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RESEARCH ARTICLE

Availability of existing early-season rice cultivars as resources for selecting high-yielding short-duration cultivars of machine-transplanted late-season rice

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Abstract

High-yielding short-duration cultivars are required due to the development of mechanized large-scale double-season rice (i.e. early- and late-season rice) production in China. The objective of this study was to identify whether existing early-season rice cultivars can be used as resources to select high-yielding, short-duration (less than 115 days) cultivars of machine-transplanted late-season rice. Field experiments were conducted in Yongan, Hunan Province, China in the early and late rice-growing seasons in 2015 and 2016. Eight early-season rice cultivars (Liangyou 6, Lingliangyou 211, Lingliangyou 268, Xiangzaoxian 32, Xiangzaoxian 42, Zhongjiazao 17, Zhongzao 39, and Zhuliangyou 819) with growth durations of less than 115 days were used in 2015, and four cultivars (Lingliangyou 268, Zhongjiazao 17, Zhongzao 39, and Zhuliangyou 819) with good yield performance in the late season in 2015 were grown in 2016. All cultivars had a growth duration of less than 110 days when grown in the late season in both years. Zhongjiazao 17 produced the maximum grain yield of 9.61 Mg ha^{-1} with a daily grain yield of 108 kg ha^{-1} d^{-1} in the late season in 2015. Averaged across both years, Lingliangyou 268 had the highest grain yield of 8.57 Mg ha^{-1} with a daily grain yield of 95 kg ha^{-1} d^{-1} in the late season. The good yield performance of the early-season rice cultivars grown in the late season was mainly attributable to higher apparent radiation use efficiency. Growth duration and grain yield of early-season rice cultivars grown in the late season were not significantly related to those grown in the early season. Our study suggests that it is feasible to select high-yielding short-duration cultivars from existing early-season rice cultivars for machine-transplanted late-season rice production. Special tests by growing alternative early-season rice cultivars in the late season should be done to determine their growth duration and grain yield for such selection.

Keywords: Apparent radiation use efficiency; Grain yield; Short-duration rice cultivar

Introduction

Rice production plays a critical role in ensuring national food security in China, since more than 65% of China's population eats rice as a staple food (Huang and Zou, 2018). The availability of short-duration rice cultivars has helped increase cropping intensity and food supplies in many major rice-producing countries including China (Khush, 2001), and further increases in cropping intensity are considered an important approach for achieving higher food security in the future (Ray and Foley, 2013). However, in recent years, changes in socioeconomic factors have posed challenges for the development of intensive rice cropping systems in China. In particular, urban expansion has led to a labor shortage and an increase in wages for agricultural production (Peng et al., 2009), both of which have reduced farmers' willingness to grow double-season rice (i.e. early- and late-season rice) (Peng, 2016). Nearly 2 million hectares of double-season rice were shifted to single-season rice from 1998 to 2006 in China, leading to a more than 10% decline in total rice planting area and approximately a 5% decline in total rice production (Xin and Li, 2009). These facts highlight the need for developing new rice production systems with high labor efficiency to maintain or increase the planting area of double-season rice in China.

Large-scale farming is a feasible way to utilize labor effectively and has developed rapidly in recent years in China under governmental guidance (Kung, 2002; Xia et al., 2017). The development of large-scale farming has promoted the adoption of mechanized transplanting techniques for rice production in China, where manual transplanting is the traditional method to establish rice. However, in intensive rice cropping systems, the shift in establishment method from manual transplanting to mechanized transplanting can shorten the rice growth duration due to the reduced seedling nursery period (10–15 days) caused by the high seeding rate (Huang and Zou, 2018). Moreover, the rice growth duration can be further shortened under large-scale farming conditions because of increases in time of farming operations (pre-crop harvesting, land preparation, and transplanting). Therefore, high-yielding rice cultivars with shorter growth durations must be developed for intensive mechanized large-scale rice production.

