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Comparison of crop yield and solar thermal utilization among different rice–wheat cropping systems

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Abstract

Planting patterns have significant effects on rice growth. Nonetheless, little is known about differences in annual crop yield and resource utilization among mechanized rice planting patterns in a rice–wheat cropping system. Field experiments were conducted from 2014 to 2017 using three treatments: pot seedling transplanting for rice and row sowing for wheat (PST-RS), carpet seedling transplanting for rice and row sowing for wheat (CST-RS) and row sowing for both crops (RS-RS). The results showed that, compared with RS-RS, PST-RS and CST-RS prolonged annual crop growth duration by 25–26 and 13–15 days, increased effective accumulated temperature by 399 and 212°C days and increased cumulative solar radiation by 454 and 228 MJ/m^2 because of the earlier sowing of rice by 28 and 16 days in PST-RS and CST-RS, respectively. Compared with RS-RS, the annual crop yield of PST-RS and CST-RS increased by 3.1–3.8 and 2.0–2.6 t/ha, respectively, because of the increase in the number of spikelets/kernels per hectare, aboveground biomass, mean leaf area index and grain–leaf ratio. In addition, temperature production efficiency, solar radiation production efficiency and solar radiation use efficiency were higher in PST-RS, followed by CST-RS and RS-RS. These results suggest that mechanized rice planting patterns such as PST-RS increase annual crop production in rice–wheat cropping systems by increasing yield and solar energy utilization.

Introduction

Rice and wheat are major grain crops in China, and high crop yields increase economic and social development by improving land use and reducing the need for solar thermal energy (Ray *et al.*, 2012; Deng *et al.*, 2015). The rice–wheat cropping system is a common cultivation system, with an annual planting area of 10.5×10^6 ha in China and approximately 24×10^6 ha in other countries (Bhatt *et al.*, 2021; Ullah *et al.*, 2021). This cropping system is used in the Yangtze river basin, with approximately 8.5×10^6 ha. This region represents more than 20% of the total grain yield in China. This system is also adopted in Jiangsu, Anhui, Hubei, Sichuan, Chongqing, Henan, Shandong, Zhejiang, Shanghai and other regions (Hu *et al.*, 2018). Thus, special attention has been paid to annual grain production in rice–wheat cropping systems in the Yangtze river basin (Deng *et al.*, 2015; Han *et al.*, 2020; Du *et al.*, 2021). Urban, rural and agricultural development decreased the number of farm jobs, stimulated large-scale crop production and more production and management modes have been the scale production of new business entities with an improved level of knowledge. Therefore, there is an urgent need for the high-yield, high-efficiency, mechanized cultivation of rice and wheat to improve grain production (Li *et al.*, 2012; Duncan *et al.*, 2020; Du *et al.*, 2021).

In the Yangtze river basin, wheat is grown by mechanical direct seeding (MDS), while rice is grown by mechanical transplanting (MT) or MDS. MDS, without the need for nurseries, is simpler than MT and is widely used (San-oh *et al.*, 2004; Liu *et al.*, 2015). However, compared with MT, grain yield and solar energy utilization efficiency are lower in MDS because of the inherent cultivation characteristics of the latter and the limited understanding of this cultivation technology in practice (Hayashi *et al.*, 2007; Rao *et al.*, 2017; Xing *et al.*, 2017*a*). In addition, MDS affects the subsequent growth of wheat with late-harvest rice and late-sowing wheat cultivation, which reduces the high-yield and high-efficient production of annual grain (Zhang and Gong, 2014; Xing *et al.*, 2017*a*). The effects of mechanized planting on annual rice production and solar energy utilization are more pronounced in areas with fewer thermal and solar energy resources (Xing *et al.*, 2017*b*). The reason is that most rice cultivars have high yields and longer growth duration selected at transplanting pattern, with delayed heading and ripening and lower accumulated temperatures and solar radiation in MDS systems. Compared with transplanted rice, direct-seeded rice is sown late and has higher plant density,

