

1 **Different nitrogen rates and methods of application for dry season rice cultivation**
2 **with alternate wetting and drying irrigation: Fate of nitrogen and grain yield**

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1 **Abstract**

2 Improvement of nitrogen use efficiency (NUE) is a challenging task because of its several losses
3 through ammonia volatilization, surface runoff, leaching and nitrification-denitrification.
4 Fertilizer deep placement (FDP) has been proven effective in increasing grain yields and NUE
5 under continuous standing water (CSW) condition. However, the impacts of FDP have not been
6 investigated under alternate wetting and drying (AWD) irrigation. Field experiments were
7 conducted in the dry seasons during 2014-2016 to determine the interaction effect of fertilizer x
8 water regime on N losses as floodwater ammonium and ammonia volatilization, grain yields and
9 NUE. Broadcast prilled urea (PU), deep placement of urea briquettes (UB) and nitrogen-
10 phosphorus-potassium fertilizer briquettes (hereafter NPK) at varied N rates and zero N were
11 tested under AWD and CSW conditions.

12 The deep placement of UB and NPK, irrespective of N rates and water regimes, reduced
13 floodwater ammonium and ammonia volatilization significantly compared to broadcast PU.
14 Deep placement of either UB-N78 or NPK-N104 increased grain yields under both AWD (21-
15 26%) and CSW (13-20%) conditions compared to broadcast PUN104. The magnitude of increase
16 was larger under AWD, because AWD significantly reduced grain yields (8%) compared to
17 CSW at PU-N104. However, yields of deep-placed UB were similar between AWD and CSW.
18 Deep placement of UB and NPK increased N recovery up to 57-66% from 36% of PUN104.
19 These results suggest that UBN78 and NPK-N104 can be utilized under AWD not only for
20 increased grain yield and NUE but also to reduce additional pumping cost for irrigation water.
21 Moreover, combined approach of AWD and FDP might be a good option for improving water
22 and fertilizer use efficiencies in rice cultivation.

23 **Keywords:** Fertilizer deep placement; nitrogen management; water-saving irrigation; ammonia
24 volatilization flux; nitrogen use efficiency; lowland rice

1

2 **1. Introduction**

3 Rice occupies about 11.4 million ha of land with the production of 51.64 million tons ([BBS,](#)
4 [2015](#)). Boro or dry season rice (grown from January/February to April/May) makes up the
5 majority of total production in Bangladesh, covering about 4.8 million ha, while Aus (from
6 May/June to August/September) and Aman (from July/August to November/December) are wet
7 seasons in which rice coverage is 1.05 and 5.6 million ha, respectively ([BBS, 2015](#)). With the
8 increasing population growth rate, it is estimated that the demand for rice will be 56% higher by
9 2050 than in 2001 (36.1million tons) ([Mukherjee et al., 2011](#); [Kabir et al., 2015](#)). Therefore, rice
10 productivity should be increased to meet the food demand of a growing population, taking into
11 account the dwindling amount of land area available for farming. This requires judicious use of
12 agricultural inputs, including quality seeds and fertilizers, and irrigation water management,
13 among other good agricultural practices.

14

15 Fertilizer application and water management are the most important practices in rice production.
16 Though nitrogen (N) fertilizer plays a major role in rice production, all fertilizers should be
17 applied in a balanced way for increasing crop productivity and improving soil fertility. However,
18 most farmers in developing countries, such as Bangladesh, are not familiar with balanced
19 fertilization practices. They often use excessive N and insufficient phosphorus (P) and potassium
20 (K) fertilizers ([Quamruzzaman, 2006](#)), with little or no secondary and micronutrient fertilizers.
21 Moreover, farmers apply fertilizers using the conventional broadcast method, which leads to
22 lower nutrient use efficiency. The nitrogen use efficiency (NUE) in lowland rice is only 30-40%,
23 particularly when prilled urea (PU) is applied via broadcast method, resulting in financial losses

1 and harm to the environment (Ladha et al., 2005; Savant and Stangel, 1990; Raun et al., 2002).
2 The low NUE is caused by N losses through ammonia (NH₃) volatilization, surface runoff,
3 nitrification and denitrification, and leaching (Savant and Stangel, 1990; Peng et al., 2006;
4 Hayashi et al., 2008; Watanabe et al., 2009; Dong et al., 2012). These losses increase when urea
5 is applied via broadcast method. One of the major loss mechanisms is NH₃ volatilization, which
6 reaches up to 50% of applied N (Sommer et al., 2004).
7 In lowland rice fields, placement of N in the root zone, i.e., urea deep placement (UDP), reduces
8 N losses and increases NUE and crop productivity (Savant and Stangel, 1990; Rochette et al.,
9 2013; Huda et al., 2016). When urea is deep-placed in continuously flooded rice soils, losses of
10 N as floodwater ammonium (NH₄⁺-N), NH₃ volatilization and nitrous oxide emissions are
11 negligible (Kapoor et al., 2008; Rochette et al., 2013; Gaihre et al., 2015; Huda et al., 2016).
12 With the reduction of these losses, UDP increases NUE up to 80% compared to 30-45% with
13 broadcast application. Thus, UDP in rice cultivation reduces N fertilizer required by 30-35% and
14 increases grain yields by up to 15-20% compared to broadcast PU. In addition to increased farm
15 profitability, UDP reduces government subsidy payments in countries where N fertilizer
16 subsidies exist. Moreover, deep placement of compound fertilizer (NPK) briquettes was recently
17 introduced in Bangladesh, supplying all three major nutrients in a compound briquette (Miah et
18 al., 2016). Since many farmers do not practice balanced fertilization (Quamruzzaman, 2006),
19 deep placement of compound fertilizer briquettes offers the potential for higher yields and
20 improves fertilizer use efficiency because of balanced use of nutrients and reduced nutrient
21 losses.

22

1 In most studies related to fertilizer deep placement, including deep placement of both urea
2 briquettes (UB) and NPK briquettes, fertilizers were tested under continuous standing water
3 (CSW) irrigation regime. Under CSW irrigation regime, deep-placed N remains in the root zone
4 as $\text{NH}_4^+\text{-N}$, ensuring continuous supply to plants throughout the growing season, depending on
5 soil type. In contrast, when the irrigation regime is changed from CSW to alternate wetting and
6 drying (AWD), the fate of N in the soil, particularly dynamics of soil C and N, may be changed,
7 affecting soil fertility. Generally, AWD makes soil C and N unstable, increasing their
8 mineralization rates (Ponnamperuma, 1972), and these, in turn, have important consequences on
9 C and N losses. Several studies were conducted in different rice-growing countries on AWD
10 regime and its effects on grain yields and farm profitability. However, the effects of AWD
11 irrigation on rice yields are not consistent and are still inconclusive (Bouman et al., 2005;
12 Chapagain and Yamaji, 2010; Liu et al., 2013; Chu et al., 2015; Wang et al., 2016). On the other
13 hand, there are still few studies on the effect of AWD irrigation regime on NUE, particularly
14 under different rates and placement methods of N fertilizers. Therefore, the main objective of
15 this study was to determine the interaction effect of N fertilizer (rates and placement methods) x
16 water management on rice yields and NUE in lowland rice during the dry season. The specific
17 objectives of this study were:

- 18 • To compare N losses, in terms of floodwater NH_4^+ and NH_3 volatilization, between broadcast
19 PU and deep-placed UB and NPK at different N rates.
- 20 • To determine yields, N uptake and NUE of Boro rice for broadcast PU, UB and NPK under
21 CSW and AWD.
- 22 • To determine optimum N rates for Boro rice cultivation as broadcast PU and deep placement
23 of UB and NPK.

