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RESEARCH ARTICLE

Effects of establishment method and water management on yield and water productivity of tropical lowland rice

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Abstract
Modification of the existing cropping practice is needed to maintain rice (*Oryza sativa* L.) productivity and reduce irrigation water input. A 2-year field experiment was conducted during the dry rice growing season of 2016 and 2017 at the Asian Institute of Technology, Pathum Thani, Thailand, to investigate the effects of establishment method and irrigation level on growth, yield, and water productivity of irrigated lowland rice. The treatments consisted of two Thai rice cultivars (Pathumthani 1 and RD57), two establishment methods (dry direct seeding [DDS] and transplanting [TP]), and three irrigation levels (continuous flooding [CF], 15 cm threshold water level below the soil surface for irrigation [AWD15], and 30 cm threshold water level below the soil surface for irrigation [AWD30]). Overall, the performance of RD57 was better than Pathumthani 1 under DDS with 50% higher grain yield and 90% higher water productivity at AWD15. RD57 also had higher shoot dry matter, number of tiller m^{-2}, and number of panicle m^{-2} across establishment methods and irrigation levels. Grain yield and water productivity of RD57 were similar under two establishment methods across irrigation levels, whereas the performance of TP was better than DDS for Pathumthani 1 irrespective of irrigation levels. The highest grain yield and water productivity of Pathumthani 1 was observed at AWD15 under TP and that of RD57 under both establishment methods at the same irrigation level. AWD15 saved 26 and 32% irrigation water under TP and DDS, respectively, compared with TP-CF treatment combination. AWD15 irrigation level could be recommended for greater water productivity without compromising yield when Pathumthani 1 is cultivated through TP and RD57 is cultivated through either DDS or TP. Although water-saving potential was higher compared with CF, AWD30 is not recommended for irrigated lowland rice cultivation due to significant yield reduction.

Keywords: Direct seeding; Pathumthani 1; RD57; Transplanting; Water management; Water savings

Introduction

Rice (*Oryza sativa* L.) plays a vital role in the socioeconomic development and food security of Thailand where it is cultivated in two main seasons, namely wet season (May–October) and dry season (November–April). Major portion of the dry season rice (~47% of the total production) is cultivated in the Central Plain of Chao Phraya River Basin, which is equipped with irrigation facilities (OAE, 2018). The sustainability of rice industry in Thailand is threatened by multiple challenges including financial such as price fluctuations in domestic and international markets, rising input cost, and rising rural wages as well as water scarcity. The Central Plain is also identified as a hot-spot of irrigation water scarcity due to an increased competition with other economic sectors and variable rainfall (Stuart *et al.*, 2018). Water- and resource-efficient methods of rice cultivation are, therefore, needed in this region to ensure food security and enhance economic opportunity.

Important water-saving technologies for irrigated lowland rice include alternate wetting and drying (AWD), direct seeding (DS), aerobic rice culture, and the system of rice intensification (Datta *et al.*, 2017; Pan *et al.*, 2017). A modern form of AWD, known as 'safe' AWD (AWD15), with a threshold of 15 cm water depth below the soil surface has been reported to provide various benefits in irrigated lowland rice production including (i) lodging and disease resistance (Bouman *et al.*, 2007), (ii) increased farmer's income (Lampayan *et al.*, 2015), (iii) reduced irrigation water input (Linquist *et al.*, 2015), and (iv) reduced methane emission (Liang *et al.*, 2016). However, this technology is not widely adopted in the Central Plain of Thailand where water scarcity is becoming increasingly likely (Maneepitak *et al.*, 2019a,b). The yield response to this technique is highly variable depending on soil type, weather conditions, and crop management practices followed.

Dry direct seeding (DDS) establishment method is another water- and input-efficient technique where dry seeds are directly sown into unsaturated, unpuddled soils (Ullah *et al.*, 2017). Increasing water and labor scarcity, rising interest in conservation agriculture, high labor and water demand for transplanting rice, and interest in crop intensification are among the major reasons behind the popularity of this method (Kumar and Ladha, 2011; Ullah *et al.*, 2017). DDS is a better alternative to traditional transplanting (TP) method in drought-prone environments. Uneven distribution of rainfall in the early wet season forces the farmers to delay planting under traditional TP system and consequently they use either old seedlings or discard these plants and prepare a new nursery bed (Ohno *et al.*, 2018), which results in a yield penalty. In contrast, DDS can efficiently utilize the early season rainfall with less demand of labor and water for land preparation as well as crop establishment. A reduction in growth duration under DDS allows the farmers to grow a post-rice crop. The yield performance of DDS is often comparable with the traditional TP method in irrigated areas with assured water availability and weed management (Sudhir-Yadav *et al.*, 2011). However, poor seedling establishment and subsequent weed infestation are among the major constraints of this method limiting yields in drought-prone rainfed lowlands (Fukai and Ouk, 2012).

Pathumthani 1 is a popular aromatic Thai rice cultivar with long grains, delicate flavor, distinctive aroma, soft texture, and high amylose content (Cha-um *et al.*, 2007). These qualities make Pathumthani 1 among the most popular cultivars having high export value (Ariyaphanphitak *et al.*, 2005). Similarly, RD57 is a newly introduced, photoperiod-insensitive cultivar (Ullah *et al.*, 2018) increasingly gaining popularity among Thai farmers. Both cultivars are generally cultivated under traditional TP method with continuous flooding (CF). However, the sustainability of the traditional practice of rice cultivation under CF is threatened by increasing irrigation water scarcity and declining resource availability (Cuong *et al.*, 2017). It is essential to explore alternative ways to produce more rice with less water to boost food supply for the growing population and sustain environmental health. Therefore, evaluation of the performance of these irrigated lowland cultivars under water-efficient techniques such as AWD and DDS is critical for the sustainability of rice production in the changing climate scenarios. To the best of our knowledge, no published literature is available dealing with the performance of irrigated lowland cultivars under different establishment methods and irrigation levels. We hypothesized that irrigated lowland cultivars would perform equally well under DDS and different threshold levels of AWD. The objective of the present study was to investigate the effects of establishment method and irrigation level on growth, yield, and water productivity of irrigated lowland rice.

