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RESEARCH ARTICLE

Dry direct-seeded rice as an alternative to transplanted-flooded rice in Central China

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Abstract Dry direct-seeded rice is an alternative cropping technique that should require less water and labor than classical transplanted-flooded rice. Here, we studied growth, yield and resource use efficiency of rice cultivation in Central China, in 2012 and 2013. We compared dry direct-seeded rice and transplanted-flooded rice. For dry direct-seeded rice, we maintained aerobic conditions up to five-leaf stage followed by anaerobic conditions until maturity. We grew three rice cultivars: Lvhan1, Huanghuazhan, and Yangliangyou6. We measured grain yield, yield components, water consumed, water productivity and nitrogen use efficiency for grain production (NUEg). Our results show that grain yield of dry direct-seeded rice, of 9.01 Mg/ha, is identical to grain yield of transplanted-flooded rice, across cultivars and for both years. The grain yield of dry direct-seeded rice is mainly controlled by the panicle number. Moreover, dry direct-seeded rice uses 15.3 % less water than transplanted-flooded rice. Dry direct-seeded rice increased the grain nitrogen use efficiency by 20.3 % in 2012 and 11.2 % in 2013.

Keywords Water and labor shortage · Dry direct-seeded rice · Transplanted-flooded rice · Grain yield · Nitrogen use efficiency (NUE) · Water productivity (WP)

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1 Introduction

Rice (*Oryza sativa* L.), a staple food for more than half of the world's population, is grown in more than 95 countries across the globe (Coats 2003; IRRI 2002). China is the main producer of rice, contributing more than 28 % of total global rice production. Therefore, stability of rice production in China plays a key role in the world's food security (FAOSTAT 2011). In China, traditional transplanted flooded rice is the major production system and nearly 95 % of the rice is grown under such conditions with prolonged periods of flooding (Peng et al. 2009). Transplanted-flooded rice consumes more than 50 % of the fresh water resources in China that are diverted for human uses (Cai and Chen 2000). However, in recent years, depleting water resources governed by climate change and labor shortage are threatening the sustainability and productivity of transplanted-flooded rice. Tuong and Bouman (2003) reported that, in Asia, 39 million ha of irrigated rice may suffer from "physical water scarcity" or "economic water scarcity" by 2025. Presently, per capita fresh water availability in China is among the lowest in Asia (Liu and Diamond 2005). Compared with other cereal crops such as wheat and maize, transplanted-flooded rice consumes two or three times more water. Transplanted-flooded rice leads to high losses of water through puddling, surface evaporation and percolation (Farooq et al. 2011). Chauhan and Opeña (2012) reported that puddling in transplanted-flooded rice systems consumes up to 30 % of the total rice water requirement. Although, puddling is favorable in rice–rice cropping systems, as it reduces soil permeability, creates hardpans and reduces water losses through percolation. Nonetheless, repeated puddling operations negatively affect the following non-rice upland crop in rotation (McDonald et al. 2006) by dismantling soil aggregates, reducing permeability in subsurface layers, and forming hardpans at shallow depths (Sharma et al. 2003).

Taking the advantages of saving water and labor and increasing system productivity, dry direct-seeded rice has been believed to be an optimal option for rice production (Kumar and Ladha 2011). Dry direct-seeded rice refers to the process of establishing the crop from seeds sown in the nonpuddled and unsaturated soil (Fig. 1a, left); in contrast, the seedlings from nursery are transplanted in the puddle soil in transplanted-flooded rice (Fig. 1a, right). Dry direct-seeding is adopted in upland rice (Gupta and O'Toole 1986) and aerobic rice (Bouman et al. 2007). In the past decades, numerous researchers worldwide have dealt with yield performance and water use efficiency or water productivity (WP) of dry direct-seeded rice, but they reported variable yield response depending upon location and type of cultivar. Some studies have reported that more than 11.2 t/ha grain yield was achieved in dry direct-seeded rice (Dong et al. 2005; Kato et al. 2009); Stevens et al. (2012) in a study conducted in Mossouri, USA, reported that dry direct-seeded rice reached 10.3 Mg ha^{-1} grain yield with 750 mm water input which was far below the water input in transplanted-flooded rice. In Japan, across various cultivars and locations, the average grain yield of dry direct-seeded rice was about 9.6 t/ha (Yun et al. 1997; Kato et al. 2009; Katsura and Nakaide 2011; Matsunami et al. 2009). In China, a grain yield of 8.4 t/ha with flush irrigation was reported in Jiangsu Province (Shi et al. 2001); Zhao et al. (2007) reported 5.33 % higher grain yields and about 25–50 % lower water use in dry direct-seeded rice than transplanted-flooded rice. Zhu (2008) documented that sowing of rice in dry direct-seeded rice system increased the grain yield by 22 % and reduced the water input by 6000 m^3 ha^{-1} compared with transplanted-flooded rice. Input water savings of 35–57 % have been reported for dry direct-seeded rice sown into non-puddled soil compared with continuously flooded (Sharma et al. 2002; Singh et al. 2002). Results of farmers' participatory trials suggested a small increase or 10 % decline in yield of dry direct-seeded rice compared with transplanted-flooded rice, and around a 20 % reduction in water requirement (Gupta et al. 2003). Kato and