The middle and lower reaches of the Yangtze River basin, especially Hunan and Jiangxi provinces, make up the major double-season rice cropping region in China. In this region, total growth durations (from sowing to maturity) of early-season rice cultivars (110–120 days) are generally shorter than those of late-season rice cultivars (120–130 days) under traditional manually transplanted conditions. This suggests that it is possible to select short-duration (less than 115 days) cultivars from existing early-season rice cultivars for machine-transplanted late-season rice production. However, there is limited information available on the yield performance of early-season rice cultivars grown as machine-transplanted late-season rice, which may be different from their yield when grown in the early season due to varied climatic conditions.

In the present study, field experiments were conducted over 2 years to determine the growing-season climatic factors (temperature and solar radiation), growth duration, and grain yield of early-season rice cultivars grown in early and late seasons under machine-transplanted conditions. The main objective of this study was to identify whether existing early-season rice cultivars are potential resources for selecting high-yielding short-duration cultivars of machine-transplanted late-season rice.

Materials and Methods

Field experiments were conducted in Yongan Town (28°09′N, 113°37′E, 43 m a.s.l.), Hunan Province, China in the early and late rice-growing seasons in 2015 and 2016. The soil of the experimental field was clayey with the following properties: pH 5.95, 28.69 g kg^{-1} organic matter, 2.89 g kg^{-1} total N, 0.85 g kg^{-1} total P, 5.89 g kg^{-1} total K, 190 mg kg^{-1} available N, 24.7 mg kg^{-1} available P, and 159 mg kg^{-1} available K in 2015; and pH 5.95, 27.16 g kg^{-1} organic matter, 2.67 g kg^{-1} total N, 0.76 g kg^{-1} total P, 5.94 g kg^{-1} total K, 198 mg kg^{-1} available N, 22.8 mg kg^{-1} available P, and 163 mg kg^{-1} available K in 2016. The soil characteristics were based on samples taken from the upper 20 cm of the soil before transplanting in the early season in both years.

Eight early-season rice cultivars, Liangyou 6, Lingliangyou 211, Lingliangyou 268, Xiangzaoxian 32, Xiangzaoxian 42, Zhongjiazao 17, Zhongzao 39, and Zhuliangyou 819, were used in both the early and late seasons in 2015. These cultivars were selected because they are widely grown by rice farmers in the study region and their total growth durations are less than 115 days. In 2016, four rice cultivars, Lingliangyou 268, Zhongjiazao 17, Zhongzao 39, and Zhuliangyou 819, were selected because of their good yield performance (more than 7.5 Mg ha^{-1}) in the late season in 2015.

Rice cultivars were arranged in a randomized complete-block design with three replications and a plot size of 30 m^2. The same plots with the same cultivars were used in early and late seasons.

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Crop management followed local standard practices. Namely, pre-germinated seeds were sown in seedling trays (length × width × height = 58 × 25 × 2 cm^3) at a rate of 120 g per tray on 27 March in the early season and on 6 July in the late season. Seedlings were transplanted at the V3 growth stage in both the early and late seasons. Transplanting was done at a hill spacing of 25 × 11 cm^2 with 4–5 seedlings per hill, using a high-speed rice transplanter (PZ80-25; Dongfeng Iseki Agricultural Machinery Co., Ltd., Xiangyang, China). All plots received 150 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1}, and 180 kg K_2O ha^{-1} in the early season and 165 kg N ha^{-1}, 100 kg P_2O_5 ha^{-1}, and 200 kg K_2O ha^{-1} in the late season. The N fertilizer was applied in three splits: 50% as basal fertilizer (1 day before transplanting), 40% at the early tillering stage (7 days after transplanting), and 10% at panicle initiation (R0 growth stage) in the early season; and 60% as basal fertilizer, 30% at the early tillering stage, and 10% at panicle initiation in the late season. P fertilizer was applied as basal fertilizer, and the K fertilizer was split equally as basal fertilizer and at panicle initiation in both the early and late seasons. The strategy for water management started with flooding, followed by midseason drainage, re-flooding, moist intermittent irrigation, and finally drainage. Weeds, insects, and pathogens were controlled by spraying chemicals according to recommendations by the local department of plant protection. Briefly, weeds were controlled by applying 25-mg penoxsulam ml^{-1} suspension concentrate at 900 ml ha^{-1}. Striped rice borer, planthopper, and leaf roller were controlled by using 20% triazophos emulsion concentrate at 750 ml ha^{-1}, 25% buprofezin wettable powder at 750 g ha^{-1}, and 45% phoxim emulsion concentrate at 900 ml ha^{-1}, respectively. Rice sheath blight and false smut were controlled by applying 5% validamycin aqueous solution at 2625 ml ha^{-1}.

