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Water-Saving Irrigation and Nitrogen Fertilizer Use Efficiency for Irrigated Rice in the Red River Delta, Vietnam

Ngo Thanh Son[1,2] & Nguyen Thu Ha[1]

[1]Faculty of Natural Resources and Environment, Vietnam National University of Agriculture, Hanoi 131000, Vietnam

[2]Consulting Center of Technological Science for Natural Resources and Environment, Hanoi 131000, Vietnam

Abstract

The objective of this research was to quantify the effects of water-saving regimes and fertilizer application improvement on water productivity, N-use efficiency, and rice yield. The results showed that the tested water treatments did not have significant effects on the growth and development, yield components, and final grain yield, but water productivity was significantly increased from 1.28 kg grain m^{-3} (W_0) water to 1.74 kg grain m^{-3} water (W_1) and 1.94 kg grain m^{-3} water (W_2). In addition, the percentage of total irrigation water saved from W_1 and W_2 were 25.24-44.52% compared to continuous flooding. Fertilizer deep placement (FDP) combined with organic compost significantly increased the grain yield of the tested hybrid rice variety. Average grain yield increased quickly from 2847 kg ha^{-1} with 0 kg N ha^{-1} to 5263 kg ha^{-1} with 120 kg N ha^{-1} under the fertilizer deep placement method. The highest total nitrogen uptake, agronomic nitrogen efficiency (ANE), and nitrogen uptake efficiency (NUE) were obtained from alternate wetting and drying at a -20cm water depth and the fertilizer deep placement method (W_1N_2). In addition, it also gave the highest income in comparison with the other treatments. Therefore, alternate wetting and drying at a -20cm water depth and fertilizer deep placement method should be encouraged for implementation in other regions of Vietnam.

Keywords

Continuous flooding, alternate wetting and drying, fertilizer deep placement, water use efficiency

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Correspondence to
Nguyen Thu Ha
ntha@vnua.edu.vn

ORCID

Ngo Thanh Son
https://orcid.org/0000-0001-9785-1933

Nguyen Thu Ha
https://orcid.org/0000-0001-6356-5015

Introduction

According to FAO (2015), as of 2014, the total area of paddy rice worldwide was 160.6 million hectares, distributed across 114 countries, and the total milled rice production was about 491.4 million tons. Irrigated rice (with a cultivated area of about 85-90 million hectares) accounts for 75% of the world's rice production (IRRI, 2010). Because the irrigated rice ecosystem plays a key role in global rice production, the sustainability of this ecosystem is a critical issue.

Rice is grown under submerged conditions mainly for agronomic advantages (such as suppression of weeds, ease of plowing, and storage of water from heavy rainfall) rather than vegetative characteristics, so it would be possible to grow rice in water shortage conditions (Datta *et al*., 2017). Nowadays, water resources are becoming scarce all over the world. In many Asian countries, the amount of water available for use has decreased about 40-60% from 1955 to 1990 (Son *et al.,* 2008; Peng *et al.,* 2011; Lampayan *et al.,* 2015). The water supply is estimated to continue decreasing 15-54% over the next 35 years due to the negative influences of climate change, forest degradation, and the water demand of other economic sectors. The challenge facing national policymakers, irrigation authorities, and farmers is how best to maintain and increase rice yields and the production of other foods while reducing agricultural inputs like water use.

In recent years, water availability has become a serious issue in Asia and in Vietnam in particular as rice is mainly grown under paddy rice conditions (Son *et al*., 2008). Irrigated paddy fields are conventionally submerged from transplanting (or sowing) to harvest resulting in water loss through evapotranspiration (ET) and percolation (Dang *et al*., 2018). Several experiments on water-saving irrigation technology for rice cultivation have been conducted in the last two decades (De Silva & Hasan, 2007; Thomas & Ramzi, 2011). Research conducted at the International Rice Research Institute (IRRI) has proved that paddy rice only needs to be flooded during the rooting and flowering stages (Tran *et al*., 2018). Consequently, they developed an alternate wetting and drying irrigation (AWD) procedure, whereby paddy fields are only intermittently irrigated except during the rooting and flowering stages. This method significantly reduces the amount of water used compared to conventional irrigation in which the fields are flooded to a depth of between three to five centimeters.

According to Lampayan *et al.* (2015), the AWD system, where the field is not continuously flooded but the soil is allowed to dry out for one to several days and then flooded again, is an efficient technology capable of reducing water demand by as much as 38% with no adverse impact on yield when practiced correctly. Besides, it also indirectly helps in reducing irrigation costs and increasing farmers' income in some Asian countries, such as Vietnam, the Philippines, and Bangladesh (Lampayan *et al.*, 2015). In some areas of Vietnam, systems of alternate wetting and drying have been reported to maintain or even increase yield and have been widely adopted by farmers (Nguyen Van Dung *et al*., 2009; Ngo Thanh Son *et al.,* 2010; Dang *et al*., 2018). However, experimental evidence is still scarce in international literature. Likewise, the hydrological and environmental conditions under which these systems are practiced are not well known.

