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Full Length Article

Effect of Different Controlled Irrigation and Drainage Regimes on Crop Growth and Water Use in Paddy Rice

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Abstract

To achieve the dual goal of water conservation and high grain production, agricultural systems must decrease water usage and increase water use efficiency (WUE). In recent years, controlled irrigation and drainage (CID) has been used and developed as a new water-saving technique for paddy rice production. The present study aimed to explore the influence of different CID regimes on the yield, agronomic traits, and WUE of paddy rice. Treatments included alternate wetting and drying (AWD), CID-I (a lower limit of irrigation to 200 mm), and CID-II (a lower limit of irrigation to 500 mm). Plant height increased but tiller number significantly decreased under CID compared with those under AWD. Implementing CID decreased irrigation water volume (IV) by 9.7%–37.1%, which increased yield irrigation water use efficiency ($IWUE_y$) by 14.6%–51.5%. Under CID-I, grain yield decreased by 2.9% in 2015 and increased by 3.5% in 2016. CID-II obtained marginally, but not significantly, lower yields (4.7% in 2015 and 2.0% in 2015) than AWD because the percent of filled grains (PFG) and spikelets per m^2 (SPM) decreased under this irrigation scheme. $IWUE_y$ and biomass irrigation water use efficiency ($IWUE_b$) were significantly higher under CID than under AWD. The highest $IWUE_y$ and $IWUE_b$ were observed under CID-II. Our results indicate that CID can reach a lower limit of irrigation to 500 mm below the topsoil and a ponding water depth of 200 mm after rainfall, with some acceptable yield penalty when water is inadequate and costly. © 2018 Friends Science Publishers

Keywords: Controlled irrigation and drainage; Growth; Water use; Yield

Introduction

Rice (*Oryza sativa* L.) is a major food crop in Asia, and providing nearly 32% of calorie uptake (Belder *et al.*, 2004). Irrigated rice is vital in maintaining high food production (Zulkarnain *et al.*, 2009). In Asia, an estimated 80% of irrigated freshwater is consumed by paddy rice (Bouman and Tuong, 2001). However, competition for freshwater is increasing among the demands associated with domestic, industrial, and agricultural consumption (Shao *et al.*, 2014; Avila *et al.*, 2015). Water availability is decreasing because of declining water quality, resource depletion, and environmental pollution (Avila *et al.*, 2015). Water scarcity is further worsened by the high water demand of irrigated rice. By 2025, approximately 18 million ha of paddy rice will experience water shortage (Tuong and Bouman, 2003). Therefore, water scarcity in agriculture is a global problem that threatens paddy rice productivity. Approaches must be sought to improve WUE without impairing the grain yield of rice. In the last decades, many water saving practices and techniques that consume less water have been used and promoted, such as the aerobic rice system, intermittent irrigation, and alternate wetting and drying (AWD) (Bouman and Tuong, 2001; Bouman *et al.*, 2005). As an advanced water-saving technique, AWD is widely practiced in many areas in Asia (Ye *et al.*, 2013). However, this approach has low rainwater use efficiency especially when rain occurs during the production cycle. Controlled drainage (CD) has gained considerable attention in recent years. CD is utilized to alter drainage intensity in response to the variation in drainage requirement during a season. In CD, adjusting the elevation of the drainage outlet controls the amount of outflow via the drainage system (Wesström *et al.*, 2001). The benefits of CD include decreased outflow volume, saving irrigation water, storm water mitigation and sedimentation, and strengthened denitrification (Xiao *et al.*, 2013; Shao *et al.*, 2014; 2015). Controlled irrigation and drainage (CID) combines the advantages of CD and AWD. In CID, high water depth (250 mm) is maintained to reduce drainage water during rainy days. Irrigation is applied when a certain water table threshold is reached (a certain degree of drought stress is produced when soil moisture content is

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lower than 80% of field capacity) (Gao *et al.*, 2016). Thus, the high water depth and low limit of the water table captures more surface water during rainfall, thus influencing irrigation water use efficiency (IWUE) (Shao *et al.*, 2014).