Daily mean temperature and solar radiation were measured from transplanting to maturity with a Vantage Pro2 weather station (Davis Instruments Corp., Hayward, CA, USA). Average daily mean temperature and incident solar radiation (i.e. the summation of daily solar radiation) were calculated. Growth duration (number of days) from transplanting to maturity (R9 growth stage) was recorded. At maturity, grain yield was determined from a 5-m^2 area for each plot and adjusted to the standard moisture content of 0.14 g H_2O g^{-1}. Daily grain yield was calculated by dividing the grain yield by the growth duration from transplanting to maturity. Apparent radiation use efficiency (RUE_A) was calculated by dividing the grain yield by the incident solar radiation over the entire season.

Data analysis was performed using analysis of variance and linear regression (Statistix 8; Analytical Software, Tallahassee, FL, USA). Means of cultivars were compared based on the least significant difference test at the 0.05 probability level.

Results

Daily mean temperature tended to increase and decrease from transplanting to maturity in the early and late seasons, respectively (Figure 1a, Figure 1b). Seasonal average daily mean temperature was lower in the early season than in the late season by 2.1 °C in 2015 and 3.1 °C in 2016.

Growth durations from transplanting to maturity of eight cultivars were 6–18 days shorter in the late season than in the early season in 2015 (Table 1). In 2016, growth duration from transplanting to maturity of Lingliangyou 268 was 1 day longer in the late season than in the early season, whereas those of the other three cultivars were 2–7 days shorter in the late season than in the early season (Table 2).

The difference in incident solar radiation between the early and late seasons was relatively small and inconsistent across cultivars in 2015 (Table 1). In 2016, incident solar radiation was more than 10% higher in the late season than in the early season for all four cultivars (Table 2).

Grain yield was significantly affected by cultivar, season, and their interaction in both 2015 and 2016 (Tables 1 and 2). In 2015, Lingliangyou 268 and Xiangzaoxian 42 produced the highest and lowest grain yield in the early season, respectively, while in the late season the highest and lowest

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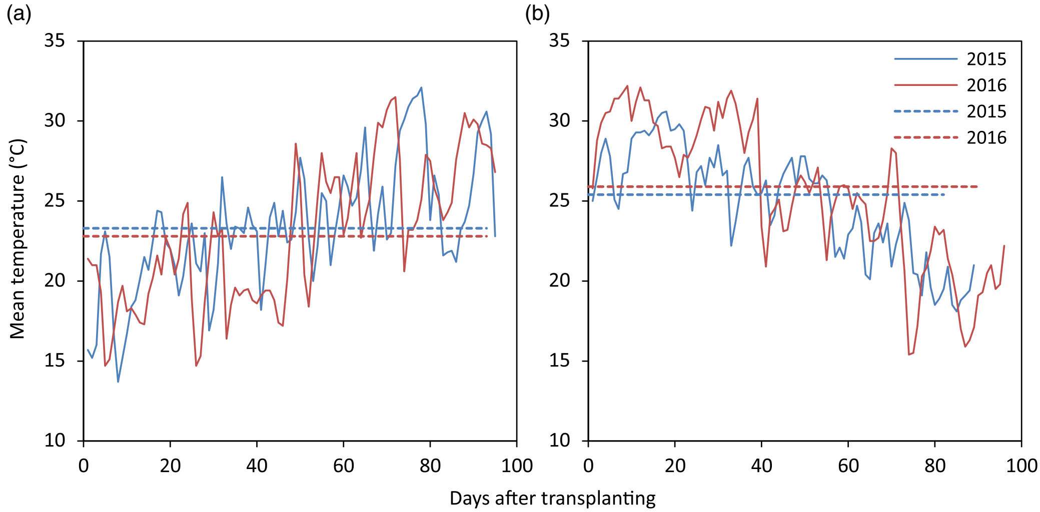