1 **2. Materials and methods**

2 2.1. Experimental site and weather conditions

3 The field experiments were conducted in the Boro seasons during 2014-2016 at the Bangladesh
4 Rice Research Institute (BRRI), Gazipur, Bangladesh (latitude: 23°59'25", longitude:
5 90°24'33"). Boro is the dry season irrigated rice, grown from January/February to April/May. In
6 the Boro season, air temperature is generally 15-30°C and rainfall is received in later growth
7 stages of the crop. Daily rainfall and mean temperature during the experiment period are shown
8 in [Fig. 1](#). The physicochemical properties of the soils before the start and after completion of the
9 experiments are presented in [Table 1](#).

10 2.2. Experimental design and treatments

11 Eight fertilizer treatments with different sources and N rates ([Table 2](#)) were arranged in a split-
12 plot design with three replications. The AWD and CSW regimes were the main plots, while
13 fertilizer treatments were sub-plot treatments. Fertilizer treatments were combinations of sources
14 and N rates. Sources of N fertilizer were PU, UB and NPK. N rates were 0, 78, 104 and 156 kg
15 ha⁻¹. For UB and NPK N rates were 78 and 104, while for PU 78, 104 and 156 kg ha⁻¹. The
16 lowest N rate (excluding control treatment) started with existing recommended rates, i.e., 78 kg
17 N ha⁻¹ for deep placement and 104 kg N ha⁻¹ for broadcast application ([Miah et al., 2016](#); [Huda
18 et al., 2016](#)).

19

20 The size and number of briquettes per placement site were determined based on N rates. Deep
21 placement of one 2.7g UB at 40×40 cm spacing (62,500 placement sites per ha) supplied
22 78 kg N ha⁻¹ ([Table 2](#)). Similarly, the deep placement of two 3.4g NPK briquettes provided the

1 same N rates ($\pm 2 \text{ kg ha}^{-1}$); while preparing NPK briquettes, the recommended rate of P and K
2 were maintained.

3 2.3. Crop management

4 Phosphorus (triple superphosphate, TSP) and potassium (muriate of potash, MoP) fertilizers
5 were applied during final land preparation as basal treatments in all plots, except the plots
6 receiving NPK at 25 kg P and 85 kg K ha^{-1} . In NPK treatments, P and K were included in the
7 briquettes. PU was applied as broadcast in three equal splits at seven to ten days after
8 transplanting (DAT), at maximum tillering and at panicle initiation stages, while UB and NPK
9 were deep-placed at 7-10 cm depth at the center of four rice hills as a single application. In
10 addition, sulfur (S) and zinc (Zn) were applied to all plots as basal treatments at 15 kg S as
11 gypsum and 3 kg Zn ha^{-1} as zinc sulfate. Two to three rice seedlings per hill of variety BRRI
12 dhan28 were transplanted with a spacing of 20×20 cm. Table 3 shows the major crop
13 management practices.

14 All the plots under CSW conditions were maintained continuously flooded until two weeks
15 before harvesting. While plots under AWD conditions were irrigated following AWD principles.
16 Plots were irrigated when water depth in AWD pipes was 12-15 cm below soil surface. AWD
17 irrigation was adopted one week after first topdressing of PU or UDP and continued until two
18 weeks before harvesting. However, plots under AWD conditions were maintained continuously
19 flooded for a week after topdressing (TD) of PU and during flowering stage as under CSW plots.

20 To monitor floodwater depth in AWD plots, a 25 cm long, 10 cm diameter PVC pipe, perforated
21 up to 15 cm, was inserted 15 cm into the soil, perforated side down, leaving 10 cm above the
22 ground. Soils inside the pipe were removed to make a hole up to the 15 cm. Water depth inside

1 the PVC pipes was monitored every day after transplanting and plots were irrigated when water
2 depth in AWD pipes were 12-15 cm below the soil surface (Fig. 2).

3 2.4. Floodwater $\text{NH}_4^+\text{-N}$ and NH_3 volatilization

4 Floodwater samples were collected for seven consecutive days after each fertilizer application,
5 i.e., basal fertilization, deep placement of fertilizers and topdressing. Floodwater samples (5 mL
6 floodwater plus 0.5 mL Nessler's reagent) were analyzed for $\text{NH}_4^+\text{-N}$ using a spectrophotometer
7 at 420 nm wave length (Bear, 1967). The concentration of $\text{NH}_4^+\text{-N}$ (ppm or mgL^{-1}) was
8 converted to kg ha^{-1} correcting area and volume of water per plot. NH_3 volatilization was
9 measured using the "dynamic closed chamber technique" and boric acid trap method described
10 by Zhong-cheng et al., 2012. A plastic bucket was used as a chamber; a vacuum pump was used
11 to suck air samples from a chamber. Nitrogen present in air samples was trapped by a boric acid
12 solution (2%) in a volumetric flask (). Plastic buckets (13 L) were placed between rice rows after
13 each N application for seven consecutive days. The NH_3 content in the volumetric flask was
14 collected until the color changed from violet to green. Then trapped NH_3 was determined by
15 titration with standard acid. Volatilization measurements were done only under CSW irrigation
16 regime in 2015 and 2016.

17 2.5. Rice yield and NUE

18 Biomass samples (16 rice hills) were collected at panicle initiation (PI) and heading stages of
19 rice plants to determine dry matter accumulation. For grain and straw yield, rice plants from a 5
20 m^2 area were harvested. The grain yield was calculated at 14% moisture content. Plant N content
21 was determined at each growth stage by the micro-Kjeldahl method (Yoshida et al., 1976). The
22 total N uptake was determined at PI, heading and maturity stages to determine the recovery
23 efficiency of N (RE_N) by rice plants. Nitrogen use efficiency, including agronomic efficiency

1 (AE_N ; kg grain per kg N applied) and RE_N (kg N uptake per kg N applied), was calculated for all
2 treatments.

3 2.6. Data analysis

4 Analysis of variance (ANOVA) of grain yield, total dry matter (TDM), total Nuptake (TNU) and
5 NUE was done with Statistical Tool for Agricultural Research (STAR2.0.1, International Rice
6 Research Institute, Philippines). A pairwise means comparison of treatments was done with
7 Tukey's honest significant difference (HSD) test at a 5% level of probability.