Vietnam is one of 20 leading countries in using chemical fertilizers in the world (Ngo *et al*., 2018). The crop requiring the most fertilizer application is rice, which accounts for approximately 65% of the demand for fertilizer, followed by corn crops with 9% (Toan *et al*., 2019). In 2017, rice farming in Vietnam consumed around 1.7 million tons of N, 1.4 million tons of P_2O_5, and 0.67 million tons of K_2O (FAO, 2017). On average, the fertilizer formulations for rice in the Red River Delta (RRD) are 100-60-90 (kg of N-P_2O_5- K_2O) for transplanting rice and 100-60-60 for sowing rice with four applications (that is, one time before transplanting or sowing, and three times after transplanting or sowing) (FAO, 2017). N-fertilizer has a strong effect on the crop growth rate and yield (Dong *et al*., 2012). As such, both the lack of and overuse of N-fertilizer negatively impact rice growth, limiting the development and potential yield. The effect of N-fertilization is variety-specific (Van Keulen, 1977; Tang *et al.*, 2007) and depends on climatic conditions. The N use efficiency of rice plants to produce grains varies with environment and variety. According to Nguyen Van Bo (2003), most plant tissues invariably require minimum amounts of N to grow. One major consequence of a lack of N in plants is that the growth of the leaf area will be reduced, thereby limiting light interception, photosynthetic rate, and finally, biomass growth and grain yield (Sinclair, 1990). Dobermann & Cassman (2002) found an average apparent N recovery of 31% in farmers' fields although higher values of 80% can be obtained under specific conditions (Schnier *et al.*, 1990; Peng & Cassman, 1998; Peng *et al*., 2010). In continuous submerged (CS) fields, N is almost solely available as ammonium (NH_4^+) and N losses are predominantly through NH_3 volatilization (Vlek & Craswell, 1981; Watanabe *et al*., 2009). Allowing the soil to become (temporarily) aerobic will enhance nitrification. If the nitrate (NO_3^-) is not taken up, it is prone to denitrification losses (Eriksen *et al.*, 1985) or leaching in more permeable soils (Keeney & Sahrawat, 1986). From a plant nutritional point of view, a mixture of NH_4^+ or NO_3^- is better for N uptake and growth of the rice plant than the sole availability of NH_4^+ or NO_3^- (Qian *et al.*, 2004). Therefore, water-saving regimes may lead to higher N uptake and biomass growth but may also lead to higher N losses and a reduced biomass growth if the availability of NO_3^- mismatches the crop N demand.

The main goal of the present study was to quantify the effects of water-saving regimes and fertilizer application improvement on water productivity, N-use efficiency, and yield. Furthermore, the study explored options for water-saving technologies and fertilizer application methods at the field scale to achieve yield security and reduced water use at a regional scale.

Materials and Methods

Study area

The field experiment was conducted in the experimental areas of Vietnam National University of Agriculture (VNUA) (20°57'30''-21°01'30" N, 105°55'10'' - 105°57'40'' E, 14m latitude), Gia Lam district, Hanoi, Vietnam. **Table 1** presents the main soil characteristics of the study site, classified as Eutric Fluvisols (FAO-UNESCO).

Field experiment

The field experiment had nine treatments with three replications (27 plots with an area of 20m^2 each). The plots were arranged in a split plot design with three water regimes as the main-plots and three nitrogen management options as the sub-plots.

Main-plot

The three water regimes during the spring season were: (1) W_0 = continuous flooding (CF), the field water depth was maintained in the range from 3cm to 5cm until 15 days before harvesting (DBH); (2) W_1 = AWD at -20kPa, when the water level dropped to 20cm below the surface of the field, irrigation was applied to re-flood the field with 3cm of ponded water, and the water was completely drained at 15 DBH; and (3) W_2 = AWD at -30kPa, when the water level dropped to 30cm below the surface of the field, irrigation was applied to re-flood the field with 3cm of ponded water, and the water was completely drained at 15 DBH. In all the water treatments, the field water depth was maintained between 1-4cm during the first ten days after transplanting (DAT).

Sub-plot

The three nitrogen management options were: N_0 (control), N_1 (traditional farmer application), and N_2 ($N_2 = N_1$, compressed NPK 16-6-12 was used). The content of all the plots was as shown in **Table 2**.

In the N_0 and N_1 plots, base fertilization was conducted one day before transplanting with 100% farmyard manure (FYM), 100% P_2O_5, and 20% K_2O; topdressing was applied two times during crop duration: at the start of tillering (50% N and 30% K_2O) and 20 days before the flowering date (20% N and 50% K_2O). In the N_2 plot, the compressed fertilizer was applied 3 DAT following the fertilizer deep placement method at a depth from 7 to 10cm below the soil surface and once among four rice hills. During the cropping season, pre-emergence herbicide was applied to control weeds. Hand-weeding was applied frequently. Pests and diseases were controlled by the applications of appropriate pesticides when necessary.

