Adapting to Water Scarcity under Climate Change: Management to Enhance Water Productivity in Irrigated Rice

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Abstract

Decreasing water availability threatens the productivity of irrigated rice systems and strategies must be sought to save water. This paper reports on experiments conducted to access the potential for saving irrigation water. The field experiment was designed to evaluate rice water use under continuous flooding (CF) and alternate wetting and drying (AWD) under 45 and 90 kg N ha^{-1} using three seedling ages (20, 30 and 40 days). The pot experiment treatments included: saturation (T1), continuous flooding to 3 cm (T2), continuous flooding to 5 cm (T3), irrigated to 5 cm 2 days after water depth dropped to 25 cm (T4), irrigated to 5 cm after water depth dropped to 25 cm but flooded to 5 cm from flowering stage (T5), irrigating to 5 cm 5 days after water depth dropped to 25 cm below surface (T6). The field study showed that, grain yield was not significantly different between CF and AWD, and that AWD saved between 4 to 10 % water. Water productivity in the field was higher for AWD compared with CF and water productivity increased with increasing nitrogen level. For the pot experiment, all treatments saved some amount of water relative to T3. Water saved ranged from 11 mm (1.2 %) for T2 to 303 mm (33.4 %) for T5. Treatment T5 recorded the lowest grain yield of 60.2 g/pot and this represents a yield loss of 23.2 % relative to T3. Therefore, mild AWD can increase water productivity and save water without reducing yield.

Keywords: Alternate wetting and drying, Climate impact adaptation, Rice irrigation, Water saving.

Introduction

Rice feeds more than 3 billion people worldwide and receives some 34–43% of the total world's irrigation water (Bouman *et al.*, 2007). Growing a water-intensive crop such as rice presents important future challenges in the face of projected climate change and variability in water supply. Climate change, along with the potential of decreasing water availability for agriculture, threatens the productivity of irrigated rice ecosystems and ways must be sought to save the situation.

Conventional water management in lowland rice systems tends to continuously submerge (CS) fields for most part of the season leading to high water demand. With growing irrigation water demand and increasing competition across water-using sectors, the world now faces a challenge to produce more food with less water. One way of reducing water use in crop production is to increase water productivity, defined as the amount or value of product per volume or value of water used (Molden *et al*., 2001).

Water inputs can be reduced and water productivity increased by introducing periods of non-submerged conditions (Bouman and Tuong, 2001). One widely promoted water-saving technique is alternate wetting and drying (AWD) irrigation (Chu *et al*., 2014), where irrigation water is applied to achieve intermittent flooded and non-flooded soil conditions. Alternate wetting and drying (AWD) has been reported to maintain or even increase yield and to be widely adopted by farmers (Yao *et al*., 2012). However, when AWD systems were tested in tropical areas in Asia, such as in India and the Philippines, yields often decreased compared with CS conditions (Tabbal *et al*., 2002). According to Belder *et al*. (2004) AWD most often reduces yield and the amount of Irrigation water that can be saved in alternate wetting and drying compared with continuous flooding without any yield loss ranged between 6 to 14 %. Belder *et al*. (2004) also observed water productivity under AWD to be 5-35 % higher than CS conditions, although characterized by 1-7 % decline in yield. Factors such as soil type, duration and level of water stress during the non-submerged periods, depth of water table, rice variety, life cycle stage of crop when water stress is imposed and many more factors could account for different results under AWD.

However, little information exists in Ghana on how AWD affects rice growth and yield**.** This study was therefore undertaken to (i) experimentally quantify how varying water use affects rice growth and yield, and (ii) determine the irrigation strategy that can increase water productivity whiles maintaining or improving yield of rice.