Materials and Methods

Experimental site

Field experiments were conducted during the dry rice growing season (December–April) of 2016–2017 and 2017–2018 at the Asian Institute of Technology, Pathum Thani, Thailand, which

Table 1. Mean monthly maximum temperature (T_{max}), minimum temperature (T_{min}), and total monthly rainfall during the dry rice growing seasons of 2016–2017 and 2017–2018

	T_{max} (°C)		T_{min} (°C)		Rainfall ($m^3\ ha^{-1}$)	
Month	2016–2017	2017–2018	2016–2017	2017–2018	2016–2017	2017–2018
December	32.2	31.8	23.4	21.8	0	166
January	33	33.1	23.4	22.9	82	601
February	35.4	33.5	22.6	22.9	0	417
March	37	35.3	24.7	24.8	1043	1159
April	37.5	36.3	25.9	25.3	976	981

is located at 14° 2′ 24″ N latitude and 100° 22′ 12″ E longitude with an elevation of 2.27 m above mean sea level. The average annual minimum and maximum temperatures of the experimental site are 24 and 35 °C, respectively, with an average annual rainfall of about 1300–1400 mm. This central region has two distinct seasons: wet (May–October) and dry (November–April) where most of the annual rainfall is received in the wet season. The soil of the experimental site is Bangkok clay soil and poorly drained with major physicochemical properties of the surface soil (0–20 cm) as follows: sand 5.2%, silt 30.7%, clay 64.1%, pH 5.4, organic matter 2.5%, total $N < 5000\ mg\ kg^{-1}$, available P 44 $mg\ kg^{-1}$, exchangeable K 304, Ca 3300, and Mg 359 $mg\ kg^{-1}$. All measurements were made after oven-drying the soil at 105 °C until constant weight. Data on mean monthly maximum and minimum temperatures as well as total monthly rainfall during the rice growing season of 2016–2017 and 2017–2018 are presented in Table 1.

Experimental treatments and agronomic management

Treatments were arranged in a randomized complete block design with split-split plot arrangement in three replications, where the factors were cultivar, establishment method, and irrigation level. The main plots included two rice cultivars (Pathumthani 1 and RD57), subplots consisted of two establishment methods (DDS and TP), and sub-subplots included three irrigation levels (CF, 15 cm threshold water level below the soil surface for irrigation [AWD15], and 30 cm threshold water level below the soil surface for irrigation [AWD30]). Main plots were 20 m (length) × 12 m (width), subplots were 20 m × 6 m, and sub-subplots were 6 m × 5 m separated by an alley of 1 m wide. Bunds of 30 cm height were constructed along each side of the plot and were covered by black plastic film inserted to a depth of 30 cm below the soil surface to prevent lateral movement of water.

Seeds of two rice cultivars were collected from the Pathum Thani Rice Research Centre. For DDS, dry seeds of both cultivars were broadcasted at 60 $kg\ ha^{-1}$ into unsaturated and unpuddled soil. For TP, 2-week-old seedlings of both cultivars were transplanted into puddled soil at a spacing of 20 cm (plant–plant) × 20 cm (row–row). On the same day, seeds for DDS were broadcasted into the main plots and those for TP were sown into the nursery beds to maintain uniformity of the treatments. Seeds were broadcasted into the main plots and nursery beds for DDS and TP, respectively, on 4 December, and were harvested on 31 March for RD57 and on 6 April for Pathumthani 1.

In the CF irrigation treatment, a water level of 2–3 cm was maintained from the emergence to 30 days after sowing (DAS) and 3–5 cm water level from 31 DAS to 2 weeks before harvest for DDS, whereas a water level of 3–5 was maintained throughout the growing season until 2 weeks before harvest for TP. For AWD15, the plot was flooded with 1–2 cm water from the first day of sowing until 30 DAS for DDS/15 days after transplanting for TP method, and then irrigation was stopped. The plot was re-irrigated to a depth of about 5 cm when the water level above the soil surface dropped to 15 cm below the soil surface. The water level in the soil was monitored by a

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perforated field water tube installed in each sub-subplot. The process for the maintenance of water level under AWD15 is the same for AWD30 irrigation level, except the plot was re-irrigated to a depth of about 5 cm when the water level dropped to 30 cm below the soil surface. The AWD cycle continues until initial flowering stage of rice (65 DAS for DDS/50 days after transplanting for TP method). This was followed by continuously maintaining standing water depth of about 5 cm until 2 weeks before harvest (110 DAS for Pathumthani and 104 DAS for RD57). Plants established through DDS and TP had no marked differences in growth duration in attaining each crop growth stage, except for maximum tillering where plants established through DDS attained this stage 2–3 days earlier than plants established through TP. There was no marked difference between plants established through DDS and TP in attaining flowering and maturity stages. The setback caused by uprooting the seedlings under TP was observed only at vegetative growth stage, and hence plants raised through TP attained maximum tillering stage 2–3 days later than plants raised through DDS. The same amount of synthetic fertilizer was applied in all plots in both years. Urea (46% N) and diammonium phosphate (46% P_2O_5) were applied at the rate of 75 and 60 kg ha^{-1}, respectively. Half of urea and total amount of diammonium phosphate were applied as basal and the rest of urea was top-dressed at panicle initiation stage. Insect pests, diseases, and weeds were chemically controlled by following the recommended plant protection measures for rice cultivation in Pathum Thani Province. For weed control, both pre- and post-emergence herbicides were applied by following the recommendations of Pathum Thani Rice Research Center.