Figure 1. Daily mean temperature during (a) the early and (b) late rice-growing seasons in 2015 and 2016. Dashed lines represent seasonal averages across cultivars.

grain yield were obtained with Zhongjiazao 17 and Xiangzaoxian 32, respectively (Table 1). In 2016, Zhuliangyou 819 had the highest grain yield followed by Zhongzao 39, Lingliangyou 268, and Zhongjiazao 17 in the early season, whereas in the late season the highest grain yield was recorded in Lingliangyou 268 followed by Zhuliangyou 819, Zhongzao 39, and Zhongjiazao 17 (Table 2). Grain yield was higher in the late season than in the early season by 6% in 2015 and by 9% in 2016 (Tables 1 and 2). Specifically, it was observed that the maximum grain yield of 9.61 Mg ha^{-1} in the late season was produced by Zhongjiazao 17 in 2015; Lingliangyou 268 had the highest average grain yield of 8.57 Mg ha^{-1} in the late season across both years.

The effects of cultivar, season, and their interaction on daily grain yield were similar to those on grain yield in both years (Tables 1 and 2). Zhongjiazao 17 produced the maximum daily grain yield of 108 kg ha^{-1} d^{-1} in the late season in 2015. Averaged across both years, Lingliangyou 268 had the highest daily grain yield of 95 kg ha^{-1} d^{-1} in the late season.

The main effect of cultivar and the interaction effect of cultivar and season on RUE_A were significant in both 2015 and 2016 (Tables 1 and 2). The main effect of season on RUE_A was significant in 2015 but was not significant in 2016. In 2015, the highest and lowest RUE_A in the early season were recorded in Lingliangyou 268 and in Xiangzaoxian 42, respectively, whereas in the late season Zhongjiazao 17 and Xiangzaoxian 32 had the highest and lowest RUE_A, respectively (Table 1). RUE_A was 7% higher in the late season than in the early season. In 2016, the highest RUE_A was obtained in Zhuliangyou 819 followed by Zhongzao 39, Lingliangyou 268, and Zhongjiazao 17 in the early season, while in the late season Lingliangyou 268 had the highest RUE_A followed by Zhuliangyou 819, Zhongzao 39, and Zhongjiazao 17 (Table 2).

Growth duration from transplanting to maturity in the late season was not significantly related to that in the early season (Figure 2a). A similar result was also observed for grain yield (Figure 2b). There was no significant relationship between grain yield and incident solar radiation in both the early and late seasons (Figure 3a). Grain yield was significantly positively related to RUE_A (Figure 3b); about 96 and 68% of yield difference among cultivars was explained by RUE_A in the early and late seasons, respectively.

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Table 1. Growth duration from transplanting to maturity, incident solar radiation, grain yield, daily grain yield, and apparent radiation use efficiency (RUE_A) of eight early-season rice cultivars grown in the early and late seasons in 2015