Materials and Methods

Field experiment

Field experiments were also conducted from April to July in 2014 (major season) and from December 2015 to March 2016 (minor season) at the Soil and Irrigation Research Centre, Kpong Kpong (6^{o} $9^{'}$ N, 0^{o} $4^{'}$ E), University of Ghana. A split-split plot design was used with two water regimes: W1 (continuous flooding to 5 cm water head above the soil surface) and W2 (irrigated to 5 cm water head when the water depth dropped to 25 cm below the soil surface) as main plot treatment, two nitrogen rates (45 and 90 kg N ha^{-1}) as subplot and three seedling ages (20, 30 and 40 days old) as sub-subplots. Three replicates were used and the rice was grown for 120 days. Prior to the start of the experiment, core soil samples from the field were taken at four depths (0-7 cm, 7-14 cm and 14-21 cm, 21-28 cm) for determination of bulk density and saturated soil moisture content. A preliminary study was conducted to ensure that a water depth of 25 cm below the soil surface was “safe” for rice. This was achieved by perforating PVC pipes (50 cm in length and 15 cm in diameter) at 1 cm spacing along the entire length. The perforated pipes (piezometers) were pushed into the soil in a rice field so that 25 cm protruded above the soil surface. The soil from the inside of the PVC tube was removed so that the bottom of the tube was visible. This allowed monitoring of the drop in water level below the soil surface by dipping a stick into the pipe and measuring the drop in water level on a ruler (IRRI, 2009). The closer spacing ensured that the level of water in the rice basin was the same as the water level in the tube. (IRRI, 2009).

The plants were monitored during the tillering, panicle initiation and flowering stages, whiles allowing the water level to drop to 25 cm below the soil surface. The rice plants at these stages did not show any signs of moisture stress or wilting and flood water was re-established each time to 5 cm height. The 25 cm water depth was therefore considered to be "safe".

For the main experiment, the perforated pipes were placed in plots as described earlier. Nitrogen (90 kg N ha^{-1}), phosphorus (45 kg P_2O_5) and potassium (45 kg K_2O) was applied using urea, triple superphosphate and muriate of potash, respectively. A medium duration rice variety, *Baika*, was used for this study. Plot sizes measured 3 m by 4 m and main plots (water treatments) were separated by a distance of 2 m. Water was delivered to plots with a small motorized pump using the velocity volume approach (Trimmer, 1994). The pump was set to the same speed of delivery each time it was used. Data was collected on rainfall from a meteorological station on site. At maturity, data was also collected on Harvest Index (ratio of grain weight to total biomass), filled grains per panicle, 1000-grain weight, tillers per hill and grain yield. Water saved in the field study was estimated as the difference in water input between AWD and CF. Water productivity was estimated as grain yield per unit water used.

Pot experiment

The experiment was conducted at the Soil and Irrigation Research Centre, Kpong (6° 9' N, 0° 4' E), University of Ghana, during the major season (April to July) of 2014 and the minor season (December, 2015 to March, 2016). It was carried out using pots with diameter of 30 cm and height of 26 cm under a rain-out shelter. The soil used was a Calcic Vertisol (FAO, 2001). Bulk density and saturated soil water content were determined. Water content of the soil was determined by following a similar procedure for the field trail. This was achieved by perforating polyvinyl chloride (PVC) pipes (30 cm in length and 2 cm in diameter) at 1 cm spacing along the entire length. The pipes were placed upright in the pots before filling the pots with 10 kg of soil. This ensured that the columns of the pipes were not filled with soil. The pots were irrigated to 5 cm water head and left to stand. The drop in water level in the pipe was monitored twice daily. As soon as the water level "disappeared" at the base of the pot (approximately 25 cm from the soil surface) the soil in the pot was mixed thoroughly and samples were taken for moisture content determination. A medium duration rice variety, *Baika*, was used for this study.

Six water treatments were used which included: saturation (T1), continuous flooding to 3 cm (T2), continuous flooding to 5 cm (T3), irrigated to 5 cm 2 days after water depth dropped to 25 cm (T4), irrigated to 5 cm after water depth dropped to 25 cm but flooded from flowering stage to 5 cm (T5), irrigating to 5 cm 5 days after water depth dropped to 25 cm below surface (T6). Twenty day old seedlings were transplanted with 2 seedlings per pot in a completely randomized design with ten replicates. The compound fertilizer NPK (15:15:15) was applied one week after transplanting as basal application at 300 kg ha^{-1}. Urea was applied at panicle initiation as top-dress at 100 kg ha^{-1}. At maturity, data was collected on filled grains per panicle, 1000-grain weight, number of tillers per hill and grain yield and water used. Water saved was estimated as the difference in water use for water treatments using T3 (continuous flooding at 5cm) as the reference as it consumed the highest amount of water.