a

b

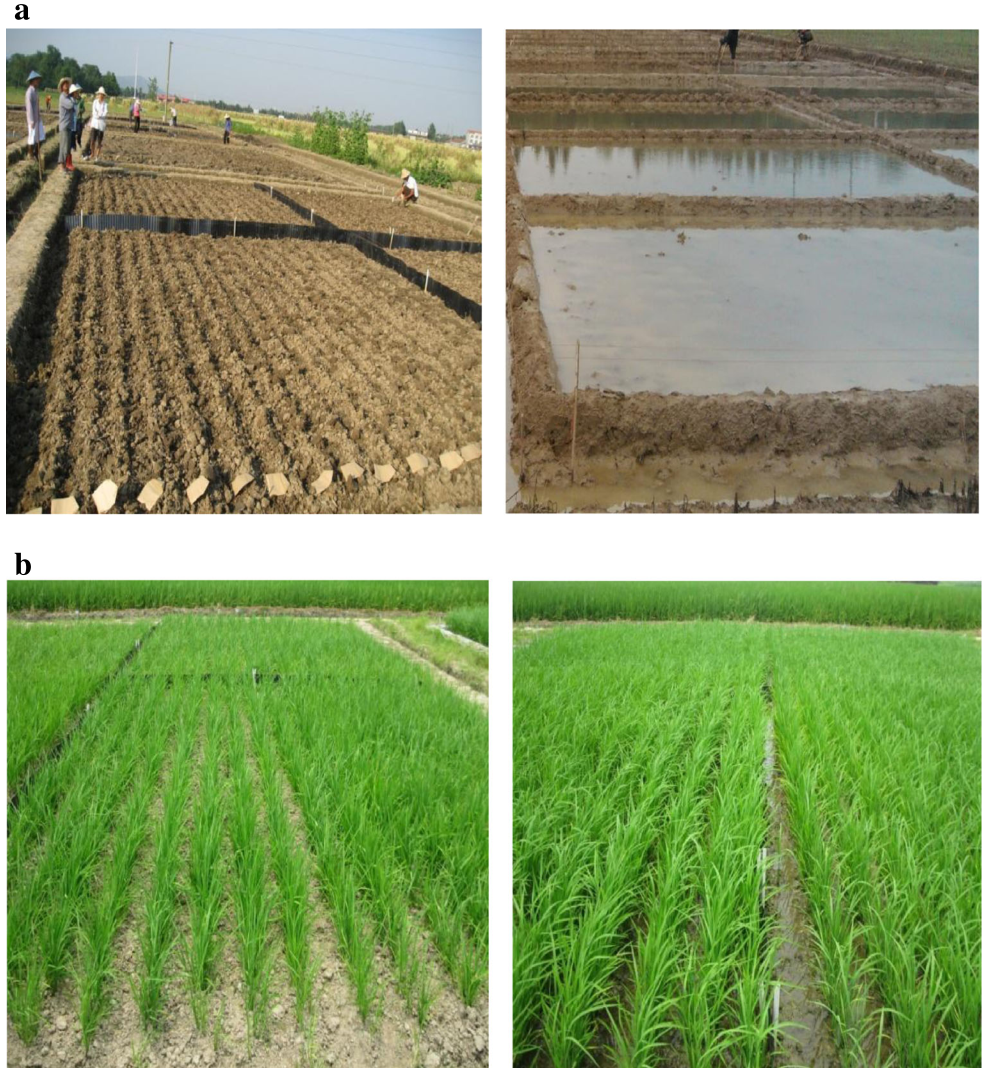

Fig. 1 **a**: Soil preparation for dry direct-seeded rice (*left*) and for traditional transplanted-flooded rice (*right*); **b** water management in dry direct-seeded rice system, before irrigation (*left*) and after irrigation (*right*)

Katsura (2014) observed that WP in dry direct-seeded rice ranged from 0.59 to 1.37 kg grain m^{-3} water among different locations and irrigation schedules. They recorded different yield and WP because of varying environment and irrigation schedule. Nitrogen use efficiency in dry direct-seeded rice was also different from that in transplanted-flooded rice. With optimal water management, dry direct-seeded rice can achieve nitrogen use efficiency of over 80 % (Wilson et al. 2000), much higher than that in transplanted-flooded rice (30–40 %) (Zheng et al. 2007).

To date, plenty of work has been done on exploring yield performance, WP and nitrogen use efficiency of dry direct-seeded rice system based on aerobic soil conditions (both rainfed and control irrigation). Nonetheless, few studies have been conducted to unravel the crop performance and resource use efficiency in dry direct-seeded rice systems under anaerobic (flooded) soil conditions. Therefore, the present study was carried out in Central China (one of the largest rice-planting regions in China) aimed at estimating fthe easibility of dry direct-seeded rice kept under anaerobic conditions against transplanted-flooded rice on the basis of rice growth and yield performance and resource use efficiency.