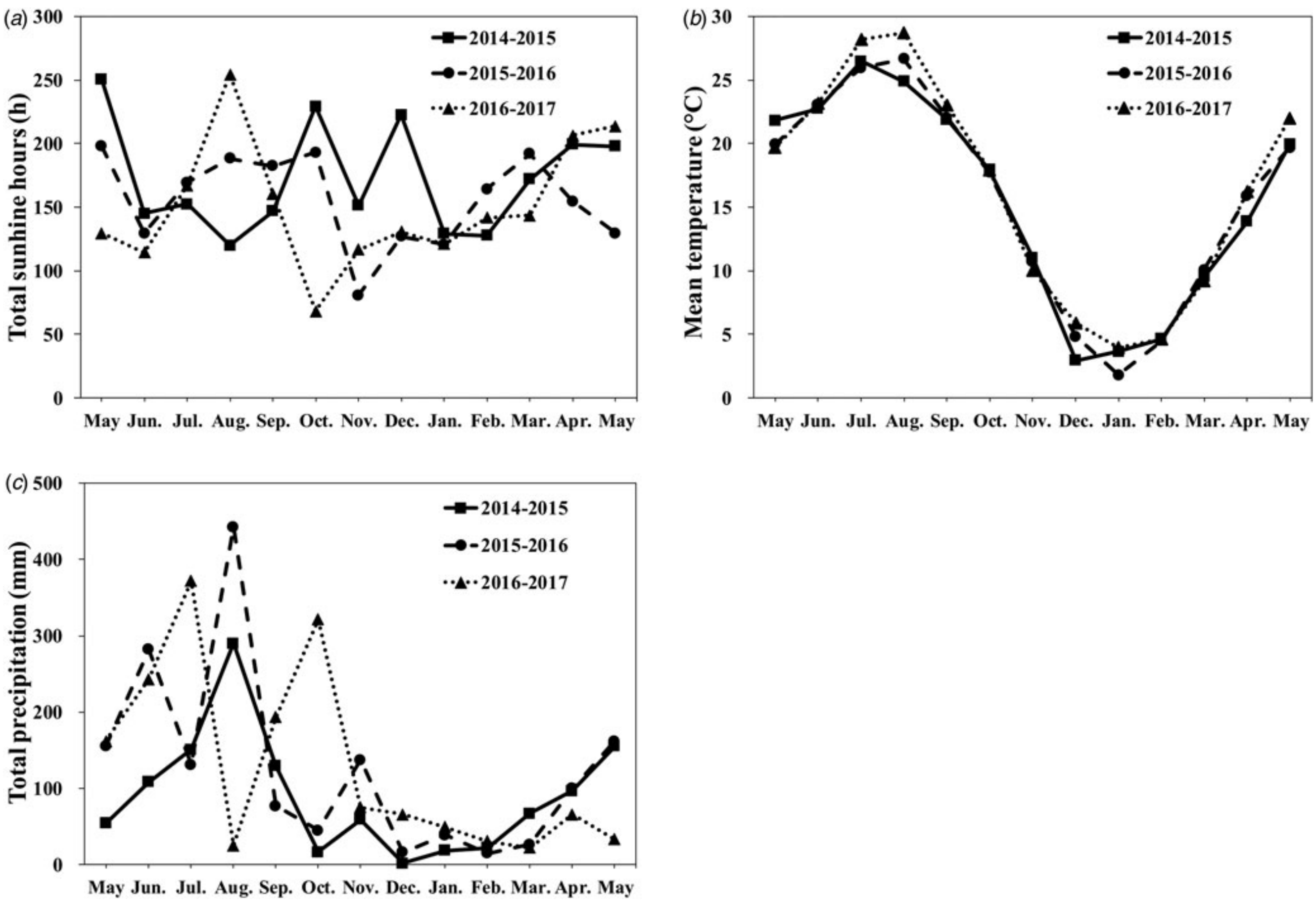

Fig. 1. Total sunshine hours (A), mean temperature (B) and total precipitation per month (C) of the experimental years from 2014 to 2017.

shorter growth duration, smaller panicles and lower lodging resistance, reducing crop yield; further, the wheat crop is sown late and has reduced growth duration and yield (Xing *et al*., 2017*a*, 2017*b*; Du *et al*., 2021; Zhang *et al*., 2021). Therefore, selecting effective planting methods is crucial to increase annual rice yield in rice–wheat cropping systems. However, few studies compared annual crop production and yield across rice planting patterns in these systems.

Previous studies have shown that annual crop yield can be improved by selecting appropriate rice and wheat varieties, adjusting the sowing date, and using new plowing and sowing techniques, fertilizers and water management systems (Timsina and Connor, 2001; Liu *et al*., 2003, 2021; Gong *et al*., 2011; Duncan *et al*., 2020; Xi *et al*., 2020). Yang *et al*. (2008) and Li *et al*. (2012) introduced cultivation approaches and key techniques for obtaining high-yield rice and wheat (annual grain yield >21 t/ha) in the Yangtze river basin. The results showed that efficient solar energy utilization increased annual grain yield (Ladha *et al*., 2003; Nagai and Makino, 2009; Xing *et al*., 2017*b*; Zhou *et al*., 2020*a*, 2020*b*). Thus, innovative cultivation technologies can prolong crop growth duration and improve plant development. The cultivation and transplanting of rice seedlings can improve solar energy utilization before wheat harvest, prolong rice growth duration, increase crop yield and quality and mature safely in rice–wheat cropping systems. Several innovative seedling cultivation methods have been used to prolong seedling age and improve natural resource utilization before wheat harvest in rice–wheat cropping systems, including pot seedling transplanting, carpet seedling transplanting and seedling throwing (Xing *et al*., 2017*b*; Liu *et al*., 2019). Previous studies assessed the effects of mechanized planting and integrated high-yield cultivation techniques on rice production in rice–wheat cropping systems (San-oh *et al*., 2004; Hayashi *et al*., 2007; Liu *et al*., 2015; Xing *et al*., 2017*a*). However, little is known about the influence of mechanized rice planting patterns on wheat sown after rice, rice–wheat cropping systems and solar radiation use efficiency (RUE).

This study analysed rice and wheat crop yield and solar thermal utilization among mechanized planting patterns in a rice–wheat cropping system in the Yangtze river basin. These data can help increase annual crop yield and resource utilization in this cropping system.

Materials and methods

Experimental site and weather conditions

Field experiments were conducted from 2014 to 2017 in a rice–wheat cropping system at Diaoyu town (33°05′N, 119°58′E, 2.5 m a.s.l.) in the Yangtze Huai valley, China. Data on total sunshine hours, mean temperature and total precipitation per month were collected from a weather station situated close to the experimental site (Fig. 1). The soil was sandy loam with the following characteristics: organic matter, 27.2 g/kg; total nitrogen, 1.8 g/kg; available phosphorus, 13.9 mg/kg and exchangeable potassium, 152.8 mg/kg.

Experimental design

Inbred *japonica* super rice variety Wuyunjing 24 and vernal wheat variety Yangmai 23 were used in rice and wheat growth seasons, respectively. Three treatments were adopted: pot seedling transplanting for rice and row sowing for wheat (PST-RS), carpet seedling transplanting for rice and row sowing for wheat (CST-RS) and row sowing for both crops (RS-RS). A randomized block design was used with three repetitions, and the plots (8 m × 12 m) were separated by soil mounds 50 cm wide containing plastic film up to a depth of 0.50 m to prevent water and fertilizer exchange across plots.

In the wheat–rice rotation season, wheat is harvested before 10 June, and rice is sown or transplanted at the test site. Accordingly, 13 and 15 June were considered the sowing date and transplanting date for direct seeding and transplanting of rice in the three experimental years. In the rice–wheat rotation season, 7 days of farm work are necessary before wheat sowing because of high soil moisture, rainfall and other conditions. Thus, wheat was sown 7 days after the rice harvest in the three experimental years. Moreover, high-yield cultivation methods were used.

For PST-RS, rice seedlings were cultivated in pot seedling nursery trays. Germinated seeds were sown on 16 May in the three experimental years, with 60 g of seeds per tray. Three seedlings were left in each pot at the one-leaf stage. Seedlings were transplanted using a seedling transplanter on 15 June at a hill spacing of $12.0 \times 33.0\ cm^2$. Seven days after harvest, wheat was sown using a drill seeder at a row spacing of 30 cm on 2 November 2014, 30 October 2015 and 2 November 2016. The number of seedlings was reduced to 300×10^4 per ha at the two-leaf stage.