Statistical analysis

The data collected from the field study was analyzed as split-split plot, whiles that from the pot experiment was analyzed as completely randomized design using Analysis of Variance. Where significant differences were detected, least significant difference (LSD) test (p = 0.05) was used to test the differences between means.

Results

Field experiment

Rainfall and physical and chemical properties of the soil

Rainfall (Appendix 1) during the 2014 major season was 483 mm which occurred in 34 rainfall events. Total rainfall during the 2015-2016 minor season was 182.8 mm and this occurred in 14 rainfall events.

The characteristics of the soil is presented in Table (1) and Table (2). The soil has a pH of 6.7 with organic carbon content of 0.81 %. Total nitrogen, available phosphorus and cation exchange capacity values were 0.1 %, 5.6 mg kg^{-1} and 34.4 cmol (+) kg^{-1}, respectively. Bulk density ranged between 1.41 to 1.55 Mg m^{-1} with a clay content of between 57 and 62 %. Saturated water varied between 32 and 40 %.

Irrigation water input

Seedling age had no significant effect (p = 0.178) on the amount of irrigation water applied. Irrigation water input for CF ranged between 631 to 643 mm whiles that for AWD ranged between 574 and 585 mm in the 2014 rainy season (Table 3). Irrigation water input during the minor season (2015-2016) season ranged between 761 and 866 mm. Total water input for both continuous flooding (CF) and *alternate wetting and drying (*AWD) was higher in the 2014 major season with values ranging between 1057 and 1126 mm compared to a range of 944 t0 1049 mm for the 2015-2016 minor season.

Table 1. Chemical properties of the soil at the experimental site at Kpong, Ghana

Property	Value
pH in water	6.70
Organic C (%)	0.81
Total N (%)	0.10
Olsen P, mg kg^{-1}	5.60
CEC, cmol kg^{-1}	34.2

Table 2. Physical properties of the soil at the experimental site at Kpong, Ghana

Soil depth (cm)	Bulk density (Mg m^{-3})	Sand	Silt	Clay	Textural class	Saturated water (% w/w)
			%			
0-10	1.41	40.5	2.5	57.0	Clay	32.4
10-20	1.48	38.9	2.7	58.4	Clay	34.6
20-30	1.55	36.0	2.4	61.6	Clay	39.7

Table 3. Water supply and averaged nitrogen rates over seedling ages in the field

Year		Irrigation (mm)			Total input (mm)		
	Rainfall (mm)	AWD	CF	LSD	AWD	CF	Difference (%)
2014							
90 N	483	574^a	643^b	16.7	1057	1126	6.1
45 N	483	585^a	631^b	25.4	1068	1114	4.1
2015-2016							
90 N	183	772^a	840^b	14.3	955	1023	6.6
45 N	183	761^a	866^b	19.0	944	1049	10.0

*AWD = Alternate wetting and drying, CF = Continuous flooding. *Means followed by the same letters in a row are not significantly different ($p < 0.05$) using LSD

Yield components

Results on yield components is presented in Table (4 and 5). Apart from CF for the 2015-2016 minor season where seedling age had no effect, panicle bearing tillers per hill for 40-day old seedlings was significantly lower ($p < 0.05$) than that for 20 and 30 day old seedlings for both CF and AWD. However, there was no difference in tillers per hill between CF and AWD. There was no difference in harvest index (HI) between CF and AWD. Filled grains per panicle ranged from 96 to 103. During the 2014 major season, filled grains per panicle was not significantly affected ($p = 0.136$) by seedling age. However, during the 2015-2016 minor season, 40-day old seedlings had significantly lower filled grains per panicle. The 1000-grain averaged 26.7 g across all treatments.