Understanding the growth performance of rice is crucial to direct future irrigation and drainage management efforts. Many reports have recorded the influence of water stress on paddy rice alone. Excessive ponding water not only adversely affects tiller number, root to shoot ratio, and dry matter production, but also promotes lodging and senescence of rice plants (Lal *et al.*, 2015). Severe water deficit, unlike flooding stress, decreases internode elongation, panicle numbers, and growth rate of rice (Lu *et al.*, 2000). Under CID, paddy rice may frequently suffer episodes of alternate drought and flooding stress to varying degrees. Moreover, the effects of CID on rice depend on the duration and severity of flooding and drought stress. The ideal growth characteristics of rice under CID, in coordination with these conjunct environments, may be distinct from those under flooding or drought stress alone (Yu *et al.*, 2012; Ye *et al.*, 2013). Understanding of the yield, growth traits, and WUE of paddy rice under different CID regimes, however, remain limited.

Although various studies have detected the growth performance and WUE of rice under AWD or CD alone (Belder *et al.*, 2004; Zhang *et al.*, 2009; Kima *et al.*, 2015), only a few studies have concentrated on the conjunct effects of CD and AWD in the paddy field. In addition, whether or not CID can increase grain yield and improve IWUE compared with AWD. The current study attempts to determine a CID system that maintains high grain yield and save water, thus enhancing IWUE at the field level. The agronomic traits of paddy rice under different CID regimes were also investigated. Soil water potential and soil moisture content are used as irrigation indices in rice (Tuong and Bouman, 2003; Yang *et al.*, 2007). Farmers, however, do not have the appropriate equipment to confirm when the lower limit of irrigation is reached. Therefore, we applied field water level (FWL) as the index for paddy rice irrigation. The use of FWL in irrigation has several advantages: first, FWL can be instantaneously confirmed through an observational well using a ruler. Second, FWL is only slightly affected by spatial variation (Xiao *et al.*, 2012).

Materials and Methods

Plant Materials and Growth Conditions

Field experiments were conducted in 2015 and 2016 at the Lianshui Water Conservancy Experiment Station (latitude 33°50′N, longitude 119°16′E), Jiangsu, China. The experimental site has a humid and subtropical climate with an annual average temperature of 14.4°C. Data from 1981 to 2010 indicate that Lianshui County has a mean annual rainfall of 979.1 mm. Meteorological parameters were measured by an automated weather station at the experimental site. The soil (0–30 cm) was loamy clay with a pH of 6.82, soil organic matter of 2.19%, field capacity of 27.9%, total nitrogen of 0.98 g kg^{-1}, and total phosphorus of 1.12 g kg^{-1}. Liangyou 9918 (hybrid cultivar) was grown in 2015 and 2016. Seedlings were cultivated in a seedbed on 25 May in 2015 (30 May in 2016), and then transplanted at a hill spacing of 0.15 m × 0.22 m with one seedling per hill on 23 June 2015 and 28 June 2016. The soil was harrowed, dry-ploughed and then soaked a day before transplanting. A compound fertilizer (N:P_2O_5:K_2O, 15:15:15) was basally applied at a rate of 900 kg/ha on 23 June 2015 and 28 June 2016. Urea (nitrogen content: 46.4%) was used at the tillering and panicle initiation at rates of 100 kg/ha on 13 July 2015 (5 July 2016) and of 50 kg/ha on 5 August 2015 (10 August 2016).

Experimental Design and Treatments

The field experiments were performed in a complete randomized block design with three replicates. Plot dimensions were 90 m × 27 m. The ridges were 30 cm wide at the base and 30 cm high. The ridges were covered with a plastic membrane and inserted into the plough layer to a depth of 35 cm. There were three treatments: AWD, CID-I, and CID-II. During the first seven days after transplanting (DAT), water depth was maintained at 30 mm for the three irrigation regimes to promote the recovery and establishment of paddy rice seedlings. Then, after seven days, the FWL was allowed to fluctuate between approximately-200 mm and 60 mm in AWD. In CID, plots were allowed to be intermittently flooding (200 mm) after storm water. Irrigation water under CID was applied a 40–60 mm water level unless FWL dropped to a certain depth below the topsoil (-200 mm in CID-I and -500 mm in CID-II). Approximately ten days before harvest, the field surface water of the three treatments was drained until no surface water remained.

