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Article

Critical Yield Factors for Achieving High Grain Yield in Early-Season Rice Grown under Mechanical Transplanting Conditions

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Abstract: Double-season rice cropping systems occupy a large portion of the rice production area in southern China. Because the problem of insufficient labor, mechanical transplanting (in contrast to the manual transplanting) was become more attractive in double-season rice system. However, the decisive yield factors which resulting in high grain yield of early-season rice are unclear under mechanical-transplanted conditions. In present study, the field experiments were conducted in the early season in 2017 and repeated in 2018 in Santang Town, Hunan Province, China. Ten early season rice cultivars (Zhuliangyou 819, Lingliangyou 268, Lingliangyou 104, Luliangyou 996, Xiangzaoxian 24, Xiangzaoxian 32, Xiangzaoxian 45, Xiangzaoxian 42, Zhongjiazao 17, and Zhongzao 39) were used as materials in this study. The difference in grain yield and closely-related agronomic and physiological traits of ten tested cultivars were compared. The range of yields (t ha^{-1} at 86% dry matter) in 2017 was 6.2 to 8.7 (mean 7.8) and in 2018 was 6.5 to 8.4 (mean 7.8). Grain weight and pre-heading biomass accumulation had potent significant positive correlations with the grain yield. The greater pre-heading biomass accumulation was major attributed to higher apparent radiation use efficiency. Our results suggested that early-season rice cultivars to achieve the high grain yield in mechanical-transplanted conditions depends on apparent radiation use efficiency in the pre-heading period and higher grain weight.

Keywords: Early-season rice; grain yield; hybrid rice; inbred rice; mechanical transplanting

1 Introduction

More than 65% of Chinese take rice as a staple food. The double rice-cropping system is regarded as an effective way to improve multiple-crop index and play a key role in ensuring the national food security [1,2]. Therefore, this system occupies a large portion of rice area in the southern China [2]. However, the area of double cropping rice especially that of early season rice area in China, has decreased significantly in the past decade [1]. This is primarily attributed to the insufficient labor because an increasing number of young people have moved to the cities for jobs, leaving only older farmers behind. Therefore, rice cultivation technologies using labour-saving methods must be developed [3]. For example, mechanical transplanting has rapidly become a prevalent and simplified cultivation method in Chinese rice production in recent years [4,5].

Full spikelets per m^2 and the grain weight determined the rice yield. The full spikelets per m^2 which including the panicles per m^2, spikelets per panicle, and spikelet filling percentage performances vary in different environments [6,7]. The grain weight is a relatively stable characteristic of cultivars [8,9]. On the other hand, grain yield is up to dry matter production and harvest index, and dry matter accumulation is up to total incident solar radiation and apparent radiation use efficiency. Since it difficult to further improve the harvest index, further advancement in grain yield depends on producing more dry matter accumulation [10]. Increasing biomass involves two phases of plant growth stage: pre-heading and post-heading. Some studies showed that high grain yield rice cultivars accumulate enormous biomass in pre-heading stage, but not much in post-heading stage [11,12].

The yield of early season rice is generally low and unstable due to the slower crop growth rate during the pre-heading stage, which is attributed to the low temperature [13–16]. The later high temperature shortened the grain filling duration in the grain formation stage, which is also harmful to grain yield formation of early-season rice [14,17,18]. However, it can be resulted from summary statistics that the early-season rice has more opportunity to improve the grain yield, compared with late-season or middle-season rice. Correlation analysis further showed that the grain sink and biomass production could not be ignored for increasing early season rice yield [15,18,19]. The above results were obtained under the condition of hand transplanting conditions. However, the growth characteristics of rice will change to some extent under the condition of mechanical transplanting [20–22].

The yield, yield components, above dry matter accumulation, crop growth rate, and apparent radiation use efficiency were investigated in the present study. The purpose of our study was to assess the yield performance of early season rice cultivars, and explore the agronomic and physiological traits closely related to the high grain yield of early-season rice cultivars under mechanical-transplanted conditions.

2 Materials and Methods

2.1 Experimental Site and Soil

The field experiments were conducted in the early season (from late-March to mid-July) in 2017 and 2018 in Santang Town, Hunan Province, China (26°53’ N, 112°28’ E, 71 m asl). The experiment region has a typical southern subtropical monsoon climate. The texture of the soil was clayey with the following properties: pH 5.86, organic matter 31.0 g kg^{-1}, available N 145.2 mg kg^{-1}, available P 14.1 mg kg^{-1}, available K 186.6 mg kg^{-1}. The soil was sampled in the upper 20 cm layer from the experimental filed in 2017 before starting the experiments.

2.2 Experimental Design and Measurements

Hybrid rice cultivars (Zhuliangyou 819, Lingliangyou 268, Lingliangyou 104, Luliangyou 996) and inbred rice cultivars (Xiangzaoxian 24, Xiangzaoxian 32, Xiangzaoxian 45, Xiangzaoxian 42, Zhongjiazao 17, and Zhongzao 39) were selected in this study. Currently, these cultivars are widely-grown in the double-season rice production region of China.