Data collection

The seasonal temperature and rainfall data were collected from the Pathum Thani Meteorological Department. Plant height data were collected at maximum tillering (45 and 43 DAS for Pathumthani 1 and RD57, respectively), panicle initiation (62–63 DAS), and before harvest (124 and 118 DAS for Pathumthani 1 and RD57, respectively). Plant height was measured from the ground level to the top most leaf/panicle. The effect of treatments on plant height was not significant at harvest stage; therefore, the data are not presented. Number of tiller m^{-2} was counted at maximum tillering stage (45 and 43 DAS for Pathumthani 1 and RD57, respectively). Fresh shoot samples were oven-dried at 75 °C until constant weight, weighted, and shoot dry matter (SDM) measured. Data on grain yield were collected from a 10 m^2 area within each plot excluding the border area and was adjusted to 14 kg kg^{-1} moisture content basis. Data on yield components (panicle number m^{-2}, number of spikelet $panicle^{-1}$, filled grain percentage, and 1000-grain weight) were collected from a 1 m^2 area in each plot. Data were not collected from the plants adjacent to the border to avoid the border effect. All data on grain yield and its components were collected on the same day at harvest. Harvest index (HI) was calculated by dividing grain yield by aboveground biomass. Data on total water input (m^3 ha^{-1}) included water input from both irrigation and rainfall. Irrigation water input to each plot was measured using a flow meter installed in the irrigation pipeline, while rainfall data were collected from the Pathum Thani Meteorological Department. Total water input for TP included the amount of water applied for raising seedlings into the nursery beds. Water productivity (kg m^{-3}) was calculated by dividing grain yield (kg) by total water input (m^3) as outlined by Liang *et al.* (2016) and Maneepitak *et al.* (2019a). Total rainfall data for the month of April were not included for the calculation of water productivity of RD57 as it was harvested on 31 March.

Statistical analysis

Data were statistically analyzed using the statistical package IRRISTAT 5.0 (IRRI, 2005). There was no significant difference between the two seasons of the study; therefore, the data were averaged across two seasons. The three-way ANOVA for the randomized complete block deign in split-split plot arrangement was performed, and the tables/figures were generated by selecting

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Table 2. Plant height, shoot dry matter, and filled grain percentage (averaged over two cultivars) of rice as affected by interaction between establishment method and irrigation level

Establishment method	Irrigation level	Plant height (cm)		Shoot dry matter (kg ha^{-1})	Filled grain percentage
		Maximum tillering	Panicle initiation		
DDS	CF	47.8 ± 2.4a	77.0 ± 3.1a	3708 ± 645ab	83.6 ± 1.0ab
	AWD15	48.4 ± 2.1a	75.2 ± 2.9ab	2772 ± 490bc	84.3 ± 1.0a
	AWD30	42.8 ± 1.9b	68.2 ± 2.2c	2700 ± 348bc	80.0 ± 1.0ab
TP	CF	41.4 ± 1.6bc	75.3 ± 2.2bc	3267 ± 544ab	78.5 ± 3.0b
	AWD15	41.3 ± 0.4bc	70.6 ± 1.4bc	4167 ± 474a	79.3 ± 3.0ab
	AWD30	39.3 ± 0.5c	67.0 ± 0.8c	3105 ± 369bc	69.5 ± 2.0c
Significance	Cultivar (C)	**	**	**	ns
	Establishment method (E)	*	*	ns	**
	Irrigation level (I)	ns	ns	ns	*
	C × E	ns	ns	ns	ns
	C × I	ns	ns	*	*
	E × I	*	*	*	*
	C × E × I	ns	ns	ns	ns

DDS, dry direct seeding; TP, transplanting; CF, continuous flooding; AWD, alternate wetting and drying; ns, not significant.
**$p < 0.01$; *$p < 0.05$; data are means ± SE of six replications. Data are average of 2 years. Different small letters indicate significant difference in a column based on least significant difference at $p < 0.05$.

the highest factorial combination that was significant in the ANOVA. When the three-way interaction was not significant, the tables/figures were drawn by pooling the data across the nonsignificant treatment. Means for significant treatment effects were separated by Fisher's protected least significant difference at the $p < 0.05$ probability level. Regression analysis between grain yield and SDM as well as between water productivity and HI over years was performed using the *drc* statistical analysis addition package (Ritz and Strebig, 2016) in R version 2.10.1 (www.r-project.org).

Results

Growth parameters

The interaction between establishment method and irrigation level significantly ($p < 0.05$) affected plant height at maximum tillering and panicle initiation stage (Table 2). At maximum tillering stage, DDS had significantly taller plants compared with TP across irrigation levels. There was about 10 and 12% decrease in plant height at AWD30 compared with CF and AWD15, respectively, under DDS; however, varying irrigation level did not significantly impact plant height under TP. At panicle initiation stage, DDS had taller plants than TP at CF, whereas both methods had similar plant height at AWD15 and AWD30. Plant height was reduced by 11 and 9% at AWD30 compared with CF and AWD15, respectively, under DDS.

SDM was significantly ($p < 0.05$) affected by the interaction of establishment method by irrigation level and of cultivar by irrigation level (Tables 2 and 3, respectively). The difference in SDM under DDS and TP was not significant at CF and AWD30, while TP had 50% higher SDM than DDS at AWD15 (Table 2). SDM was similar across irrigation levels under DDS, whereas TP had 34% higher SDM at AWD15 than AWD30. RD57 had significantly higher SDM than Pathumthani 1 at all irrigation levels (Table 3). SDM of Pathumthani 1 was similar across irrigation levels; however, RD57 had significantly lower SDM at AWD30 compared with CF and AWD15.