Table 4. Number of Tillers per hill and Harvest Index of rice with two N rates in 2014 and 2015-2016

	Tillers per hill		Harvest Index	
Seedling age (DAE)	CF	AWD	CF	AWD
2014				
20	12.4±0.72^a	12.3±0.17^a	0.42±0.04^a	0.43±0.02^a
30	12.1±0.75^a	12.3±0.44^a	0.46±0.05^a	0.43±0.05^a
40	10.0±0.53^b	10.3±0.46^b	0.45±0.03^a	0.41±0.03^a
LSD	0.45	0.38	0.03	0.05
2015-2016				
20	11.2±1.01^a	11.8±0.42^a	0.48±0.03^a	0.47±0.03^{ab}
30	11.5±0.98^a	11.9±0.30^a	0.45±0.06^a	0.45±0.05^a
40	10.3±0.20^a	10.7±0.44^b	0.46±0.06^a	0.48±0.05^b
LSD	1.60	0.45	0.06	0.02

Values are means ± Standard deviation, DAE = days after emergenc e. Means followed by the same letters in a column are not significantly different ($p < 0.05$) using LSD.

Table 5. Number of filled grains per panicle and 1000 grain weight over two N rates in 2014 and 2015-2016

Seedling age (DAE)	Number of filled grains per panicle CF	Number of filled grains per panicle AWD	1000-grain weight (g) CF	1000-grain weight (g) AWD
2014				
20	101±1.7^{a}	103±1.0^{a}	26.6±0.7^{a}	26.2±0.8^{a}
30	102±3.6^{a}	101±3.6^{a}	26.9±1.0^{a}	26.1±0.9^{a}
40	102±2.7^{a}	100±3.6^{a}	27.0±0.8^{a}	25.8±0.4^{a}
LSD	7.5	6.1	1.9	1.6
2015-2016				
20	101±2.0^{a}	98±3.1^{a}	27.1±0.9^{a}	27.3±0.3^{a}
30	103±1.7^{a}	99±1.7^{a}	26.9±0.7^{a}	26.1±0.5^{a}
40	97±3.0^{b}	96±1.0^{b}	26.7±0.5^{a}	26.5±0.9^{a}
LSD	3.3	1.8	1.7	1.4

Values are means ± Standard deviation, DAE = days after emergence . Means followed by the same letters in a column are not significantly different ($p < 0.05$) using LSD

Yield and water productivity

Over the two seasons, seedling age generally had a significant ($p < 0.05$) effect on grain yield with 40-day old seedlings recording significantly lower grain yield (Table 6). Nitrogen rate significantly influenced yield with 90 kg N ha^{-1} recording higher yield than 45 kg N ha^{-1}. Over the two seasons, there was no difference in yield between CF and AWD. Water productivity for the 2014 major season was generally higher than for the 2015-2016 minor season (Table 7). Water productivity values for AWD (0.24-0.85 kg m^{-3}) were generally higher than for CF (0.19-0.78 kg m^{-3}).

Table 6. Grain yield of rice transplanted at different seedling ages in 2014 and 2015-2016

Seedling Age (DAE)	Grain yield (kg ha^{-1}) N45 CF	N45 AWD	N90 CF	N90 AWD
2014				
20	2122±175.3^{a}	2073±95.6^{a}	4161±450.2^{a}	3988±267.6^{a}
30	2166±142.5^{a}	2134±237.4^{a}	4187±367.3^{a}	4080±279.8^{a}
40	1863±239.6^{b}	1856±219.3^{a}	3780±184.7^{b}	3674±221.0^{a}
LSD	227.7	330.0	326.7	380.2
2015-2016				
20	1622±182.1^{a}	1740±171.3^{a}	3541±248.6^{a}	3605±234.7^{a}
30	1533±239.9^{a}	1534±246.9^{a}	3596±94.4^{a}	3489±387.2^{a}
40	1362±133.7^{b}	1589±166.5^{a}	3080±271.4^{b}	3274±373.9^{a}
LSD	138.5	543.5	417.7	592.7

Values are means ± Standard deviation, DAE = days after emer gence. Means followed by the same letters in a column are not significantly different ($p < 0.05$) using LSD