Ten selected cultivars were ordered according to the randomized block design, and with three replications. The size of plot is 30 m^2. Sow the rice seeds according to the methods of Huang et al. [23]. The seeds were sown on 31 March. A rice transplanter (2ZGQ-8B, Jiubaotian Agricultural Machinery

Co., Ltd., Suzhou, China) with high-speed was used to transplant the twenty-four days old seedlings in both years, at the density of 25 cm × 12 cm.

Plots were fertilized as follows: Nitrogen (150 kg N ha^{-1}) was applied equally at basal and top dressing, top dressing applied in two parts: 60% at mid-tillering stage and 40% at panicle initiation stage. Urea was used as nitrogen fertilizer. All the phosphorus (75 kg P_2O_5 ha^{-1}) was applied 1 d before transplanting as basal dose. Potassium (150 kg K_2O ha^{-1}) was split in two parts: 50% as basal and 50% at panicle initiation stage. Water management included a series of shallow irrigation (2–3 cm), middle growth duration drainage (10–15 d) and, late growth duration shallow irrigation. In order to avoid yield reduction, weed growth, pest damage, and disease were strictly controlled by chemicals. No major diseases and pests which caused a decrease in yield were appeared in this study.

At full heading stage (the time about 80% of the panicles appeared from the flag leaf sheath), ten hills of rice plants were diagonally sampled in the middle of each plot. Rice plants were handly separated into straw and panicles. All parts were dried to a constant weight in the oven at 70°C.

Ten hills of rice plants were sampled according the diagonal in the center of each plot at physiological maturity stage. Panicles per m^2 were calculated by counting panicle number. Straw (including rachis) and spikelets were separated from the samples with hand. Spikelets were submerged in tap water in order to separate them into filled and unfilled spikelets. All unfilled spikelets and three subsamples (each 30 g) of filled grain were counted. The dry weight of straws, filled spikelets, and unfilled spikelets were dried to a constant weigh at 70°C in an oven. Then calculated the yield components of spikelets per panicle, spikelet filling percentage (100 × filled spikelets number/total spikelets number). The harvest index (filled spikelets weight/aboveground total biomass weight) was also calculated. Grain yield was established using a 5 m^2 harvest area taken from the center of each plot, which was then adjusted to a standard moisture content of 14%. The weight of straw, filled spikelets, and unfilled spikelets constituted total biomass accumulation. Dry matter accumulation of post-heading was the difference value of total dry matter accumulation and pre-heading dry matter accumulation. Crop growth rates of pre-heading and post-heading were the rate of pre-heading biomass accumulation to growth duration (transplanting to full heading) and post-heading biomass accumulation to growth duration (full heading to maturity), respectively.

The apparent radiation use efficiency of transplanting to full heading, full heading to physiological maturity, and transplanting to physiological maturity were calculated according the rate of biomass accumulation to incident solar radiation in each stage. An automatic weather station (Vantage Pro2, Davis Instruments Corp., Hayward, CA, USA) was used daily to record the solar radiation, and temperature (including minimum and maximum temperature). The weather station was installed approximately 2 meters above the ground.

2.3 Data Analysis

Data analysis methods used in this study were analysis of variance, linear regression analysis, and Pearson's correlation analysis (Statistix 8.0, Analytical Software, Tallahassee, FL, USA). Means of cultivars were compared based on the least significant difference test (LSD) at the 0.05 probability level.

3 Results

3.1 Weather at Experimental Site

For the pre-heading period (from transplanting to full heading), average maximum temperature and minimum temperature were 0.3°C and 2.3°C higher in 2018 than 2017, respectively (Tab. 1). For the post-heading period (from full heading to maturity), average maximum temperature and minimum temperature were 3.7°C and 2.6°C higher in 2018 than 2017, respectively. The seasonal average daily solar radiation was also different between 2017 and 2018 (Tab. 1). The daily solar radiation was

Table 1: Climate conditions in crop growth duration for the early-season rice cultivars under mechanical transplanting conditions in 2017 and 2018