8 **3. Results**

9 3.1. Dynamics of floodwater NH_4^+ -N and NH_3 volatilization

10 Deep placement of either UB or NPK, irrespective of N rates, reduced floodwater NH_4^+ -N
11 compared to broadcast PU (Fig. 3). These results were consistent across water regimes and years.
12 The broadcast PU resulted in a significant amount of NH_4^+ -N in floodwater, which varied over
13 time. The peaks in NH_4^+ -N were observed after two to three days of fertilizer application and
14 then sharply declined. Moreover, the amount of NH_4^+ -N increased with larger N rates of PU. In
15 contrast, increasing N rates in UB and NPK treatments had no significant effect on floodwater
16 NH_4^+ -N. On the other hand, effects of water regimes were not apparent. Both CSW and AWD
17 plots showed similar pattern and magnitudes under each fertilizer treatment.

18 As with floodwater NH_4^+ -N, the magnitude of NH_3 volatilization in PU treatment was higher,
19 while it was negligible from UDP treatments (Fig. 4). Deep placement of UB significantly
20 reduced NH_3 volatilization compared to broadcast PU in all measurements. Since UB was deep-
21 placed once at 7-10 cm below the soil surface during the first TD of PU, the magnitude of NH_3
22 volatilization in UB treatments was comparatively higher during the first TD compared to the
23 second and third TD periods over the years. The pattern of NH_3 volatilization in PU treatments

1 was similar in all measurement periods. The N loss as NH₃ volatilization in PU treatments was
2 about 4% of the applied N, while in UB treatments it was only about 1%.

3 3.2. Grain yield and aboveground biomass

4 Fertilizer treatments had significant interaction effects with water regime and year on the number
5 of panicles, grain yields and aboveground TDM (Table 4). Nitrogen fertilizer, irrespective of
6 rates and methods of application, significantly increased the number of panicles per unit area,
7 grain yields and TDM under both irrigation regimes compared to the control treatment. AWD
8 irrigation significantly reduced grain yields and TDM compared to CSW irrigation when N
9 fertilizer was applied as broadcast method. Therefore, under AWD irrigation, increasing the N
10 rate from 104 kg to 156 kg (broadcast) significantly increased grain yields and TDM, but the
11 effects were not significant under CSW regime. On the other hand, for UB, increasing N rates
12 from 78 kg to 156 kg had no significant effect on grain yields under both water regimes. Grain
13 yields showed a declining trend beyond 104 kg. In contrast to UB, deep placement of NPK
14 increased grain yields when the N rate was increased from 78 kg to 104 under the AWD regime,
15 although it was not significant under the CSW irrigation regime. In general, deep-placed
16 treatments increased grain yields compared to PU broadcast treatments. Deep placement of either
17 UB (N78) or NPK (N104) significantly increased grain yields compared to broadcast PU at 104
18 kg N ha⁻¹ under both irrigation regimes. The magnitude of increase was higher under AWD (21-
19 26%) compared to CSW (13-20%). The AWD regime significantly reduced grain yields,
20 particularly at lower N rates as PU (N104) and NPK (N78), and in higher N rate as UB (N156).
21 Though the deep placement of NPK fertilizer significantly increased grain yields and TDM over
22 PU (N104), it did not have a significant effect over UB. Similar effects were observed for TDM.

1 Grain yields were significantly higher in 2014 compared to 2015-2016, except at UB N104
2 (Table 4). The UB at N104 consistently increased grain yields compared to PU N104 in 2014
3 and PU N104 and N156 in 2015-2016. Grain yields were not significantly different between UB
4 N78 and N104.

5 3.3. Nitrogen uptake and agronomic efficiency

6 Increasing N rates, either as broadcast or deep placement, increased N uptake significantly up to
7 N156 over control. There were significant water regime x year () and fertilizer treatment x year
8 () interactions on total N uptake (Table 5). AWD and CSW had similar N uptake in 2014 and
9 2016, but AWD had reduced uptake in 2015 (Table 5). Generally, in all fertilizer treatments
10 except the control, N uptake was significantly higher in 2014 compared to 2015 and 2016. There
11 were significant fertilizer x water regime and fertilizer x year interactions on AE_N . Under the
12 CSW regime, increasing the N rate in either deep-placed or broadcast treatments decreased AE_N .
13 But under AWD, AE_N decreased significantly with N rate only in UB treatments. The highest N
14 uptake and AEN was observed in UB N78 under both water regimes, which was significantly
15 larger compared to broadcast treatments. Both UB and NPK treatments showed a similar trend
16 under CSW. However, under AWD, NPK reduced AE_N compared to UB, particularly at N78.
17 AWD irrigation significantly reduced AEN compared to CSW, except at PU N156 (Table 5). UB
18 N78 had significantly higher AE_N compared to PU broadcast and NPK, except in 2016 (Table 5).
19 In 2016, both UB and NPK at N78 had similar AE_N .

20

21

22 3.4. Recovery efficiency of N

1 Water regime had no interaction effects with fertilizer treatment and year on N recovery at any
2 growth stages. N recovery was increased consistently throughout the rice growth stage in all
3 fertilizer treatments. Among the fertilizer treatments, UB at N78 had the highest recovery at each
4 growth stage (Table 6). The N recovery at UB N78 was similar to that of UB N104. NPK N78
5 had reduced N recovery compared to UB N78, except at the heading stage. At maturity stage,
6 there was significant fertilizer x year interaction (Table 6). Generally, in all fertilizer treatments,
7 the highest N recovery was observed in 2014 compared to 2015 and 2016). In each of the years,
8 N recoveries were significantly higher in deep-placed than broadcast PU treatments.

9 **4. Discussion**

10 4.1. Dynamics of floodwater NH_4^+ -N and NH_3 volatilization

11 Dynamics of floodwater NH_4^+ -N (patterns and magnitudes) in all fertilizer treatments were
12 similar between AWD and CSW conditions as both plots were continuously flooded during the
13 measurement period. The negligible N losses as floodwater NH_4^+ -N and NH_3 volatilization from
14 deep-placed fertilizer treatments that were observed agree closely with those from previous
15 studies (Rochette et al., 2013; Mohanty et al., 1999; Huda et al., 2016). Generally, the amounts
16 of floodwater NH_4^+ -N in deep-placed treatments were similar to the control treatment (N0),
17 irrespective of N rate. This is because the movement of NH_4^+ from the deep soil layer to the
18 surface soil or floodwater is very slow, resulting in a significant reduction of NH_3 volatilization
19 (Rochette et al., 2013). Moreover, there might be less soil urease activity in the deeper soil layer,
20 leading to less NH_4^+ -N in soils and floodwater from hydrolyzed N fertilizers (Drury et al., 2006;
21 Liu et al., 2006, 2015). In contrast, the amount of floodwater NH_4^+ -N and NH_3 volatilization was
22 consistently higher in broadcast PU treatment, which increased with N rate. These results were in
23 close agreement with previous studies (Hayashi et al., 2006; Rochette et al., 2013). However, in

