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

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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 (W₀) water to 1.74 kg grain m⁻³ (W₁) water and 1.94 kg grain m⁻³ (W₂) water. In addition, the percentage of total irrigation water saved from W₁ and W₂ 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 (W₁N₂). 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

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 P2O5, and 0.67 million tons of K2O (FAO, 2017). On average, the fertilizer formulations for rice in the Red River Delta (RRD) are 100-60-90 (kg of N-P2O5- K2O) 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$_2$O$_5$, and 20% K$_2$O; topdressing was applied two times during crop duration: at the start of tillering (50% N and 30% K$_2$O) and 20 days before the flowering date (20% N and 50% K$_2$O). 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<sub>H2O</sub> | 6.8    |
| NO<sub>3</sub> (mg kg<sup>-1</sup>) | 1.1 |
| NH<sub>4</sub> (mg kg<sup>-1</sup>) | 22.8 |
| Texture (0-30cm) | Sandy loam |

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

| No. | Plots | Content |
|-----|-------|---------|
| 1   | N<sub>0</sub> | W<sub>0</sub> | CF; 0N + 70P<sub>2</sub>O<sub>5</sub> + 70K<sub>2</sub>O + 10 tons FYM |
| 2   | N<sub>1</sub> | W<sub>1</sub> | CF; N<sub>0</sub> + 120N - Using urea |
| 3   | N<sub>2</sub> | W<sub>2</sub> | CF; N<sub>0</sub> + 120N - Using compressed NPK 16-6-12 |
| 4   | N<sub>0</sub> | W<sub>0</sub> | AWD at -20kPa; N<sub>0</sub> |
| 5   | N<sub>1</sub> | W<sub>1</sub> | AWD at -20kPa; N<sub>1</sub> |
| 6   | N<sub>2</sub> | W<sub>2</sub> | AWD at -20kPa; N<sub>2</sub> |
| 7   | N<sub>0</sub> | W<sub>0</sub> | AWD at -30kPa; N<sub>0</sub> |
| 8   | N<sub>1</sub> | W<sub>1</sub> | AWD at -30kPa; N<sub>1</sub> |
| 9   | N<sub>2</sub> | W<sub>2</sub> | AWD at -30kPa; N<sub>2</sub> |

Note: N<sub>0</sub>: 0 N + 70 P<sub>2</sub>O<sub>5</sub> (super phosphate) + 70 K<sub>2</sub>O (potassium chloride) + 10 tons OF
N<sub>1</sub>: 120 N (using urea) + 70 P<sub>2</sub>O<sub>5</sub> (super phosphate) + 70 K<sub>2</sub>O (potassium chloride) + 10 tons OF
N<sub>2</sub>: 120 N + 70 P<sub>2</sub>O<sub>5</sub> + 70 K<sub>2</sub>O + 10 tons OF, Using compressed NPK 16-6-12
FYM (farmyard manure): pH = 5.8; OM (%) = 29.1; N (%) = 1.39; P<sub>2</sub>O<sub>5</sub> (%) = 0.93; K<sub>2</sub>O (%) = 1.32.

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<sub>1</sub> and W<sub>2</sub> 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:

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

**Measuring the water level for the W2 treatment**: The water level below the surface ($D$) was determined in the same way with the W1 treatment but:

$$D = d_1 - d_1 \quad (i \geq 2)$$

**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:

$$WUE = \frac{\text{Grain yield}}{\text{Total irrigation water}} (\text{kg paddy rice m}^{-3} \text{water})$$

**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 m², 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:

$$ANE = \frac{[\text{yield at } N_i \ (\text{kg ha}^{-1}) \ - \ \text{yield at } N_0 \ (\text{kg ha}^{-1})]}{\text{amount of applied N} \ (\text{kg ha}^{-1})}$$.  

To calculate the nitrogen uptake efficiency (NUE), the following equation was used:
NUE (%) = [Total N uptake at N<sub>x</sub> (kg ha<sup>-1</sup>) – Total N uptake at N<sub>0</sub> (kg ha<sup>-1</sup>)] * 100/amount of applied N (kg ha<sup>-1</sup>).