The two-way interaction between cultivar and irrigation level as well as between cultivar and establishment method significantly ($p < 0.05$ and $p < 0.01$, respectively) affected number

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Table 3. Shoot dry matter, tiller number m^{-2}, panicle number m^{-2}, spikelet number $panicle^{-1}$, filled grain percentage, and harvest index (averaged over two establishment methods) of rice as affected by interaction between cultivar and irrigation level

Cultivar	Irrigation level	Shoot dry matter (kg ha^{-1})	Tiller number m^{-2}	Panicle number m^{-2}	Spikelet number $panicle^{-1}$	Filled grain percentage	Harvest index
Pathumthani 1	CF	2592 ± 125bc	124 ± 4.6b	107 ± 645bc	163.0 ± 12a	80.6 ± 4.6ab	0.33 ± 0.01b
	AWD15	2556 ± 132bc	126 ± 2.9b	111 ± 490bc	172.8 ± 9a	80.5 ± 3.9ab	0.33 ± 0.01b
	AWD30	2268 ± 152c	113 ± 3.4c	88 ± 348c	149.4 ± 11ab	73.1 ± 3.4c	0.31 ± 0.01b
RD57	CF	4707 ± 524a	132 ± 1.2a	156 ± 544a	124.3 ± 13bc	80.1 ± 1.5ab	0.42 ± 0.03a
	AWD15	4383 ± 456a	134 ± 1.4a	162 ± 474a	124.3 ± 11bc	83.0 ± 1.4a	0.36 ± 0.03a
	AWD30	3303 ± 398b	128 ± 1.0ab	118 ± 369b	103.1 ± 10c	77.9 ± 1.4bc	0.40 ± 0.03ab
Significance	Cultivar (C)	**	**	**	**	ns	**
	Establishment method (E)	ns	**	**	ns	**	**
	Irrigation level (I)	ns	*	ns	Ns	*	**
	C × E	ns	**	ns	ns	ns	ns
	C × I	*	*	*	*	*	*
	E × I	*	ns	ns	ns	*	ns
	C × E × I	ns	ns	ns	ns	ns	ns

CF, continuous flooding; AWD, alternate wetting and drying; ns, not significant.
$^{**}p < 0.01$; $^{*}p < 0.05$; data are means ± SE of six replications. Data are average of 2 years. Different small letters indicate significant difference in a column based on least significant difference at $p < 0.05$.

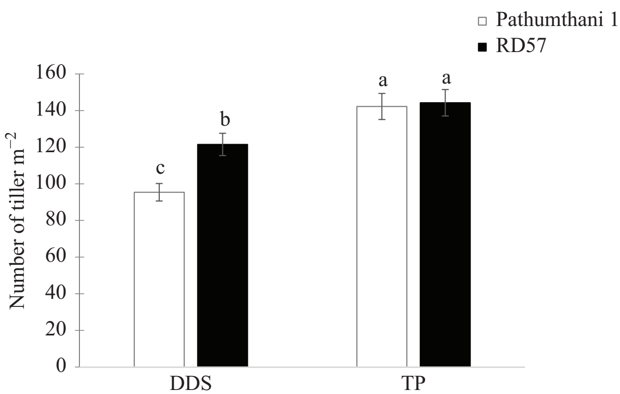

Figure 1. Tiller number m^{-2} of Pathumthani 1 and RD57 Thai rice cultivars as affected by establishment method (averaged over three irrigation levels). DDS, dry direct seeding; TP, transplanting. Bars show means ± SE of six replications. Bars with same letters are not significantly different based on least significant difference at $p < 0.05$.

of tiller m^{-2} (Table 3 and Figure 1, respectively). RD57 had higher number of tiller m^{-2} compared with Pathumthani 1 across irrigation levels (Table 3). Pathumthani 1 had 9 and 10% decrease in number of tiller m^{-2} at AWD30 compared with CF and AWD15, respectively. The two tested cultivars produced similar number of tiller m^{-2} under TP, while RD57 had 27% more number of tiller m^{-2} than Pathumthani 1 under DDS (Figure 1). Both cultivars had significantly higher number of tiller m^{-2} under TP compared with DDS.

Yield components and grain yield

Number of panicle m^{-2} was significantly ($p < 0.05$) affected by the two-way interaction between cultivar and irrigation level (Table 3). RD57 had significantly higher number of panicle m^{-2} than

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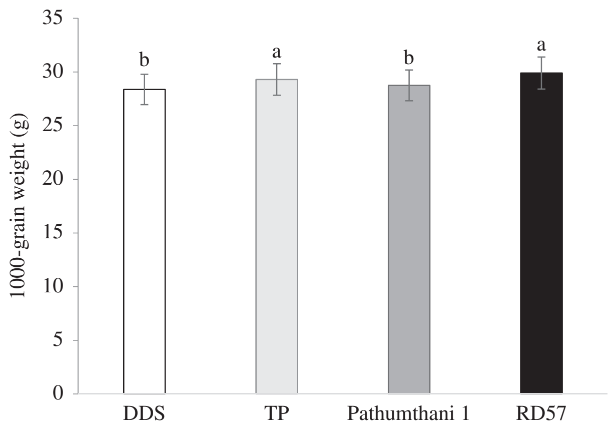

Figure 2. 1000-grain weight (g) of rice (averaged over two cultivars and three irrigation levels for establishment methods, and averaged over two establishment methods and three irrigation levels for cultivars). DDS, dry direct seeding; TP, transplanting. Bars show means ± SE of six replications. Bars with same letters are not significantly different based on least significant difference at $p < 0.05$.

Pathumthani 1 irrespective of irrigation levels. Number of panicle m^{-2} of RD57 was reduced by 24 and 27% compared with CF and AWD15, respectively, at AWD30. Number of spikelet panicle^{-1} was significantly ($p < 0.05$) affected by the two-way interaction between cultivar and irrigation level; however, the main effect of irrigation level was not significant (Table 3). Spikelet number panicle^{-1} of both cultivars was similar among irrigation levels. Pathumthani 1 had significantly higher number of spikelet panicle^{-1} regardless of irrigation levels. The highest difference (31%) in spikelet number panicle^{-1} between the two cultivars was evident at AWD30.