Seven-day lowland rice seedlings (Bac Thom variety) were transplanted with the spacing

Table 1. Soil characteristics of the study site before conducting the experiment

Soil properties	Values
OC (%)	1.8
pH_{H2O}	6.8
NO_3^- (mg kg^{-1})	1.1
NH_4^+ (mg kg^{-1})	22.8
Texture (0-30cm)	Sandy loam

Table 2. The content of the plots in the field experiment

No.	Plots		Content
	Main plots	Sub-plots	
1	W_0	N_0	CF; 0N + $70P_2O_5$ + $70K_2O$ + 10 tons FYM Using super phosphate and potassium cloride
2		N_1	CF; N_0 + 120N - Using urea
3		N_2	CF; N_0 + 120N - Using compressed NPK 16-6-12
4	W_1	N_0	AWD at -20kPa; N_0
5		N_1	AWD at -20kPa; N_1
6		N_2	AWD at -20kPa; N_2
7	W_2	N_0	AWD at -30kPa; N_0
8		N_1	AWD at -30kPa; N_1
9		N_2	AWD at -30kPa; N_2

Note: N_0: 0 N + 70 P_2O_5 (super phosphate) + 70 K_2O (potassium chloride) + 10 tons OF

N_1: 120 N (using urea) + 70 P_2O_5 (super phosphate) + 70 K_2O (potassium chloride) + 10 tons OF

N_2: 120 N + 70 P_2O_5 + 70 K_2O + 10 tons OF, Using compressed NPK 16-6-12

FYM (farmyard manure): pH = 5.8; OM (%) = 29.1; N (%) = 1.39; P_2O_5 (%) = 0.93; K_2O (%) = 1.32.

of 20cm x 15cm to ensure the density of 35 hills m^{-2}. The field experiment was conducted in the spring season of 2014 (Febuary 21, 2014 to June 14, 2014).

Data collection and analysis

Meteorological data

The microclimatic data, namely radiation, air temperature, air relative humidity, and precipitation, were collected from the VNUA-JICA weather station. Data on the amount of actual rainfall were obtained from the VNUA-JICA meteorological station and were used to adjust the actual amount of irrigation water applied to each plot.

Soil moisture content

Soil moisture content was measured by collecting soil samples from representative locations of the field, weighing the samples after being oven dried at 105°C, and using the following formula:

$$P_w = \frac{W_w - W_d}{W_d} \times 100$$

where P_w is the moisture content of the soil on a dry weight basis (%), W_w is the weight of the moist soil (grams), and W_d is the weight of the water-free soil (grams).

Water management

Irrigation water input was measured by flow meters in each subplot. Irrigation was applied when the desired soil tension had been reached as indicated in the treatment specifications during the stress period. In plots in which CF practices were applied, when the field water depth was lower than 2cm, water was applied until the field water depth reached 5cm. In plots in which the W_1 and W_2 practices were applied, when the water level was 20 and 30cm below the soil surface, respectively, water was supplied until the field water depth reached 3cm.

Field water depth measurement: Field water depth was monitored in each plot daily using a field water tube system and ruler. The field water tube was installed in each subplot using 50cm long PVC tubes with a diameter of 20cm. The tubes were perforated with holes on all sides and buried in the soil so that 10cm protruded above the soil surface. The top of the tube was checked to ensure it was level and the soil from the inside the tube was removed so that the bottom of the tube was visible. The water table inside the tube was checked to make sure it was the same as outside the tube.

Measuring the field water depth for the W1 treatment: On the first day, a ruler was used to measure the distance from the top of the field water tube to the soil surface (d_1). In the days following, the distance from the top of the tube to the water level (d_i) was measured by a ruler. The field water depth (d) was determined using the equation:

$$d = d_1 - d_i \qquad (i \geq 2)$$

Measuring the water level for the W_2 treatment: The water level below the surface (D) was determined in the same way with the W_1 treatment but:

$$D = d_i - d_1 \qquad (i \geq 2)$$

Evapotranspiration (ET): Evaporation was measured using a hook gauge at 7 am daily. The hook gauge measured the rate of evapotranspiration by the change in level from a water surface in the field. The water level in the field was measured, usually every 24 hours, by adjusting the height of the hook until its point just broke the surface. The water balance equation used was:

$$I + R = ET + P + S + SD \pm CWS$$

where ET is the evapotranspiration (outflow; beneficial use), P is the deep percolation (outflow, unproductive water loss), S is the net seepage (outflow; unproductive water loss), SD is the surface drainage (outflow; unproductive water loss), CWS is the change in water status (residual water in the rice field), I is the irrigation supply (inflow), and R is the rainfall (inflow).

Water use efficiency (WUE) was calculated by using the equation:

WUE = Grain yield/Total irrigation water (kg paddy rice m^{-3} water)

Crop measurement

Growth components: Ten hills per subplot were randomly selected, marked, and observed for the growth components at the maturity and early maturity stages. The selected hills had a distance of 50cm to the plot border to avoid the “border effect”. The plant height was measured from the soil surface to the tip of the tallest leaf. The number of tillers was recorded as the count of all tillers having at least three green leaves.

Plant sampling: Plant samples were taken from three hills in each sub-plot at the physiological maturity stage. After measuring the fresh weight of the above-ground parts, the rice hills were dried in an oven for 48 hours before the dry matter weights were measured. The biomass of the above ground parts including the weights of the stems, green leaves, dead leaves, and panicles were determined. Based on these data, leaf area index (LAI) and the above ground mass were calculated. The values were then averaged for each sub-plot.

Yield and yield components: For the determination of the yield component, three hills of each sub-plot were taken at the mature grain stage for calculating the number of panicles per m^2, number of spikelets per panicle, number of filled grain per panicle, and 1000 grain weight. Actual yields were determined by harvesting whole sub-plots.