For CST-RS, rice seedlings were planted in carpet seedling nursing trays. Germinated seeds were sown on 28 May in the three experimental years, with 110 g of seeds per tray. Seedlings were transplanted at a hill spacing of $12.0 \times 30.0\ cm^2$ using a seedling transplanter on 15 June, with three seedlings per hill. Seven days after harvest, wheat was sown using a drill seeder at a row spacing of 30 cm on 8 November 2014, 6 November 2015 and 10 November 2016. The number of seedlings was reduced to 375×10^4 per ha at the two-leaf stage.

For RS-RS, germinated seeds were sown using a drill seeder at a row spacing of 30 cm on 13 June in the three experimental years. The number of seedlings was reduced to 90×10^4 per ha at the one-leaf stage. Seven days after harvest, wheat was sown using a drill seeder at a row spacing of 30 cm on 15 November 2014, 14 November 2015 and 20 November 2016. The number of seedlings was reduced to 450×10^4 per ha at the two-leaf stage.

During the rice growing season in the three experimental years, 270 kg/ha nitrogen was applied as urea, of which 30, 30, 20 and 20% was applied before transplanting (in PST-RS and CST-RS) or sowing (in RS-RS), initial tillering stage, stem elongation stage and penultimate leaf elongation stage, respectively. In addition, 135 kg/ha P_2O_5 (as calcium superphosphate) and 162 kg/ha K_2O (as potassium chloride) were applied before transplanting (in PST-RS and CST-RS) or sowing (in RS-RS). During the wheat growing season in the three experimental years, 120 kg/ha N, 120 kg/ha P_2O_5 and 120 kg/ha K_2O were applied as compound fertilizers before sowing. In addition, 120 kg/ha N was applied as urea in two splits: 20% at the tillering stage and 80% at the stem elongation stage.

The rice plots in PST-RS and CST-RS were flooded with 1–2 cm of water during transplanting. In RS-RS, intermittent irrigation was performed after sowing to promote seedling emergence. All rice plots were flooded with 2–3 cm water at the tillering stage. When the number of main stems and tiller nodes was approximately 80% of prospective panicles, water was drained to control tillering. After the stem elongation stage, alternate wetting and moderate soil irrigation management were used in each plot until 1 week before the final harvest. Irrigation management was not required in the wheat season, and a set of water drainage ditches was made in each plot for water draining. Other field practices (the control of weeds, insects and diseases) conformed to local requirements.

Sampling and measurements

Meteorological data collection

Data on temperature, sunshine hours and precipitation were collected from a full-automatic meteorological station located near the test field.

Leaf area index (LAI)

Rice green leaf area was measured at the transplanting, middle tillering, stem elongation, booting, heading, milk and maturity stages. Five representative holes of transplanted rice plants and 15 representative samples of direct-seeded rice plants were sampled from each plot. Wheat green leaf area was measured at overwintering (28 December), returning green (20 February), stem elongation, booting, flowering, grain filling (25 days after flowering) and maturity stages. The 100 representative wheat plants at overwintering, returning green and stem elongation stages, and 100 representative individual wheat stems at other stages were sampled from five sites in each plot. The green leaf area was measured with a leaf area meter (LI-3100, LI-COR, USA) to calculate the LAI. The mean leaf area index (MLAI) was calculated using Eqns (1) and (2) (Hirooka *et al.*, 2016):

$$\begin{aligned}\mathrm{MRLAI} &= \int_{t_1}^{t_2}\left(\frac{a+bx}{1+cx+\mathrm{d}x^2}\right)\\ &= \frac{b}{2d}\ln\left(x^2+\frac{c}{d}x+\frac{1}{d}\right)\\ &\quad+\frac{2ad-bc}{d\sqrt{4d-c^2}}\arctan\frac{2dx+c}{\sqrt{4d-c^2}}\end{aligned} \tag{1}$$

$$\mathrm{MLAI} = \mathrm{MRLAI} \times \mathrm{LAI}_{max} \tag{2}$$

where MRLAI is the average relative LAI of the whole growth period, and LAI_{max} is the LAI at the booting stage.

Aboveground biomass and grain yield

Five representative holes of transplanted rice plants, 15 representative samples of direct-seeded rice plants and 100 representative wheat stems from five sites were sampled from each plot to determine the aboveground biomass at the maturity stage. All samples were oven-dried at 80°C to a constant weight and weighed.

All rice or wheat plants in an area of $10\ m^2$ at the centre of each plot were hand-harvested, and grain yield was calculated. The final yield of rice and wheat crops was adjusted to 14 and 13% moisture content, respectively. The number of rice panicles and wheat spikes per hectare was determined from three representative $1\ m^2$ plots. The plants were randomly sampled at the centre

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Table 1. Main growth stage date and growth duration of rice and wheat from 2014 to 2017

	Sowing-transplanting-heading/flowering-maturity date (month/day)		Growth duration (days)		
Year/pattern	Rice	Wheat	Rice	Wheat	OP
2014–15					
PST-RS	5/16-6/15-9/4-10/26	11/2-4/21-6/4	163	214	19
CST-RS	5/28-6/15-9/9-11/1	11/8-4/24-6/4	157	208	7
RS-RS	6/13-9/16-11/8	11/15-4/28-6/6	148	203	
2015–16					
PST-RS	5/16-6/15-9/3-10/23	10/30-4/20-6/6	160	220	21
CST-RS	5/28-6/15-9/7-10/30	11/6-4/23-6/6	155	213	9
RS-RS	6/13-9/14-11/7	11/14-4/29-6/9	147	208	
2016–17					
PST-RS	5/16-6/15-8/31-10/26	11/2-4/22-6/2	163	212	17
CST-RS	5/28-6/15-9/5-11/3	11/10-4/25-6/2	160	204	5
RS-RS	6/13-9/11-11/13	11/20-4/30-6/4	153	196	

PST-RS, pot seedling transplanting for rice and row sowing for wheat; CST-RS, carpet seedling transplanting for rice and row sowing for wheat; RS-RS, row sowing for both crops; OP, overlapping period.

of each plot. The number of spikelets per panicle, number of filled grains, 1000-grain weight of rice, number of kernels per spike and 1000-grain weight of wheat were measured from two representative two-rows in 0.5 m at the centre of each plot.