Filled grain percentage was significantly ($p < 0.05$) affected by the two-way interaction between establishment method and irrigation level as well as between cultivar and irrigation level (Tables 2 and 3, respectively). Filled grain percentage was similar between DDS and TP at CF and AWD15, whereas TP had significantly lower (13%) filled grain percentage than DDS at AWD30 (Table 2). DDS had similar filled grain percentage across irrigation levels, whereas it was reduced by 11% under TP at AWD30 compared with CF or AWD15. Filled grain percentage of the two cultivars was similar at all irrigation levels (Table 3). RD57 had significantly higher filled grain percentage at AWD15, which was statistically at par with CF, but 7% higher than filled grain percentage at AWD30. Pathumthani 1 had 10% higher filled grain percentage at CF and AWD15 compared with AWD30. The main effect of cultivar and establishment method significantly ($p < 0.05$) affected 1000-grain weight (Figure 2). TP had significantly higher 1000-grain weight than DDS, and RD57 had significantly higher 1000-grain weight than Pathumthani 1.

Grain yield was significantly ($p < 0.05$) affected by the three-way interaction among cultivar, establishment method, and irrigation level (Table 4). Reducing irrigation rate from CF to AWD30 had no significant impact on grain yield of Pathumthani 1 either for DDS at all irrigation levels or for TP at CF and AWD15. A significant reduction in grain yield of RD57 was evident under both establishment methods at AWD30 compared with CF and AWD15. At AWD15, Pathumthani 1 established through TP produced significantly greater (66%) yield than DDS. This was also true for either DDS or TP of RD57 compared with DDS of Pathumthani 1 at CF and AWD15 irrigation levels. Pathumthani 1 had no significant difference in grain yield between CF and AWD30 under both cultivation methods, whereas RD57 had significantly lower grain yield at AWD30 versus CF and AWD15 when either planted by DDS or TP. Interaction between cultivar and irrigation level significantly ($p < 0.05$) affected HI (Table 3). RD57 had higher HI than Pathumthani 1 at CF and

Table 4. Grain yield and water productivity of Pathumthani 1 and RD57 Thai rice cultivars as affected by establishment method and irrigation level

		Grain yield (kg ha^{-1})			Water productivity (kg m^{-3})		
Cultivar	Establishment method	CF	AWD15	AWD30	CF	AWD15	AWD30
Pathumthani 1	DDS	3240 ± 638b,A	3750 ± 120b,A	2850 ± 634a,A	0.62 ± 0.01c,B	0.83 ± 0.05c,A	0.65 ± 0.04b,B
	TP	4830 ± 423a,AB	6240 ± 330a,A	3330 ± 638a,B	0.89 ± 0.03b,B	1.32 ± 0.03b,A	0.72 ± 0.03ab,C
RD57	DDS	4710 ± 482a,A	5610 ± 840a,A	2820 ± 624a,B	1.11 ± 0.03a,B	1.58 ± 0.08a,A	0.82 ± 0.07a,C
	TP	4830 ± 760a,A	5520 ± 876a,A	2910 ± 79a,B	1.09 ± 0.01a,B	1.47 ± 0.07a,A	0.80 ± 0.05a,C
Significance	Cultivar (C)		ns			*	
	Establishment method (E)		*			*	
	Irrigation level (I)		**			**	
	C × E		*			**	
	C × I		**			**	
	E × I		ns			*	
	C × E × I		*			*	

CF, continuous flooding; AWD, alternate wetting and drying; DDS, dry direct seeding; TP, transplanting.Data are means ± SE of six replications. Data are average of 2 years. Different small letters indicate significant difference in a column and capital letters indicate significant difference in a row based on least significant difference at $p < 0.05$.

AWD15. The two tested cultivars had statistically similar HI at AWD30. Decreasing irrigation level had no effect on HI of both cultivars.

The relationship between grain yield and SDM is presented in Figure 3a–c. The correlation between grain yield and SDM was higher for Pathumthani 1 ($r = 0.66$) where grain yield was maximized (6570 kg ha^{-1}) at 4050 kg ha^{-1} of SDM (Figure 3a). Similarly, the maximum grain yield for RD57 (6930 kg ha^{-1}) was observed at 4158 kg ha^{-1} of SDM with a positive linear relationship ($r = 0.46$). A positive linear relationship was also observed between grain yield and SDM for the two establishment methods (Figure 3b). DDS had a maximum grain yield of 6930 kg ha^{-1} at 4158 kg ha^{-1} of SDM ($r = 0.48$) and TP had a maximum grain yield of 6570 kg ha^{-1} at 4050 kg ha^{-1} of SDM ($r = 0.39$). The positive linear relationship between grain yield and SDM progressively weakened with decreasing water input ($r = 0.67$ for CF, $r = 0.56$ for AWD15, and $r = 0.20$ for AWD30) (Figure 3c).

Water productivity

The three-way interaction among cultivar, establishment method, and irrigation level was significant ($p < 0.05$) for water productivity (Table 4). RD57 had significantly higher water productivity under both establishment methods across irrigation levels. Pathumthani 1 had the highest reduction (47%) in water productivity under DDS at AWD15 compared with RD57. Establishment method did not significantly influence water productivity of RD57, while Pathumthani 1 had higher water productivity under TP than DDS at CF (44%) and AWD15 (59%). Both the tested cultivars had significantly higher water productivity at AWD15 than CF and AWD30 under both establishment methods. Water productivity of RD57 was reduced by 48 and 46% at AWD30 compared with AWD15 under DDS and TP, respectively. A reduction of 45 and 22% in water productivity of Pathumthani 1 was evident at AWD30 than AWD15 under TP and DDS, respectively. Averaged across 2 years, plants maintained under CF and established through TP had the highest water input regardless of cultivars (Table 5). Irrigation water savings ranged between 7 and 37% for different treatment combinations compared with TP-CF combination, which is a common practice of rice cultivation in the study area.

