92.3	87.2
	$SRIP_D$	8.46 b	10.30 a	94.9	99.7
	Mean	8.53 B	9.88 B	–	–
YLY6	FP	10.50 a	11.02 a	100.0	100.0
	$SRIP_N$	10.32 a	10.05 b	98.3	91.2
	$SRIP_D$	10.50 a	11.15 a	100.0	101.2
	Mean	10.44 A	10.74 A	–	–

Within a column for each cultivar in a year, means followed by different letters are significantly different according to LSD (0.05). Lower-case and upper-case letters indicate comparisons among treatments of each cultivar and between two cultivars in a year, respectively.
FP, farmers' practice; $SRIP_N$, reduced nitrogen input; $SRIP_D$, reduced planting density.

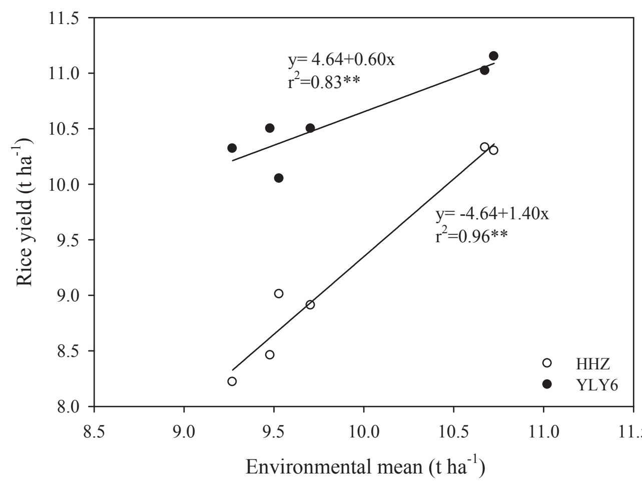

Fig. 2. Yield stability of Huanghuazhan (HHZ) and Yangliangyou 6 (YLY6) at Wuxue County, Hubei Province, China in 2014 and 2015. Environmental mean was calculated as the mean yield of the two cultivars at each treatment and for each year following the procedure of Finlay and Wilkinson (1963). ** significant at P ≤ 0.01.

the two cultivars had inconsistent difference in solar radiation during reproductive period and maximum temperature during ripening period between the two years.

Table 3 shows the analysis of variance for yield and yield-related traits. Effects of year on grain yield and 1000-grain weight were significant. Treatment had significant effects on yield and yield-related traits, while cultivar also had significant effects on these traits except for harvest index. Interactive effects between year and treatment and between year and cultivar were not significant for spikelets per panicle and spikelets m^{-2}, respectively. Interaction between treatment and cultivar had similar effects on yield and yield-related traits as the interaction among year, treatment, and cultivar except on panicle m^{-2}. Although the interactive effect between treatment and cultivar on grain yield was insignificant at the probability level of 0.05, it was significant at the probability level of 0.10 (P = 0.06).

Compared with farmers' practice (FP), treatment with reduced N input ($SRIP_N$) significantly decreased the grain yield of HHZ in both years (Table 4). However, $SRIP_N$ reduced the grain yield of YLY6 significantly only in 2015. Furthermore, yield reduction by $SRIP_N$ was greater in HHZ (7.7–12.8%) than in YLY6 (1.7–8.8%). Reducing planting density ($SRIP_D$) did not affect grain yield as much as $SRIP_N$. Compared with FP, $SRIP_D$ significantly decreased grain yield only in HHZ in 2014. On average, YLY6 produced 22.4% and 8.7% higher grain yield than HHZ in 2014 and 2015, respectively. In general, grain yield was higher in 2015 than in 2014, especially for HHZ. Overall, YLY6 demonstrated higher yield stability than HHZ across growing environments (Fig. 2).

$SRIP_N$ reduced spikelets m^{-2} significantly except for YLY6 in 2014, whereas $SRIP_D$ had insignificant effect on spikelets m^{-2} compared with FP (Table 5). $SRIP_N$ reduced spikelets m^{-2} by reducing both panicle m^{-2} and spikelets per panicle or panicle m^{-2} alone. In contrast, $SRIP_D$ reduced panicle m^{-2} but increased spikelets per panicle. There were small and inconsistent differences among treatments in grain filling percentage and 1000-grain weight. HHZ had significantly higher spikelets m^{-2} and panicle m^{-2} but lower spikelets per panicle and 1000-grain weight than YLY6, whereas difference in grain filling percentage was small and inconsistent between the two cultivars. Higher grain filling percentage and 1000-grain weight contributed to higher grain yield of HHZ in 2015 compared with 2014. Cultivar and $SRIP_D$ did not have consistent effect on partially filled spikelets m^{-2}, whereas it was reduced significantly by $SRIP_N$ compared with FP (data not shown).