The harvest index was the ratio of dry grain weight to aboveground biomass dry weight.

Effect of temperature and solar radiation on crop productivity

The effective accumulated temperature (EAT) and temperature production efficiency (TPE) in the growth period were calculated using Eqns of (3) and (4), respectively:

$$\text{EAT}\,(^{\circ}\text{C days}) = \sum (T - T_0) \times \text{growth duration} \quad (3)$$

$$\text{TPE}\,(\text{kg}/(\text{ha}\,^{\circ}\text{C})) = \text{grain yield}/\text{EAT} \quad (4)$$

where T and T_0 (10°C for rice and 0°C for wheat) are the mean daily temperature and biological zero temperature, respectively.

The cumulative solar radiation (CSR) and solar radiation production efficiency (SPE) in the growth period were calculated using Eqns (5), (6) and (7):

$$\text{CSR}\,(\text{MJ/m}^2) = \sum Q \times \text{growth duration} \quad (5)$$

$$\text{SPE}\,(\text{kg}/(\text{ha MJ})) = \text{grain yield}/\text{CSR} \quad (6)$$

$$Q(\text{MJ}/(\text{m}^2\,\text{d})) = Q_0(a + b \times S/S_0) \quad (7)$$

where Q_0 (MJ/(m^2 d)) is the extra-terrestrial radiation, S is the actual daily sunshine hours and S_0 is the potential daily sunshine hours. The coefficients a and b were measured at the local meteorological station. The calculations were described by Wang *et al.* (2015) and Mohammadi *et al.* (2016).

Solar RUE

RUE was expressed as % and was calculated using Eqn (8):

$$\text{RUE} = \left[\Delta W \times H/\left(\sum Q \times \text{growth duration}\right)\right] \times 100\% \quad (8)$$

where ΔW (t/ha) is the grain yield or aboveground biomass and H is the energy released by the complete combustion of dry matter per g (1.680×10^{-2} and 1.747×10^{-2} MJ/g for rice and wheat, respectively) (Gong *et al.*, 2014).

Statistical analysis

Data were analysed using SPSS version 20.0. A significance level of 5% was used in the statistics by the least significant difference test. The significance of differences between means was determined by one-way analyses of variance and Duncan's multiple range test. The P-values smaller than 0.05 were considered statistically significant.

Results

Growth stage and duration

Rice sowing was performed 12 days earlier in PST-RS than in CST-RS (Table 1). Compared with RS-RS, rice heading dates were 11–12 and 6–7 days earlier, and maturity dates were 13–18 and 7–10 days earlier in PST-RS and CST-RS, respectively. Compared with PST-RS, wheat flowering occurred 3 and 8 days later in CST-RS and RS-RS, respectively. Wheat maturity was delayed by 2–3 days in RS-RS.

Compared with PST-RS, rice growth duration was 3–6 days shorter in CST-RS and 10–15 days shorter in RS-RS, and wheat growth duration was 6–8 days shorter in CST-RS and 11–16

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Table 2. EAT and CSR in rice and wheat durations from 2014 to 2017

Year/pattern	EAT (°C days)		CSR (MJ/m^2)	
	Rice (nursery + field periods)	Wheat	Rice (nursery + field periods)	Wheat
2014–15				
PST-RS	423 + 1771 a	2096 a	563 + 1818 a	2563 a
CST-RS	261 + 1806 b	2024 b	328 + 1852 b	2501 b
RS-RS	1857 c	2004 b	1954 c	2481 b
2015–16				
PST-RS	387 + 1788 a	2257 a	521 + 1892 a	2369 a
CST-RS	259 + 1823 b	2152 b	300 + 1954 b	2310 b
RS-RS	1898 c	2119 b	2050 c	2298 b
2016–17				
PST-RS	336 + 2028 a	2416 a	398 + 1892 a	2268 a
CST-RS	216 + 2046 b	2355 b	228 + 1965 b	2168 b
RS-RS	2105 c	2322 b	2066 c	2074 c
ANOVA				
Year (Y)	3554**	6180**	166**	1290**
Pattern (P)	5841**	734**	3696**	148**
Y × P	39**	17**	116**	17**

PST-RS, pot seedling transplanting for rice and row sowing for wheat; CST-RS, carpet seedling transplanting for rice and row sowing for wheat; RS-RS, row sowing for both crops; ANOVA, analysis of variance.
Note: Different small letters show significant difference at the 0.05 level; ** show significant difference at the 0.01 level.

days shorter in RS-RS (Table 1). In addition, rice–wheat growth duration was 375–380, 364–368 and 349–355 days in PST-RS, CST-RS and RS-RS, with an overlap of 17–21 and 5–9 days in PST-RS and CST-RS, respectively.

EAT and CSR

EAT and CSR in rice or wheat tended to decrease in the order PST-RS > CST-RS > RS-RS (Table 2). Differences in EAT and CSR in rice crops varied significantly among treatments. Compared with RS-RS, EAT in rice and wheat was 291 and 108°C days more in PST-RS and 184 and 29°C days more in CST-RS, respectively. CSR in rice and wheat was 338 and 116 MJ/m^2 higher in PST-RS than in RS-RS and 186 and 42 MJ/m^2 higher in CST-RS than in RS-RS, respectively.

Grain yield and yield components

Compared with RS-RS, PST-RS increased rice and wheat yield by 2.2 and 1.2 t/ha, while CST-RS increased rice and wheat yield by 1.5 and 0.8 t/ha, respectively (Table 3). Compared with RS-RS, annual grain yield was 3.4 and 2.2 t/ha higher in PST-RS and CST-RS, respectively. There were no significant differences in the 1000-grain weight of rice and wheat among treatments. The percentage of filled rice and wheat grains was lower in RS-RS than in CST-RS and PST-RS.