Figure 4 shows the relationship between water productivity and HI at three irrigation levels. A positive linear relationship was observed between water productivity and HI for all irrigation levels. This indicates that water productivity increased with increasing HI. However, the relationship was stronger for CF ($r = 0.71$) followed by AWD30 ($r = 0.31$) and AWD15 ($r = 0.20$). The slope of the regression line was higher for CF (1.4) followed by AWD15 (0.4) and AWD30 (0.2).

Discussion

The need of water-efficient cultivation techniques such as DDS and AWD is increasingly becoming critical for the sustainability of rice production system due to decreasing irrigation water availability. In the present study, there was a visible difference in grain yield, water productivity (Table 4), SDM (Tables 2 and 3), number of tiller m^{-2} (Table 3), number of panicle m^{-2} (Table 3), number of spikelet panicle^{-1} (Table 3), filled grain percentage (Tables 2 and 3), 1000-grain weight (Figure 2), and HI (Table 3) of the two tested cultivars in response to establishment methods and irrigation levels. The performance of RD57 was better than Pathumthani 1 under DDS and AWD indicating its wider adaptability to water-saving cultivation techniques. The poor grain yield and consequently lower water productivity of Pathumthani 1 under DDS at all irrigation levels could be due to higher weed infestation observed during the early vegetative growth stage. Weeds were controlled using the recommended chemical method soon after their emergence in DDS plots of both of the tested cultivars to avoid significant yield loss. However, the better performance of RD57 under the same establishment method might partly be attributed to its greater competitive ability against weeds. Weed infestation is one of the major constraints in direct-seeded rice and thus an effective weed

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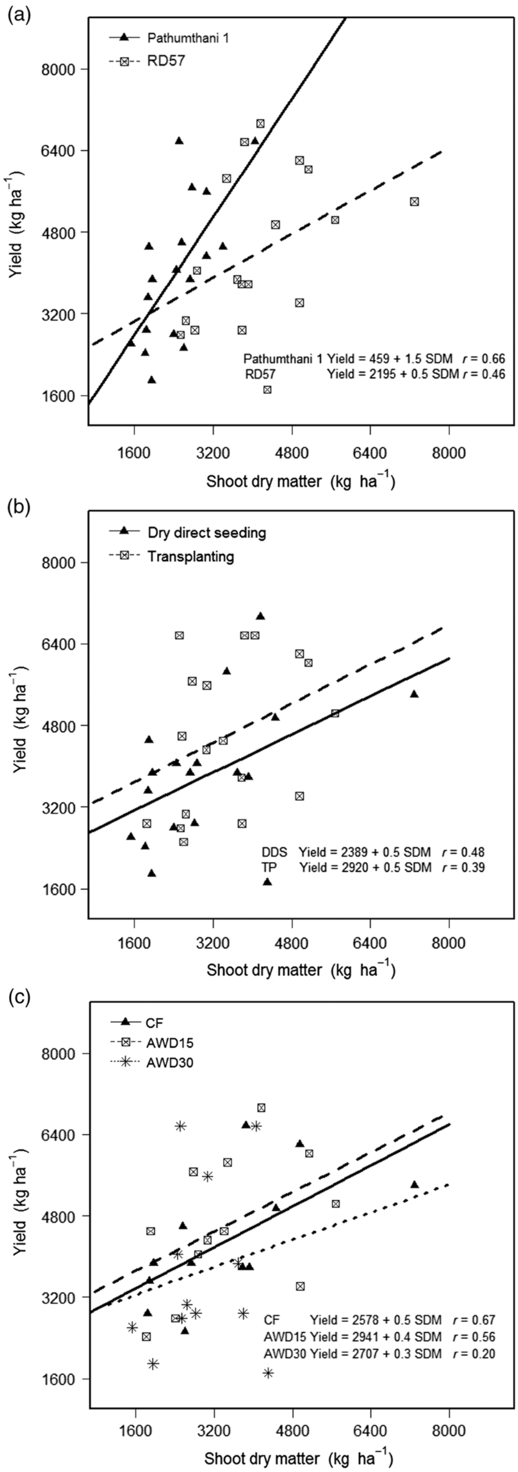

Figure 3. Relationship between grain yield and shoot dry matter (SDM) of rice as influenced by cultivar (a), establishment method (b), and irrigation level (c) averaged across 2 years.

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Table 5. Seasonal irrigation water input ($m^3 ha^{-1}$), total water input ($m^3 ha^{-1}$), and irrigation water savings during the dry rice growing seasons of 2016–2017 and 2017–2018

			Irrigation water input (m^3 ha^{-1})		Total water input (m^3 ha^{-1})			Irrigation water savings compared with TP-CF averaged across 2 years (%)
Cultivar	Establishment method	Irrigation level	2016–2017	2017–2018	2016–2017	2017–2018	Average of 2 years	
Pathumthani 1	TP	CF	3344	2057	5445	5378	5411.5	–
		AWD15	2658	1360	4759	4684	4721.5	26
		AWD30	2514	1243	4615	4559	4587	30
	DDS	CF	3152	1880	5253	5204	5228.5	7
		AWD15	2466	1183	4567	4507	4537	32
		AWD30	2322	1066	4423	4390	4406.5	37
RD57	TP	CF	3344	2057	4469	4397	4433	
		AWD15	2658	1360	3783	3703	3743	
		AWD30	2514	1243	3639	3578	3608.5	
	DDS	CF	3152	1880	4277	4223	4250	
		AWD15	2466	1183	3591	3526	3558.5	
		AWD30	2322	1066	3447	3409	3428	

TP, transplanting; DDS, dry direct seeding; CF, continuous flooding; AWD, alternate wetting and drying.