Both $SRIP_N$ and $SRIP_D$ reduced total dry weight and crop growth rate compared with FP, although the reduction was not always significant (Table 6). Significant reduction in total dry weight and crop growth rate by $SRIP_N$ was observed in HHZ but not in YLY6. Total dry weight of YLY6 was higher than that of HHZ, but the difference was not significant in 2015. Higher total dry weight of YLY6 was mainly attributed to its longer total growth duration (13–21 d) because YLY6 did not have higher crop growth rate than HHZ. Significant increase in harvest index by $SRIP_N$ was observed in YLY6 but not in HHZ compared with FP. Treatment of planting density and cultivar had inconsistent effects on harvest index across the two years.

Compared with FP, $SRIP_N$ reduced maximum leaf area index significantly except for HHZ in 2014, while $SRIP_D$ reduced maximum leaf

Table 5
Yield components for Huanghuazhan (HHZ) and Yangliangyou 6 (YLY6) under different treatments at Wuxue County, Hubei Province, China in 2014 and 2015.

Cultivar	Treat.	Panicles m^{-2}	Spikelets $panicle^{-1}$	Spikelets m^{-2} ($\times 10^3$)	Grain filling (%)	1000-grain weight (g)
2014						
HHZ	FP	290.1 a	176.3 ab	50.9 a	82.9 a	19.6 b
	$SRIP_N$	270.9 ab	170.8 b	46.2 b	87.6 a	19.9 a
	$SRIP_D$	260.6 b	191.8 a	50.0 a	85.1 a	19.3 c
	Mean	273.0 A	179.6 B	49.0 A	85.1 A	19.6 B
YLY6	FP	233.4 a	183.3 b	42.7 a	85.3 a	28.0 a
	$SRIP_N$	230.8 a	176.8 b	40.7 a	87.6 a	27.8 a
	$SRIP_D$	197.6 b	206.2 a	40.7 a	78.9 b	27.1 b
	Mean	220.6 B	188.7 A	41.4 B	83.9 A	27.6 A
2015						
HHZ	FP	348.4 a	148.9 b	51.9 a	90.0 a	21.0 b
	$SRIP_N$	252.6 c	160.3 ab	40.5 b	90.6 a	21.5 a
	$SRIP_D$	297.8 b	168.3 a	50.1 a	88.9 a	20.4 c
	Mean	299.6 A	159.2 B	47.5 A	89.8 A	21.0 B
YLY6	FP	227.1 a	207.9 a	47.1 a	76.2 c	26.7 b
	$SRIP_N$	204.7 b	179.2 b	36.6 b	92.3 a	28.6 a
	$SRIP_D$	211.9 ab	207.1 a	43.9 a	83.9 b	26.6 b
	Mean	214.6 B	198.1 A	42.5 B	84.1 B	27.3 A

Within a column for each cultivar in a year, means followed by different letters are significantly different according to LSD (0.05). Lower-case and upper-case letters indicate comparisons among treatments of each cultivar and between two cultivars in a year, respectively.
FP, farmers' practice; $SRIP_N$, reduced nitrogen input; $SRIP_D$, reduced planting density.

Table 6
Growth duration in the main field, total dry weight, harvest index, and crop growth rate for Huanghuazhan (HHZ) and Yangliangyou 6 (YLY6) under different treatments at Wuxue County, Hubei Province, China in 2014 and 2015.

Cultivar	Treat.	Growth duration in the main field (d)	Total dry weight ($t\ ha^{-1}$)	Harvest index (%)	Crop growth rate ($g\ m^{-2}\ d^{-1}$)
2014					
HHZ	FP	99	16.1 a	51.4 a	16.2 a
	$SRIP_N$	99	15.2 b	53.0 a	15.4 b
	$SRIP_D$	99	15.4 ab	53.5 a	15.5 ab
	Mean	99	15.6 B	52.6 A	15.7 A
YLY6	FP	120	19.9 a	51.2 b	16.6 a
	$SRIP_N$	120	18.7 ab	53.0 a	15.6 ab
	$SRIP_D$	120	17.6 b	49.3 c	14.7 b
	Mean	120	18.8 A	51.5 B	15.6 A
2015					
HHZ	FP	100	19.2 a	51.0 ab	19.2 a
	$SRIP_N$	100	15.6 b	50.6 b	15.6 b
	$SRIP_D$	100	17.2 b	53.0 a	17.2 b
	Mean	100	17.3 A	51.5 B	17.3 A
YLY6	FP	115	19.1 a	50.3 b	16.6 a
	$SRIP_N$	108	17.6 a	54.9 a	16.3 a
	$SRIP_D$	115	18.1 a	54.1 a	15.7 a
	Mean	113	18.3 A	53.1 A	16.2 B