Amount of soil NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub>–

Each soil sample was a composite of five soil sub-samples collected diagonally from one experimental plot, taken one day after reflooding. 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<sub>4</sub><sup>+</sup> and NO<sub>3</sub>–. Both NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub>– 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](image-url)
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 W₀ 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 W₁ and W₂ treatments (alternate wetting and drying) had larger fluctuations in comparison to that of the W₀ treatment. The highest water depth recorded on May 28 was caused by heavy rainfall. There were three irrigation applications for the W₁ 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 W₂ 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 W₀ treatment and smallest in...
the W2 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 W0, W1, and W2 treatments were 6,380 m³ ha⁻¹, 5,475 m³ ha⁻¹, and 4,772 m³ ha⁻¹, respectively. Moreover, the water loss (ET&P) in W1 and W2 were lower than W0 so the amounts of irrigation water were 782 m³ ha⁻¹ and 634 m³ ha⁻¹, respectively, whereas in W0, it was 1,236 m³ ha⁻¹.

Total irrigation water was highest in the W0 treatment (3,605 m³ ha⁻¹) and lowest in W2 (2,000 m³ ha⁻¹), while irrigation water in W1 was 2,695 m³ ha⁻¹. This means about 910–1,605 m³ of water savings out of the total irrigation water amount if the W1 and W2 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 NH₄⁺ and NO₃⁻ 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 N0 treatment and highest in

| **Table 3. Effects of water and N-fertilizer management practices on NH₄⁺ and NO₃⁻ contents in the soil (mg kg⁻¹)** |
|------------------|-----------------|-------------|-------------|
| **Items**        | **Irrigation patterns** | **N-fertilizer** | **Tillering** | **Panicle initiation** | **Flowering** |
|                  |                  |              |              |                    |              |
| **NH₄⁺**         | W₀               | N₀           | 3.40a        | 4.70c        | 2.80b        |
|                  |                  | N₁           | 13.00ab      | 47.00b       | 25.30ab      |
|                  |                  | N₂           | 14.50a       | 89.00ab      | 44.10a       |
|                  | W₁               | N₀           | 4.60c        | 55.00c       | 3.40a        |
|                  |                  | N₁           | 12.00b       | 46.00c       | 23.30b       |
|                  |                  | N₂           | 13.50ab      | 97.00a       | 48.70a       |
| **NO₃⁻**         | W₀               | N₀           | 4.10c        | 4.90c        | 3.50c        |
|                  |                  | N₁           | 13.30ab      | 56.00ab      | 17.00ab      |
|                  |                  | N₂           | 14.00ab      | 62.20ab      | 21.00ab      |
|                  | W₁               | N₀           | 4.00a        | 4.18a        | 3.95a        |
|                  |                  | N₁           | 13.30a       | 42.83a       | 17.46a       |
|                  |                  | N₂           | 18.70a       | 48.90a       | 19.15a       |
|                  | W₂               | N₀           | 6.27a        | 6.80a        | 5.90a        |
|                  |                  | N₁           | 16.40a       | 45.70a       | 12.72ab      |
|                  |                  | N₂           | 18.20a       | 49.70a       | 19.81a       |
|                  |                  | N₀           | 5.43a        | 5.33a        | 3.48a        |
|                  |                  | N₁           | 12.10a       | 38.90a       | 16.70a       |
|                  |                  | N₂           | 14.20ab      | 44.70a       | 17.86a       |

**Note:** Within a column of each parameter, means followed by the same letters are not significantly different according to LSD 0.05.
N\textsubscript{2}. The sharp increase in ammonium in the N\textsubscript{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\textsuperscript{-1} to 49.70 mg kg\textsuperscript{-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 reflooding 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\textsubscript{1}N\textsubscript{0} plots) (Table 4). However, different water and N-fertilizer applications (W\textsubscript{1}N\textsubscript{1} and W\textsubscript{1}N\textsubscript{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\textsubscript{1}N\textsubscript{1} and W\textsubscript{1}N\textsubscript{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\textsubscript{2}N\textsubscript{0} (alternate wetting and drying at a -30cm water depth + 0 kg N ha\textsuperscript{-1}) produced the minimum grain yield represented by 2,620 kg N ha\textsuperscript{-1}. It was significantly smaller than the rest of the treatments. The highest grain yield was achieved under W\textsubscript{1}N\textsubscript{2} (alternate wetting and drying at a -20cm water depth + 120 kg N ha\textsuperscript{-1} using fertilizer deep placement) represented by 5,700 kg N ha\textsuperscript{-1} and was followed by W\textsubscript{1}N\textsubscript{1} (alternate wetting and drying at a -20cm water depth + 120 kg N ha\textsuperscript{-1} using conventional farmer’s applications) with 5,550 kg N ha\textsuperscript{-1}.