Cultivar	Max T			Min T			RAD		
	TP to HD	HD to MA	TP to MA	TP to HD	HD to MA	TP to MA	TP to HD	HD to MA	TP to MA
2017									
Zhuliangyou 819	29.0	30.1	29.4	19.7	23.7	21.3	13.3	11.5	12.6
Lingliangyou 268	28.7	31.4	29.6	19.9	24.4	21.4	12.5	13.7	12.9
Lingliangyou 104	28.7	31.4	29.6	19.9	24.4	21.4	12.5	13.7	12.9
Luliangyou 996	28.6	31.2	29.6	19.8	24.2	21.4	12.8	13.3	12.9
Xiangzaoxian 24	28.8	30.2	29.3	19.8	23.7	21.2	12.9	10.9	12.2
Xiangzaoxian 32	28.9	29.8	29.3	19.6	23.5	21.2	13.4	10.3	12.2
Xiangzaoxian 45	28.9	30.2	29.4	19.8	23.7	21.3	13.1	11.6	12.6
Xiangzaoxian 42	28.6	29.6	29.6	19.8	21.4	21.4	12.6	20.7	12.9
Zhongjiazao 17	28.8	30.4	29.3	19.8	23.8	21.2	12.9	11.5	12.4
Zhongzao 39	28.7	31.4	29.6	19.8	24.4	21.4	12.5	13.7	12.9
Mean	28.8	30.6	29.5	19.8	23.7	21.3	12.9	13.1	12.7
2018									
Zhuliangyou 819	28.9	34.2	30.8	21.9	26.3	23.5	12.6	17.1	14.1
Lingliangyou 268	29.4	35.0	31.2	22.3	26.7	23.7	12.7	18.9	14.7
Lingliangyou 104	29.3	34.7	31.1	22.2	26.6	23.7	12.59	18.4	14.5
Luliangyou 996	29.3	34.3	30.8	22.2	26.5	23.5	12.70	17.4	14.2
Xiangzaoxian 24	28.9	34.2	30.8	21.9	26.3	23.5	12.6	17.1	14.1
Xiangzaoxian 32	28.9	33.5	30.8	21.9	25.6	23.5	12.8	16.0	14.1
Xiangzaoxian 45	28.9	34.2	30.8	21.9	26.3	23.5	12.6	17.1	14.1
Xiangzaoxian 42	29.2	34.2	30.8	22.1	26.3	23.5	12.8	17.0	14.1
Zhongjiazao 17	29.0	34.2	30.7	22.0	26.4	23.4	12.8	16.4	14.0
Zhongzao 39	29.3	34.3	30.8	22.2	26.5	23.5	12.7	17.4	14.2
Mean	29.1	34.3	30.8	22.1	26.3	23.5	12.7	17.3	14.2

Min T, average daily minimum temperature (°C); Max T, average daily maximum temperature (°C); RAD, average daily solar radiation (MJ m^{-2} day^{-1}).
TP, HD, and MA are transplanting, heading, and maturity, respectively.

12.7 MJ m^{-2} d^{-1} in 2017 and 14.2 MJ m^{-2} d^{-1} in 2018 in rice growing season. Higher average daily solar radiation was observed in 2018 compared to 2017 from full heading to maturity, while the opposite result was showed from transplanting to full heading.

3.2 Crop Growth Rate and Development

The differences of growth duration from transplanting to full heading were not observed in 2017 and 2018 (Tab. 2). However, there were significant differences in duration from transplanting to heading between different cultivars. Lingliangyou 268 and Lingliangyou 104 had the longest duration from

Table 2: Grain yield and growth duration for the early-season rice cultivars under mechanical transplanting conditions in 2017 and 2018

Cultivar	Grain yield (t ha^{-1})	Growth duration (d)		
		TP to HD	HD to MA	TP to MA
2017				
Zhuliangyou 819	8.15 ab	49	34	83
Lingliangyou 268	8.33 ab	56	30	86
Lingliangyou 104	8.35 ab	56	30	86
Luliangyou 996	7.93 ab	53	33	86
Xiangzaoxian 24	6.87 cd	52	29	81
Xiangzaoxian 32	6.21 d	48	33	81
Xiangzaoxian 45	7.71 bc	50	33	83
Xiangzaoxian 42	7.80 b	54	32	86
Zhongjiazao 17	7.63 bc	52	30	82
Zhongzao 39	8.72 a	55	31	86
Mean	7.77	53	32	84
2018				
Zhuliangyou 819	8.20 ab	53	29	82
Lingliangyou 268	7.99 ab	60	29	89
Lingliangyou 104	8.42 a	58	29	87
Luliangyou 996	7.92 bc	57	26	83
Xiangzaoxian 24	7.27 d	53	29	82
Xiangzaoxian 32	6.49 e	48	34	82
Xiangzaoxian 45	7.83 bc	53	29	82
Xiangzaoxian 42	8.01 ab	56	26	82
Zhongjiazao 17	7.90 bc	54	27	81
Zhongzao 39	7.52 cd	57	26	83
Mean	7.76	55	28	83
Analysis of variance (F-value)				
Years	0.02			
Cultivars	9.27**			
Years × Cultivars	1.34			

TP, HD, and MA are transplanting, heading, and maturity, respectively.
Within a column for each year, means not sharing any letter are significantly different by LSD test at the 0.05 probability level.
**denotes significant at the 0.01 probability level.

transplanting to heading of 56 d in 2017; Lingliangyou 268 also had the longest duration from transplanting to full heading of 60 d in 2018. There were also differences in duration from full heading to maturity between different cultivars. Zhuliangyou 819 had a 1–5 d longer growth duration in the post-heading period than the other cultivars in 2017, and Xiangzaoxian 32 had a 5–8 d longer growth duration in 2018. Overall, the growth durations of Lingliangyou 268 and Lingliangyou 104 were longer than that of the other cultivars in both years, the longer growth duration of these cultivars was mainly contributed to the difference in the pre-heading period.