1 this study, cumulative losses of N as NH₃ volatilization were relatively low, i.e., < 5 kg N ha⁻¹, or
2 about 4% of applied N. The highest NH₃ volatilization loss occurred after first topdressing at 6%
3 of applied N when the rice crop was relatively weak sink for N uptake. Lower N loss as NH₃
4 volatilization was also reported by [Tian et al. \(2001\)](#) (1-6% of applied N) at 60-180 kg N ha⁻¹
5 and by [Wang et al. \(2011\)](#) (4.16% of applied N) at 159.8 kg N ha⁻¹. In contrast to our results, [Liu](#)
6 [et al. \(2015\)](#) reported a larger loss (18-33%) of applied N as NH₃ volatilization. The discrepancy
7 between our findings and their results may be due to variations in soils, environmental
8 conditions, and measurement techniques. Our experiment was conducted in clay loam soil, while
9 theirs was conducted in sandy loam soil. Clay soils promote NH₄⁺ fixation in soil ([Scherer and](#)
10 [Ahrens, 1996](#)), thus reducing NH₃ volatilization. In contrast, sandy soils help to promote NH₄⁺
11 released from soils into the floodwater ([Nieder et al., 2011](#)), thus increased NH₃ volatilization.
12 The daily air temperature (20-25°C) during topdressing was also comparatively low in this study
13 ([Fig. 1](#)) compared to [Liu et al. \(2015\)](#) (30-35°C). Furthermore, we observed high NH₄⁺-N (10
14 ppm) in drain water, indicating more lateral seepage loss of N.

15 4.2. Grain yields and aboveground biomass

16 Fertilizer placement methods affected grain yields differently with irrigation regimes. Generally,
17 UDP increased grain yields consistently compared to broadcast PU under both irrigation
18 regimes. However, the magnitude of yield increase varied with irrigation regime. UDP with 25%
19 less urea than broadcast PU (N78 vs. N104) increased grain yields by 24% and 13% under AWD
20 and CSW irrigation regimes, respectively. The larger yield increment under AWD was due to
21 lower yield of broadcast PU ([Table 4](#)). In broadcast PU treatment, particularly at N104, AWD
22 irrigation significantly reduced grain yields compared to CSW. It is likely that AWD irrigation
23 increased N loss in broadcast PU treatment, causing a limited supply of N to the plants,

1 particularly at a lower N rate (N104), that resulted in lower yields. These results suggest that an
2 N rate of 104 kg ha⁻¹ for broadcast PU under AWD irrigation is not sufficient to produce
3 optimum grain yields and should be increased to 156 kg ha⁻¹. On the other hand, for UDP, 78 kg
4 N ha⁻¹ was confirmed to be an optimum N rate for both irrigation regimes, since increasing the N
5 rate beyond 78 kg ha⁻¹ had no significant effect on grain yields. Grain yields showed a declining
6 trend beyond N104. Our results, particularly with CSW irrigation, are consistent with previous
7 studies conducted across different agro-ecological zones of Bangladesh ([Huda et al., 2016](#); [Miah
8 et al., 2016](#)). The benefits of UDP, including increased grain yield by 15-20% and urea savings of
9 25-30% compared with broadcast PU in lowland rice fields, are well-documented ([Savant and
10 Stangel, 1990](#); [Mohanty et al., 1999](#); [Bulbule et al., 2005](#); [Kapoor et al., 2008](#); [Bandaogo et al.,
11 2015](#)). Increased grain yields with UDP is mainly associated with an increased number of
12 panicles ([Table 3](#)).

13 On the other hand, deep placement of NPK briquettes, albeit at lower N rates, produced yields
14 similar to broadcast PU, reducing grain yields significantly compared to UDP under both
15 irrigation regimes. In contrast to our results, previous studies reported larger grain yields with
16 NPK than with UDP ([Miah et al., 2016](#); [Kapoor et al., 2008](#)). The decrease in grain yields in this
17 study is probably associated with a limited supply of P and K, particularly at early stages of plant
18 growth, because of less P and K in the soils ([Table 1](#)). Similar results reported by [Kapoor et al.
19 \(2008\)](#), in which soils with low level of P and K showed poor crop growth at early stages and
20 consequently decrease rice yield. Since P and K are not mobile in the soils, rice plants may not
21 have been able to take the required P and K from deep-placed treatments until the rice root is
22 established and reaches the placement site. Thus, deep placement of P and K should be site-
23 specific and is generally not recommended for soils with low P and K. As for broadcast PU,

1 AWD irrigation further reduced grain yields at NPK N78. However, increasing the N rate from
2 78 kg to 104 kg in NPK briquettes produced similar yields with UDP N78 under both AWD and
3 CSW irrigation regimes. Our results confirmed that NPK deep placement should be increased to
4 104 kg ha⁻¹. Further research is needed to study availability of deep-placed P and K under AWD
5 irrigation. Nevertheless, the deep placement of NPK has additional benefits of supplying all
6 primary nutrients at one time, ensuring balanced fertilization. This is important in countries like
7 Bangladesh, where farmers often use an excessive amount of N fertilizers with insufficient P and
8 K and where one-time application of NPK results in labor savings.

9 Previous studies have suggested that the effects of AWD irrigation on grain yields are not
10 consistent and still inconclusive ([Liu et al., 2013](#); [Chu et al., 2015](#); [Wang et al., 2016](#); [Chapagain](#)
11 [and Yamaji, 2010](#); [Dong et al., 2012](#); [Bouman and Tuong, 2001](#); [Bouman et al., 2005](#); [Sun et al.,](#)
12 [2012](#)). In a recent literature review, [Lampayan et al. \(2015\)](#) reported that AWD irrigation saves
13 water by up to 38% without any significant effects on grain yields. However, in this study, we
14 observed significant interaction of AWD x fertilizer treatment and AWD x year. The effects of
15 AWD on grain yields may depend on soil types, intensity of soil drying, timing of irrigation,
16 climatic conditions during the rice-growing season, N fertilizer management and rice cultivars
17 ([Bouman and Tuong,2001](#); [Belder et al., 2004](#); [Zhang et al., 2008, 2009](#); [Liu et al., 2013](#)). Severe
18 yield reductions may occur in heavy soils due to root damage, which affects plant growth
19 ([Sanchez, 1973a, 1973b](#)). The larger reduction in grain yields in 2015 could be due to a longer
20 dry period ([Fig. 2](#)), leading to increased N loss as nitrification-denitrification ([Liu et al., 2010](#);
21 [Dong et al., 2012](#)). However, deep placement of urea briquettes ensured larger grain yields under
22 both irrigation regimes, which confirms that adoption of UB N78 with AWD irrigation saves

1 both N fertilizers and irrigation water for Boro rice cultivation in the areas with climate, soils and
2 management practices similar to this experimental site.