Nitrogen use efficiency

To calculate the agronomic nitrogen efficiency (ANE) (kg grain yield increase per kg of application of applied N), the follow equation was used:

ANE = [yield at N_x (kg ha^{-1}) - yield at N_0 (kg ha^{-1})]/amount of applied N (kg ha^{-1}).

To calculate the nitrogen uptake efficiency (NUE), the following equation was used:

NUE (%) = [Total N uptake at N_x (kg ha^{-1}) – Total N uptake at N_0 (kg ha^{-1})] * 100/amount of applied N (kg ha^{-1}).

Amount of soil NH_4^+ and NO_3^-

Each soil sample was a composite of five soil sub-samples collected diagonally from one experimental plot, taken one day after re-flooding. Soil samples were taken at the stages of tillering, panicle initiation, and flowering to determine the effects of the different management options of irrigation and fertilizer on the amount of soil NH_4^+ and NO_3^-. Both NH_4^+ and NO_3^- in the fresh soil (after sampling) were extracted by 1M KCl. Ammonium was determined by the Kjeldahl procedure with the presence of MgO. Nitrate was analyzed according to the Kjeldahl procedure with the aid of Devarda's alloy.

Cost and value analysis

Total cost was defined as all the costs for rice cultivation, including costs for seed, fertilizers, pesticides, outsourced labor, energy, etc. Gross income was calculated by yield multiplied by sales price. Net income was the difference between the gross income and the total cost.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) for the three water management practices and three nitrogen levels in a split-plot design, using IRRISTAT version 5.0. To determine the significance of the difference between the means of the treatments, least significant difference (LSD) was applied at the 5% probability level.

Results and Discussion

Climate data during the time period of the field experiment

The monthly average values of temperature, rainfall, and evaporation are presented in **Figure 1**. It can be seen that monthly evaporation was always higher than the monthly rainfall. The total amount of rainfall during the crop growth period was distributed over time from February to June 2014. The total monthly rainfall was the cumulative amounts of all rainfalls within that particular month. While the frequency of rainfall ranged from seven to nine times in a month, there was a minimal amount of rainfall, thus the water treatment management was not affected. The soil