2 Materials and methods

2.1 Site description

The present study was conducted at Zhougan Village (29°51′ N, 115°33′E), Dajin Town, Wuxue County, Hubei Province, China, during the 2012 and 2013 growing seasons. The organic matter, total nitrogen (N), available phosphorus, and potassium of upper 20 cm soil were 17.7 g kg^{-1}, 0.17 %, 30.4 mg kg^{-1}, and 80.7 mg kg^{-1}, respectively.

2.2 Experimentation and data collection

The proposed study was laid out in a randomized complete block design under split plot arrangements with four replications. Different planting patterns, viz., dry direct-seeded rice and transplanted-flooded rice, were assigned to main plots while three different indica cultivars (Lvhan1, Huanghuazhan, and Yangliangyou 6) with different growth durations (Table 2) were kept in subplots (6 m×5 m). Lvhan1 is a typical drought r-sistant inbred cultivar with short growth duration, while the inbred cultivar Huanghuazhan and hybrid cultivar Yangliangyou 6 are mega varieties and commonly grown by rice farmers in Central China.

In order to minimize the seepage losses, the main plots were separated with triple bunds to avoid flow of water between the dry direct-seeded rice and transplanted-flooded rice plots. All bunds were covered with plastic film installed to a depth of 20 cm below the soil surface. In the dry direct-seeded rice plots, dry seeds were sown manually during first week of May in both years keeping 25-cm-wide rows. The soil in the dry direct-seeded rice plot was dry-ploughed and harrowed, without puddling. The seeding rate for each cultivar was 60 kg ha^{-1}. In the transplanted-flooded rice plots, pre-germinated seeds were sown in a seedbed at the beginning of May. During soil preparation, 125 mm water was applied in the main plots with an area of 120 m^2 for soil ploughing, harrowing and puddling in both years. Twenty-five-day-old seedlings were transplanted into the well-prepared paddy soil at the end of May in both years. Transplanting was done at a hill spacing of 25×13.3 cm with three seedlings per hill. No irrigation was applied to the dry direct-seeded rice plots until the five-leaf stage; the plots before irrigation are shown in Fig. 1b, left. After the five-leaf stage, the water level was allowed to fluctuate between 5 and 10 cm during the whole rice-growing season (Fig. 1b, right), whereas, in the transplanted-flooded rice plots, a 1- to 3-cm water layer was kept during the first week after transplanting, and then the flooded water was kept at the same level with 5- to 10-cm water depth for all plots. A flow meter installed in the irrigation pipelines was used to monitor the amount of irrigation water. Data regarding daily rainfall were recorded by a rain gauge located in the center of the experimental field. Total water use and WP were calculated based on water used for puddling during land preparation, irrigation and rainfall during the growing season.

A fertilizer dose of 150:40:00 kg N:P_2O_5:K_2O ha^{-1} was applied equally to all treatments. The whole of the phosphorus pentoxide, 26 % of the N, and 50 % of potassium oxide was applied as a starter basal dose, while residual N was equally split at the middle tillering stage and the panicle initiation stage, and 50 % of the potassium was top-dressed at panicle initiation at a rate of 50 kg K_2O ha^{-1}. An amount of Zn (5 kg ha^{-1}) was also applied to the soil as starter dose. Weeds, diseases and insects were intensively controlled during the whole growing season in both years.

At maturity, 0.5 m^2 (15 hills for transplanted-flooded rice and 10 sub-samples divided from 1 m along the adjacent two rows for dry direct-seeded rice) plants were sampled to determine yield components, aboveground total biomass and harvest index. Panicle number was counted in each sample to determine the panicle number per m^2, and then plants were separated into straw and panicles. Through hand-threshing, all spikelets parted from the rachis were submerged into the tap water to separate the filled grains from the others. Further screening was completed by a winnowing cleanliness instrument (FJ-1; China Rice Research Institute, China) to separate the half-filled spikelets from the unfilled spikelets. Three sub-samples of 30.0 g of filled spikelets, 2.0 g of unfilled spikelets, and all of the half-filled spikelets were taken to count the number of spikelets. After oven-drying at 70 °C to constant weight, dry weight of straw, rachis and filled, half-filled and unfilled spikelets were determined. Aboveground total dry weight is the summation of straw, rachis and all the spikelets. Spikelets per panicle, grain-filling percentage (100×filled spikelets number/total spikelets number), and harvest index (100×filled spikelets weight/aboveground total biomass) were calculated. Grain yield was determined from a 5-m^2 area in each plot and adjusted to the standard moisture content of 0.14 g H_2O g^{-1} fresh weight. WP (kg m^{-3}) was calculated as the grain yield per unit total water input including water used for puddling, irrigation and rainfall during growing season. Tissue N concentration was determined by the C/N analyzer (Vario Max CN, Hannau, Germany) to calculate the N content in grains and straw. Nitrogen use efficiency for grain production (NUE_g) was calculated as the ratio of filled grain weight to total N uptake.

2.3 Weather data

Except for rainfall, other meteorological data were collected from a weather station (CR800; Campbell, USA) near the experimental field. Data collected included daily average temperature and solar radiation.