Cultivar	Growth duration (days)	Incident solar radiation (MJ m^{-2})	Grain yield (Mg ha^{-1})	Daily grain yield (kg ha^{-1} d^{-1})	RUE_A (g MJ^{-1})
Early season					
Liangyou 6	95	1347	7.57cd	80fg	0.56ef
Lingliangyou 211	93	1326	7.96c	86de	0.60cd
Lingliangyou 268	95	1347	8.47b	89cd	0.63bc
Xiangzaoxian 32	89	1232	6.51h	73hi	0.53gh
Xiangzaoxian 42	94	1343	5.42j	58j	0.40i
Zhongjiazao 17	95	1347	7.69cd	81efg	0.57def
Zhongzao 39	94	1343	6.68gh	71i	0.50h
Zhuliangyou 819	91	1278	7.07ef	78gh	0.55fg
Mean	93	1320	7.17	77	0.54
Late season					
Liangyou 6	77	1261	6.94fg	90cd	0.55fg
Lingliangyou 211	80	1289	7.39de	92c	0.57def
Lingliangyou 268	86	1345	8.78b	102b	0.65b
Xiangzaoxian 32	73	1211	6.11i	84ef	0.50h
Xiangzaoxian 42	83	1312	6.92fg	83ef	0.53gh
Zhongjiazao 17	89	1393	9.61a	108a	0.69a
Zhongzao 39	83	1312	7.54d	91c	0.57def
Zhuliangyou 819	82	1295	7.66cd	93c	0.59de
Mean	82	1302	7.62	93	0.58
Analysis of variance (*F*-value)					
Cultivar			92*	53*	61*
Season			43*	396*	57*
Cultivar × season			25*	10*	17*

Within a column, means followed by the same letter are not significantly different according to least significant difference (0.05).
*Denotes significance at the 0.01 probability level.

Discussion

Growth durations from transplanting to maturity of all early-season rice cultivars were reduced when grown in the late season than when grown in the early season in 2015 due to higher seasonal temperature. In 2016, higher seasonal temperature also resulted in reduced growth durations from transplanting to maturity of three of the four rice cultivars in the late season compared with the early season, but the magnitudes were smaller than those in 2015 because low temperature events during the ripening period prolonged growth duration in the late season in 2016 (Figure 1b). Overall, all cultivars had a total growth duration (seedling age plus growth duration from transplanting to maturity) of less than 110 days when grown in the late season. This total growth duration can meet the requirement of a short duration (less than 115 days) for the machine-transplanted late-season rice.

In addition, our results showed that some early-season rice cultivars had good yield performance when grown in the late season. In particular, Zhongjiazao 17 had a daily grain yield of 108 kg ha^{-1} d^{-1} and a grain yield of 9.61 Mg ha^{-1} in the late season in 2015, and Lingliangyou 268 had a daily grain yield of 95 kg ha^{-1} d^{-1} and a grain yield of 8.57 Mg ha^{-1} in the late season averaged across both years. These daily grain yields are comparable to or even higher than those obtained from late-season rice cultivars with longer growth durations (125–132 days) grown in the same location (Jiang et al., 2011). This finding demonstrates that it is feasible to select short-duration cultivars with high productive efficiency from existing early-season rice cultivars for machine-transplanted late-season rice production. This could be a useful strategy at the early period of developing mechanized late-season rice production, because no specific short-duration late-season rice cultivars have been developed.

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Table 2. Growth duration from transplanting to maturity, incident solar radiation, grain yield, daily grain yield, and apparent radiation use efficiency (RUE_A) of four early-season rice cultivars grown in the early and late seasons in 2016

Cultivar	Growth duration (days)	Incident solar radiation ($MJ\ m^{-2}$)	Grain yield ($Mg\ ha^{-1}$)	Daily grain yield ($kg\ ha^{-1}\ d^{-1}$)	RUE_A ($g\ MJ^{-1}$)
Early season					
Lingliangyou 268	95	1369	6.61e	70f	0.48d
Zhongjiazao 17	93	1339	5.90f	63g	0.44e
Zhongzao 39	92	1321	7.09d	77e	0.54b
Zhuliangyou 819	92	1321	8.70a	95a	0.66a
Mean	93	1338	7.08	76	0.53
Late season					
Lingliangyou 268	96	1520	8.36a	87bc	0.55b
Zhongjiazao 17	90	1485	7.17cd	80de	0.48d
Zhongzao 39	90	1485	7.53bc	84cd	0.51cd
Zhuliangyou 819	85	1458	7.77b	91ab	0.53bc
Mean	90	1487	7.71	86	0.52
Analysis of variance (*F*-value)					
Cultivar			59*	77*	78*
Season			49*	83*	3ns
Cultivar × season			42*	22*	48*

Within a column, means followed by the same letter are not significantly different according to least significant difference (0.05).
ns denotes non-significance at the 0.05 probability level.
*Denotes significance at the 0.01 probability level.