Sample Collection and Measurement

Three perforated PVC pipes (60 mm diameter) were installed vertically at a depth of 1800 mm in each plot to observe FWL. FWL was observed at 9 o'clock daily with a ruler at morning. When the minimum level of FWL was reached the system would be irrigated to the maximum water level. The soil water content was measured via time domain reflectometry (TRIME-T3, USA) twice weekly. Irrigation water volume (IV) was estimated by electronic water meters. Drainage volume was measured with runoff collecting barrels.

The evapotranspiration for paddy rice was calculated using Eq. (1), as given (Garrity *et al.*, 1981).

$$ET = P + I - R_f - D_p \pm \Delta S (1)$$

Where ET is evapotranspiration (mm), P is rainfall (mm), I is irrigation water (mm), R_f is surface runoff (mm), and D_p is deep percolation (mm) in crop root depth. ΔS is the variation of soil water content at crop root depth (mm). During the experiment period, the variation in soil water content at 0–10 cm, 10–30 cm, and 30–50 cm soil depth in each treatment was continuously measured when the water depth did not exist at the topsoil.

To determine above-ground biomass, three hills were sampled from each plot at the beginning of each stage. Above-ground biomass from the three selected plants was measured after oven drying at 75°C for 48 h. Height and tiller numbers were measured from six selected hills. Plant height was measured from the stem base to the highest leaf tip before the flowering stage and to the tip of the highest spikelet at other stages. Internode length was measured using a ruler at harvest. Tiller numbers were counted as tillers with at least three green leaves. At harvest, plants were cleaned with distilled water. The stems and roots were separated from each plant. Yield components, including spikelets per panicle (SP), panicle per m^2 (PM), spikelets per m^2 (SM), thousand-grain weight (TGW), and percent of filled grains (PFG) for each individual plant were recorded from thirty hills and randomly selected from each plot (except border plants). The harvest index (HI) was calculated as the ratio of dry grain yield to aboveground plant (shoot) biomass at crop harvest.

Statistical Analysis

Data were analyzed by one-way ANOVA with least significant difference (LSD) test at the 0.05 probability level. All statistical analyses were performed with SPSS Software Version 19.0 (SPSS Inc, Chicago, USA).

Results

Agro-hydrological Conditions

Daily rainfall, irrigation, drainage and FWL under different treatments for both years are presented in Fig. 1. The distribution of precipitation varied between the two years and was more uniform in 2015 than in 2016. Maximum daily precipitation was 181.0 mm on July 31 (38 DAT) in 2015 and 92.2 mm on June 30 (3 DAT) in 2016. The frequency of drainage and irrigation were different among different treatments in both years and the lowest frequency was observed under CID-II.

The total rainfall, available rainfall (AI), irrigation water volume (IV), drainage volume, evapotranspiration (ET), and total water input (TWI) during the whole growth period under different treatments are shown in Table 1. The volume of AI under CID treatments was significantly higher (32.6% to 41.5%) than under AWD for both years. Compared with AWD, the IV under CID-I significantly decreased by 16.1% in 2015 and by 9.7% in 2016. Compared with AWD, the IV under CID-I decreased by 37.1% in 2015 and by 26.2% in 2016. The discrepancy in IV for two years resulted from the distribution of precipitation, which was more uniform in 2015 (Fig. 1). The volume of ET was not significantly different among treatments. The highest ET was observed under CID-II. Compared with AWD, CID reduced drainage volume by 33.0 to 53.3% in both years.

Growth Components

Plant height exhibited a rising trend and obtained the maximum at maturity. The lowest plant height was observed under AWD (111.0 cm in 2015 and 120.5 cm in 2016), whereas the highest was under CID-I (126.0 cm in 2015 and 133.0 cm in 2016). At the end of the experiment, there was a significant difference between plant height under CID-I and AWD, but none between CID-II and AWD. Compared with AWD, plant height under CID-I was increased by 13.5% in 2015 and 10.4% in 2016 and under CID-II increased by 6.8% in 2015 and 5.1% in 2016 at maturity (Fig. 2).