Under both continuously flooded conditions (W\textsubscript{0}) and alternate wetting and drying conditions (W\textsubscript{1} and W\textsubscript{2}), N application, especially using compressed fertilizer, caused an increase in grain yield. The lowest grain yield (2,620 kg ha\textsuperscript{-1}) was

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**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 (m² leaf m² ground) | Above ground biomass (kg ha\textsuperscript{-1}) |
|--------------------|--------------|--------------------|--------------------|-------------------------------------|---------------------------------------------|
| W\textsubscript{0}  | N\textsubscript{0} | 100.70\textsuperscript{a} | 4.67\textsuperscript{c} | 3.78\textsuperscript{b} | 6819\textsuperscript{d} |
|                    | N\textsubscript{1} | 110.17\textsuperscript{ab} | 8.56\textsuperscript{ab} | 6.89\textsuperscript{a} | 9848\textsuperscript{b} |
|                    | N\textsubscript{2} | 111.67\textsuperscript{ab} | 8.33\textsuperscript{ab} | 6.77\textsuperscript{ab} | 10950\textsuperscript{a} |
| W\textsubscript{1}  | N\textsubscript{0} | 104.83\textsuperscript{ab} | 5.22\textsuperscript{ab} | 4.05\textsuperscript{a} | 7035\textsuperscript{c} |
|                    | N\textsubscript{1} | 113.98\textsuperscript{a} | 9.11\textsuperscript{a} | 6.70\textsuperscript{a} | 10684\textsuperscript{a} |
|                    | N\textsubscript{2} | 115.54\textsuperscript{a} | 9.67\textsuperscript{a} | 6.96\textsuperscript{a} | 10371\textsuperscript{ab} |
| W\textsubscript{2}  | N\textsubscript{0} | 102.10\textsuperscript{b} | 4.76\textsuperscript{bc} | 3.63\textsuperscript{a} | 67955\textsuperscript{c} |
|                    | N\textsubscript{1} | 105.83\textsuperscript{ab} | 6.89\textsuperscript{ab} | 5.65\textsuperscript{a} | 8848\textsuperscript{b} |
|                    | N\textsubscript{2} | 107.90\textsuperscript{ab} | 7.56\textsuperscript{ab} | 5.89\textsuperscript{a} | 8937\textsuperscript{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 (N₀), 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 (N₂). 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 (W₁) 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 (W₁ and W₂) (Table 6). In conventional irrigation, 1m³ water produced 1.28kg of grain while in alternate wetting and drying, 1.74kg of grain (W₁) and 1.97kg of grain (W₂) 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 N₀ < N₁ < N₂. 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

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**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) |
|-------------------|-------------|-------------------|--------------------------|---------------------------|-----------------|---------------------|
| W₀                | N₀          | 178.31           | 140.27                   | 67.66                     | 23.07           | 3070                |
|                   | N₁          | 275.17           | 165.21                   | 66.12                     | 23.35           | 5350                |
|                   | N₂          | 282.38           | 172.94                   | 56.33                     | 22.00           | 5480                |
| W₁                | N₀          | 175.07           | 141.33                   | 69.75                     | 24.00           | 2850                |
|                   | N₁          | 295.71           | 199.14                   | 69.60                     | 24.61           | 5550                |
|                   | N₂          | 290.93           | 194.76                   | 59.03                     | 23.30           | 5700                |
| W₂                | N₀          | 173.66           | 138.95                   | 67.26                     | 23.53           | 2620                |
|                   | N₁          | 226.31           | 158.62                   | 66.90                     | 22.91           | 4560                |
|                   | N₂          | 242.62           | 170.03                   | 52.20                     | 21.48           | 4610                |