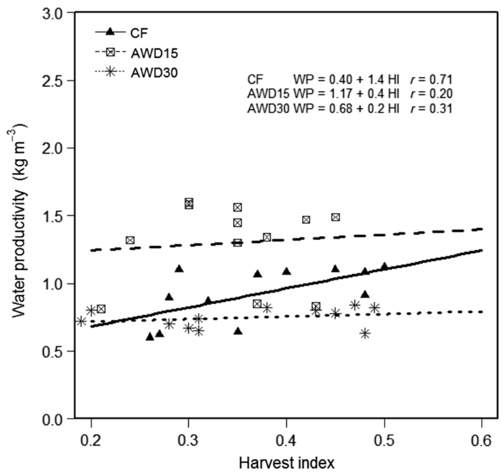

Figure 4. Relationship between water productivity (WP) and harvest index (HI) of rice as influenced by irrigation level averaged across 2 years.

management strategy is of prime importance. Effective weed control in direct-seeded rice using a single pre- and post-emergence herbicide is challenging due to the presence of a complex weed flora in this production system. Improved weed control in direct-seeded rice has been reported with simultaneous (tank-mixed) or sequential application of herbicide compared with a single herbicide application (Mahajan and Timsina, 2011). Better weed control has been observed with sequential applications of pre- and post-emergence herbicides compared with the sole application of pre- and post-emergence herbicides in direct-seeded rice (Mahajan and Chauhan, 2013). Mahajan and Chauhan (2015) recommended tank-mix application of post-emergence herbicide in direct-seeded rice with a weed control up to 98%. Moreover, genetic background of the tested cultivars might also be responsible for this differential response to the establishment method. This claim is also supported by higher SDM, number of tiller m^{-2}, number of panicle m^{-2}, and 1000-grain weight of RD57 compared with Pathumthani 1. RD57, therefore, could be a better choice for DDS. Weed infestation is among the major constraints to widespread adoption of DDS (Datta *et al.*, 2017), and a cultivar with better competitive ability against weeds would be a better choice for this method of crop establishment. Ullah *et al.* (2019) evaluated the performance of Pathumthani 1, RD57, and RD41 under integrated nutrient management practices and cultivation methods subjected to AWD irrigation and observed similar grain yields of Pathumthani 1 and RD57 under DDS and TP; however, spikelet panicle^{-1} and filled grain percentage were significantly lower for Pathumthani 1 than RD57. The comparable grain yield in Ullah *et al.* (2019) study was credited to organic matter application and hence is a recommended practice for Pathumthani 1 when cultivated under water-saving cultivation techniques. The slope of the regression line for Pathumthani 1 was higher than RD57 in the relationship between grain yield and SDM (Figure 3a). This indicates that an increase in SDM had less influence on grain yield of Pathumthani 1 as against RD57 where the slope of the regression line was lower showing greater influence of SDM on grain yield. RD57 produced significantly higher SDM, number of tiller m^{-2}, number of panicle m^{-2}, and 1000-grain weight compared with Pathumthani 1, which might have contributed to larger grain yield of this cultivar. The response of the root systems of the same cultivars was different under greenhouse condition where Pathumthani 1 produced more extensive root system than RD57 at soil moisture deficit condition of −30 kPa (Ullah and Datta, 2018). We observed cultivar differences in water productivity where both of the cultivars had higher water productivity at AWD15 compared with CF and AWD30 regardless of establishment methods. Overall, water productivity was also lower at CF than

AWD15 regardless of cultivars and establishment methods. Bueno *et al.* (2010) also found varietal difference in water productivity under three levels of irrigation (CF, AWD30, and AWD60). Liang *et al.* (2016) reported significantly different water productivity between two rice cultivars where it was higher at AWD15 irrigation compared with CF and AWD30 depending on cultivar. Song *et al.* (2018) compared growth, yield, and water-use efficiency response of two lowland and two upland rice cultivars under CF, AWD15, and AWD30. The authors observed a cultivar-induced variation in water-use efficiency, which was the lowest under CF. As cultivar response is primarily determined by genetic makeup, the performance of a lowland irrigated cultivar should be evaluated before recommending for growing under water-saving cultivation techniques such as DDS and AWD.

Changing establishment method from TP to DDS did not significantly influence grain yield of RD57 across irrigation levels; however, Pathumthani 1 had lower grain yield under DDS than TP at CF and AWD15 (Table 4). Some of the growth and yield contributing characters such as plant height at maximum tillering and panicle initiation stage (Table 2) and filled grain percentage (Table 2) had better performance under DDS than TP. Lower grain yield of Pathumthani 1 under DDS could be due to lower number of tiller m^{-2} (Table 3) and 1000-grain weight (Figure 2). A significantly higher SDM and 1000-grain weight of RD57 might have contributed to higher grain yield and water productivity compared with Pathumthani 1 under DDS at AWD15. It is interesting to note that water productivity was slightly higher under DDS than TP for RD57. Similarly, Joshi *et al.* (2013) and Liu *et al.* (2015) also reported higher water productivity of rice established through DDS than TP, although varietal difference was evident. Many investigators have reported an increased grain yield of rice under DDS (Harada *et al.*, 2007; Sharma *et al.*, 2004), which contradicts the present findings for both of the tested cultivars. The present results for plant height are in line with Du *et al.* (2014), who also observed an increased plant height under DDS, but different for 1000-grain weight as we observed lower 1000-grain weight under DDS than TP (Figure 2). The difference in 1000-grain weight of the two cultivars could be attributed to their genetic background (Yoshida, 1981). Grain yields of RD57 were statistically similar between DDS and TP establishment methods regardless of irrigation levels (Table 4). Similarly, Liu *et al.* (2015) also reported a 15.3% reduction in irrigation water input under DDS without compromising grain yield in comparison with TP. Grain yield was equally influenced by SDM as indicated by the same slope of the regression line for both DDS and TP with a positive and linear relationship between grain yield and SDM (Figure 3b). Relatively fewer studies are available dealing with synchronize application of DDS and AWD. The combination of these two techniques could significantly increase water productivity while maintaining/increasing grain yield. Grain yield and water productivity were significantly higher under DDS and AWD15 combination compared with CF confirming the suitability of these cultivars for water-saving cultivation techniques (DDS and AWD15). However, the threshold level of AWD could be different for different cultivars and soil conditions, which should be defined before recommending a cultivar for such water-efficient cultivation techniques. Talebnejad and Sepaskhah (2014) reported a 53% reduction in irrigation water input for DDS establishment method when irrigation was scheduled at 4 days interval (intermittent irrigation) without any considerable yield loss. Thus, application of AWD15 along with either DDS or TP for RD57 and along with TP for Pathumthani 1 could be safely recommended for irrigated lowland rice cultivation system in situations comparable to the present soil and weather conditions.