Maximum tiller density occurred at about 40 DAT for both years. The percentage of productive tillers under CID-I was 51.6% in 2015 and 63.5% in 2016. The percentage of productive tillers under CID-II was 56.8% in 2015 and 68.8% in 2016 lower than (63.0% in 2015 and 70.5% in 2016) under AWD. The difference between CID and AWD in tiller numbers gradually widened from the end of stage I in 2015. However, the difference in tiller numbers between CID and AWD gradually widened from the middle of the tillering stage in 2016. The discrepancy in the change of tiller numbers in the two years resulted from the difference in rainfall during the different growth periods. Moreover, a higher FWL, which was caused by rainstorm at 10 DAT and 16 DAT in 2016, contributed to this difference. The average tiller numbers at maturity across the two years were 263.6 m^{-2} to CID-I and 277.2 m^{-2} to CID-II, 82.1 and 86.3% of those under AWD (Fig. 3).

Root length (RL), root mass (RM), shoot mass (SM), root/shoot ratio (RSR), total dry mass (TDM) and HI of paddy rice at harvest under different treatments in 2015 except for RM between CID and AWD, were not significantly different at harvest (Table 2). Compared with AWD, SM, RM, and TDM under CID-I increased for both years. CID-II achieved the highest RM, SM and TDM among the three treatments. However, the lowest RL was also observed under CID-II. Additionally, the SM and TDM under CID-II were significantly lower than under AWD in 2016. The harvest index (HI) of the three treatments was not significantly different and ranged from 0.48 to 0.53 for both years.

Grain Yield and Yield Components

Compared with under AWD, the grain yield under CID-I decreased by 2.9% in 2015 and increased by 3.5% in 2016. The difference might be explained by the longer flooding period during growth in 2015. The grain yield under CID-II was the lowest among three treatments and decreased by 4.7% in 2015 and 2.0% in 2016.

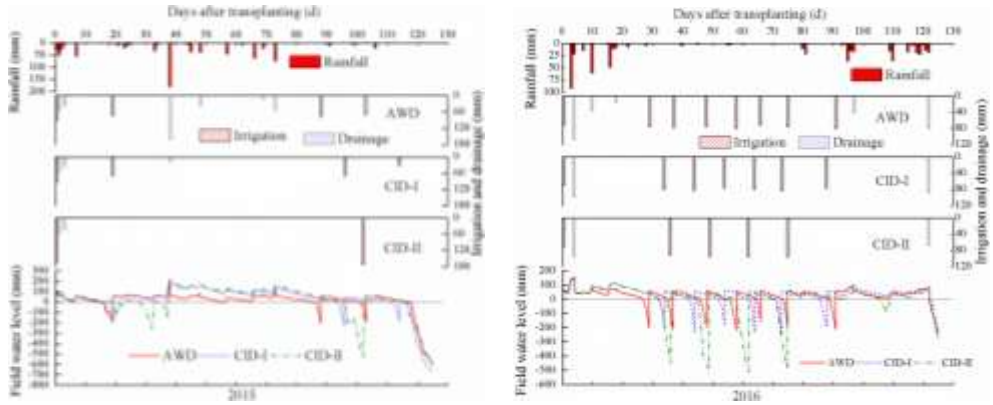

Fig. 1: Daily rainfall, irrigation and drainage, and filed water level from transplanting to harvest of paddy rice under different treatments

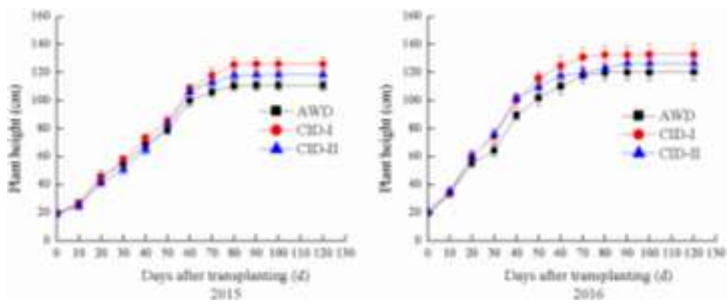

Fig. 2: Influence of different water regimes on plant height in 2015 and 2016. Vertical bars represent ± standard error (SE) of the mean. The SE was calculated across three replicates for each year