2.4 Data analysis

Data were analyzed to confirm its variability following analysis of variance using Statistix 8.0. The differences between treatments were separated using Least Significance Difference (LSD) test at 0.05 probability level in each year.

3 Results and discussion

3.1 Weather conditions

The weather data revealed that daily average temperature and solar radiation during the course of study was similar in 2012 and 2013 (Fig. 2). Nonetheless, data regarding rainfall and daily maximum temperature showed significant variations between 2 years, but it was not much different from the previous 10-year average (data not shown). Both the amount and frequency of rainfall during the rice growing season were higher in 2012 than in 2013 (Table 1; Fig. 2e, f). High temperature (daily maximum temperature≥35˚C) occurred more frequently in 2013 (Fig. 2b) than 2012 (Fig. 2a).

3.2 Irrigation and total water input

Compared with transplanted-flooded rice, dry direct-seeded rice consumed 17.6, 14.9, and 15.4 % less water (puddling, irrigation, and rainfall) in Lvhan1, Huanghuazhan, and Yangliangyou6, respectively, in 2012, and 16.0, 14.1, and 13.7 % less water in 2013 (Table 1). Across the cultivars and years, dry direct-seeded rice used 15.3 % less water than transplanted-flooded rice. In both years, rainfall in dry direct-seeded rice was comparable to that in transplanted-flooded rice. Rainfall during the whole growing season accounted for approximately 50 and 35 % of total water input in 2012 and 2013, respectively. Additionally, accompanied by less irrigation times, the amount of irrigation in dry direct-seeded rice was always lower than transplanted-flooded rice in all cultivars (Table 1). Regardless of rainfall, and taking the water used for puddling into consideration, dry direct-seeded rice saved water up to 26 % on average.

Compared with transplanted-flooded rice, dry direct-seeded rice with 4–5 fewer irrigations saved the water input and consequently reduced the labor cost. Bouman et al. (2002) reported that dry direct-seeded rice could save 50 % of total water input, compared with transplanted-flooded rice. However, water saving in this study was not as high as reported by previous studies. This might be attributed to the anaerobic conditions and lack of hardpan in the dry direct-seeded rice field, which led to loss of water by seepage. Sudhir-Yadav et al. (2011) argued that seepage could result in the large amount of water use in dry direct-seeded rice, because it is one of primary ways to consume water in agriculture, especially in fields without puddling.

The data depicted that total water input with a low rainfall and a high irrigation in 2013 was significantly different from that in 2012. One reason is that high temperature increases the water evaporation, and the other is that the extra water is used to cool the crop population for counteracting extremely high temperatures. Cooling of crop plants by water usage in response to high temperature is important to avoid a yield penalty, as previous studies have reported that extremely high temperatures can lead to a huge yield loss (Mohammed and Tarpley 2011; Prasad et al. 2006).

3.3 Grain yield, water productivity and nitrogen use efficiency

Grain yield did not vary between the dry direct-seeded rice and transplanted-flooded rice across three cultivars in both years (Table 2). Nevertheless, the differences in panicle number per m^2 between dry direct-seeded rice and transplanted-flooded rice were significant and consistent across cultivars and years. On average, dry direct-seeded rice produced 28.6 and 19.5 % more panicles per m^2 than transplanted-flooded rice in 2012 and 2013, respectively. In contrast, the spikelets per panicle showed an opposite tendency with panicle number per m^2. Across the cultivars, number of spikelets per m^2 were 25.5 and 16.7 % higher in transplanted-flooded rice than that in dry direct-seeded rice in 2012 and 2013, respectively, but the difference between cropping patterns were non-significant except in Huanghuazhan and Yangliangyou6 during 2012 (Table 2). There were inconsistent differences in grain weight and grain filling percentage between dry direct-seeded rice