Defining the threshold level of AWD for different soil and weather conditions and rice cultivars is a prerequisite for maximizing water productivity. In the present study, we found a consistent trend of better results at AWD15 compared with AWD30, which was either at par with CF such as plant height (Table 2), SDM (Tables 2 and 3), number of tiller m^{-2} (Table 3), number of panicle m^{-2} (Table 3), number of spikelet $panicle^{-1}$ (Table 3), filled grain percentage (Tables 2 and 3), and grain yield (Table 4), or significantly higher than both CF and AWD30 such as water productivity of both cultivars under both establishment methods (Table 4). The strong and positive relationship between grain yield and SDM at CF with greater slope of the regression line (Figure 3c) indicates that yield was more dependent on SDM under well-watered conditions (CF). However, both the relationship and the

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slope of the regression line progressively decreased at AWD15 and AWD30 indicating that yield was less dependent on SDM and better yields could even be obtained with low SDM with decreasing water input. These results also point out that selection of shorter rice cultivars with more extensive root systems could be a better option under AWD than longer cultivars. The experimental soil in the present study is characterized by a higher water holding capacity and withholding irrigation until water level drops 15 cm below the soil surface provides partly aerobic environment to the root system, which positively influence its growth and development. This enhancement in root system development plays a major role in water-nutrient uptake by plant and confers high and stable yield under AWD (Sandhu *et al.*, 2017). At this soil depth, the soil water potential is around –20 kPa (Pan *et al.*, 2017). However, the lower portion of rice root system generally present at 15–20 cm depth appears to uptake more water and nutrients from the soil to the root system, which results in an enhancement in grain filling under AWD irrigation (Sandhu *et al.*, 2017; Yang and Zhang, 2010). The poor performance of both of the tested cultivars at AWD30 could be due to a shallow and improper root system development as the soil water potential often drops below –20 kPa when the water level reaches 30 cm below the soil surface (Liang *et al.*, 2016). This condition causes water stress resulting in an insufficient uptake of water and nutrients, which is responsible for lower grain yield.

AWD15, known as 'safe' AWD, is a novel water management technology and is effective in maximizing water productivity without a yield penalty (Maneepitak *et al.*, 2019a,b; Pan *et al.*, 2017). In the present study, plots maintained under CF and AWD15 had similar yields regardless of cultivars and establishment methods (Table 4). Some authors also reported no yield penalty under AWD15 compared with CF (Liang *et al.*, 2016; Maneepitak *et al.*, 2019a,b; Pan *et al.*, 2017; Yao *et al.*, 2012). Lampayan *et al.* (2015) reported that correct implementation of 'safe' AWD had no effect on grain yield compared with traditional farmer's practice, but irrigation water savings could be up to 38%. We observed a significantly higher water productivity at AWD15 (Table 4) and an average irrigation water savings of 26–32% (Table 5) for 2 years compared with TP-CF combination, which is in accordance with the previous findings. Pan *et al.* (2017) observed between 24 and 71% reduction in irrigation water input under AWD15 compared with CF in a 2-year study without any yield loss. Belder *et al.* (2004) reported higher water productivity under AWD than CF, while the difference in grain yield was not significant. Reduced water input and high water productivity under AWD has been attributed to a reduction in unproductive water loss through seepage and percolation as well as evaporation from the soil surface (Cabangon *et al.*, 2004).

The strong and positive relationship between water productivity and HI as well as greater slope of the regression line for CF (Figure 4) indicate that water productivity at this irrigation level is more dependent on HI. This shows that water productivity could be better explained by the variation in HI when water is not a limiting factor. However, this relationship was weak at AWD15 and AWD30 indicating that variation in water productivity at AWD15 and AWD30 is less influenced by variation in HI. The outcome of the present study contradicts the findings of Yang and Zhang (2010) at AWD15, who observed a significantly higher HI and water-use efficiency at alternate wetting and moderate drying irrigation. However, the present results are in close agreement with the findings of Yang and Zhang (2010) at AWD30 as they found a significant reduction in grain yield and HI at alternate wetting and severe drying irrigation compared with CF. The outcomes of the present study suggest that AWD15 could be safely applied for soil and environmental conditions comparable to the present study; however, AWD30 might not be a feasible option due to significant yield reduction although water-saving potential was greater than CF.

Conclusions

The tested cultivars responded differently to water-saving cultivation techniques. RD57 had higher grain yield and water productivity than Pathumthani 1 for most of the treatment

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combinations, especially under DDS. AWD15 could be safely recommended in maintaining yield stability and improving water productivity for both of the tested cultivars along with either establishment method for RD57 and TP for Pathumthani 1. These results were confirmed by an average irrigation water savings of 26–32% pooled over years by AWD15 compared with TP-CF combination. Grain yield at AWD15 was not significantly different from that produced under CF, which indicates water savings without any yield loss. Although water-saving potential was higher compared with CF, AWD30 might not be a feasible water management option for irrigated lowland rice cultivation due to significant yield loss. Site and soil-specific testing is recommended before designing a threshold level of AWD.

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