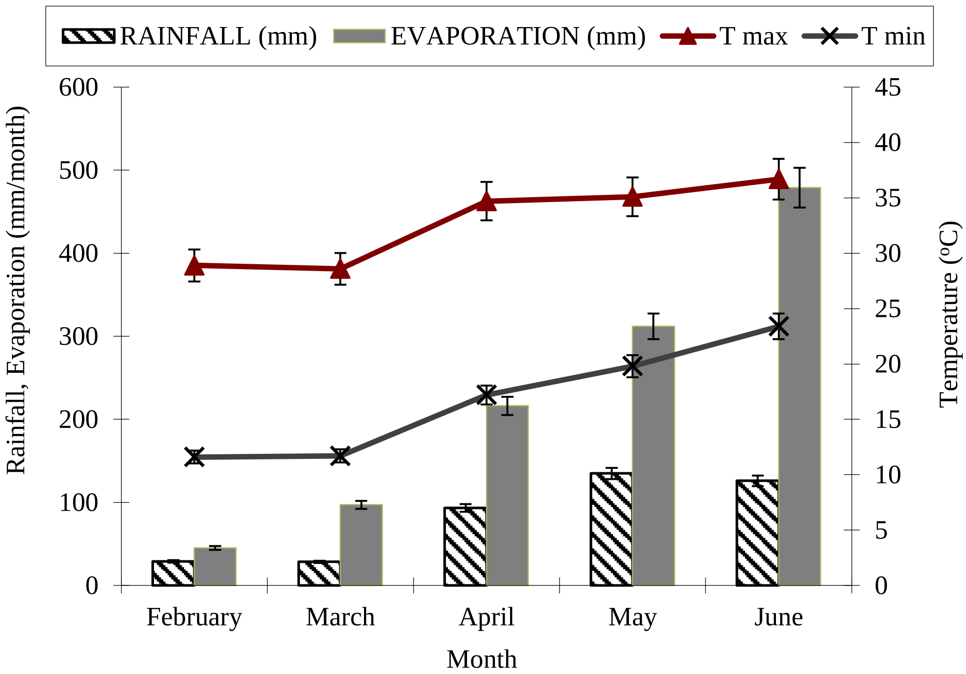

Figure 1. Meteorological data during the implemented experiment

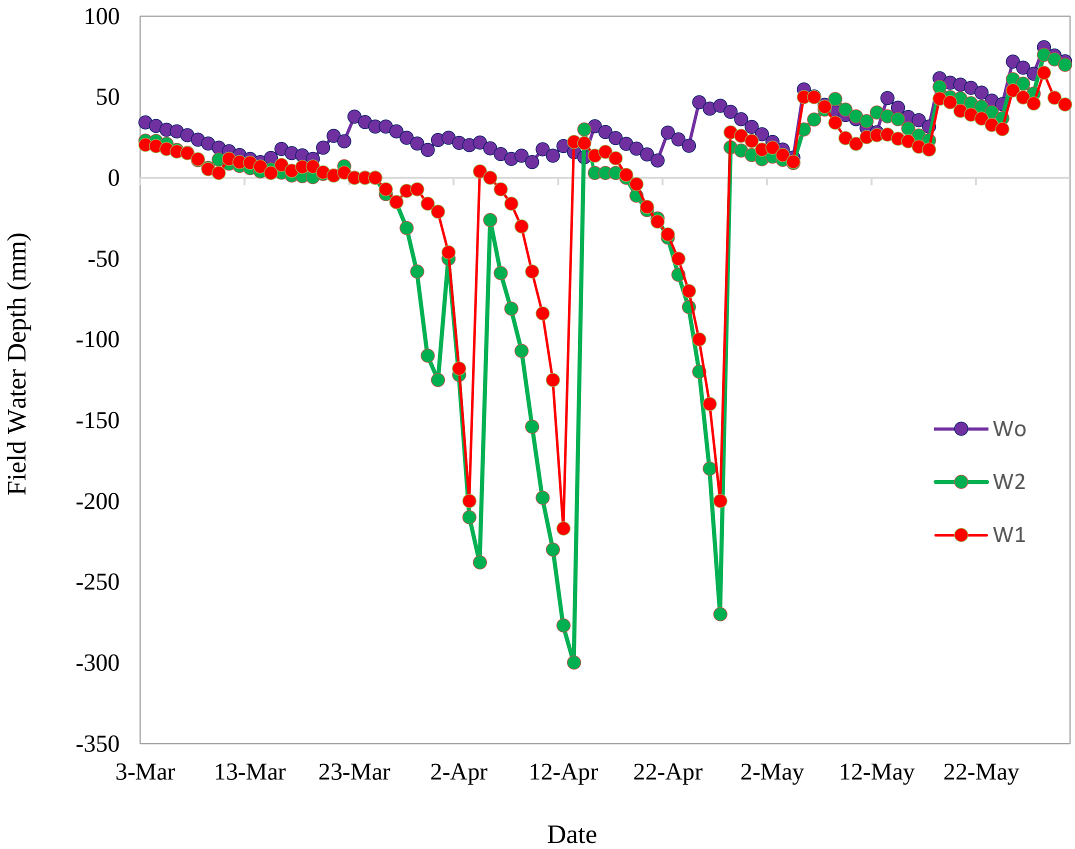

Figure 2. Field water depth

moisture regime was always decreasing; hence, the soil would have become very dry if no irrigation was applied. The amount of evaporation also increased as the monthly temperature increased leading to decreases in soil moisture. Relative air humidity was always above 75% during the experimental period, which may have exerted a positive effect in controlling the temperature and also indirectly in controlling evaporation.

Field water depth and irrigation water requirements for rice

During the first 10 DAT, the water depths in the field were shallow and continuously flooded (1.0-4.0cm). Then, the water depths in all the experimental plots were measured to ensure the two water management treatments and irrigation was applied if needed.

Figure 2 shows the fluctuations of field water depths during the time from 10 DAT to a fortnight before harvesting. Under the W_0 treatment (conventional irrigation practices with continuous flooding), the mean water depth primarily fluctuated in the range from 1.0cm to 5.0cm. However, on some days, such as May 28th to 30th, the water depth reached 7.0 to 8.0cm due to the influence of heavy rainfall. Under these conditions, the soil moisture was kept saturated throughout the crop season.

Obviously, the average water depths under the W_1 and W_2 treatments (alternate wetting and drying) had larger fluctuations in comparison to that of the W_0 treatment. The highest water depth recorded on May 28 was caused by heavy rainfall. There were three irrigation applications for the W_1 treatment with a total of 27.75cm water supplied during the growth and development period because the field water depth reached 20.0cm below the soil surface in this period. In the W_2 treatment, irrigation was supplied one time on April 14, with a total of 20.0cm water.

Total water loss (ET, S&P) was most significant in the W_0 treatment and smallest in the W_2 treatment. This was attributed to the differences in the effects of the water regimes in the rice development stage. The amount of water loss from evapotranspiration, seepage, and vertical percolation in the W_0, W_1, and W_2 treatments were 6,380 m^3 ha^{-1}, 5,475 m^3 ha^{-1}, and 4,772 m^3 ha^{-1}, respectively. Moreover, the water loss (ET&P) in W_1 and W_2 were lower than W_0 so the amounts of irrigation water were 782 m^3 ha^{-1} and 634 m^3 ha^{-1}, respectively, whereas in W_0, it was 1,236 m^3 ha^{-1}.

Total irrigation water was highest in the W_0 treatment (3,605 m^3 ha^{-1}) and lowest in W_2 (2,000 m^3 ha^{-1}), while irrigation water in W_1 was 2,695 m^3 ha^{-1}. This means about 910-1,605m^3 of water savings out of the total irrigation water amount if the W_1 and W_2 irrigation schemes are employed. The water-saving used for crop cultivation could contribute to the re-channeling of this limited resource to other areas of need, such as industries and households, etc.

Effect of water and N-fertilizer management practices on NH_4^+ and NO_3^- contents during the rice growth period

Nitrogen is the most important nutrient for lowland rice. The efficiency of rice plant utilization of N-fertilizer is directly related to other production factors such as water management, rice growth stage, N source, and the chemical transformations of N after it is applied to the soil (Fageria & Baligar, 2003).