The results of this study showed that the cultivars with good yield performance were not consistent in the early and late seasons, and growth duration and grain yield of early-season rice cultivars grown in the late season were not significantly related to those grown in the early season. These facts indicate that the selection of short-duration cultivars of machine-transplanted late-season rice from existing early-season rice cultivars should not be based on their performance in the early season but should instead be selected according to special tests where alternative early-season rice cultivars are grown in the late season to determine their performance.

Solar radiation is a critical factor in crop production because of the role it has in photosynthesis and the energy balance of plant systems (Hatfield and Prueger, 2015). Reports have shown that grain yield is correlated with incident solar radiation in rice (Huang et al., 2016a; Katsura et al., 2008; Zhang et al., 2009). However, in this study, the better yield performance of Zhongjiazao 17 in the late season in 2015 and Lingliangyou 268 in the late season in 2015 and 2016 was mainly attributable to higher RUE_A compared to other cultivars. Moreover, our results showed that grain yield was not related to incident solar radiation but instead to RUE_A in both early and late seasons. This finding suggests that RUE_A could be used as a criterion for selecting high-yielding cultivars of double-season rice. Overall, a grain yield of 7.5 $Mg\ ha^{-1}$ can be achieved at a RUE_A of about 0.55 g MJ^{-1}, and a further increase in each 0.1 g MJ^{-1} in RUE_A can lead to an increase in grain yield of approximately 15% (Figure 3b). The results of this study also highlight that further investigations are required for a fundamental understanding of the physiological processes governing high RUE_A in double-season rice, and Lingliangyou 268 would be a useful cultivar for such investigations of late-season rice due to its good performance in RUE_A across 2 years.

Higher grain yield in the late season compared to the early season was observed in both 2015 and 2016. However, the reason for the seasonal difference in grain yield varied with year. The higher grain yield in the late season compared to the early season was due to higher RUE_A in 2015 and to higher incident solar radiation in 2016. These yearly differences could be partly explained by the low temperature events that occurred during ripening in 2016 (Figure 1b),

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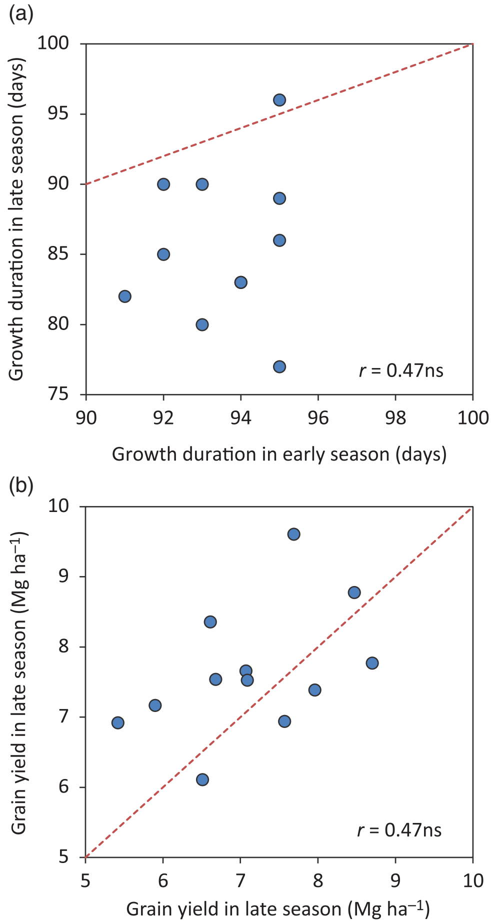

Figure 2. Scatterplots of (a) growth duration from transplanting to maturity, and (b) grain yield of early-season rice cultivars grown in the late season versus those grown in the early season. Data were pooled across 2015 and 2016. Each data point is the mean of three replications for one cultivar in 1 year. Dashed lines are 1:1 lines. ns denotes non-significance at the 0.05 probability level.

namely: (i) low temperature can reduce leaf photosynthesis and radiation use efficiency in rice (Huang et al., 2016b; Maruyama et al., 1990); and (ii) low temperature can prolong growth duration in rice and increase incident solar radiation during the growing season.