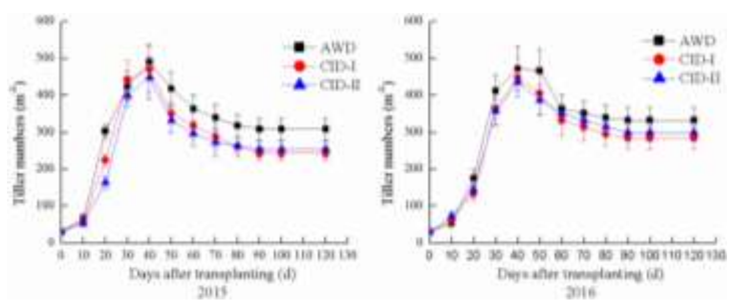

Fig. 3: Influence of different water regimes on tiller numbers in 2015 and 2016.Vertical bars represent±standard error (SE) of the mean. The SE was calculated across three replicates for each year

Grain yield under CID-II decreased, because the reduction of PFG and SPM. PM significantly was decreased under CID, whereas SP significantly increased. CID-I achieved the highest PFG and the lowest TGW among three treatments. Unlike CID-I, CID-II achieved the highest TGW and the lowest PFG. These different results might be attributed to the different degrees of water deficit rice plants experienced under the two CID treatments and various climatic conditions (Table 3).

Water Productivity

Among different treatments, yield water use efficiency (WUE_y) and yield irrigation water use efficiency ($IWUE_y$) ranged from 1.48 to 1.73 kg m^{-3} and from 1.48 to 4.15 kg m^{-3}, respectively. WUE_y under CID was not significantly different from under AWD. The highest $IWUE_y$ was obtained under CID-II, whereas the lowest obtained under AWD (Table 1). Compared with under AWD, $IWUE_y$ under CID-I significantly increased by 15.7% in 2015 and 14.6% in 2016. Compared with under AWD, $IWUE_y$ under CID-II was significantly increased by 51.5% in 2015 and 32.7% in 2016. Yield total water use efficiency ($TWUE_y$) under CID was higher than under AWD in both years. The greatest biomass irrigation water use efficiency ($IWUE_b$) was achieved under CID-II, and the differences between AWD and CID treatments were significant. There was no

Table 1: Yield water use efficiency (WUE_y), yield irrigation water use efficiency ($IWUE_y$), yield total water use efficiency ($TWUE_y$), biomass water use efficiency (WUE_b), biomass water use efficiency ($IWUE_b$), and biomass total water use efficiency (($TWUE_b$) for different treatments in two years of experiments

Treatments	WUE_y (kg m^{-3})		$IWUE_y$ (kg m^{-3})		$TWUE_y$ (kg m^{-3})		WUE_b (kg m^{-3})		$IWUE_b$ (kg m^{-3})		$TWUE_b$(kg m^{-3})	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
AWD	1.61a	1.72a	2.74c	1.48c	0.75a	0.77b	3.55a	3.94a	6.03c	3.40c	1.64b	1.77b
CID-I	1.49a	1.73a	3.17b	1.70b	0.76a	0.84a	3.49a	3.92a	7.45b	3.85b	1.77a	1.90a
CID-II	1.48a	1.73a	4.15a	1.97a	0.79a	0.87a	3.48a	3.75a	9.76a	4.25a	1.85a	1.89a

*In the same column and in the same year, means followed by the same letter do not differ significantly at the 5 % level by LSD

Table 2: Root length (RL), root mass (RM), shoot mass (SM), root to shoot ratio (RSR), total dry mass (TDM) and harvest index (HI) of paddy rice at harvest under different treatments

Year	Treatments	RL (cm)	SM (g hill^{-1})	RM (g hill^{-1})	RSR (g g^{-1})	TDM (g hill^{-1})	HI
2015	AWD	16.5a	54.4a	8.3ab	0.15a	62.7a	0.52a
	CID-I	15.9a	57.0a	8.9a	0.16a	65.9a	0.48a
	CID-II	16.9a	53.8a	8.0b	0.15a	61.8a	0.50a
2016	AWD	18.3b	58.9a	9.2a	0.16a	68.1a	0.51a
	CID-I	17.6b	61.4a	10.0a	0.16a	71.4a	0.50a
	CID-II	20.2a	54.6b	8.3b	0.15a	62.9b	0.53a