3 4.3. Nitrogen uptake and nitrogen use efficiency

4 UDP significantly increased nitrogen uptake and nitrogen recovery compared to broadcast PU
5 (Table 5-6). Our results were in accord with previous studies (Kapoor et al., 2008; Bandaogo et
6 al., 2015; Liu et al., 2015; Huda et al., 2016; Islam et al., 2016). The larger N uptake and
7 recovery were observed in deep-placed treatment, probably because of continuous availability of
8 applied N for plant growth and consequently low N loss through NH₃ volatilization and other
9 losses (Fig. 3-4). Deep placement ensures a continuous supply of N to the plants because N in
10 reduced soil layer retains as NH₄⁺-N for a longer time, ensuring prolonged N availability for the
11 rice crop (Kapoor et al., 2008). A continuous supply of N in deep-placed treatments is evident
12 from N recovery at different growth stages, which increased consistently from PI to maturity
13 stages (Table 6). At maturity, the largest N recovery was observed at UB N78, which was almost
14 double (66%) that of PU N104 (36%). Moreover, UB N78 significantly increased N recovery
15 compared to NPK N78. In contrast, previous studies reported similar N recovery between UDP
16 N78 and NPK N78 (Huda et al., 2016; Islam et al., 2016). Though there was a significant
17 fertilizer x water regime interaction effect on grain yields, no interaction effect was noted on
18 total N uptake and N recovery. These findings are in agreement with the previous findings (Shad
19 and De Datta, 1988; Belder et al., 2004; Dong et al., 2012; Huda et al., 2016; Islam et al., 2016)
20 that water regimes insignificantly influenced TNU and RE_N. Our results suggest that though
21 AWD irrigation has a direct effect on grain yields, it may not affect N uptake and N recovery, at
22 least in the short term. Since there was significant fertilizer x year interaction on nitrogen uptake
23 and grain yields, more studies are needed to investigate whether AWD irrigation affects NUE

1 and soil fertility along with grain yields in the long term. The long-term studies should focus on
2 different N rates and sources, particularly NPK briquettes, across different rice-growing seasons
3 and sites.

4 **5. Conclusions**

5 AWD irrigation produced grain yields similar with CSW irrigation when N fertilizer was applied
6 as deep placement. But it reduced grain yields significantly under conventional N fertilizer
7 management (broadcast application), particularly at current recommended rate (104 kg N ha⁻¹).
8 These results suggest that under AWD irrigation, N rate for broadcast urea should be increased
9 from 104 kg ha⁻¹ to 156 kg ha⁻¹ to achieve similar yield with UDP (78 kg N ha⁻¹). Fertilizer deep
10 placement reduced floodwater ammonium and ammonia volatilization compared to broadcast
11 PU. UB N78 produced significantly higher yields compared to broadcast PU and NPK treatments
12 under both AWD and CSW irrigation regimes. N recovery efficiency in deep-placed treatments
13 (UB and NPK) (57-66%), particularly at N78, was almost double than that of broadcast PU
14 (36%). Our results confirm that the optimum N rate as deep placement of UB for Boro rice
15 cultivation is 78 kg ha⁻¹, irrespective of irrigation regime. On the other hand, deep placement of
16 NPK briquette had no yield advantage compared with UDP at N78. Therefore, it can be
17 concluded that combination AWD irrigation and UDP could be used to increase both fertilizer
18 and water use efficiencies for dry season rice (Boro) cultivation.

19

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1 **List of tables**

2 **Table 1**

3 Physicochemical properties of soils before the experiment and after harvest of Boro 2016.

Soil properties	Initial soil (2013)		After harvest of Boro 2016	
	AWD	CSW	AWD	CSW
pH-H ₂ O	5.8	6.0	6.2	6.2
Organic carbon (%)	1.27	1.25	1.26	1.25
Total N (%)	0.14	0.13	0.12	0.11
Available P (mg kg ⁻¹)	11.47	11.33	11.37	11.53
Available K (cmol _c kg ⁻¹)	0.12	0.11	0.10	0.11
Texture	Clay loam			

4 AWD and CSW represent alternate wetting and drying, and continuous standing water,
5 respectively.

1 **Table 2**

2 Nitrogen rates and sources used in Boro seasons.

Fertilizer/N sources	N rate	Briq wt. (g) and no/four hills	Basal/deep placed N	2 nd Top- dress N	3 rd Top- dress N
kg ha ⁻¹					
Control	0	–	–	–	–
Prilled urea (PU)	104	–	34.6	34.6	34.6
	156	–	52	52	52
Urea briquette (UB)	78	2.7 (1)	78	–	–
	104	1.8 (2)	104	–	–
	156	2.7 (2)	156	–	–
NPK briquette (NPK)	78	3.4 (2)	78	–	–
	104	2.4 (3)	104	–	–

3 The treatments were the same for both alternate wetting and drying (AWD) and continuous
 4 standing water (CSW) conditions in all three Boro seasons, i.e., 2014, 2015 and 2016. The
 5 number in parenthesis indicates the number of briquettes used per application site.

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1 **Table 3.**

2 Dates of crop management practices for different rice growing seasons

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Management practices	Rice-growing season		
	Boro 2014	Boro 2015	Boro 2016
Puddling and land preparation	08-01-2014	04-01-2015	09-01-2016
Basal fertilization (P and K fertilizers)	10-01-2014	07-01-2015	11-01-2016
Transplanting	11-01-2014	08-01-2015	12-01-2016
First topdressing and UDP	22-01-2014	16-01-2015	22-01-2016
Second topdressing	18-02-2014	19-02-2015	23-02-2016
Third topdressing	10-03-2014	10-03-2015	14-03-2016
Final drainage			
Harvest	24-04-2014	20-04-2015	24-04-2016

4 [UDP, urea deep placement](#)

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1 **Table 4**

2 The effects of interaction of water regime x fertilizer treatment and water regime x year on
 3 panicles, grain yield, straw yield, aboveground total dry matter (TDM) and harvest index (HI) in
 4 Boro season.