Within a column for each cultivar in a year, means followed by different letters are significantly different according to LSD (0.05). Lower-case and upper-case letters indicate comparisons among treatments of each cultivar and between two cultivars in a year, respectively.
FP, farmers' practice; $SRIP_N$, reduced nitrogen input; $SRIP_D$, reduced planting density.

area index significantly except for YLY6 in 2015 (Table 7). Maximum stem number per m^2 of $SRIP_D$ was consistently lower than that of FP. $SRIP_N$ had lower productive tiller percentage than FP and $SRIP_D$, but the difference was not always significant. Significant reduction in productive tiller percentage by $SRIP_N$ was observed in HHZ but not in YLY6. YLY6 had higher maximum leaf area index and lower productive tiller percentage than HHZ, whereas there was no consistent difference in maximum stem number per m^2 between the two cultivars in 2014 and 2015.

Table 7
Maximum leaf area index, maximum stems m^{-2}, and productive tiller percentage for Huanghuazhan (HHZ) and Yangliangyou 6 (YLY6) under different treatments at Wuxue County, Hubei Province, China in 2014 and 2015.

Cultivar	Treat.	Maximum leaf area index	Maximum stems m^{-2}	Productive tiller percentage (%)
2014				
HHZ	FP	6.15 a	371.4 a	74.9 a
	$SRIP_N$	5.58 ab	389.1 a	65.4 b
	$SRIP_D$	5.03 b	305.4 b	83.0 a
	Mean	5.59 B	355.3 B	74.4 A
YLY6	FP	8.15 a	430.8 a	48.5 b
	$SRIP_N$	6.86 b	437.0 a	47.2 b
	$SRIP_D$	6.94 b	331.6 b	55.1 a
	Mean	7.31 A	399.8 A	50.3 B
2015				
HHZ	FP	7.12 a	500.5 a	66.5 a
	$SRIP_N$	5.38 c	461.5 ab	49.3 b
	$SRIP_D$	6.21 b	432.1 b	67.0 a
	Mean	6.24 B	464.7 A	60.9 A
YLY6	FP	8.27 a	449.5 a	44.3 a
	$SRIP_N$	5.47 b	405.2 b	43.6 a
	$SRIP_D$	8.03 a	412.7 b	47.2 a
	Mean	7.26 A	422.5 B	45.0 B

Within a column for each cultivar in a year, means followed by different letters are significantly different according to LSD (0.05). Lower-case and upper-case letters indicate comparisons among treatments of each cultivar and between two cultivars in a year, respectively.
FP, farmers' practice; $SRIP_N$, reduced nitrogen input; $SRIP_D$, reduced planting density.

$SRIP_N$ reduced plant N concentration and plant N accumulation but increased N use efficiency for grain production significantly compared with FP except for YLY6 in 2014 (Table 8). $SRIP_N$ had inconsistent effect on N harvest index. Large increase in partial factor productivity of applied N fertilizer was observed in $SRIP_N$. In contrast, $SRIP_D$ did not affect these N-related parameters as much as $SRIP_N$. HHZ had significantly higher plant N concentration but lower N harvest index and partial factor productivity of applied N fertilizer than YLY6, while there was inconsistent difference in plant N accumulation and N use efficiency for grain production between the two cultivars. Treatment and cultivar had insignificant effects on grain N concentration (data not shown).

4. Discussion

Significant yield reduction was observed in $SRIP_N$ in three out of four cultivar and year combinations. However, the highest yield reduction was only 12.8% even though total N application rate was reduced by 50.0% and the number of N application was reduced by one time in $SRIP_N$ compared with FP. Reducing planting density by 33.3% in $SRIP_D$ caused significant yield reduction in one out of four cultivar and year combinations and the rate of yield reduction was only 5.1%. Li et al. (2013) and Wang et al. (2014) reported that there was no significant reduction in yield as planting density was reduced from 22 to 17 hills m^{-2}. Overall, $SRIP_D$ did not affect yield as much as $SRIP_N$.