3.3 Grain Yield and Yield Components

Grain yield changed significantly in different cultivars in 2017 and 2018 (Tab. 2). The interactive effects between years and cultivars on grain yield was insignificant. Zhongzao 39 showed significantly higher than that in Xiangzaoxian 24, Xiangzaoxian 32, Xiangzaoxian 42, and Xiangzaoxian 45, respectively, which had the highest grain yield of 8.72 t ha^{-1} in 2017. Lingliangyou 104 produced the highest grain yield (8.42 t ha^{-1}) in 2018. The grain yield of Zhuliangyou 819, Lingliangyou 268, Lingliangyou 104, and Xiangzaoxian 42 were higher than those of the other cultivars in 2018. Overall, Zhuliangyou 819, Lingliangyou 268, and Lingliangyou 104 had relatively higher grain yield in both years. Xiangzaoxian 24 and Xiangzaoxian 32 had relatively lower grain yield in both years. The differences in yield between the two years were no greater than 0.40 t ha^{-1} except for Zhongzao 39 which had 16% higher yield (by 1.20 t ha^{-1}) in 2017 than 2018.

The yield components varied greatly in different cultivars and years (Tab. 3). Panicles m^{-2}, spikelet filling percentage, and grain weight were significantly affected by the interactions of years and cultivars.

The panicles m^{-2} and spikelets $panicle^{-1}$ were showed lower in 2018 than in 2017, but the spikelet filling percentage and the grain weight were higher in 2018. Xiangzaoxian 45 had the highest panicle m^{-2} in 2017, and showed 22% higher than Luliangyou 996, 11% higher than Xiangzaoxian 42, 22% higher than Zhongjiazao 17, and 28% higher than Zhongzao 39. Zhongjiazao 17 had the highest panicle m^{-2} in 2018, which showed 43% higher than Luliangyou 996, 29% higher than Xiangzaoxian 42, and 62% higher than Zhongzao 39. The highest spikelets per panicle was Zhongzao 39 in both years. Spikelet filling percentage of Xiangzaoxian 32 was the highest among the ten cultivars in 2017 and 2018. Lingliangyou 104 had the highest grain weight of 31.0 mg in 2018, followed by Luliangyou 996 which had the highest grain weight of 29.3 mg in 2017.

A positive significant correlation between the grain weight and grain yield was showed in 2017 and 2018 (Tab. 4). A negative correlation was showed between spikelet filling percentage and grain yield in 2018. In 2017, the spikelets per panicle had negative correlations with panicles m^{-2}, and also with spikelet filling percentage. In 2018, the panicles m^{-2} had a significant negative correlation with spikelets per panicle, and also showed between grain weight and spikelet filling percentage.

3.4 Biomass Accumulation, Harvest Index and Crop Growth Rate

The total aboveground biomass including the biomass accumulation of pre-heading and post-heading were shown in Tab. 5. Zhongzao 39 and Lingliangyou 268 accumulated the most biomass of pre-heading in 2017 and 2018, respectively. No significant difference showed in biomass of post-heading in 2017. But in 2018, Zhongjiazao 17 produced the highest biomass of post-heading. The total biomass of Xiangzaoxian 24 was the lowest in both years. Zhongzao 39 and Zhongjiazao 17 produced the highest total biomass in 2017 and 2018, respectively. Total biomass accumulation and harvest index were significantly affected by the interactions of years and cultivars.

The harvest index in 2018 was 8% higher than in 2017. Xiangzaoxian 32 had the highest harvest index in both years. The crop growth rate of pre-heading and post-heading were 9% and 6% higher in 2017 than in 2018, respectively (Tab. 6). It was observed that high positive linear correlation existed in grain yield and total biomass (Fig. 1a) and biomass of pre-heading (Fig. 1c), while there were no direct correlations between the grain yield and harvest index (Fig. 1b) and biomass of post-heading (Fig. 1d). The biomass of pre-heading was positively affected by the growth duration (Fig. 2a) and the crop growth rate (Fig. 2b) from transplanting to full heading.

Table 3: Yield components of early-season rice cultivars under mechanical transplanting conditions in 2017 and 2018