*Note: Within a column of each parameter, means followed by the same letters are not significantly different according to LSD 0.05.*
Ngo Thanh Son & Nguyen Thu Ha (2021)

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 (m³ ha⁻¹) | Irrigation water savings (%) | WUE (kg m⁻³) |
|--------------------|--------------|------------------------|---------------------------|---------------------|----------------------------|-------------|
| W₀                 | N₀           | 3070⁵⁶               |                           | 3605                |                            | 0.85⁶⁴     |
|                    | N₁           | 5350⁸⁷               | 74.27                     | 2695                | 25.24                      | 1.48⁷⁶     |
|                    | N₂           | 5480⁸⁷               | 78.50                     | 2000                | 44.52                      | 1.52⁸⁸     |
| W₁                 | No           | 2850⁵⁶               |                           | 3605                |                            | 1.05⁹⁸     |
|                    | N₁           | 5550⁸⁷               | 94.74                     | 2695                | 25.24                      | 2.06⁹⁸     |
|                    | N₂           | 5700⁸⁷               | 100.00                    | 2000                | 44.52                      | 2.12⁹⁸     |
| W₂                 | N₀           | 2620⁵⁶               |                           | 3605                |                            | 1.31⁹⁸     |
|                    | N₁           | 4560⁸⁷               | 74.05                     | 2695                | 25.24                      | 2.28⁹⁸     |
|                    | N₂           | 4610⁵⁶               | 75.95                     | 2000                | 44.52                      | 2.31⁹⁸     |

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

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 (W₁N₁). 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
Water-saving irrigation and nitrogen fertilizer use efficiency for irrigated rice in the Red River Delta, Vietnam

### 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 (%) |
|--------------------|--------------|------------------------|------------------|----------------------------|---------------|---------|
| W₀                 | N₀           | 3070                   | 0                | 35.73                      | -             | -       |
|                    | N₁           | 5350                   | 120              | 83.86                      | 19.00abc      | 40.11a  |
|                    | N₂           | 5480                   | 120              | 104.74                     | 20.08abc      | 56.89b  |
| W₁                 | N₀           | 2850                   | 0                | 37.88                      | -             | -       |
|                    | N₁           | 5550                   | 120              | 95.30                      | 22.50ab       | 47.85bc |
|                    | N₂           | 5700                   | 120              | 112.14                     | 23.75a        | 61.88b  |
| W₂                 | N₀           | 2620                   | 0                | 35.29                      | -             | -       |
|                    | N₁           | 4560                   | 120              | 81.16                      | 16.92abc      | 38.23a  |
|                    | N₂           | 4610                   | 120              | 94.23                      | 16.58c        | 49.12bc |

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       | W₀N₀ | W₀N₁ | W₀N₂ | W₁N₀ | W₁N₁ | W₁N₂ | W₂N₀ | W₂N₁ | W₂N₂ |
|------------------|------|------|------|------|------|------|------|------|------|
| Total costs      | 16825| 19244| 18685| 16484| 19449| 18285| 16341| 18251| 18000|
| Gross income     | 14122| 24610| 25208| 13110| 25530| 26220| 12052| 20976| 21206|
| Net income       | -2703| 5366 | 6523 | -3374| 6081 | 7935 | -4289| 2726 | 3206 |

Note: Selling price: 4.6 thousand VND.

in the net return of the three groups (W₀N₁, W₀N₂, and W₁N₁) although application of compressed fertilizer with the deep placement method showed a slightly higher value. We therefore concluded that the adoption of W₁N₂ 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 (W₁N₂). The percentage of total irrigation water saved from W₁ and W₂ 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 (W₁N₂) produced paddy rice with highest grain yield. W₁N₂ 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 W₁N₂ 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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References

Akter M., Deroo H., De Grave E., Van Alboom T., Kader M. A., Pierreux S., Begum M. A., Boeckx P. & Sleutel S. (2018). Link between paddy soil mineral nitrogen release and iron and manganese reduction examined in a rice pot growth experiment. Geoderma. 326: 9-21.

Cashman A., Nurse L., & John C. (2010). Climate change in the Caribbean: the water management implications. The Journal of Environment and Development. 19(1): 42-67.

Datta A., Ullah H., & Ferdous Z. (2017). Water management in rice. In Rice production worldwide. Springer, Cham. 255-277.