Table 7. Water productivity of different seedling ages of rice in 2014 and 2015-2016

	Water productivity (kg m^{-3})			
Seedling	**N45**		**N90**	
Age (DAE)	**CF**	**AWD**	**CF**	**AWD**
2014				
20	0.40±0.02^{a}	0.43±0.03^{a}	0.78±0.04^{a}	0.83±0.02^{ab}
30	0.41±0.05^{a}	0.44±0.04^{a}	0.78±0.05^{a}	0.85±0.05^{a}
40	0.35±0.03^{a}	0.38±0.03^{a}	0.71±0.03^{b}	0.77±0.05^{b}
LSD	0.07	0.09	0.06	0.07
2015-2016				
20	0.22±0.05^{a}	0.27±0.02^{a}	0.51±0.05^{a}	056±0.03^{a}
30	0.21±0.03^{a}	0.24±0.03^{a}	0.51±0.03^{a}	0.54±0.03^{a}
40	0.19±0.04^{a}	0.25±0.04^{a}	0.44±0.05^{b}	0.51±0.03^{a}
LSD	0.08	0.03	0.06	0.07

Values are means ± Standard deviation, DAE = days after emergence . Means followed by the same letters in a column are not significantly different ($p < 0.05$) using LSD

Pot experiment

The amount of water consumed by each treatment and the amount of water saved relative to 5 cm continuous flooding (CF) is shown in Table (8). The lowest amount of water consumed was recorded by irrigating to 5 cm after water depth dropped to 25 cm but flooded from flowering stage to 5 cm with a value of 633 mm and this was significantly lower compared with the other treatments. Relative to CF to 5 cm, all treatments saved some amount of water. Water saved ranged between 11 mm for continuous flooding to 3 cm and 303 mm for irrigated to 5 cm after water depth dropped to 25 cm but flooded from flowering stage to 5 cm. This translates into a water saving ranging from 1.2 to 33.4 %. Saturated soil condition saved 5.6 % of water.

Table 8. Water saved under the various water management treatments in 2014 and 2015-2016

		Water saved compared to 5 cm continuous flooding	
Treatment	**Irrigated water (mm)**	**(mm)**	**(%)**
T1	884±34.4^{b}	53	5.6
T2	925±24.8^{a}	11	1.2
T3	936±19.1^{a}	0	0
T4	839±14.4^{c}	98	10.5
T5	633±19.4^{d}	303	33.4
T6	914±13.9^{a}	23	2.4
LSD	28.9		

*Saturation (T1), continuous flooding to 3 cm (T2), continuous flooding to 5 cm (T3), irrigated to 5 cm 2 days after water depth dropped to 25 cm (T4), irrigated to 5 cm after water depth dropped to 25 cm but flooded from flowering stage to 5 cm (T5), irrigating to 5 cm 5 days after water depth dropped to 25 cm below surface (T6).
Values are means ± Standard deviation, DAE = days after emergence. Means followed by the same letters in a column are not significantly different ($p < 0.05$) using LSD.

Yield and water productivity of the different treatments is presented in Table (9). Irrigating to 5 cm after water depth dropped to 25 cm but flooded from flowering stage to 5 cm recorded the lowest grain yield of 60.2 g/pot and this was significantly lower ($p < 0.05$) than all the other treatments. This represents a yield loss of 23.2 % relative to 5 cm continuous flooding. Water productivity for all treatments ranged between 1.19 kg m^{-3} water for continuous flooding to 5 cm to 1.35 kg m^{-3} water for irrigating to 5 cm after water depth dropped to 25 cm but flooded from flowering stage to 5 cm. Water productivity for irrigating to 5 cm after water depth dropped to 25 cm but flooded from flowering stage to 5 cm was significantly higher ($p < 0.05$) compared to the other water treatments.