Cultivar	Panicles m^{-2}	Spikelets panicle^{-1}	Spikelet filling (%)	Grain weight (mg)
2017				
Zhuliangyou 819	394 ab	120 d	71.0 b	27.2 bc
Lingliangyou 268	391 ab	117 d	71.1 b	27.3 bc
Lingliangyou 104	386 ab	117 d	70.0 bc	28.1 b
Luliangyou 996	334 cd	137 b	72.8 b	29.3 a
Xiangzaoxian 24	381 ab	119 d	66.0 cd	23.9 f
Xiangzaoxian 32	399 ab	119 d	81.6 a	24.2 f
Xiangzaoxian 45	406 a	122 cd	71.9 b	26.0 de
Xiangzaoxian 42	367 bc	134 bc	62.8 d	25.4 e
Zhongjiazao 17	333 cd	156 a	57.8 e	26.8 cd
Zhongzao 39	316 d	165 a	56.9 e	27.6 bc
Mean	371	130	68.2	26.6
2018				
Zhuliangyou 819	351 ab	112 bc	83.4 ab	28.4 bc
Lingliangyou 268	384 a	109 c	62.5 d	30.4 a
Lingliangyou 104	379 a	110 c	69.0 cd	31.0 a
Luliangyou 996	269 cd	127 a	78.3 b	30.9 a
Xiangzaoxian 24	344 ab	100 c	87.8 a	25.6 f
Xiangzaoxian 32	364 a	101 c	89.4 a	24.5 g
Xiangzaoxian 45	369 a	106 c	82.9 ab	27.1 e
Xiangzaoxian 42	299 bc	124 ab	81.2 ab	27.6 de
Zhongjiazao 17	386 a	124 ab	76.3 bc	27.9 cd
Zhongzao 39	238 d	135 a	81.2 ab	29.1 b
Mean	338	115	79.2	28.2
Analysis of variance (F-value)				
Years	20.1**	62.7**	107**	138**
Cultivars	11.4**	20.3**	12.2**	72.9**
Years × Cultivars	2.79*	2.02	9.54**	3.58**

Within a column for each year, means not sharing any letter are significantly different by LSD test at the 0.05 probability level.
** and * denote significant at the 0.01 and 0.05 probability levels, respectively.

3.5 Apparent Radiation Use Efficiency

The apparent radiation use efficiency varied greatly in different cultivars and years, and it was lower in the pre-heading period than post-heading (Tab. 7). Zhongzao 39 and Lingliangyou 104 showed the highest apparent radiation use efficiency in the pre-heading period in 2017 and 2018, respectively. The cultivars which had higher biomass accumulation also had higher apparent radiation use efficiencies in the pre-heading period but not the post-heading period. There was no direct correlation between the crop growth

Table 4: Correlation coefficients (r, n = 10) among grain yield and yield components of early-season rice cultivars under mechanical transplanting conditions in 2017 and 2018

Parameter	Grain yield	Panicles m^{-2}	Spikelets $panicle^{-1}$	Spikelet filling percentage
2017				
Panicles m^{-2}	–0.372			
Spikelets $panicle^{-1}$	0.341	–0.922**		
Spikelet filling percentage	–0.479	0.703	–0.765**	
Grain weight	0.792**	–0.455	0.306	–0.149
2018				
Panicles m^{-2}	0.080			
Spikelets $panicle^{-1}$	0.316	–0.719*		
Spikelet filling percentage	–0.642*	–0.277	0.156	
Grain weight	0.776**	–0.186	–0.478	–0.801**

* and ** denote significance at the 0.05 and 0.01 probability levels, respectively.

rate of pre-heading and incident solar radiation (Fig. 3a), while crop growth rate had a strong positive linear correlation with apparent radiation use efficiency (Fig. 3b).

4 Discussion

There was a range in yields of 2.51 t ha^{-1} in 2017 and 1.93 t ha^{-1} in 2018. The total growth duration (including 24 days from sowing to transplanting) was 105–113 d across the cultivars and years in our study. Generally, the yield of rice is most directly related to the growth duration, and the total duration of growth is an important factor that can limit the yield [24,25]. However, some cultivars had high yields and relatively short growth durations in our study, such as Zhuliangyou 819 and Luliangyou 996 (2018). This result indicated that high yields could be obtained over short growth duration. The reasons for the high yields are very meaningful and deserve the further research.

The higher grain yield was attributed to improvement in high grain weight in the present study. Some researchers believed that grain weight is important in determining grain yield [8,9,26]. But reports demonstrated that high grain yield was achieved by increasing spikelets per m^2 (panicle per m^2 and/or spikelets per panicle) [21,27]. The difference of the present study and previous studies may be due to the different growth seasons. Rice in our study was planted in the early season which had a shorter vegetative growth period than previous studies where rice was planted in the late season or middle season. It was therefore hard to get more spikelets per m^2 due to the shorter vegetative growth period.

Furthermore, grain yield increased with the biomass accumulation not the harvest index in our study. The results were consistent with previous studies [10,15,18], which indicated that improving in rice yield depends on increasing biomass accumulation. When the biomass accumulation was divided into pre-heading and post-heading, we found that the biomass accumulation of pre-heading was positively correlated with grain yield. This indicated that yield improvements in early season cultivars could be achieved by improving pre-heading biomass accumulation. The low temperature during the vegetative phase might well be the factor restricting canopy development, and cause the biomass accumulation of pre-heading become the yield limiting factor of early-season rice.