The number of spikelets/kernels per hectare of rice and wheat was 8290/2910 × 10^4 and 4874/2037 × 10^4 lower in RS-RS than in PST-RS and CST-RS, respectively. The number of panicles/spikes per hectare and spikelets/kernels per panicle/spike tended to decrease in the order RS-RS > CST-RS > PST-RS and PST-RS > CST-RS > RS-RS, respectively. The number of rice spikelets per panicle was 32.7 and 18.3 higher in PST-RS and CST-RS than in RS-RS, respectively, while the number of rice panicles per hectare was 21.3 × 10^4 and 12.7 × 10^4 lower in PST-RS and CST-RS than in RS-RS, respectively. PST-RS and CST-RS decreased the number of wheat spikes per hectare by 41 × 10^4 and 11 × 10^4 and increased the number of kernels per spike by 9 and 5, respectively, compared with RS-RS.

Grain yield per day and aboveground biomass

The rice, wheat and annual grain yield per day decreased in the order PST-RS > CST-RS > RS-RS (Table 4). Compared with RS-RS, PST-RS increased the rice, wheat and annual grain yield per day by approximately 0.9, 0.4 and 0.9 g/(m^2 d), while CST-RS increased these yields by 0.6, 0.3 and 0.6 g/(m^2 d), respectively. Differences in these yields were significant between PST-RS and RS-RS.

Compared with RS-RS, the rice, wheat and annual aboveground biomass was approximately 3.4, 2.3 and 5.6 t/ha higher in PST-RS, and approximately 2.3, 1.5 and 3.8 t/ha higher in CST-RS, respectively (Table 4). The harvest indexes (3-year averages) were higher in PST-RS (0.498 for rice and 0.374 for wheat) and CST-RS (0.491 for rice and 0.370 for wheat) than in RS-RS (0.483 for rice and 0.362 for wheat).

LAI and grain–leaf ratio

The MLAI and LAI at the heading/flowering stage decreased in the order PST-RS > CST-RS > RS-RS (Table 5). Compared with RS-RS, the MLAIs of rice and wheat increased by approximately 0.78 and 0.32 in PST-RS and approximately 0.53 and 0.25 in CST-RS, respectively. The LAIs at the heading/flowering stage of rice and wheat were approximately 0.53 and 0.42 higher in PST-RS and approximately 0.30 and 0.26 higher in CST-RS than in RS-RS, respectively.

Compared with RS-RS, the number of spikelets and grains and grain weight per LAI at the booting stage of rice increased by 0.073 spikelet/cm^2, 0.080 grain/cm^2 and 2.1 mg/cm^2 in PST-RS and by 0.048 spikelet/cm^2, 0.057 grain/cm^2 and 1.5 mg/cm^2 in CST-RS, respectively. Compared with RS-RS, the number of grains and grain weight per LAI at the booting stage of wheat were 0.024 grain/cm^2 and 1.0 mg/cm^2 higher in PST-RS and 0.020 grain/cm^2 and 0.8 mg/cm^2 higher in CST-RS, respectively (Table 5).

TPE and SPE

Compared with RS-RS, PST-RS increased the rice, wheat and annual TPE by approximately 0.36, 0.38 and 0.42 kg/(ha °C), while CST-RS increased these parameters by approximately 0.26, 0.31 and 0.33 kg/(ha °C), respectively (Table 6). There were no significant differences in the SPE of rice among the three treatments in 2014–15 and 2015–16. In turn, in 2016–17, the SPE of rice was 0.73 and 0.60 kg ha/MJ higher in PST-RS and CST-RS, respectively, than in RS-RS. In addition, the SPE of wheat and annual increased by approximately 0.36 and 0.38 kg ha/MJ in PST-RS and by 0.28 and 0.32 kg ha/MJ in CST-RS, respectively, compared with RS-RS.

RUE

The annual RUE of rice grain and biomass decreased in the order PST-RS > CST-RS > RS-RS (Table 7). Compared with RS-RS, the

Table 3. Grain yield and yield components of rice and wheat from 2014 to 2017

Crop/year	Pattern	Grain yield (t/ha)	Panicles/spikes per ha ($\times 10^4$)	Spikelets/kernels per panicle/spike	Spikelets/kernels per ha ($\times 10^4$)	Filled grain (%)	1000-grain weight (g)
Rice							
2014–15	PST-RS	11.37 a	322 c	146 a	46 924 a	92.5 a	27.2 a
	CST-RS	10.58 b	334 b	130 b	43 462 b	92.9 a	27.3 a
	RS-RS	9.36 c	350 a	112 c	39 190 c	89.4 b	27.9 a
2015–16	PST-RS	11.72 a	325 b	147 a	47 711 a	92.6 a	27.5 a
	CST-RS	10.98 b	331 b	134 b	44 445 b	93.3 a	27.5 a
	RS-RS	9.69 c	339 a	119 c	40 165 c	90.2 b	27.9 a
2016–17	PST-RS	11.59 a	334 c	144 a	48 095 a	91.2 a	27.3 a
	CST-RS	10.81 b	342 b	130 b	44 576 b	91.0 a	27.5 a
	RS-RS	8.94 c	356 a	108 c	38 505 c	89.7 a	27.1 a
ANOVA							
Year (Y)		13**	44**	11**	NS	14**	6*
Method (M)		388**	126**	329**	244**	58**	5*
Y × M		5*	5*	NS	NS	4*	5*
Wheat							
2014–15	PST-RS	6.77 a	470 b	40.6 a	19 088 a		37.8 a
	CST-RS	6.38 a	496 a	36.8 b	18 252 a		37.4 a
	RS-RS	5.64 b	504 a	32.4 c	16 299 b		37.0 a
2015–16	PST-RS	7.28 a	506 a	40.0 a	20 277 a		38.0 a
	CST-RS	6.82 a	529 a	36.1 b	19 088 b		37.7 a
	RS-RS	6.05 b	535 a	31.7 c	16 926 c		37.6 a
2016–17	PST-RS	6.20 a	421 b	42.0 a	17 669 a		37.9 a
	CST-RS	5.87 a	461 a	37.0 b	17 075 a		37.7 a
	RS-RS	5.10 b	481 a	31.4 c	15 077 b		37.5 a
ANOVA							
Year (Y)		41**	60**	NS	26**		NS
Pattern (P)		56**	22**	106**	49**		NS
Y × P		NS	NS	NS	NS		NS

PST-RS, pot seedling transplanting for rice and row sowing for wheat; CST-RS, carpet seedling transplanting for rice and row sowing for wheat; RS-RS, row sowing for both crops; ANOVA, analysis of variance.