The obtained results (**Table 3**) show that both ammonium and nitrate increased sharply from tillering to the panicle initiation stage and started decreasing in the flowering stage. Under the different water treatments, there were no significant differences in ammonium levels. In contrast, there were significant differences in ammonium amounts among the nitrogen levels and application methods. Ammonium was always lowest in the N_0 treatment and highest in

Table 3. Effects of water and N-fertilizer management practices on NH_4^+ and NO_3^- contents in the soil (mg kg^{-1})

Items	Irrigation patterns	N-fertilizer	Tillering	Panicle initiation	Flowering
NH_4^+	W_0	N_0	3.40^c	4.70^c	2.80^b
		N_1	13.00^{ab}	47.00^b	25.30^{ab}
		N_2	14.50^a	89.00^{ab}	44.10^a
	W_1	N_0	4.60^c	55.00^c	3.40^b
		N_1	12.00^b	46.00^{bc}	23.30^{ab}
		N_2	13.50^{ab}	97.00a	48.70^a
	W_2	N_0	4.10^c	4.90^c	3.50^b
		N_1	13.30^{ab}	56.00^{ab}	17.00^{ab}
		N_2	14.00^{ab}	62.20^{ab}	21.00^{ab}
NO_3^-	W_0	N_0	4.00^a	4.18^b	3.95^b
		N_1	13.30^a	42.83^a	17.46^a
		N_2	18.70^a	48.90^a	19.15^a
	W_1	N_0	6.27^a	6.80^b	5.90^b
		N_1	16.40^a	45.70^a	12.72^{ab}
		N_2	18.20^a	49.70^a	19.81^a
	W_2	N_0	5.43^a	5.33^b	3.48^b
		N_1	12.10^a	38.90^a	16.70^a
		N_2	14.20^{ba}	44.70^a	17.86^a

Note: Within a column of each parameter, means followed by the same letters are not significantly different according to LSD 0.05.

N_2. The sharp increase in ammonium in the N_2 treatment was because one month from application coincides with the mineralization of the organic fertilizer, as well as the slow breakdown of ammonium from compressed NPK. This was followed by a sharp decrease in ammonium, corresponding to the high N demand during the vegetative stage of the plants.

In terms of nitrate levels, there were also no significant differences among the water treatments, whereas different nitrogen levels and applications were highly affected by the nitrate levels at the different development stages. The greatest fluctuation was observed in the panicle stage from 4.18 mg kg^{-1} to 49.70 mg kg^{-1}. Similar to ammonium, the nitrate content in all the plots increased from tillering to panicle initiation but decreased in the flowering stage. The reasons proposed are as follows: (1) the oxidation process while the field water depth was kept dry for a short time caused an increase in the nitrate content from the vegetative to panicle stages; and (2) the reduction process took place after re-flooding and promoted the transformation from nitrate to ammonium.

Effect of water and N-fertilizer management practices on rice growth and grain yield

Rice cultivation without N-fertilizer application causes a decrease in plant height under different water management treatments (W_xN_0 plots) (**Table 4**). However, different water and N-fertilizer applications (W_xN_1 and W_xN_2 plots) did not affect the rice plant heights. Similar results were found for the number of productive tillers and leaf area index. As a result, the biomass of the rice plants was also higher than that of the N-fertilizer application (W_xN_1 and W_xN_2 plots), and was equal between the urea and compressed NPK fertilizer plots. The obtained results in **Table 4** indicate that N in compressed NPK fertilizer is released in time for rice.

The interaction between the water regime and nitrogen application was found to be significant among the treatments (**Table 5**). Rice grown under W_2N_0 (alternate wetting and drying at a -30cm water depth + 0 kg N ha^{-1}) produced the minimum grain yield represented by 2,620 kg N ha^{-1}. It was significantly smaller than the rest of the treatments. The highest grain yield was achieved under W_1N_2 (alternate wetting and drying at a -20cm water depth + 120 kg N ha^{-1} using fertilizer deep placement) represented by 5,700 kg N ha^{-1} and was followed by W_1N_1 (alternate wetting and drying at a -20cm water depth + 120 kg N ha^{-1} using conventional farmer's applications) with 5,550 kg N ha^{-1}.

Under both continuously flooded conditions (W_0) and alternate wetting and drying conditions (W_1 and W_2), N application, especially using compressed fertilizer, caused an increase in grain yield. The lowest grain yield (2,620 kg ha^{-1}) was

Table 4. Effects of water and fertilizer management practices on rice growth (at the maturity stage)

Irrigation pattern	N-fertilizer	Plant heights (cm)	Productive tillers	Leaf area index (m^2 leaf m^{-2} ground)	Above ground biomass (kg ha^{-1})
W_0	N_0	100.70^{b}	4.67^{c}	3.78^{b}	6819^{d}
	N_1	110.17^{ab}	8.56^{ab}	6.89^{a}	9848^{b}
	N_2	111.67^{ab}	8.33^{ab}	6.77^{ab}	10950^{a}
W_1	N_0	104.83^{ab}	5.22^{bc}	4.05^{b}	7035^{d}
	N_1	113.98^{a}	9.11^{a}	6.70^{ab}	10684^{a}
	N_2	115.54^{a}	9.67^{a}	6.96^{a}	10371^{ab}
W_2	N_0	102.10^{b}	4.76^{bc}	3.63^{b}	6795^{d}
	N_1	105.83^{ab}	6.89^{ab}	5.65^{ab}	8848^{c}
	N_2	107.90^{ab}	7.56^{ab}	5.89^{ab}	8937^{c}

Note: Within a column of each parameter, means followed by the same letters are not significantly different according to LSD 0.05.

obtained on the non-N fertilized plots (N_0), whereas the highest yield (5,700 kg ha^{-1}) was observed in the combination of AWD at -20kPa and 120 kg N ha^{-1} using compressed fertilizer with the fertilizer deep placement method (N_2). The same trend was also recognized with the yield components, especially the number of productive tillers.