*In the same column and in the same year, means followed by the same letter do not differ significantly at the 5 % level by LSD

Table 3: Panicle per m^2 (PM), spikelets per panicle (SP), spikelets per m^2 (SPM), percent of filled grains (PFG), thousand grain weight (TGW) and grain yield in both years under different treatments

Year	Treatments	PM	SP	SPM	PFG (%)	TGW (g)	Grain yield (kg ha^{-1})
2015	AWD	309	119	36778	88.9	26.0	8501
	CID-I	242	145	35148	91.2	25.7	8252
	CID-II	254	135	34360	88.2	26.7	8101
2016	AWD	333	128	42662	85.0	24.8	9008
	CID-I	291	148	43050	88.1	24.6	9319
	CID-II	300	139	41695	82.8	25.6	8824

Table 4: Total rainfall, available rainfall (AI), irrigation water volume (IV), drainage volume, evapotranspiration (ET), and total water input (TWI) during the whole growth period of paddy rice under different treatments

	Treatments	Rainfall (mm)	AI (mm)	IV (mm)	Drainage volume (mm)	ET (mm)	TWI (mm)
2015	AWD	831	484b	310a	347a	527a	1141a
	CID-I	831	652a	260b	179b	555a	1076ab
	CID-II	831	669a	195c	162b	547a	1026b
2016	AWD	561	282b	665a	279a	524a	1168a
	CID-I	561	374a	587b	187b	538a	1109ab
	CID-II	561	399a	491b	162b	509a	1009b

*In the same column and in the same year, means followed by the same letter do not differ significantly at the 5 % level by LSD

significant difference in biomass water use efficiency (WUE_b) between AWD and CID treatments, but biomass total water use efficiency ($TWUE_b$) under CID was significantly higher than under AWD.

Discussion

The best water saving strategies for paddy rice production maintains high grain yield and IWUE. AWD irrigation with less irrigation water and low irrigation frequency throughout the whole growth period was used in the rice cultivation (Ye *et al.*, 2013). However, low ponding rainfall depth under AWD is not favorable to the use of rainfall. CID provides both a similar or even lower limit of irrigation and greater excess water storage depth relative to AWD. Consequently, the amount and occurrence of surface runoff decreased to a certain degree when encountered extreme rainstorm or consecutive heavy rain events, resulting in higher AI and lower irrigation and drainage frequencies (Table 4 and Fig. 1). Similar results have been previously reported (de Vries *et al.*, 2010; Shao *et al.*, 2014). Reducing irrigation and drainage frequencies and IV meant water resources, pumping energy, and labor forces were saved.

Rice growth is remarkably affected by environmental variables including water regime changing factor (Xu *et al.*, 2010). Excess ponding rainwater under CID obviously promoted the plant height of paddy rice (Fig. 2). Under flooding condition, rapid growth of internode promoted by ethylene accumulation can benefit to plant survival (Sakagami *et al.*, 2009). However, rapid growth of internode increases the potential possibility of lodging (Shao *et al.*, 2014). Conversely, lower FWL below the topsoil exerts drought stress, which inhibits plant height and enhances stem strength (Sarvestani *et al.*, 2008). Therefore, plant height under CID-II was lower than under CID-I at the end of experiment; the differences between the two treatments were not significant (Fig. 2). Tillering is negatively influenced by excess ponding water in the early growth stages (Ito *et al.*, 1999). Our study indicated that tiller numbers under CID treatments were significantly reduced compared to AWD (Fig. 3). Improved root growth is vital to achieve a high yield in paddy rice production (Zhang *et al.*, 2009). High RM and root activity signify strong nutrient and water absorption capacity. High RM observed under continuous flooding has been reported previously (Kato and Okami, 2010). In the present study, the active response of root growth to partial submergence after rainstorm was observed under CID-I, as evident by the higher RM at harvest compared with AWD (Table 2). Plants strengthen their root systems to absorb soil water under water deficits. After long-term and severe drought, the complete recovery of the plant following re-watering depends on the intensity or duration of the pre-drought event (Xu *et al.*, 2010). Our study demonstrated that RL was significantly increased in 2016, while the RM, SM, and TDM significantly reduced (Table 2), which might be because of low root proliferation (Mahajan *et al.*, 2012). Generally, RM was closely correlated with SM, and root and shoot growth are interdependent (Zhang *et al.*, 2009; Chu *et al.*, 2016). Therefore, CID-I achieved the highest RM, SM, and TDM in both years among three treatments, indicating that appropriate CID regime can improve root growth, which contributes to dry matter accumulation, leading to higher grain yield.