Note: Different small letters and * show significant difference at the 0.05 level; ** show significant difference at the 0.01 level; NS meant not significant.

annual RUE of grain and biomass was 0.12 and 0.20% higher in PST-RS and 0.08 and 0.13% higher in CST-RS, respectively. In 2016–17, the RUE of rice grain and biomass was 0.12 and 0.17% higher in PST-RS and 0.10 and 0.15% higher in CST-RS, respectively, than in RS-RS. Similarly, the RUE of wheat grain and biomass was 0.063 and 0.113% higher in PST-RS and 0.050 and 0.097% higher in CST-RS on average of three experimental years, respectively, than in RS-RS.

Discussion

Crop yield and solar energy utilization efficiency

Several studies evaluated strategies to increase annual grain yield and solar energy utilization in multiple cropping systems. For instance, Zhou *et al.* (2015) found that increasing solar energy conversion efficiency and dry matter production of maize by adjusting the sowing and harvest time of winter wheat and summer corn and using a double corn cropping cultivation system increased grain production in the Huang-Huai-Hai plain. Li *et al.* (2015) found that replacing early rice with maize with high photosynthetic efficiency increased the efficiency of utilization of environmental resources, economic benefits and the diversity of planting patterns in the Yangtze river basin. Gong *et al.* (2011) proposed that a 'late-ripening rice-late-sown wheat' cultivation system and delaying rice–wheat rotation time improved the annual yield of rice and wheat in the Yangtze river basin. Yang *et al.* (2008) reported that increasing sink size and strength, coordinating the source–sink relationship and increasing dry matter production were key approaches to obtaining super high-yielding rice and wheat in the Yangtze river basin. Therefore, changing the crop sowing date to increase resource utilization

Table 4. Rice, wheat and annual grain yield per day and aboveground biomass from 2014 to 2017

Year/pattern	Grain yield per day (g/(m^2 d))			Aboveground biomass (t/ha)		
	Rice	Wheat	Annual	Rice	Wheat	Annual
2014–15						
PST-RS	6.97 a	3.17 a	4.97 a	19.64 a	15.57 a	35.21 a
CST-RS	6.74 b	3.07 a	4.65 b	18.52 b	14.83 a	33.35 b
RS-RS	6.33 c	2.78 b	4.11 c	16.70 c	13.55 b	30.25 c
2015–16						
PST-RS	7.33 a	3.31 a	5.19 a	20.11 a	16.67 a	36.77 a
CST-RS	7.08 b	3.20 a	4.86 b	19.10 b	15.73 a	34.83 b
RS-RS	6.59 c	2.91 b	4.30 c	17.05 c	14.16 b	31.22 c
2016–17						
PST-RS	7.10 a	2.92 a	4.87 a	20.18 a	14.79 a	34.97 a
CST-RS	6.77 a	2.88 ab	4.57 a	19.04 b	14.21 a	33.25 b
RS-RS	5.83 b	2.60 b	3.85 b	16.07 c	12.57 b	28.64 c
ANOVA						
Year (Y)	38**	20**	36	6*	29**	30**
Pattern (P)	154**	27**	27	350**	55**	244**
Y × P	8**	NS	NS	5*	NS	NS

PST-RS, pot seedling transplanting for rice and row sowing for wheat; CST-RS, carpet seedling transplanting for rice and row sowing for wheat; RS-RS, row sowing for both crops; ANOVA, analysis of variance.

Note: Annual grain yield per day = (rice yield + wheat yield)/number of days in a year; annual aboveground biomass was the sum of rice aboveground biomass and wheat aboveground biomass.

Different small letters and * show significant difference at the 0.05 level; ** show significant difference at the 0.01 level; NS meant not significant.

efficiency, selecting suitable plant varieties to coordinate crop growth duration and using appropriate cultivation techniques to optimize heading and maturity time increase crop yield (Xing *et al.*, 2017*b*; Xi *et al.*, 2020; Zhang *et al.*, 2021). As crop yield and solar energy utilization are positively correlated (Deng *et al.*, 2015; Xing *et al.*, 2017*b*; Zhou *et al.*, 2020*a*, 2020*b*), annual crop yield, EAT, CSR, TPE and RUE tended to decrease in the order PST-RS > CST-RS > RS-RS because, compared with RS-RS, the crops in PST-RS and CST-RS presented longer growth duration, larger sink, higher photosynthetic capacity and higher aboveground biomass accumulation of rice and wheat (Xing *et al.*, 2017*a*). This result is because the 18-day carpet seedling, 30-day pot seedling and their matching transplanting patterns and high-yield cultivation techniques in CST-RS and PST-RS could shift the sowing date of rice and wheat to an earlier time, increasing natural resource utilization efficiency and crop yield in a rice–wheat cropping system in the Yangtze river basin (Zhang and Gong, 2014; Xing *et al.*, 2017*b*). However, crop yield decreased in the order PST-RS > CST-RS > RS-RS, indicating that long-term higher yield output would inevitably lead to more barren soil. Thus, measures to improve soil fertility should be implemented more widely and efficiently in PST-RS than in CST-RS and RS-RS.