We also found that the high pre-heading biomass accumulation of the early-season cultivars was mainly due to the high pre-heading crop growth rate. Further evidence, the higher crop growth rate contributed to the higher apparent radiation use efficiency. The representativeness of apparent radiation use efficiency has been

Table 5: Aboveground biomass accumulation and harvest index of early-season rice cultivars under mechanical transplanting conditions in 2017 and 2018

Cultivar	Biomass accumulation (g m^{-2})		Total biomass (g m^{-2})	Harvest index
	Pre-heading	Post-heading		
2017				
Zhuliangyou 819	646 bcd	737 a	1383 bc	0.57 a
Lingliangyou 268	766 abc	681 a	1447 ab	0.52 b
Lingliangyou 104	718 abcd	707 a	1425 abc	0.53 b
Luliangyou 996	691 bcd	831 a	1522 ab	0.55 ab
Xiangzaoxian 24	623 d	650 a	1273 c	0.48 c
Xiangzaoxian 32	636 cd	761 a	1397 abc	0.57 a
Xiangzaoxian 45	661 bcd	830 a	1492 ab	0.53b
Xiangzaoxian 42	678 bcd	731 a	1409 abc	0.48 cd
Zhongjiazao 17	775 ab	703 a	1477 ab	0.47 cd
Zhongzao 39	852 a	697 a	1549 a	0.45 d
Mean	705	732	1437	0.52
2018				
Zhuliangyou 819	632 c	705 ab	1337 abc	0.60 abc
Lingliangyou 268	768 a	647 abc	1415 ab	0.48 f
Lingliangyou 104	757 a	693 abc	1450 ab	0.52 e
Luliangyou 996	710 abc	570 bc	1281 bcd	0.55 de
Xiangzaoxian 24	646 bc	454 c	1100 d	0.60 ab
Xiangzaoxian 32	499 d	606 abc	1105 d	0.62 a
Xiangzaoxian 45	662 bc	682 abc	1344 abc	0.56 cd
Xiangzaoxian 42	697 abc	567 bc	1264 bcd	0.56 cd
Zhongjiazao 17	671 bc	839 a	1510 a	0.58 bcd
Zhongzao 39	722 ab	463 bc	1186 cd	0.55 de
Mean	677	622	1299	0.56
Analysis of variance (*F*-value)				
Years	2.19	9.55**	24.5**	87.0**
Cultivars	5.03**	1.53	4.32**	16.1**
Years × Cultivars	1.29	1.16	2.31*	12.2**

Within a column for each year, means not sharing any letter are significantly different by LSD test at the 0.05 probability level.
** and * denote significant at the 0.01 and 0.05 probability levels, respectively.

confirmed in a previous study [26], which could be used to reflect the use efficiency of radiation. The importance of radiation use efficiency to biomass production has been shown in many studies [7,14,28].

The weather was different in the two years in this study. However, there mean grain yield between two years were showed no significant differences. This result might be related to the compensation effect between the yield components. Compared with 2017, 2018 was reached lower dry matter accumulation but higher harvest

Table 6: Crop growth rate of early-season rice cultivars under mechanical transplanting conditions in 2017 and 2018

Cultivar	Crop growth rate (g m^{-2} d^{-1})	
	Pre-heading	Post-heading
2017		
Zhuliangyou 819	13.19 abc	21.67 a
Lingliangyou 268	13.67 abc	22.71 a
Lingliangyou 104	12.82 bc	23.55 a
Luliangyou 996	13.04 abc	25.19 a
Xiangzaoxian 24	11.99 c	22.41 a
Xiangzaoxian 32	13.25 abc	23.07 a
Xiangzaoxian 45	13.23 abc	25.16 a
Xiangzaoxian 42	12.56 bc	22.85 a
Zhongjiazao 17	14.90 ab	23.43 a
Zhongzao 39	15.49 a	22.50 a
Mean	13.41	23.25
2018		
Zhuliangyou 819	11.93 a	24.30 ab
Lingliangyou 268	12.80 a	22.30 ab
Lingliangyou 104	13.06 a	23.88 ab
Luliangyou 996	12.46a	21.93 b
Xiangzaoxian 24	12.19 a	15.65 b
Xiangzaoxian 32	10.40 b	17.83 b
Xiangzaoxian 45	12.50 a	23.51 ab
Xiangzaoxian 42	12.45 a	21.81 b
Zhongjiazao 17	12.43 a	31.06 a
Zhongzao 39	12.67 a	17.82 b
Mean	12.29	22.01
Analysis of variance (*F*-value)		
Years	9.99**	1.02
Cultivars	1.47	1.48
Years × Cultivars	1.13	1.17

Within a column for each year, means not sharing any letter are significantly different by LSD test at the 0.05 probability level.
** denotes significant at the 0.01 probability level.

index. The lower dry matter accumulation of 2018 was major attributed to lower apparent radiation use efficiency of post-heading phases than in 2017. Meanwhile, the differences in harvest index between two years could be explained by the differences in spikelet filling percentage, which was lower in 2017 (68%) than in 2018 (79%). Furthermore, there were higher average daily maximum temperature, minimum temperature, and solar