Among yield components, yield reduction under $SRIP_N$ was mainly associated with few spikelets m^{-2}. $SRIP_N$ reduced spikelets m^{-2} by 5.0–28.7% across two cultivars and two years. Reduction in spikelets m^{-2} under $SRIP_N$ was due to decreased panicle m^{-2} and spikelets per panicle or due to decreased panicle m^{-2} alone compared with FP. Cassman et al. (1998) also reported that decreased spikelets m^{-2} was

Table 8
Nitrogen use efficiency for Huanghuazhan (HHZ) and Yangliangyou 6 (YLY6) under different treatments at Wuxue County, Hubei Province, China in 2014 and 2015.

Cultivar	Treat.	NC (%)	TN (kg ha^{-1})	NUEg (kg kg^{-1})	NHI (%)	PFP_N (kg kg^{-1})
2014						
HHZ	FP	1.18 a	188.9 a	44.1 b	58.5 b	49.5 b
	$SRIP_N$	1.02 b	155.7 b	51.8 a	64.8 a	91.4 a
	$SRIP_D$	1.13 ab	173.1 ab	47.7 ab	62.7 ab	47.0 b
	Mean	1.11 A	172.6 B	47.9 A	62.0 B	62.6 B
YLY6	FP	1.08 a	215.3 a	47.6 ab	64.1 ab	58.3 b
	$SRIP_N$	1.01 a	189.2 a	52.5 a	68.3 a	114.7 a
	$SRIP_D$	1.10 a	194.6 a	44.9 b	59.3 b	58.3 b
	Mean	1.06 B	199.7 A	48.3 A	63.9 A	77.1 A
2015						
HHZ	FP	1.16 a	222.9 a	44.2 b	61.1 a	57.4 b
	$SRIP_N$	0.98 b	153.2 b	51.8 a	63.0 a	100.0 a
	$SRIP_D$	1.19 a	204.3 a	44.7 b	61.5 a	57.2 b
	Mean	1.11 A	193.5 A	46.9 B	61.9 B	71.6 B
YLY6	FP	1.13 a	213.8 a	44.8 c	63.5 b	61.2 b
	$SRIP_N$	0.91 b	159.4 b	60.8 a	73.1 a	111.7 a
	$SRIP_D$	1.06 a	192.3 a	51.3 b	67.6 ab	62.0 b
	Mean	1.03 B	188.5 A	52.3 A	68.1 A	78.3 A

Within a column for each cultivar in a year, means followed by different letters are significantly different according to LSD (0.05). Lower-case and upper-case letters indicate comparisons among treatments of each cultivar and between two cultivars in a year, respectively.

NC, TN, NUEg, NHI, and PFP_N are plant nitrogen concentration, plant nitrogen accumulation, nitrogen use efficiency for grain production, nitrogen harvest index, and partial factor productivity of applied nitrogen fertilizer, respectively.

FP, farmers' practice; $SRIP_N$, reduced nitrogen input; $SRIP_D$, reduced planting density.

responsible for the yield reduction in low N treatment. However, slightly increased grain filling percentage and/or 1000-grain weight was observed in $SRIP_N$ compared with FP. Likewise, $SRIP_D$ reduced panicle m^{-2} but increased spikelets per panicle. The compensation among yield components explained why the large reduction in resource inputs did not cause substantial yield losses compared with FP. Our results indicated that there is large potential to reduce resource inputs and production costs without significant effects on crop productivity in rice production in China.

Plant N accumulation was 164.4 and 200.7 kg ha^{-1} for the N rates of 90 and 180 kg ha^{-1}, respectively. Nitrogen use efficiency for grain production, N harvest index, and partial factor productivity of applied N fertilizer ranged from 44.1 to 60.8 kg kg^{-1}, from 58.5 to 73.1%, and from 47.0 to 114.7 kg kg^{-1}, respectively. These values were comparable to rice N use efficiency in China at the N rates of 90–180 kg ha^{-1} (Che et al., 2015). There was no zero-N plot in this study. However, plant N accumulation was measured in zero-N plots in adjacent fields of this study in 2012 by Chen et al. (2015). They reported that plant N accumulation of zero-N plots was 88.6–91.5 kg ha^{-1}. Xu et al. (2016) took 416 measurements for indigenous N supply of middle-season rice across middle and lower reaches of the Yangtze River and reported 98.2 kg ha^{-1} of average plant N accumulation in zero-N plots. This suggests that our experimental field is representative for most rice paddy in China in terms of indigenous N supply. Potential for the reduction of fertilizer-N input is applicable for rice production in China.