Table 9. Mean yield and water productivity of the different water treatments in 2014 and 2015-2016

	Yield		Water productivity	
Treatment	**(g/pot)**	**Difference (%)**	**(kg m^{-3})**	**Difference (%)**
T1	74.8±3.6^b	-4.6	1.20±0.3^b	1.0
T2	78.1±5.3^b	-0.4	1.20±0.2^b	1.0
T3	78.4±5.9^b	0.0	1.19±0.1^b	0.0
T4	74.6±10.9^b	-4.8	1.25±0.2^b	5.0
T5	60.2±4.8^a	-23.2	1.35±0.2^a	13.6
T6	79.8±6.0^b	1.8	1.23±0.2^b	3.4
LSD	6.1		0.09	

*Saturation (T1), continuous flooding to 3 cm (T2), continuous flooding to 5 cm (T3), irrigated to 5 cm 2 days after water depth dropped to 25 cm (T4), irrigated to 5 cm after water depth dropped to 25 cm but flooded from flowering stage to 5 cm (T5), irrigating to 5 cm 5 days after water depth dropped to 25 cm below surface (T6).

Values are means ± Standard deviation, DAE = days after emergence. Means followed by the same letters in a column are not significantly different ($p < 0.05$) using LSD.

Discussion

The lower amount of water input from rainfall accounted for the higher amount of irrigation water input during the minor season. Although irrigation water input was higher during the minor season, total water input for both continuous flooding (CF) and *alternate wetting and drying (*AWD) was higher in the major season and this is due to the higher amount of rainfall in the major rainy season. Relative to CF, there was between 6 to 10 % reduction in water input when AWD was applied.

This reduction was higher during the minor season than the rainy season. Cabangon (2011) reported that mild stress of AWD reduced irrigation water input by 8–20 % and severe stress by 19–25 % compared with CF. Tantawi and Ghanem (2001) comparing AWD and CF reported a water saving of 16.7% with a corresponding yield reduction of 4.2 %. In a related study, Stanslaus *et al*. (2018) observed higher amount of irrigation water use in the dry season than in the wet season.

The lack of any significant difference in tillers per hill between CF and AWD is an indication that stress from AWD was mild (Cabangon, 2011). Under water stress, evapotranspiration is reduced in plants, which leads to decrease in photosynthesis which in turn induces a decrease in height and number of tillers (Kima *et al*., 2014). Nguyen *et al*. (2009) who compared various water saving systems in rice found no significant difference in number of tillers among treatments and suggested that tillering was less sensitive than other characteristics such as plant height and leaf area. Akram *et al*. (2013) also noted that number of tillers per hill of different rice cultivars were not significantly affected by soil moisture stress in all growth stages. Pramanik and Bera (2013) in a related study observed that the lowest number of tillers was produced in crop receiving the oldest seedlings.

Harvest index (HI), is a measure of partitioning to plant parts and high HI implies more portioning to reproductive plant parts. Moisture stress hinders grain filling and this can reduce yield, eventually reducing HI (Surapaneni *et al*., 2016). The similar HI observed for CF and AWD could be due to the fact that, the level of water stress from the AWD used did not reduce grain filling. Water stress induced from irrigation interval in this study for CF was 3 to 5 days and 7 to 10 days for AWD. On the other hand, Freedom-Timon *et al*. (2015) observed significantly lower HI for rice irrigated over longer intervals (9-day intervals) compared with 6 and 3 days irrigation intervals.

Water stress affected the number of filled grains and hence yield in this study. Studies by Jones (2004) showed that water stress reduced average number of grains per panicle, grain weight per panicle, grain filling rate, 1000 grain weight and also slowed down carbohydrate synthesis (Rahman *et al*., 2002). As a result, the similarity in number of filled grains per panicle for CF and AWD, perhaps is due to the low level of water stress from the AWD used in this study. Belder *et al*. (2004) indicated that, the level of water stress from AWD determines whether the rice plant is water stressed enough to reduce yield. According to Ali *et al*. (1995), among the various factors that influence rice productivity, seedling age is rated high because it has tremendous effect on characters contributing to grain yield. The higher grain yield in the younger seedlings is due to the development of more productive tillers and leaves ensuring greater resource utilization as compared to older seedlings. Vijayakumar *et al*. (2005) observed similar results with higher grain yield in younger seedlings. Nitrogen rate had a significant effect on grain yield but grain yield was not significantly different between CF and AWD for both seasons. The lower yield observed for 40 day old seedlings is probably due to the relatively lower number of panicle bearing tillers per hill.