The results in **Table 5** also reveal that the irrigation method did not have many significant effects on the yield components or grain yield. But the alternate wetting and drying method (W_1) saved 46% of irrigated water in comparison to continuous flooding irrigation without a reduction in yield. Different from the water factor, nitrogen significantly influenced the grain yield and yield components except for the 1,000 grain weight, which has always been considered a stable varietal quantitative character of rice. In addition, application of nitrogen in the form of compressed fertilizer with the deep placement method gave the highest rice yield (4,610-5,700 kg ha^{-1}) regardless of the water regime.

Water use efficiency (WUE)

One disadvantage of the lowland rice production system is the high water demand, and hence, low water use efficiency (WUE). The high-water demand is due to high water loss through evaporation (16-18%), surface run-off, and percolation (50-72%) (Stoop *et al.*, 2002).

In the present study, despite no difference in grain yield, the amount of irrigation water and WUE significantly varied with the irrigation treatments, and was lowest in conventional irrigation and highest in alternate wetting and drying (W_1 and W_2) (**Table 6**). In conventional irrigation, 1m^3 water produced 1.28kg of grain while in alternate wetting and drying, 1.74kg of grain (W_1) and 1.97kg of grain (W_2) were produced. This means AWD helped save 25.24% to 44.52% of the total water input without significantly influencing grain yield. This result is similar to the findings of Xu *et al.* (2015) in which intermittent irrigation helped saved water up to 36% in Nanjing (China), and Thiyagarajan *et al.* (2002) in which the amount of water saved was 56% in Coimbatore (India).

Nitrogen uptake and nitrogen use efficiency

Nitrogen uptake

It has been shown that nitrogen significantly influences the total nitrogen uptake (Dixit & Khanda, 1994, Ya-Juan *et al*., 2012; Akter *et al.*, 2018). In fact, under all the water treatments, the amounts of nitrogen taken up by the grain (kg ha^{-1}) increased in the order of $N_0 < N_1 < N_2$. Under the conditions in which no nitrogen was applied, plants absorbed nitrogen from the soil, rainfall, etc., which was derived from mineralization and other activities of soil microbes. In other

Table 5. Effects of the water and fertilizer management practices on rice yield and yield components

Irrigation pattern	N-fertilizer	No. of panicle m^{-2}	No. of spikelets $panicle^{-1}$	Percentage of filled grain (%)	1000 grain weight (g)	Grain yield (kg ha^{-1})
W_0	N_0	178.31^{d}	140.27^{c}	67.66	23.07^{abc}	3070^{cd}
	N_1	275.17^{b}	165.21^{b}	66.12	23.35^{ab}	5350^{ab}
	N_2	282.38^{ab}	172.94^{b}	56.33	22.00^{abc}	5480^{ab}
W_1	N_0	175.07^{d}	141.33^{c}	69.75	24.00^{abc}	2850^{cd}
	N_1	295.71^{a}	199.14^{a}	69.60	24.61^{a}	5550^{ab}
	N_2	290.93^{ab}	194.76^{a}	59.03	23.30^{abc}	5700^{a}
W_2	N_0	173.66^{d}	138.95^{c}	67.26	23.53^{bc}	2620^{d}
	N_1	226.31^{c}	158.62^{bc}	66.90	22.91^{abc}	4560^{c}
	N_2	242.62^{c}	170.03^{b}	52.20	21.48^{c}	4610^{cd}

Note: Within a column of each parameter, means followed by the same letters are not significantly different according to LSD 0.05.

Table 6. Effects of water and fertilizer management practices on water use efficiency

Irrigation pattern	N-fertilizer	Grain yield (kg ha^{-1})	Grain yield increasing (%)	Irrigation (m^3 ha^{-1})	Irrigation water savings (%)	WUE (kg m^{-3})
W_0	N_0	3070^{cd}		3605		0.85^{g}
	N_1	5350^{ab}	74.27	2695	25.24	1.48^{de}
	N_2	5480^{ab}	78.50	2000	44.52	1.52^{d}
W_1	No	2850^{cd}		3605		1.05^{f}
	N_1	5550^{ab}	94.74	2695	25.24	2.06^{c}
	N_2	5700^{a}	100.00	2000	44.52	2.12^{bc}
W_2	N_0	2620^{d}		3605		1.31^{e}
	N_1	4560^{c}	74.05	2695	25.24	2.28^{ab}
	N_2	4610^{cd}	75.95	2000	44.52	2.31^{a}

Note: Within a column of each parameter, means followed by the same letters are not significantly different according to LSD 0.05.

treatments, besides the above sources, plants also used soluble N from fertilizers. However, the difference in the values of nitrogen taken up between N_1 and N_2 was non-significant due to the small change in grain yield (**Table 7**). In addition, the ANE using traditional (N_1) and compressed fertilizer (N_2) were similar, indicating that the method of N-fertilizer application did not have much effect on the incremental crop yield per applied nitrogen. Under the W_2 irrigation conditions, the value of ANE slightly decreased, possibly due to the lack of water in the root layer that partially reduced the solubility of N in fertilizers, especially from the pellets.