Paddy rice is frequently exposed to alternate drought and flooding stress under CID conditions. Studies have shown that compared with AWD, rice yield decreased by 3.0%–23.3% at different growth stages at a threshold level of 250 mm after rainstorms (Shao *et al.*, 2014; Shao *et al.*, 2015). Our study found that the grain yield under CID-I decreased by 2.9% in 2015 and increased by 3.5% in 2016 at a threshold level of 200 mm after rainstorms (Table 3). The duration for drought stress before re-watering can vary from one day to more than ten days (Bouman *et al.*, 2007). Drought duration is closely associated with weather, hydrological conditions, crop stage, and soil type (Tuong *et al.*, 2005; Dong *et al.*, 2012). Bouman *et al.* (2007) suggested that FWL reaches a depth of 150 mm below the topsoil where rice roots can still take up water from saturated soil and perched water in the rhizosphere. However, Wiangsamut (2010) did not find any grain yield loss with a FWL of 150–420 mm below the topsoil, which never reached below the root zone in clay loam. Lampayan *et al.* (2015) reported that comparable yields were obtained at the threshold of 300 mm below the topsoil. Compared with AWD, our study found that the grain yield under CID-II was decreased by 4.7% in 2015 and 2.0% in 2016 (Table 3). Comparable yields were also achieved under CID-I and CID-II (Table 3).

The low WUE and IWUE for irrigated rice are generally caused by various water losses (percolation, seepage, evaporation, transpiration, and drainage), all of which are critical to WUE and IWUE in paddy rice production (Lu *et al.*, 2000; Bouman, 2007). Studies have demonstrated that increasing ponding water after rainstorm in paddy field would result in low water losses (de Vries *et al.*, 2010; Shao *et al.*, 2014). Higher $IWUE_y$ and $IWUE_b$ were consistently observed in CID than AWD (Table 4). The highest $IWUE_y$ and $IWUE_b$ under CID-II resulted from a lower limit of irrigation. IWUE is related to the ability of fields to store rainwater based on the depth of water above the topsoil, which in turn is affected by different rainfall patterns (Avila *et al.*, 2015). Therefore, $IWUE_y$ and $IWUE_b$ in 2015 were higher than in 2016 due to differences in rainfall patterns. The uneven rainfall patterns that occurred during this study highlight the importance of optimizing the use of in-season rainfall, particularly during relatively wet growing seasons. Generally, higher seasonal WUE at biomass levels of plant can increase WUE at grain yield level (Qiu *et al.*, 2008). Our study showed that WUE_y was consistent with WUE_b, both WUE_y and WUE_b under CID presented similar values to AWD.

Conclusion

Compared with AWD, CID implementation in paddy field increased the plant height, but the tiller numbers were significantly decreased. The CID regime improved root growth, which benefited dry matter accumulation, leading to higher grain yield. Compared with AWD, the IV under CID-I was significantly decreased by 16.1% in 2015 and 9.7% in 2016; the IV under CID-II significantly decreased by 37.1% in 2015 and 26.2% in 2016. The reduced IV meant that pumping energy, labor force, and water resources were saved. Under CID, farmers can adopt a lower limit of irrigation to 500 mm and a threshold level of 200 mm after rainstorm, with the marginal reductions in grain yield. $IWUE_y$ and $IWUE_b$ under CID were significantly higher than under AWD. The highest $IWUE_y$ and $IWUE_b$ were observed under CID-I. The uneven rainfall patterns that occurred during this study highlight the importance of optimizing the use of in-season rainfall, particularly during relatively wet growing seasons. Thus, this new water management approach will play a vital role in saving irrigation water, maintaining high yield and improving the IWUE in rice growth, as well as provide a favorable option for farmers to efficiently manage irrigation and drainage in grain production when water is inadequate.

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