Dang T., Pedroso R., Laux P. & Kunsmann H. (2018). Development of an integrated hydrological-irrigation optimization modeling system for a typical rice irrigation scheme in Central Vietnam. Agricultural Water Management. 208: 193-203.

Dobermann A. & Cassman K. G. (2002). Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia. Plant and Soil. 247(1): 153-175.

Dong N. M., Brandt K. K., Sørensen J., Hung N. N., Van Hach C., Tan P. S. & Dalsgaard T. (2012). Effects of alternating wetting and drying versus continuous flooding on fertilizer nitrogen fate in rice fields in the Mekong Delta, Vietnam. Soil Biology and Biochemistry. 47: 166-174.

De Silva S. S. & Hasan M. R. (2007). Feeds and fertilizers: the key to long-term sustainability of Asian aquaculture. In: Hasan M. R., Hecht T., De Silva S. S. & Tacon A. G. J. (Eds). Study and Analysis of Feeds and Fertilizers for Sustainable Aquaculture Development. FAO Fisheries Technical Paper No. 497. FAO Fisheries Department; Food and Agriculture Organization of the United Nations, Rome: 19-47.

Dixit L. & Khanda C. (1994). Effect of zinc and nitrogen fertilization on yield and yield attributes of summer rice (Oryza sativa L.). Orissa Journal of Agricultural Research (India).

Eriksen A. B., Kjeldby M. & Nilsen S. (1985). The effect of intermittent flooding on the growth and yield of wetland rice and nitrogen-loss mechanism with surface applied and deep placed urea. Plant and Soil. 84(3): 387-401.

Fageria N. K. & Baligar V. C. (2003). Methodology for evaluation of lowland rice genotypes for nitrogen use efficiency. Journal of Plant Nutrition. 26(6): 1315-1333.

FAO (2015). World food and agriculture. Statistical yearbook 2015. The Food and Agriculture Organization of the United Nations: 369.

FAO (2017). FAOSTAT on-line database. Retrieved from http://faostat.fao.org on December 2, 2019.

Jin X., Zuo Q., Ma W., Li S., Shi J., Tao Y., Zhang Y., Liu Y., Liu X., Lin S. & Ben-Gal, A. (2016). Water consumption and water-saving characteristics of a ground cover rice production system. Journal of Hydrology. 540: 220-231.

IRRI (2010). Global Rice Science Partnership (GRiSP). Council for Partnership on Rice Research in Asia: Metro Manila, Philippines.

Keeney D. R. & Sahrawat K. L. (1986). 2. Nitrogen transformations in flooded rice soils. Fertilizer Research. 9(1-2): 15-38.

Lampayan R. M., Rejesus R. M., Singleton G. R. & Bouman B. A. (2015). Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. Field Crops Research. 170: 95-108.

Moya P., Hong L., Dawe D., & Chongde C. (2004). The impact of on-farm water saving irrigation techniques on rice productivity and profitability in Zhanghe Irrigation System, Hubei, China. Paddy and Water Environment. 2(4): 207-215.

Ngo Thanh Son, Nguyen Huu Thanh, Nguyen Van Dung, Ngo Thi Dung, Nguyen Thi Giang & Nguyen Thuy Ha (2010). Research on water regime for potassium change in soil and rice yield in the Red River Delta. Journal of Science and Development. 3: 488-498 (in Vietnamese).

Ngo T. T., Le N. T., Hoang T. M., & Luong D. H. (2018). Water scarcity in Vietnam: a point of view on virtual water perspective. Water Resources Management. 32(11): 3579-3593.

Nguyen Van Bo (2003). Balanced fertilization for crops in Vietnam: Theory to practice. Agriculture Publishing House (in Vietnamese).

Nguyen Van Dung, Nguyen Tat Canh, Chu Anh Tiep, Ngo Thi Dung, Ha Thi Thanh Binh, Ngo Thanh Son & Nguyen Thi Giang (2009). Effective water management in rice cultivation and water resource conservation, Journal of Science and Development. 7(2):151-158.