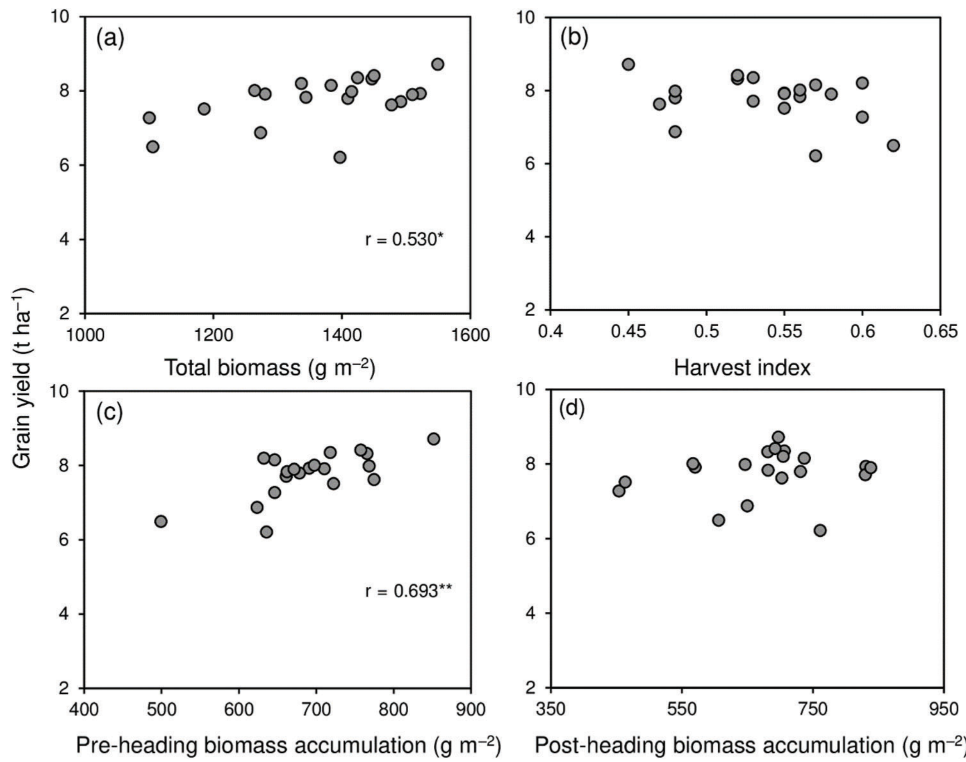

Figure 1: Relationships of grain yield to total biomass (a), harvest index (b), biomass of pre-heading (c), and biomass of post-heading (d) of early-season rice cultivars under mechanical transplanting conditions in 2017 and 2018. * and ** denote significance at the 0.05 and 0.01 probability levels, respectively

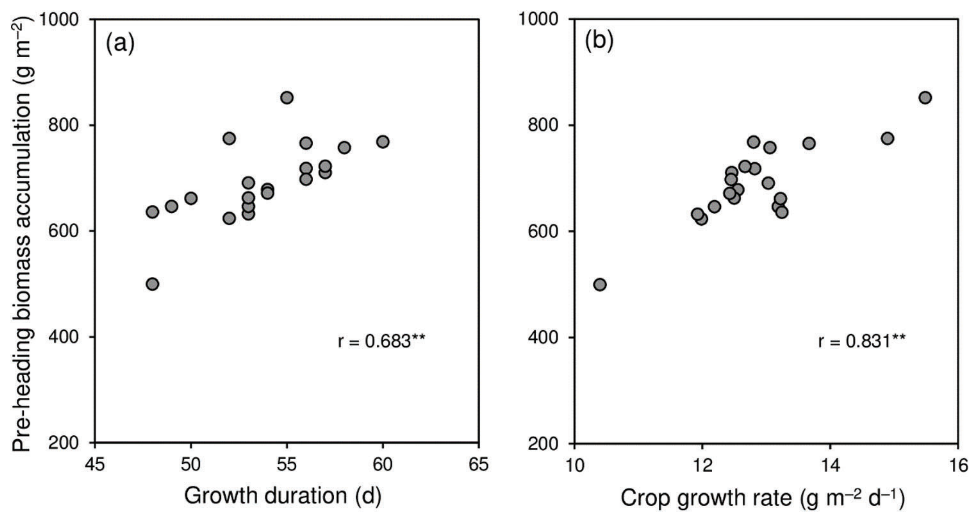

Figure 2: Relationships of pre-heading biomass accumulation to growth duration (a) and crop growth rate (b) of early-season rice cultivars under mechanical transplanting conditions in 2017 and 2018. ** denotes significance at the 0.01 probability level

Table 7: Cumulative incident solar radiation and apparent radiation use efficiency of early-season rice cultivars under mechanical transplanting conditions in 2017 and 2018