Grain yield between CF and AWD was not different and this may be due to the lack of water stress from the AWD used. Yang and Zhang (2010) in a related study observed that practicing AWD throughout the plant cycle reduces grain yield significantly due to reduced soil moisture. Howell *et al*. (2015) reported a similar grain yield between AWD and continuous submerged treatments whereas, Chu *et al*. (2015) observed a higher grain yield in AWD plants than continuous submergence plants. These different findings may be due to the fact that AWD varies in terms of frequency and duration of drying periods and the type of soil used (Bouman and Tuong 2001; Belder *et al*., 2004).

The relatively higher water productivity observed for AWD over CF is mainly due to the higher grain yield during the major season as well as the higher irrigation water input during the minor season. In a similar study, Dahmardeh *et al*. (2015) observed that reduction in irrigation water increased water productivity. However, they did not observe a significant difference in water productivity between CF and AWD from their study. This was attributed to the mild stress AWD (Cabangon, 2011) used in the study. The results from the current study agree with Chu *et al.* (2015) who observed higher water productivity for AWD over continuous flooding. Yangyuoru *et al.* (2010) in Ghana also showed water productivity for irrigated rice to be 0.24-0.66 kg m^{-3}. Water productivity increased with increasing nitrogen rate and this is due to the higher yield at higher N rate.

Water saved from the pot experiment translated into water saving of 1.2-33.4 %. Saturated soil condition saved 5.6 % of water relative to 5 cm continuous flooding. This value is low compared to studies by Tabbal *et al*. (2002) who observed 45 % water saving by saturated soil condition relative to continuous flooding. This is perhaps due to the fact that this experiment was conducted in pots, thereby reducing the extent to which the roots could explore the soil for water.

Keeping the soil saturated led to a 4.6 % reduction in yield relative to continuous flooding to 5 cm. Similar result was observed by Tabbal *et al*. (2002) who recorded a 5 % yield reduction for saturated condition relative to continuous flooding. Irrigating to 5 cm 2 days after water depth dropped to 25 cm and irrigating to 5 cm 5 days after water depth dropped to 25 cm below surface which are forms of alternate wetting and drying (AWD) also had similar yields as 5 cm continuous flooding. Irrigating to 5 cm 2 days after water depth dropped to 25 cm and irrigating to 5 cm 5 days after water depth dropped to 25 cm below surface saved 10.5 and 2.4 % water respectively, relative to 5 cm continuous flooding. The water saved in this study is lower compared to Belder *et al*. (2004), who noted that, the amount of irrigation water that can be saved in alternate wetting and drying compared with continuous flooding without any significant yield loss ranged between 6 to 14 %. The higher water productivity observed for irrigating to 5 cm after water depth dropped to 25 cm but flooded from flowering stage to 5 cm is due to the low water use associated with this treatment, though, characterized by a significant reduction in yield. Irrigating to 5 cm 2 days after water depth dropped to 25 cm, irrigating to 5 cm after water depth dropped to 25 cm but flooded from flowering stage to 5 cm, and irrigating to 5 cm 5 days after water depth dropped to 25 cm below soil surface, all of which are forms of AWD recorded higher water productivity than 5 cm continuous flooding. Belder *et al*. (2004) observed water productivity under AWD to be 5-35 % higher than continuous submergence conditions.

Conclusion

The AWD evaluated in this study did not reduce paddy rice yield compared with CF in the field, although there was a reduction in irrigation water use for AWD. Using AWD in the field and pots saved irrigation water and resulted in higher water productivity. Increasing N rate in the field study also increased yield. From the field study, seedling ages between 20-30 days old did not differ in their yield. Water productivity can be increased by using AWD. Using AWD in this study saved up to10 % irrigation water in the field when the water level in the field was allowed to drop to 25 cm below the surface before re-establishing flood water. Therefore, mild AWD can increase water productivity and save water without reducing yield. Water savings is more enhanced when AWD is applied during the major rainy season.

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