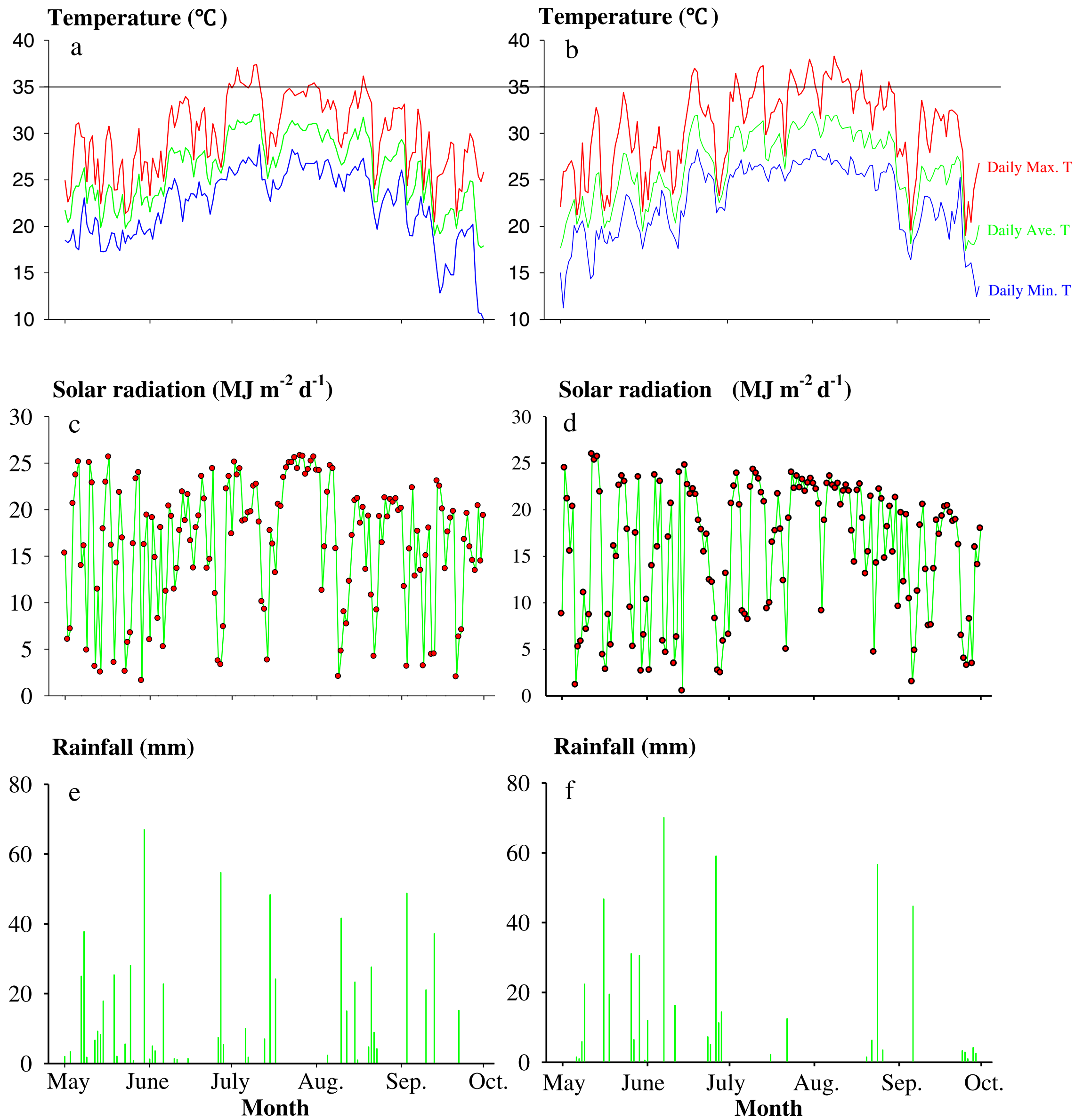

Fig. 2 Temperature (daily maximum, daily average and daily minimum), solar radiation and rainfall during the rice-growing season at Wuxue County, Hubei Province, China, in 2012 (**a**, **c**, **e**) and 2013 (**b**, **d**, **f**)

Table 1 Water input of three cultivars under dry direct-seeded rice (DSR) and traditional transplanted-flooded rice (TFR) conditions at Wuxue County, Hubei Province, China, in 2012 and 2013

Cultivar	Establishment method	2012					2013				
		Irrigation times	Puddling (mm)	Irrigation (mm)	Rainfall (mm)	Total water input[a] (mm)	Irrigation times	Puddling (mm)	Irrigation (mm)	Rainfall (mm)	Total water input (mm)
Lvhan1	DSR	13	0	456	454	910	11	0	659	376	1035
	TFR	17	125	536	443	1104	16	125	731	376	1232
Huanghuazhan	DSR	13	0	456	524	980	13	0	769	444	1214
	TFR	17	125	536	489	1150	18	125	844	444	1413
Yangliangyou6	DSR	13	0	456	576	1032	13	0	769	489	1258
	TFR	17	125	536	559	1220	18	125	844	489	1458

[a] Total water input=Puddling+Irrigation+Rainfall

Table 2 Yield and yield components of three cultivars under dry direct-seeded rice (DSR) and traditional transplanted-flooded rice (TFR) conditions at Wuxue County, Hubei Province, China, in 2012 and 2013