Cultivar	Cumulative incident solar radiation (MJ m^{-2})			Apparent radiation use efficiency (g MJ^{-1})		
	TP to HD	HD to MA	TP to MA	TP to HD	HD to MA	TP to MA
2017						
Zhuliangyou 819	664	390	1054	0.97 bc	1.89 a	1.31 abc
Lingliangyou 268	715	411	1126	1.07 abc	1.66 a	1.28 bc
Lingliangyou 104	715	411	1126	1.00 bc	1.72 a	1.27 bc
Luliangyou 996	689	437	1126	1.00 bc	1.90 a	1.35 abc
Xiangzaoxian 24	682	317	999	0.91 c	2.05 AM	1.27 bc
Xiangzaoxian 32	658	341	999	0.97 bc	2.23 AM	1.40 abc
Xiangzaoxian 45	670	384	1054	0.99 bc	2.16 AM	1.41 ab
Xiangzaoxian 42	695	431	1126	0.98 bc	1.69 a	1.25 c
Zhongjiazao 17	682	344	1027	1.14 ab	2.04 AM	1.44 AM
Zhongzao 39	701	425	1126	1.22 AM	1.64 a	1.38 abc
Mean	687	389	1076	1.03	1.9	1.34
2018						
Zhuliangyou 819	681	492	1173	0.93 a	1.43 ab	1.14 ab
Lingliangyou 268	772	547	1319	0.99 a	1.18 b	1.07 bc
Lingliangyou 104	743	533	1276	1.02 AM	1.30 b	1.14 b
Luliangyou 996	737	453	1190	0.96 a	1.26 b	1.08 bc
Xiangzaoxian 24	681	492	1173	0.95 a	0.92 b	0.94 c
Xiangzaoxian 32	628	545	1173	0.79 b	1.11 b	0.94 c
Xiangzaoxian 45	681	492	1173	0.97 a	1.38 ab	1.15 ab
Xiangzaoxian 42	730	443	1173	0.95 a	1.28 b	1.08 bc
Zhongjiazao 17	703	444	1147	0.96 a	1.89 a	1.32 AM
Zhongzao 39	737	453	1190	0.98 a	1.02 b	1.00 bc
Mean	709	489	1198	0.95	1.28	1.09
Analysis of variance (*F*-value)						
Years				7.24*	52.1**	108**
Cultivars				2.09	1.86	3.72**
Years × Cultivars				1.13	1.33	2.11

Within a column for each year, means not sharing any letter are significantly different by LSD test at the 0.05 probability level.
** and * denote significant at the 0.01 and 0.05 probability levels, respectively.
TP, HD, and MA are transplanting, heading, and maturity, respectively.

radiation in 2018 than 2017 during the post-heading period, which could induce early rice senescence (lower crop growth rate and shorter grain filling duration). But the spikelet filling percentage and grain weight were not reduced in 2018. This result might be due to the compensation of biomass before heading [29–31].

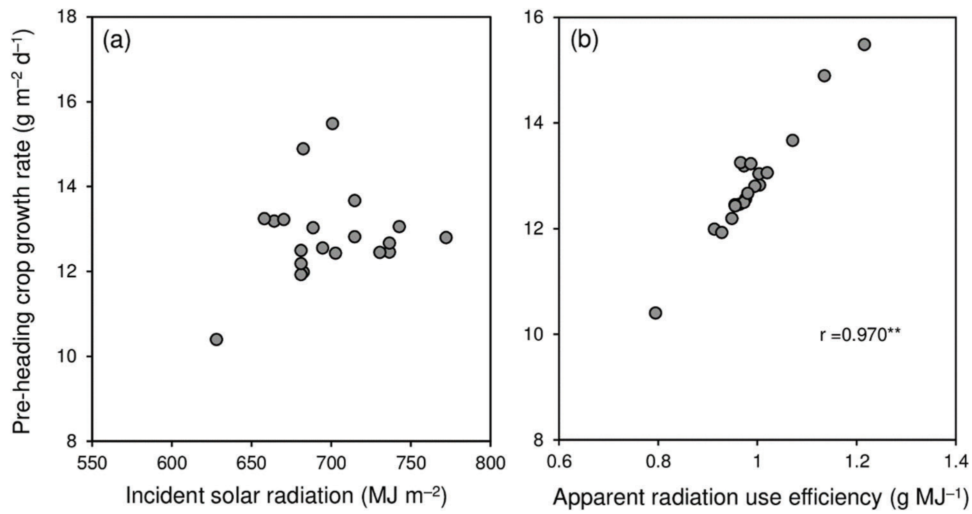

Figure 3: Relationships of pre-heading crop growth rate to incident solar radiation (a) and apparent radiation use efficiency (b) of early-season rice cultivars under mechanical transplanting conditions in 2017 and 2018. ** denotes significance at the 0.01 probability level

5 Conclusions

Early season rice cultivars showed a large yield difference under mechanical transplanting conditions of our experiments. The critical yield factors for achieving high grain yield were grain weight and apparent radiation use efficiency of pre-heading stage (transplanting to full heading).

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