Peng S. & Cassman K. G. (1998). Upper thresholds of nitrogen uptake rates and associated nitrogen fertilizer efficiencies in irrigated rice. Agronomy Journal. 90(2): 178-185.
Peng S., Buresh R. J., Huang J., Zhong X., Zou Y., Yang J., Wang G., Liu Y., Hu R., Tang Q., Cui K., Zhang F. & Dobermann A. (2010). Improving nitrogen fertilization in rice by site specific N management: A review. Agronomy for Sustainable Development. 30(3): 649-656.

Peng S. Z., Yang S. H., Xu J. Z., Luo Y. F. & Hou H. J. (2011). Nitrogen and phosphorus leaching losses from paddy fields with different water and nitrogen managements. Paddy and Water Environment. 9(3): 333-342.

Qian X., Shen Q., Xu G., Wang J. & Zhou M. (2004). Nitrogen Form Effects on Yield and Nitrogen Uptake of Rice Crop Grown in Aerobic Soil. Journal of Plant Nutrition. 27(6): 1061-1076.

Sinclair T. R. (1990). Nitrogen influence on the physiology of crop yield. Theoretical production ecology: Reflections and prospects. 181pp.

Schnier H. F., Dingkuhn M., De Datta S. K., Mengel K. & Faronilo J. E. (1990). Nitrogen fertilization of direct-seeded flooded vs. transplanted rice: I. Nitrogen uptake, photosynthesis, growth, and yield. Crop Science. 30(6): 1276-1284.

Son N. T., Badayos R. B., Sanchez P. B., Cruz P. C. S., Dung N. V. & Thanh N. H. (2008). Water productivity and soil chemical properties under varying water regimes on Spring rice (Oryza sativa L.) in Hanoi, Vietnam. Philippine Journal of Crop Science. 33(3): 56-70.

Stoop W. A., Uphoff N., & Kassam A. (2002). A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers. Agricultural Systems. 71(3): 249-274.

Tang Q., Peng S., Buresh J. R., Zou Y., Castilla P. N., Mew W. T., Zhong X. (2007). Rice varietal difference in sheath blight development and its association with yield loss at different levels of N fertilization. Field Crops Research. 102(3): 219-227.

Thiyagarajan T. M., Velu V., Ramasamy S., Durgadevi D., Govindarajan K., Priyadarshini R., Sudhalakshmi C., Senthilkumar K., Nisha P. T., Gayathry G., Hengsdijk H. & Bindraban P. S. (2002). Effects of SRI practices on hybrid rice performance in Tamil Nadu, India. Water-Wise Rice Production. 119-127.

Thomas V. & Ramzi A. M. (2011). SRI contributions to rice production dealing with water management constraints in northeastern Afghanistan. Paddy and Water Environment. 9(1): 101-109.

Toan P. V, Minh N. D., & Thong D. V. (2019). Organic Fertilizer Production and Application in Vietnam. In: Larramendy M. L. & Soloneski S. (Eds.). Organic Fertilizers-History, Production and Applications. IntechOpen. DOI: 10.5772/intechopen.87211.

Tran D. H., Hoang T. N., Tokida T., Tirol-Padre A. & Minamikawa K. (2018). Impacts of alternate wetting and drying on greenhouse gas emission from paddy field in Central Vietnam. Soil science and plant nutrition. 64(1): 14-22.

Van Keulen H. (1977). Nitrogen requirement of rice with special reference to Java. Central research Institute for Agriculture, Bogor (Indonesia). No. 30: 67pp.

Vlek P. & Craswell E. T. (1981). Ammonia volatilization from flooded soils. Fertilizer Research. 2: 227-245.

Watanabe T., Son T. T., Hung N. N., Truong N. V., Giau T. Q., Hayashi K. & Ito O. (2009). Measurement of ammonia volatilization from flooded paddy fields in Vietnam. Soil Science and Plant Nutrition. 55(6): 793-799.

Xu Y., Ge J., Tian S., Li S., Nguyen-Robertson A. L., Zhan M. & Cao C. (2015). Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. Science of the Total Environment. 505: 1043-1052.

Ya-Juan L. I., Xing C. H. E. N., Shamsi I. H., Ping F. A. N. G. & Xian-Yong L. I. N. (2012). Effects of irrigation patterns and nitrogen fertilization on rice yield and microbial community structure in paddy soil. Pedosphere. 22(5): 661-672.