Cultivar	Establishment method	Growth duration (day)	Grain yield (Mg ha^{-1})	Total biomass (Mg ha^{-1})	Harvest index	Panicles (m^{-2})	Spikelets per panicle	Spikelets m^{-2} (×1000)	Grain filling (%)	1000-grain weight (g)
2012										
Lvhan1	DSR	105	8.71 a	16.56 a	0.49 b	363 a	105.7 b	38.2 a	86.8 b	24.7 a
	TFR	105	8.23 a	14.05 b	0.54 a	255 b	140.1 a	35.7 a	91.5 a	23.1 b
Huanghuazhan	DSR	116	9.73 a	17.34 a	0.51 a	369 a	144.1 b	53.2 a	82.6 b	20.2 a
	TFR	116	9.24 a	17.81 a	0.49 a	317 b	155.1 a	49.1 b	88.2 a	20.1 a
Yangliangyou6	DSR	133	10.39 a	19.15 a	0.48 a	310 a	137.9 b	42.7 b	79.6 a	27.3 b
	TFR	133	10.56 a	19.99 a	0.49 a	244 b	188.0 a	45.9 a	76.7 a	27.7 a
2013										
Lvhan1	DSR	104	6.77 a	13.29 a	0.47 a	281 a	98.2 b	27.5 a	91.9 a	24.8 a
	TFR	104	6.83 a	13.24 a	0.48 a	244 b	117.0 a	28.4 a	91.7 a	24.3 b
Huanghuazhan	DSR	118	8.51 a	15.94 a	0.53 a	332 a	147.5 b	49.0 a	86.4 b	19.9 a
	TFR	118	8.94 a	15.57 a	0.52 a	281 b	165.6 a	46.4 a	88.8 a	19.5 a
Yangliangyou6	DSR	132	9.96 a	18.71 a	0.51 a	272 a	150.6 b	40.8 a	83.7 a	27.7 a
	TFR	132	10.25 a	17.73 a	0.52 a	217 b	178.8 a	38.7 a	85.4 a	27.7 a

Within a column for each cultivar in 1 year, means followed by the different letters are significantly different from each other at LSD (0.05)

and transplanted-flooded rice. Likewise, the total biomass and harvest index did not differ between dry direct-seeded rice and transplanted-flooded rice in both years, except for Lvhan1 in 2012. In this study, WP was significantly higher in dry direct-seeded rice as compared to transplanted-flooded rice. WP in dry direct-seeded rice ranged from 0.96 to 1.02 and from 0.70 to 0.79 kg grain m^{-3} water in 2012 and 2013, respectively. Total N content (grains and straw) was not significantly different among cultivars, and it was lower in dry direct-seeded rice than in transplanted-flooded rice (Table 3). The differences in NUE_g between dry direct-seeded rice and transplanted-flooded rice were significant and consistent, except for Yangliangyou6 in 2013. Compared with transplanted-flooded rice, dry direct-seeded rice had 26.0, 10.4, and 24.5 % higher NUE_g in 2012, and 12.9, 14.4, and 6.3 % higher NUE_g in 2013 in Lvhan1, Huanghuazhan, and Yangliangyou6, respectively.

Overall, dry direct-seeded rice production system can furnish comparable grain yield and greater resource use efficiency (WP and NUE_g) than transplanted-flooded rice (Fig. 3). The positive effect of dry direct-seeded rice system may be due to the increased root growth caused by the aerobic soil condition and slight drought stress at the early vegetative stage. Previous studies have shown that the aerobic soil condition can effectively increase tiller emergence and improve rhizosphere environment (Flessa and Fischer 1992), and slight drought stress in early stages can stimulate the root growth, thus improving the absorbing ability of root system before flooding (Kondo et al. 2000). Patrick et al. (1985) reported that the aerobic soil condition increased the amount of soil microorganisms which could increase the decomposition of organic matter and benefit the nutrient availability. In addition, Yang et al. (2007) reported that water-saving irrigation could increase the root activity and nutrient absorbing ability.

Taking the advantage of more panicles per m^2, grain yield of about 10.4 t/ha can be achieved in dry direct-seeded rice system which was comparable to that in transplanted-flooded rice. It demonstrated that, in terms of grain yield, dry direct-seeded rice can replace transplanted-flooded rice in Central China. However, there are still some differences on yield components between dry direct-seeded rice and transplanted-flooded rice, which exist regarding panicles per m^2 and spikelets per panicle (Table 2). Dry direct-seeded rice significantly increase the panicles per m^2, and justified the previous study that higher panicles per m^2 is the most important attribute for high yield (Peng et al. 2008; Tao et al. 2006). In present study, more number of panicles per m^2 in direct-seeded rice mainly occurred due to larger numbers of plant per unit area. High seeding rate (60 kg ha^{-1}) in direct-seeded system resulted in more plant population in unit area that ultimately led to more number of panicles. Spikelets per panicle was negatively correlated with plant population, thus with a higher panicles per m^2, spikelets per panicle of dry direct-seeded rice were lower than that in transplanted-flooded rice. While variations between dry direct-seeded rice and transplanted-flooded rice regarding other yield components did not show the same tendency with grain yield.

To prevent environment pollution caused by excessive use of N and tackle water crisis, reducing N and water inputs without yield loss has been the attractive approach for many years. Due to 29 days less flooding period in the whole growing season, the water requirement in dry direct-seeded rice was lower than that of transplanted-flooded rice (Table 3).