The over use of N fertilizer has been a major problem in crop production in China for many years (Nosengo, 2003; Peng et al., 2009). The high N fertilizer input in crop production caused a large decline in N use efficiency and widespread environmental damage in China (Peng et al., 2002; Fan et al., 2008). Peng et al. (2010) and Fan et al. (2011) reported that the amount of N fertilizer applied in paddy field could be reduced significantly to increase N use efficiency with no substantial reduction in yield. In this study, reducing N input increased both N use efficiency for grain production and partial factor productivity of applied N fertilizer. Increased N use efficiency implies a reduction in N losses, which is beneficial to the environment (Peng et al., 2002; Fan et al., 2008). Furthermore, plant population was smaller in SRIP due to lower leaf area index and stem number m^{-2} compared with FP. Such smaller rice canopy is less inducible to disease and insect damages, and consequently requires less pesticide input for crop protection (Stuthman et al., 2007). In 2015, Ministry of Agriculture in China started to advocate "two reductions" (i.e. reducing the inputs of fertilizers and pesticides) in agricultural production (Fang et al., 2016). The specific goal of Chinese government is to reach zero percent increase in the consumptions of fertilizers and pesticides by 2020 (MOA, 2015). Clearly, implementation of SRIP in rice production is in accordance with the goal of Chinese government.

Average yield of YLY6 was 1.91 and 0.86 t ha^{-1} higher than that of HHZ in 2014 and 2015, respectively, which was associated with higher spikelets per panicle and 1000-grain weight in YLY6 compared with HHZ. Total dry weight rather than harvest index explained the yield advantage of YLY6. Higher total dry weight of YLY6 was attributed to its longer total growth duration (13–21 d) and higher leaf area index. Ying et al. (1998) and Zhang et al. (2009) also reported that higher yield of hybrid rice was associated with higher sink size (i.e. product of spikelet number and grain weight), total dry weight, and longer total crop growth duration compared with inbred rice.

Yield stability of YLY6 was also significantly higher than that of HHZ across growing environments. High total dry weight, large leaf area index and sink size, and long crop growth duration might have contributed to the high yield stability of YLY6. The critical importance of total dry weight to yield stability was previously emphasized by Peng et al. (2015) and Wang et al. (2016). Yield in 2015 was 15.8% and 2.9% higher than that in 2014 for HHZ and YLY6, respectively. The difference in rice yield between the two years was mainly resulted from the lower minimum temperature and higher solar radiation in the crop growing season in 2015, especially during the grain filling period (Peng et al., 2004; Wang et al., 2016). YLY6 not only had less variation in yield across the two years, but also exhibited the smaller yield variability across crop management treatments compared with HHZ. Compared with FP, SRIP reduced yield by 2.4% and 6.9% for YLY6 and HHZ, respectively. Therefore, the reduced resource inputs in SRIP did not decrease the yield of YLY6 as much as in HHZ. In other words, the hybrid rice cultivar was less sensitive to reduced inputs than the inbred rice cultivar. Average yield of YLY6 was 16.8% and 11.9% higher than that of HHZ in SRIP and FP, respectively. Therefore, the yield advantage of YLY6 over HHZ was greater in SRIP than in FP. This is because the reduction in total dry weight by SRIP was greater in HHZ than YLY6, whereas the increase in harvest index by SRIP was smaller in HHZ than YLY6. These results suggest that hybrid rice is more suitable to SRIP than inbred rice.

Comparison between inbred and hybrid rice cultivars is often conducted under optimum growing conditions without considering the costs of labor and other resource inputs (Islam et al., 2007; Katsura et al., 2007). It is well known that hybrid rice cultivars have yield advantage over inbred rice cultivars when large amount of resources are provided (Zhang et al., 2009). Our study indicated that hybrid rice cultivar also yielded higher than inbred rice cultivar when they were grown under simplified crop management practices with reduced inputs of labor and N fertilizer. This implies that hybrid rice not necessarily requires more agronomic and labor inputs than inbred rice to achieve high yield. Further experiments on more inbred and hybrid rice cultivars with similar growth duration should be conducted to confirm the superiority of hybrid over inbred under SRIP.

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