Year	Fertilizer treatment	Panicles (m ⁻²)		Grain yield (t ha ⁻¹)			TDM (t ha ⁻¹)		HI Mean of 2 water regimes		
		AWD	CSW	AWD	CSW	AWD	CSW				
Fertilizer treatment and water regimes interaction (T × W)											
Mean	N0	147d	143c	2.1c	1.9d	4.0e	3.6e	0.53a			
	PU N104	259c	283b	4.2b	4.6c	8.0d	8.8d	0.53a			
	PU N156	292ab	281b	4.9a	4.9bc	9.4c	9.5cd	0.53a			
	UB N78	306a	301ab	5.2a	5.2ab	10.2ab	9.9bc	0.52ab			
	UB N104	311a	319a	5.3a	5.5a	10.6a	10.6ab	0.51ab			
	UB N156	297ab	317a	5.0a	5.4ab	10.2a	10.8a	0.49b			
	NPK N78	272bc	297ab	4.4b	5.0bc	9.4bc	9.8bc	0.49b			
	NPK N104	302a	298ab	5.1a	5.2ab	10.0abc	10.1abc	0.51ab			
	Mean	273B	280A	4.5B	4.7A	9.0A	9.1A				
Year and water regimes interaction (Y × W)											
2014	Mean	294a	298a	5.0a	5.1a	10.5a	10.2a	0.49b			
2015	Mean	267b	286a	4.0c	4.5b	7.8c	8.6b	0.52a			
2016	Mean	258b	256b	4.5b	4.5b	8.6b	8.6b	0.53a			
	Mean	273B	280A	4.5B	4.7A	9.0A	9.1A				
Fertilizer treatment and year interaction (T × Y)											
Mean of water regimes	Fertilizer treatment	Panicles (m ⁻²)			Grain yield (t ha ⁻¹)			TDM (t ha ⁻¹)			–
		2014	2015	2016	2014	2015	2016	2014	2015	2016	–
	N0	151c	145d	138c	2.3d	1.7d	2.0dA	4.5d	3.2e	3.7c	
	PU N104	308ab	273bc	231b	5.2bc	4.0c	4.1c	10.4c	7.5d	7.4b	
	PU N156	335a	297abc	227b	5.9a	4.5bc	4.4bc	11.8ab	8.4cd	8.1b	
	UB N78	330a	296abc	284a	5.5ab	4.8ab	5.1a	11.1bc	9.0abc	10.0a	
	UB N104	325a	323a	297a	5.6ab	5.3a	5.4a	11.5ab	9.9a	10.4a	
	UB N156	326a	307ab	289a	5.8a	4.8ab	4.9ab	12.2a	9.9ab	9.5a	
	NPK N78	283b	269c	302a	4.8c	4.2c	5.1a	10.2c	8.9bc	9.7a	
	NPK N104	307ab	305abc	287a	5.4abc	4.8ab	5.2a	11.1bc	9.1abc	10.0a	
	Mean	296A	277B	257C	5.1A	4.3C	4.5B	10.3A	8.2B	8.6B	
ANOVA (p values)											
	Year (Y)	0.000			0.000			0.000		0.004	
	Water regime (W)	0.046			0.013			0.041		0.142	
	Treatment (T)	0.000			0.000			0.000		0.000	
	T × W	0.033			0.011			0.059		0.162	
	Y × W	0.045			0.011			0.001		0.099	
	Y × T	0.00			0.000			0.000		0.132	
	Y × W × T	0.867			0.603			0.112		0.071	

5 Within a column, means followed by same lowercase letters and within a row, means followed by
 6 the same uppercase letters for each response variable are not significantly different at 5% level of
 7 probability. CSW, AWD, PU, UB and NPK represent continuous standing water, alternate
 8 wetting and drying, prilled urea, urea briquette and NPK fertilizer briquette, respectively.
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1 **Table 5**

2 The effects of interaction of water regime x fertilizer treatment and water regimes x year on total
 3 nitrogen uptake (TNU), N harvest index (NHI) and agronomic efficiency (AE_N) in Boro season.

Year	Fertilizer treatment	TNU (kg ha ⁻¹)			NHI		AE _N (kg grain kg ⁻¹ N)			
		Mean of 2 water regimes			Mean of 2 water regimes		AWD	CSW		
Fertilizer treatment and water regimes interaction (T × W)										
Mean	N0	24.8f			0.62a		-	-		
	PU N104	62.6e			0.62a		20.3c	26.0c		
	PUN156	76.7c			0.62ab		18.0c	19.7d		
	UBN78	76.2c			0.61abc		38.9a	42.0a		
	UBN104	88.2b			0.61abc		30.7b	34.7b		
	UBN156	95.4a			0.57bc		18.1c	22.3cd		
	NPKN78	69.5d			0.57c		29.6b	39.9a		
	NPKN104	77.5c			0.60abc		28.5b	31.7b		
	Mean						26.3B	30.9A		
Year and water regimes interaction (Y × W)										
		AWD	CSW	Mean of 2 water regimes			Mean of 2 water regimes			
2014	Treat Mean	88.9a	88.5a	0.58b			29.7a			
2015	Treat Mean	56.8c	63.0b	0.62a			28.1a			
2016	Treat Mean	65.2b	65.7b	0.61a			28.1a			
	Mean	70.3B	72.4A							
Fertilizer treatment and year interaction (T × Y)										
Mean of water regimes	Fertilizer treatment	TNU (kg ha ⁻¹)			NHI			AE _N (kg grain kg ⁻¹ N)		
		2014	2015	2016	2014	2015	2016	2014	2015	2016
	N0	28.6f	21.5d	24.3f	0.63a	0.61ab	0.62a	-	-	-
	PU N104	88.5de	49.0c	50.3e	0.57ab	0.65a	0.63a	27.6bc	22.2c	19.6c
	PUN156	105.7ab	60.5b	64.1d	0.58ab	0.66a	0.61	22.9c	18.3c	15.4c
	UBN78	93.2d	63.6b	71.7bcd	0.57ab	0.65a	0.60a	41.5a	39.9a	39.9a
	UBN104	104.7bc	77.3a	82.6ab	0.57ab	0.64a	0.62a	31.4b	34.3ab	32.4b
	UBN156	115.8a	86.0a	84.3a	0.58ab	0.56b	0.59a	22.5c	19.9	18.3c
	NPKN78	79.1e	58.4bc	71.1cd	0.55b	0.55b	0.62a	32.2b	32.2b	39.9a
	NPKN104	94.3cd	62.9b	75.1abc	0.57ab	0.61ab	0.62a	29.4b	29.8b	31.0c
	Mean	88.7A	59.9C	65.5B	0.58B	0.62A	0.61A	29.7A	28.1A	28.1A
ANOVA (p values)										
	Year (Y)	0.000**			0.045*			0.435 ^{NS}		
	Water regime (W)	0.048*			0.277 ^{NS}			0.000**		
	Treatment (T)	0.000**			0.001**			0.000**		
	T × W	0.087 ^{NS}			0.732 ^{NS}			0.007**		
	Y × W	0.037*			0.360 ^{NS}			0.108 ^{NS}		
	Y × T	0.000**			0.007**			0.000**		
	Y × W × T	0.645 ^{NS}			0.645 ^{NS}			0.845 ^{NS}		

4 Within a column, means followed by same lowercase letters and within a row, means followed by
 5 the same uppercase letters for each response variable are not significantly different at 5% level of
 6 probability. CSW, AWD, PU, UB and NPK represent continuous standing water, alternate wetting
 7 and drying, prilled urea, urea briquette and NPK fertilizer briquette, respectively.

1 **Table 6**

2 The effects of interaction of water regime x fertilizer treatment on recovery efficiency of N
 3 (RE_N) in panicle initiation (PI), heading and maturity stages of rice plant in Boro season.