Growth duration

A longer growth duration is significantly correlated with a higher grain yield when the crop can be seeded on a suitable date and mature safely (Zhang *et al.*, 2013; Chen *et al.*, 2018). In a rice–wheat cropping system, the selection and high-yield planting of rice and wheat varieties, planting patterns, nitrogen and water management and more efficient farming operations prolonged rice–wheat growth duration, improved natural resource utilization efficiency and increased grain yield (Zhang *et al.*, 2013; Xing *et al.*, 2017*b*; Liu *et al.*, 2020). Planting pattern selection was a key strategy to maximize crop growth and prolong growth duration. Selecting different rice planting patterns in PST-RS, CST-RS and RS-RS induced significant differences in rice–wheat growth duration and grain yield. Compared with RS-RS, PST-RS and CST-RS prolonged growth duration by approximately 26 days for rice and 14 days for wheat, reduced rice and wheat field growth period by 17 and 10 days, and increased annual crop yield by 3.4 and 2.2 t/ha, respectively. Thus, seedling nursing increased rice and wheat growth, improved solar energy utilization, increased annual crop yield and freed time for farming in the wheat to rice season and even in rice to wheat season. In addition, rice sowing was performed 12 days earlier in PST-RS than in CST-RS, and the transplanted seedlings in PST-RS were more vigorous and resistant than those in CST-RS. The three rice planting patterns adjusted the growth stage of rice and wheat. The rice heading stage and wheat flowering and maturity stages occurred earlier in PST-RS and CST-RS than in RS-RS. Therefore, longer growth duration and earlier growth stages increased grain yield in transplanted rice compared with direct-seeded rice. Thus, selecting a seedling method with long rice seedling age and adequate planting technology, such as PST-RS or CST-RS, can increase crop yield in a rice–wheat cropping system. The presence of rain in early November could make the soil unsuitable for mechanical farming. For this reason, the wheat sowing date was postponed, and wheat yield was decreased. Thus, a transplanting

Table 5. MLAI, LAI at heading/flowering stage and grain–leaf ratio of rice and wheat from 2014 to 2017

Crop/year	Pattern	MLAI	LAI at Heading/ flowering stage	Grain–leaf ratio		
				Spikelets per LAI at booting stage (spikelet/cm^2)	Grains per LAI at booting stage (grain/cm^2)	Grain weight per LAI at booting stage (mg/cm^2)
Rice						
2014–15	PST-RS	4.40 a	7.69 a	0.593 a	0.549 a	14.4 a
	CST-RS	4.20 a	7.45 b	0.567 b	0.526 b	13.8 b
	RS-RS	3.68 b	7.12 c	0.529 c	0.473 c	12.6 c
2015–16	PST-RS	4.61 a	7.77 a	0.596 a	0.552 a	14.6 a
	CST-RS	4.29 b	7.56 a	0.574 b	0.535 b	14.2 b
	RS-RS	3.78 c	7.27 b	0.535 c	0.482 c	12.9 c
2016–17	PST-RS	4.63 a	7.84 a	0.590 a	0.538 a	14.2 a
	CST-RS	4.40 a	7.59 b	0.561 a	0.510 a	13.6 a
	RS-RS	3.84 b	7.31 c	0.495 b	0.444 b	11.5 b
ANOVA						
Year (Y)		23**	9**	6*	13**	17**
Method (M)		368**	94**	80**	128**	121**
Y × M		NS	NS	NS	NS	NS
Wheat						
2014–15	PST-RS	2.79 a	5.64 a		0.266 a	9.4 a
	CST-RS	2.74 a	5.45 ab		0.264 a	9.2 ab
	RS-RS	2.48 b	5.19 b		0.246 a	8.5 b
2015–16	PST-RS	2.74 a	5.42 a		0.294 a	10.6 a
	CST-RS	2.65 a	5.26 b		0.289 a	10.3 ab
	RS-RS	2.38 b	5.05 c		0.265 b	9.5 b
2016–17	PST-RS	2.67 a	5.50 a		0.267 a	9.3 a
	CST-RS	2.61 a	5.38 a		0.262 a	9.0 ab
	RS-RS	2.39 b	5.06 b		0.244 b	8.2 b
ANOVA						
Year (Y)		9**	7**		21**	27**
Pattern (P)		79**	38**		18**	17**
Y × P		NS	NS		NS	NS

PST-RS, pot seedling transplanting for rice and row sowing for wheat; CST-RS, carpet seedling transplanting for rice and row sowing for wheat; RS-RS, row sowing for both crops; LAI, leaf area index; MLAI, mean leaf area index; ANOVA, analysis of variance.
Note: Different small letters and * show significant difference at the 0.05 level; ** show significant difference at the 0.01 level; NS meant not significant.

method with early harvesting of paddy can prolong the time for wheat sowing.

Sink

Sink size is positively correlated with rice and wheat yield. Sink size can be increased by increasing the number of panicles/spikes per hectare and increasing the number of spikelets/kernels per panicle/spike using high-yield plant varieties and cultivation technologies (Yang *et al*., 2008; Liu *et al*., 2020). Rice transplanting was associated with a higher number of spikelets/kernels per hectare and a larger sink size than MDS (Yang *et al*., 2008; Zhang and Gong, 2014). Compared with RS-RS, PST-RS and CST-RS decreased the number of rice panicles per hectare by 21.3×10^4 and 12.7×10^4 and increased the number of spikelets per panicle by 32.7 and 18.3, respectively. Further, compared with RS-RS, PST-RS and CST-RS decreased the number of wheat spikes per hectare by 41.0×10^4 and 11.3×10^4 and increased the number of kernels per spike by 9 and 5 in wheat, respectively. The earlier rice sowing date, stronger seedlings, smaller number of seedlings at the initial growth stage in the field, longer vegetative growth duration and lower number of ineffective tillers in rice transplanting decreased the number of panicles per hectare, increased the number of spikelets per panicle and increased the sink size of rice, consequently increasing rice yield. The earlier wheat sowing date, lower number of seedlings at the initial growth stage in the

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Table 6. Rice, wheat and annual TPE and SPE from 2014 to 2017

Year/pattern	TPE (kg/(ha °C))			SPE (kg ha/MJ)		
	Rice	Wheat	Annual	Rice	Wheat	Annual
2014–15						
PST-RS	5.18 a	3.23 a	4.23 a	4.77 a	2.64 a	3.67 a
CST-RS	5.12 ab	3.15 a	4.15 a	4.86 a	2.55 a	3.62 a
RS-RS	5.04 b	2.82 b	3.89 b	4.79 a	2.27 b	3.38 b
2015–16						
PST-RS	5.39 a	3.23 a	4.29 a	4.86 a	3.07 a	3.97 a
CST-RS	5.27 b	3.17 a	4.20 a	4.87 a	2.95 a	3.90 a
RS-RS	5.11 c	2.85 b	3.92 b	4.73 a	2.63 b	3.62 b
2016–17						
PST-RS	4.90 a	2.56 a	3.72 a	5.06 a	2.73 a	3.90 a
CST-RS	4.78 a	2.49 a	3.61 a	4.93 a	2.71 a	3.83 a
RS-RS	4.25 b	2.20 b	3.17 b	4.33 b	2.46 b	3.39 b
ANOVA						
Year (Y)	156**	118**	291**	NS	34**	45**
Pattern (P)	52**	35**	114**	35**	31**	101**
Y × M	11**	NS	NS	19**	NS	3*

PST-RS, pot seedling transplanting for rice and row sowing for wheat; CST-RS, carpet seedling transplanting for rice and row sowing for wheat; RS-RS, row sowing for both crops; ANOVA, analysis of variance.
Note: Different small letters and * show significant difference at the 0.05 level; ** show significant difference at the 0.01 level; NS meant not significant.