Although high grain yield has been, and probably will be, the chief objective in rice production, good rice quality has been increasingly important as people's living standards improve (Yang et al., 2013). Hence, it is also important to evaluate the grain quality of early-season rice cultivars grown in the late season. There was a large difference between the early and late seasons in temperature during the grain-filling period, which was higher in the early than in the late season (Figure 1a, Figure 1b). It has been well documented that high temperature during grain filling can accelerate the grain-filling rate in rice, resulting in loosely packed rice starch granules, decreased head milled rice rate, and increased abnormal and chalky rice grains (Zhong et al., 2005). Consistently, Huang *et al.* (2017) observed that average daily mean temperature during the grain-filling period was higher in the early than in the late season, which resulted in poorer grain quality in rice grown in the early than in the late season. These facts indicate that growing early-season rice cultivars in the late season can lead to an improvement in the grain quality.

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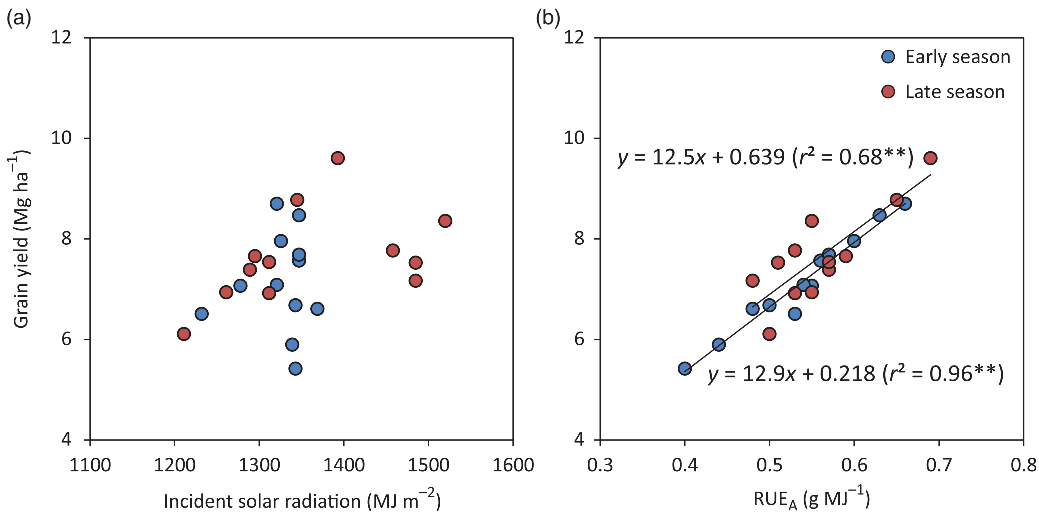

Figure 3. Relationships between grain yield with (a) incident solar radiation and (b) apparent radiation use efficiency (RUE_A) of early-season rice cultivars grown in the early and late seasons. Data were pooled across 2015 and 2016. Each data point is the mean of three replications for one cultivar in 1 year. ** denotes significance at the 0.01 probability level.

Conclusions

Existing early-season rice cultivars can be used as resources for selecting high-yielding short-duration cultivars of machine-transplanted late-season rice, and special tests where alternative early-season rice cultivars are grown in the late season should be done to determine their performance of growth duration and grain yield for such selection. RUE_A could be used as a criterion for selecting high-yielding short-duration rice cultivars, and Lingliangyou 268 would be a useful cultivar for determining the physiological processes governing high RUE_A in short-duration late-season rice.

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