Table 3 Flooding duration, water productivity (*WP*), nitrogen content in grains and straw, and nitrogen use efficiency for grain production (NUE_g) of three cultivars under dry direct-seeded rice (*DSR*) and traditional transplanted-flooded rice (*TFR*) conditions at Wuxue County, Hubei Province, China, in 2012 and 2013, respectively

Cultivar	Establish-ment method	2012					2013				
		Flooding duration	WP (kg m^{-3})	N content in grains (kg ha^{-1})	N content in straw (kg ha^{-1})	NUE_g[a] (kg kg^{-1})	Flooding duration	WP (kg m^{-3})	N content in grains (kg ha^{-1})	N content in straw (kg ha^{-1})	NUE_g (kg kg^{-1})
Lvhan1	DSR	76	0.96 a	124.6 a	62.6 a	46.1 a	75	0.70 a	87.5 a	69.0 a	40.2 a
	TFR	105	0.72 b	131.3 a	65.9 a	36.6 b	104	0.55 b	95.6 a	82.2 a	35.6 b
Huanghuazhan	DSR	87	0.99 a	134.2 a	55.6 b	47.7 a	89	0.70 a	105.1 a	64.6 a	51.5 a
	TFR	116	0.80 b	125.9 a	70.9 a	43.2 b	118	0.63 b	101.9 a	71.4 a	45.0 b
Yangliangyou6	DSR	104	1.02 a	130.6 a	39.1c	54.4 a	103	0.79 a	116.0 a	58.2 a	54.4 a
	TFR	133	0.86 b	147.7 a	79.7 ab	43.7 b	132	0.70 b	117.3 a	61.7 a	51.2 a

Within a column for each cultivar in 1 year, means followed by different letters are significantly different from each other at LSD (0.05)

[a] *NUE_g* grain yield per ha/(N content in grains+N content in straw) per ha

Furthermore, WP in dry direct-seeded rice was significantly higher than that of transplanted-flooded rice. This result indicated that, consistent with other water-saving practices, dry direct-seeded rice could increase WP, but the positive effect was influenced by cultivars and the environment. However, 29 days of flooding period gap did not lead to a tremendous difference in water saving between dry direct-seeded rice and transplanted-flooded rice, the reason perhaps being that the hardpan in transplanted-flooded rice reduced the water loss from percolation, while, in the dry direct-seeded rice system, percolation was higher at the beginning of flooding.

Compared with transplanted-flooded rice, dry direct-seeded rice significantly increased NUE_g in both years. Contrary to Katsura et al. (2010), la arger rice population during the vegetative stage in dry direct-seeded rice did not lead to high N uptake, compared with transplanted-flooded rice. Ammonia volatilization before flooding (Qi et al. 2012) and serious seepage at the beginning of flooding (Sudhir-Yadav et al. 2011) caused nutrient losses, which might be the most important reasons for low N uptake in dry direct-seeded rice. It suggests that the fertilizer should not be applied at tillering in dry direct-seeded rice to avoid the possibility of seepage occurring at the beginning of flooding. In this experiment, higher NUE_g in dry direct-seeded rice might be due to higher N translocation from straw to grains, which indicates that rice plants in dry direct-seeded rice could use less N to

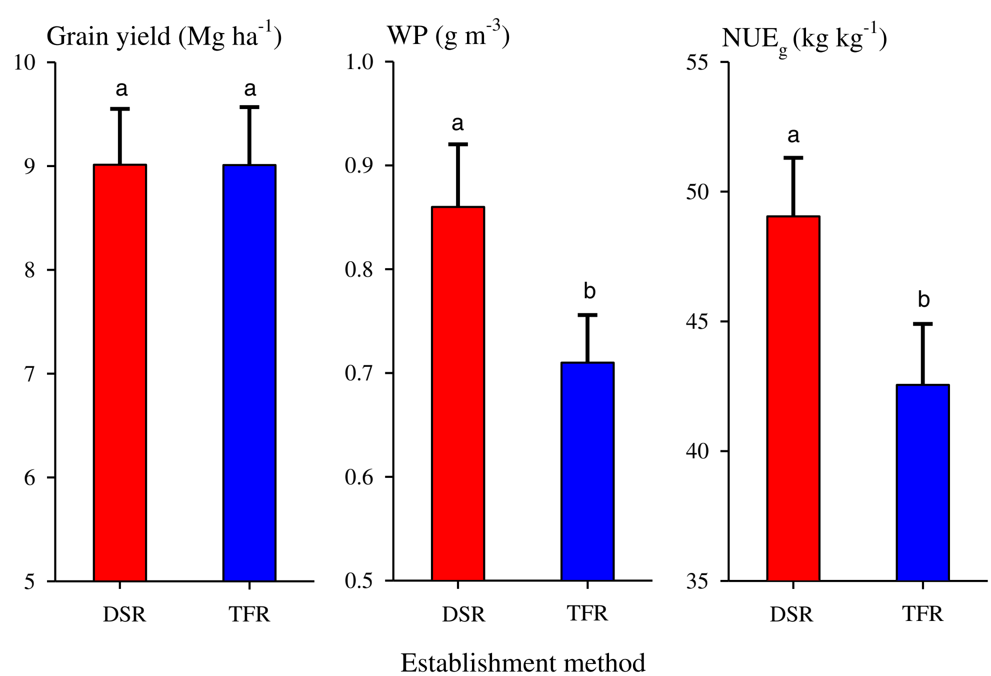

Fig. 3 Comparison of grain yield, water productivity (*WP*) and nitrogen use efficiency for grain production (*NUE_g*) between different establishment methods, dry direct-seeded rice (*DSR*) and traditional transplanted-flooded rice (*TFR*), across three cultivars and 2 years. *Different letters above the bars* mean that the difference between two bars is significant at LSD (0.05)

produce more grains, compared with transplanted-flooded rice. Zhang et al. (2006) reported that total N uptake and NUE_g were positively correlated with grain yield of rice. They suggested that, based on high total N uptake at maturity, it was important to improve NUE_g to both increase yields and profit, and thus suitable for improving the cultivation and breeding in dry direct-seeded rice.