Year	Fertilizer treatment	RE_N (%)		
		PI Mean of 2 water regimes	Heading Mean of 2 water regimes	Maturity Mean of 2 water regimes
Fertilizer treatment and water regimes interaction (T × W)				
Mean	PU N104	18e	34c	36d
	PU N156	16e	30c	33d
	UB N78	36a	57a	66a
	UB N104	32ab	54a	61ab
	UB N156	26cd	41b	45c
	NPK N78	30bc	55a	57b
	NPK N104	23d	46b	51c
ANOVA (p values)				
Year (Y)		0.001**	0.003**	0.000**
Water regime (W)		0.041*	0.002**	0.010**
Treatment (T)		0.000**	0.000**	0.000**
T × W		0.515 ^{NS}	0.165 ^{NS}	0.128 ^{NS}
Y × W		0.336 ^{NS}	0.115 ^{NS}	0.465 ^{NS}
Y × T		0.000**	0.217 ^{NS}	0.000**
Y × W × T		0.237 ^{NS}	0.508 ^{NS}	0.657 ^{NS}

4 Within a column, means followed by same letters for each response variable are not significantly
 5 different at 5% level of probability. PU, UB and NPK represent prilled urea, urea briquette and
 6 NPK fertilizer briquette, respectively.

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1 Figure Captions

2 **Fig. 1.** Daily average of rainfall and air temperature for rice-growing seasons during 2014-2016.

3 (Data source: Weather station, Bangladesh Rice Research Institute, Gazipur.)

4 **Fig. 2.** Daily field water depth from transplanting to harvesting of rice plant in Boro season at

5 different N rates and sources under alternate wetting and drying (AWD) and continuous

6 standing water (CSW) conditions

7 **Fig.3.** Dynamics of floodwater $\text{NH}_4^+\text{-N}$ at different N rates and application methods under

8 alternate wetting and drying (AWD) and continuous standing water (CSW) conditions in

9 Boro seasons. PU, UB and NPK stand for broadcast prilled urea, urea briquette deep

10 placement and NPK briquette deep placement, respectively. TD-1, TD-2 and TD-3

11 represent first, second and third topdressing of PU, respectively. Vertical bars indicate

12 standard error of mean (n = 3)

13 **Fig.4.** NH_3 volatilization losses from broadcast prilled urea (PU) and urea briquette deep

14 placement (UB) at 104 kg N ha^{-1} in Boro seasons. First-TD, second-TD and third-TD

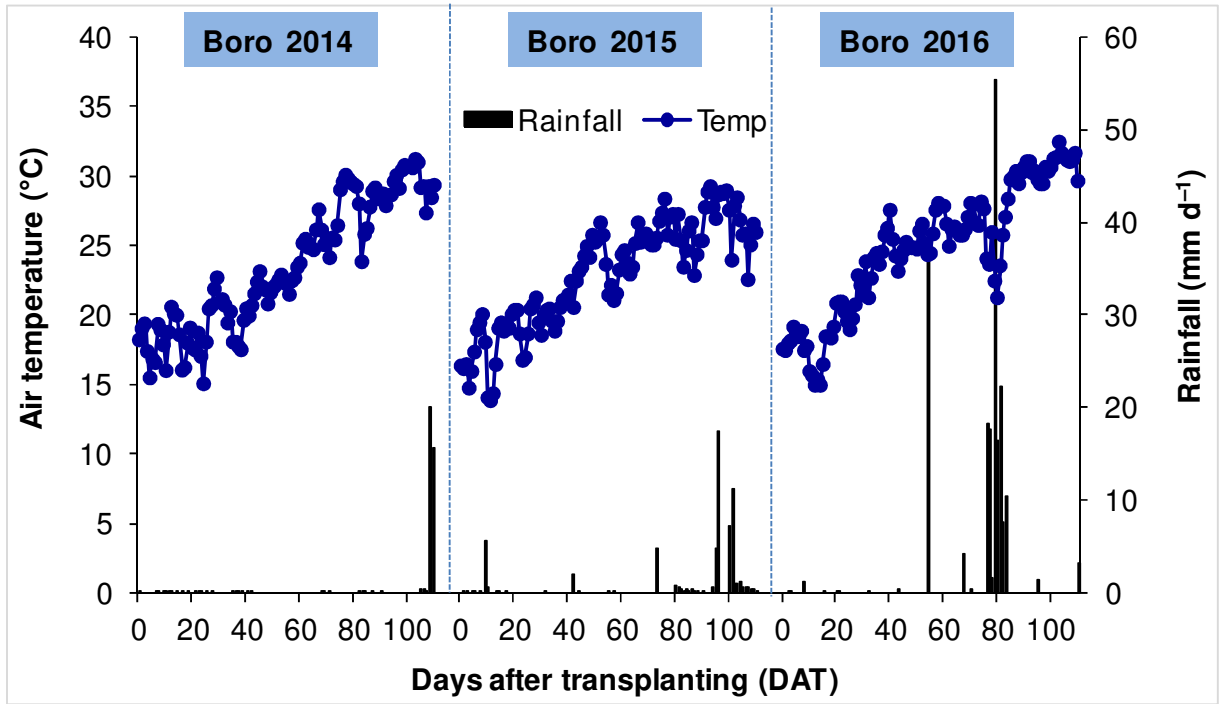
15 represent first, second and third topdressing of PU, respectively. Vertical bars indicate

16 standard error of mean (n = 3). Measurements were done under continuous standing

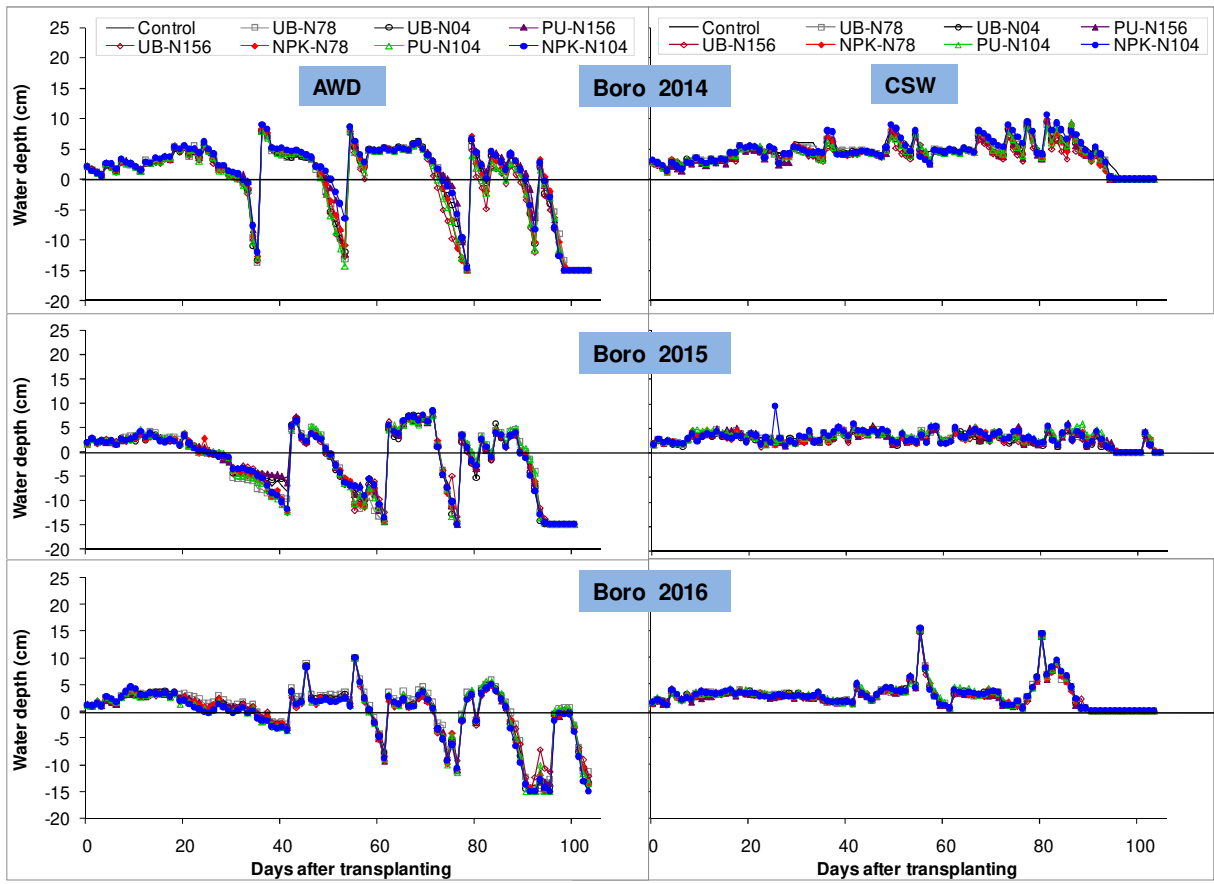
17 water (CSW) conditions in 2015 and 2016.