Table 7. Rice, wheat and annual solar RUE from 2014 to 2017

Year/pattern	Solar RUE of grain (%)			Solar RUE of biomass (%)		
	Rice	Wheat	Annual	Rice	Wheat	Annual
2014–15						
PST-RS	0.80 a	0.46 a	0.67 a	1.39 a	1.06 a	1.30 a
CST-RS	0.82 a	0.45 a	0.63 b	1.43 a	1.04 a	1.23 b
RS-RS	0.81 a	0.40 b	0.55 c	1.44 a	0.95 b	1.12 c
2015–16						
PST-RS	0.82 a	0.54 a	0.71 a	1.40 a	1.23 a	1.38 a
CST-RS	0.82 a	0.52 a	0.67 b	1.42 a	1.19 a	1.32 b
RS-RS	0.79 a	0.46 b	0.60 c	1.40 a	1.08 b	1.20 c
2016–17						
PST-RS	0.85 a	0.48 a	0.66 a	1.48 a	1.14 a	1.31 a
CST-RS	0.83 a	0.47 a	0.62 b	1.46 a	1.15 a	1.24 b
RS-RS	0.73 b	0.43 a	0.52 c	1.31 b	1.06 b	1.07 c
ANOVA						
Year (Y)	NS	34**	84**	NS	41**	63**
Pattern (P)	35**	31**	319**	18**	27**	247**
Y × P	20**	NS	NS	26**	NS	NS

PST-RS, pot seedling transplanting for rice and row sowing for wheat; CST-RS, carpet seedling transplanting for rice and row sowing for wheat; RS-RS, row sowing for both crops; ANOVA, analysis of variance.
Note: Different small letters show significant difference at the 0.05 level; ** show significant difference at the 0.01 level; NS meant not significant.

field, higher accumulated temperature and stouter seedlings wheat seedlings at the overwintering stage increased the sink size and crop yield in PST-RS and CST-RS.

Biomass production and accumulation

Aboveground biomass is positively associated with rice and wheat yield as the harvest index reaches a plateau (Ponti *et al.*, 2012; Deng *et al.*, 2019). Aboveground biomass and daily rice and wheat yield were higher in PST-RS and CST-RS than in RS-RS, which were correlated with higher LAI at the heading stage and higher MLAI during the growth period, increasing the photosynthetic area and prolonging the effective time of photosynthesis (Sun *et al.*, 2007; Zhou *et al.*, 2015). The earlier sowing date, improved rice seedling quality, wide row spacing and narrow plant spacing in rice cultivation, and longer wheat growth before overwintering can improve the microclimate and increase photosynthetic efficiency and biomass accumulation in PST-RS and CST-RS compared with RS-RS. In addition, the grain–leaf ratio of rice and wheat was higher in PST-RS and CST-RS, increasing photosynthate transport and grain yield.

Suggestions to increase crop yield in rice–wheat cropping systems

The experiment was carried out in a rice–wheat cropping system in Jiangsu province, with limited temperature and solar radiation in two crop seasons. Jiangsu is the main producer of *japonica* rice in south China using the 'late-maturing rice, late-sowing wheat' cultivation method, in which wheat growth duration is shortened by delaying its sowing date, and rice yield is increased with prolonged growth duration and increased temperature and solar radiation (Gong *et al.*, 2011; Liu *et al.*, 2020). This cultivation method was applied in Anhui province and other provinces (Xi *et al.*, 2020). Thus, wheat was sown later than the sowing date of high-yield wheat crops. Delaying sowing by 1 day increased the sowing rate by approximately 500 g in this cultivation method. Nonetheless, wheat yield decreased because of the reduced total number of ears and lower resistance (Spink *et al.*, 2000; Zhou *et al.*, 2020*a*, 2020*b*). Accordingly, whether coordinating rice and wheat cultivation improves wheat and annual grain yield is a research hotspot. Our results showed that seedling transplanting prolonged rice growth duration, shortened the growth period in the field and shifted the wheat sowing date to an early time. In addition, PST-RS was the most effective seedling transplanting method, and rice and wheat growth duration was over 366 days with an overlapping growth period of approximately 23 days, which greatly increased solar thermal utilization efficiency, provided sufficient time for agricultural operations, enhanced photosynthetic capacity and increased annual crop yield (Xing *et al.*, 2017*a*; Xi *et al.*, 2020). In addition, an increase in EAT, CSR, TPE and RUE was associated with higher yield and energy efficiency of PST-RS in the rice–wheat cropping system.

Conclusion

Rice and wheat yield and solar energy utilization efficiency varied significantly across mechanized rice planting patterns. Compared with RS-RS, the annual grain yield increased by 3.1–3.8 and 2.0–2.6 t/ha, respectively, in PST-RS and CST-RS by (1) increasing sink size, LAI and aboveground biomass accumulation and translocation; (2) alleviating the contradiction between rice and wheat rotation, prolonging crop growth duration and increasing the utilization of temperature and solar radiation, and increasing crop yield and annual grain production.

Author contributions. H. C. Zhang conceived and designed the study. Z. P. Xing, Z. C. Huang and Y. J. Hu conducted the field test and data gathering. Y. Yao performed statistical analyses. B. W. Guo provided suggestions on writing. Z. P. Xing wrote the article.

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