Considerable variations regarding yield and resource use efficiencies existed among cultivars. Super hybrid rice, "Yangliangyou6" with a high biomass accumulation, achieved the highest grain yield and WP in dry direct-seeded rice, while Lvhan1 with a low biomass accumulation achieved the lowest yield and WP in transplanted-flooded rice compared with the rest of the cultivars in both years. These results are consistent with those of Bouman et al. (2007), who reported that higher yield potential leads to higher WP. Crop maturity time also plays an important role in determining grain yield (Tirol-Padre et al. 1996). Inthapanya et al. (2000) reported that late maturing cultivars accumulated more N, while in contrast, maturity had a negative effect on total nutrient content and grain yield. Our results are in accordance with these arguments. Yangliangyou6 as transplanted-flooded rice with the longest growth duration had the highest total biomass and total N uptake, while the shortest growth duration in Lvhan1 resulted in the lowest total biomass among the three varieties. Variation in N uptake among cultivars might be attributed to differences in nutrient uptake periods depending upon maturity time. All these indicated that the "super hybrid rice" Yangliangyou6 with higher yield potential and the inbred cultivar Huanghuazhan in the transplanting rice system can also perform well in dry direct-seeded rice systems. However, panicle size of Yangliangyou6 was much decreased in the dry direct-seeded rice system (Table 2).

The response of the rice crop significantly differed between the 2012 and 2013 growing seasons. Consistent with the difference of grain yield between the 2 years, panicles per m^2, spikelets per m^2, and total biomass in 2013 were also much lower than those in 2012, which could fully explain the yield decline in 2013. The reason for the lower yield in 2013 was the lower tiller number at the panicle initiation stage. The lower tiller number led to a lower leaf area index (LAI) which could subsequently result in the poor radiation interception and decreased biomass accumulation (Katsura et al. 2007). High temperature (daily maximum temperature $\geq$35 °C) might be another reason for the lower yield in 2013 (Fig. 2b), because high temperatures inhibit photosynthesis and increase dark respiration (Turnbull et al. 2002), and can also up-regulate ethylene production (Hays et al. 2007), causing oxidative stress in the plants (Moeder et al. 2002). All these are unfavorable for biomass accumulation, leading to lower grain yield.

In our present study, the grain yield of dry direct-seeded flooded rice declined in 2013; however, such a decline was minimal as compared with the findings of Kreye et al (2009), who reported severe yield decline under monocropping in dry direct-seeded aerobic rice. We also found yield decline in transplanted-flooded rice in our study, which showed that the climatic variation, especially maximum daily high temperature, was responsible for the yield decline in both establishment methods. The yield decline of dry direct-seeded flooded rice did not reflect the influence of continuous cropping in the present study, suggesting the yield stability of this cropping system. However, long-term studies are inevitable to get sound conclusions regarding the yield trend of the dry direct-seeded flooded rice system.

In dry direct-seeded flooded rice, demand of water and labor input were lower, while WP and NUE_g were higher than transplanted-flooded rice, which justifies its feasibility in terms of eco-efficient resource management. Although greenhouse gas emissions were not investigated in the present study, yet there was a 29-day shorter flooding duration in the dry direct-seeded rice as compared to the transplanted-flooded rice could predict less CH_4 emission, and may also reduce N_2O emission as compared to aerobic rice. Furthermore, flooding in the direct-seeded rice system will also lower the weed burden, which will ultimately reduce the use of pesticides. All these illustrate that dry direct-seeded flooded rice would be more competitive to mitigate the threat on resources and the environment in the near future.

4 Conclusion

Dry direct-seeded rice is a sustainable and very feasible alternative to TPR in Central China, based on comparable yield performance and higher resource use efficiencies. Without sprout cultivation and transplanting, it consumed less irrigation water and demands less labor, thus reducing the total inputs. Comparable rice yield in the dry direct-seeded rice system and low input demand justifies the higher output to input ratio. In addition, compared with transplanted-flooded rice, the higher NUE_g and lower total N uptake in dry direct-seeded rice illustrated that improved N uptake of rice plants through cultivation and breeding can make a further increase in grain yield of dry direct-seeded rice. The Yangliangyou6 breed appeared superior to the rest of the varieties regarding its performance on yield, WP, and NUE_g, and can be successfully used in dry direct-seeded rice culture.

However, the evaluation of yield and resource use efficiency was limited by time and space, thus overall evaluation needs multi-location–multi-year experiments. Furthermore, evaluations regarding integrated economic efficiency and ecological benefits of dry direct-seeded flooded rice are required. In addition, there is need to study soil ecology in dry direct-seeded rice culture and develop site-specific production technologies for dry direct-seeded rice.

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