1 Fig. 1

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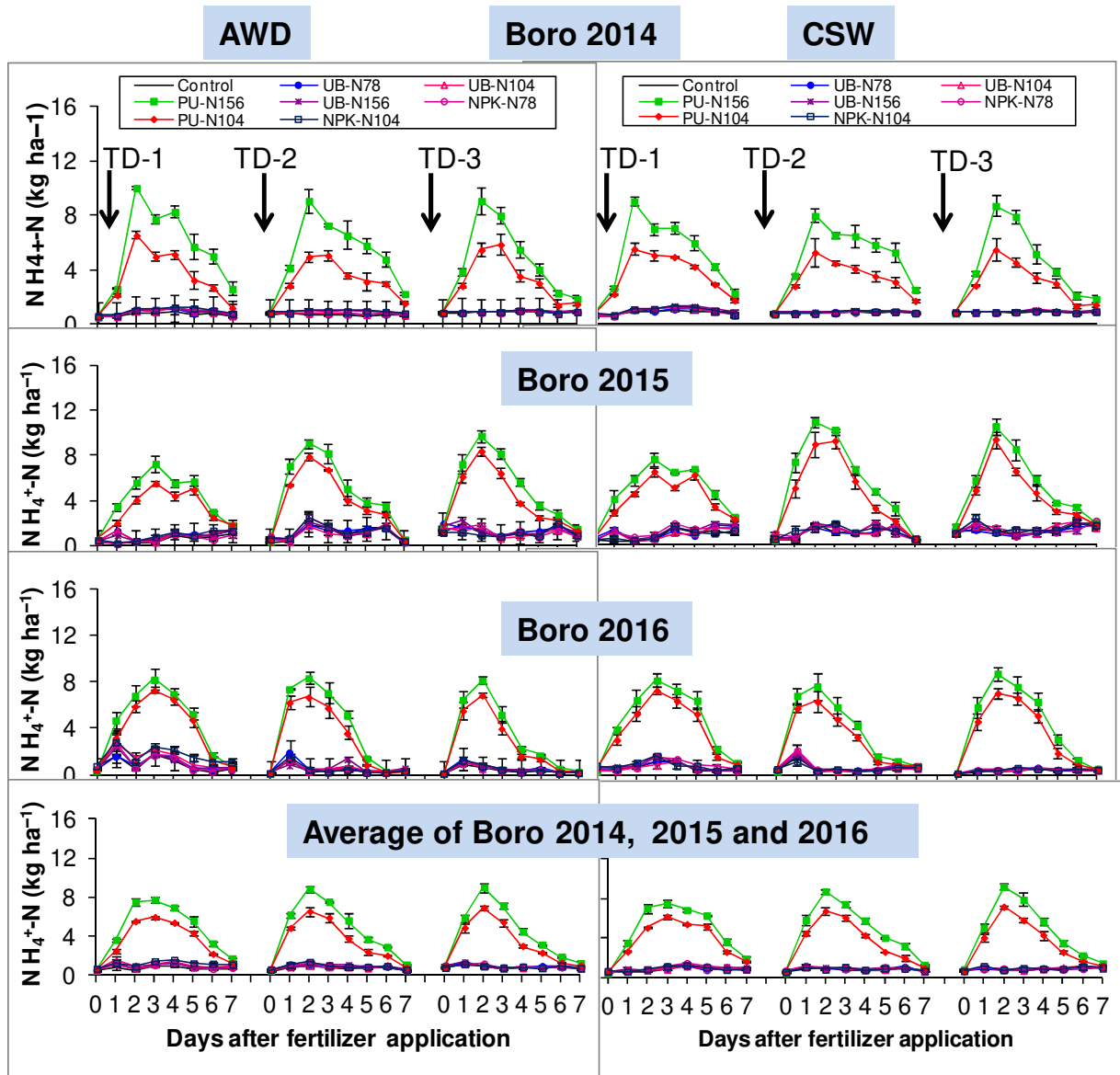


1 **Fig. 2**



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1 Fig. 3



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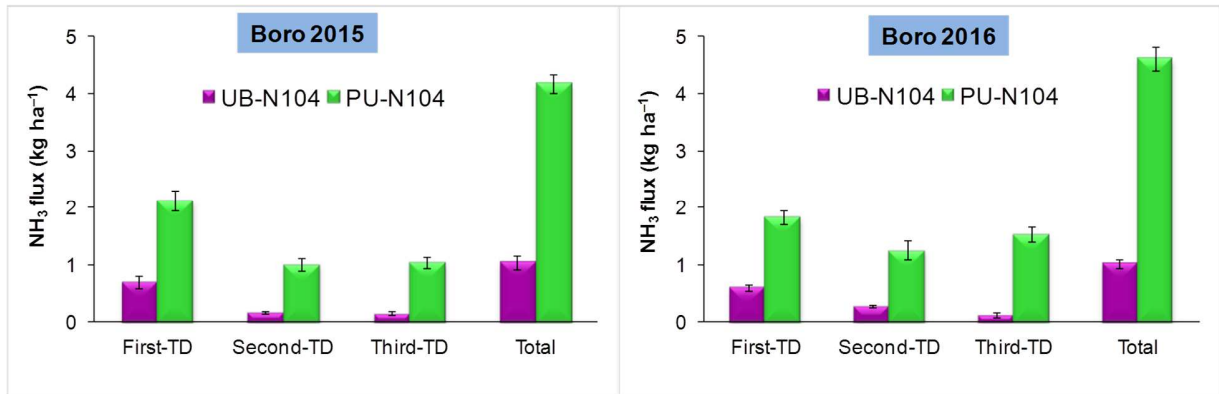
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1 **Fig. 4**



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