Nitrogen use efficiency (NUE)

The obtained results show that under continuous flooding conditions (W_0 treatment), the nitrogen use efficiency (NUE) increased in the compressed fertilizer application (N_2). Under the AWD application, the NUE values were similar between the traditional and compressed fertilizer treatments. The NUE, however, tended to be the largest in the plots with a combination of AWD at a -20 cm water depth and compressed fertilizer. Therefore, the NUE was significantly affected by the water regime, especially in the spring season in Vietnam, which typically has very little precipitation and a lack of irrigation water for rice growth and development. This finding is in line with the report of Cashman *et al.* (2010) who found that NUE in irrigated. systems is typically 0.50 under good management

Cost and value analysis

During rice production, the costs of production were divided into input costs and labor costs. Input costs came from fertilizers , insecticides, pesticides, seeds, power (fuel, oil, and rental costs for machinery), and irrigation fee payments. Labor costs consisted of hired labor and imputed family labor. Labor cost was dominant, accounting for more than 50% of the total costs. The amount spent on fertilizer differed only between adopters and partial adopters, but the amount spent on it was not a major cost item as it accounted for only about 15-20% of the total costs. This is similar to the previous findings of Moya *et al.* (2004). In addition to fertilizer costs, discrepancies in amounts were observed only on minor items like the costs of pesticides and hired labor. Total returns only came from selling grain yield, hence, net return was calculated by total return minus total cost. **Table 8** shows that no fertilizer application gave a negative net return and the highest net return came from alternate wetting and drying at a -20cm water depth and compressed fertilizer under fertilizer deep placement method (W_1N_1). Alternate wetting and drying at a -30cm water depth (under stress conditions in the specific time) gave a very low net return in comparison to the two-water treatment. There were no significant differences

Table 7. Effects of water and fertilizer management practices on nitrogen uptake and nitrogen use efficiency

Irrigation pattern	N-fertilizer	Grain yield (kg ha^{-1})	N input (kg ha^{-1})	N uptake by grain (kg ha^{-1})	ANE (kg kg^{-1})	NUE (%)
W_0	N_0	3070	0	35.73	-	
	N_1	5350	120	83.86	19.00^{abc}	40.11^{a}
	N_2	5480	120	104.74	20.08^{abc}	56.89^{b}
W_1	N_0	2850	0	37.88	-	
	N_1	5550	120	95.30	22.50^{ab}	47.85^{ab}
	N_2	5700	120	112.14	23.75^{a}	61.88^{b}
W_2	N_0	2620	0	35.29	-	
	N_1	4560	120	81.16	16.92^{bc}	38.23^{a}
	N_2	4610	120	94.23	16.58^{c}	49.12^{ab}

Note: Within a column of each parameter, means followed by the same letters are not significantly different according to LSD 0.05.

Table 8. Cost and value analysis

Parameters	W_0N_0	W_0N_1	W_0N_2	W_1N_0	W_1N_1	W_1N_2	W_2N_0	W_2N_1	W_2N_2
Total costs (1,000 VND ha^{-1})	16825	19244	18685	16484	19449	18285	16341	18251	18000
Gross income (1,000 VND ha^{-1})	14122	24610	25208	13110	25530	26220	12052	20976	21206
Net income (1,000 VND)	-2703	5366	6523	-3374	6081	7935	-4289	2726	3206

Note: *Selling price: 4.6 thousand VND.*

in the net return of the three groups (W_0N_1, W_0N_2, and W_1N_1) although application of compressed fertilizer with the deep placement method showed a slightly higher value. We therefore concluded that the adoption of W_1N_2 gave the highest profitability of rice production (~397USD) in the area of study whereas no fertilizer application is ineffective in the Red River Delta.

Conclusions

Improved water availability after AWD has enhanced irrigation efficiency and contributed to diverting this limited resource to other areas experiencing water shortages in Vietnam. The highest water use efficiency (WUE) and nitrogen use efficiency (NUE) were obtained under the application of AWD irrigation at a -20cm water depth and compressed fertilizer under the deep placement method (W_1N_2). The percentage of total irrigation water saved from W_1 and W_2 were 25.24 to 44.52%, respectively.

With regards to the water regime in combination with fertilizer on rice yield, the combination of AWD irrigation at a -20cm water depth and compressed fertilizer under the deep placement method (W_1N_2) produced paddy rice with highest grain yield. W_1N_2 may be recommended as the most appropriate water management and fertilizer application methods for increasing production of the Bac Thom rice variety. The implementation of the subsequent intermittent irrigation and compressed fertilizer can improve rice growth and the resultant grain yield.

The net income was higher in the W_1N_2 than of those in other plots. The obtained results indicate that a combination of AWD irrigation at a -20cm water depth and compressed fertilizer with deep placement should be encouraged for wide adoption in other regions of Vietnam. Our findings showing the positive effects of AWD and compressed fertilizer under deep placement on rice productivity will be a key to spread useful information to local farmers.

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