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Mitigation of Nitrous Oxide Emissions from Rice–Wheat Cropping Systems with Sub-Surface Application of Nitrogen Fertilizer and Water-Saving Irrigation

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Abstract: Management of nitrogen (N) fertilizer and irrigation can play a critical role to increase nitrogen use efficiency (NUE). However, the impacts of N application at the root zone via urea briquette deep placement (UDP) and water-saving irrigation alternate wetting and drying (AWD) on N_2O emissions are not well-understood. A greenhouse study was conducted to investigate the impacts of UDP on N_2O emissions, NUE, and grain yields of rice and wheat compared with broadcast prilled urea (PU). For rice, the effect of UDP was evaluated under continuous flooding (CF) and AWD, while the control (no N) and PU were tested only under CF. In rice, UDP under CF irrigation produced similar emissions to PU-CF, but UDP under AWD irrigation increased emissions by 4.5-fold compared with UDP under CF. UDP under CF irrigation increased ($p < 0.05$) rice grain yields and N recovery efficiency (RE) by 26% and 124% compared with PU-CF, respectively. In wheat, UDP had no effects ($p > 0.05$) on emissions compared with PU. However, it produced higher wheat grain yields (9%) and RE (35%) over PU. In conclusion, UDP under CF irrigation increases the RE and grain yields of rice without increasing N_2O emissions, but the yield may reduce and N_2O emissions may increase under AWD.

Keywords: greenhouse gas emissions; nitrous oxide; nitrogen recovery efficiency; urea deep placement; rice–wheat systems

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1. Introduction

Agriculture is a major source of nitrous oxide (N_2O) emissions that contribute two-thirds of the current anthropogenic N_2O emissions [1]. These anthropogenic emissions, which are dominated by nitrogenous fertilizer addition to croplands, increased by 30% over the past four decades [2]. N_2O emissions are regulated by multiple environmental and biological factors such as temperature, water and oxygen levels in soils, acidity, and substrate availability. In crop cultivation, the substrate availability, which is linked with N inputs from fertilizers and organic inputs, and N content in soils, affects two biochemical processes, i.e., nitrification and denitrification, where N_2O is produced as a by-product in the nitrification process and as an obligatory product during the denitrification process [3].

The magnitudes and patterns of the emissions are mainly influenced by soil moisture content, oxygen availability, and nitrogen inputs to the soils [4]. Therefore, the mitigation of N_2O emissions requires efficient N fertilizer management systems. In general, applying more N to the soils than the plant demand can increase N losses through different mechanisms, including N_2O emissions, and then reduce nitrogen use efficiency (NUE) [5]. Synchronizing crop N need and supply can be an effective strategy to mitigate N losses to the environment [6]. Better synchrony can be achieved by adopting more efficient N management strategies such as selection of the right source, optimizing the rate, the appropriate application time, and the right placement methods [7,8]. Adopting an efficient placement method, for example, root-zone fertilization or the commonly called urea deep placement

(UDP), into sub-surface soils (mostly anoxic in irrigated rice fields) helps to protect N losses and retain N in the anoxic layer for a longer period by halting the nitrification process. As a result, sub-surface applied N may continuously be utilized by plants as and when needed and increase crop yields, decrease N_2O emissions [9,10], and reduce N losses via surface runoff and ammonia volatilization [11].

In irrigated rice cultivation, fields are maintained continuously flooded through frequent irrigation, which requires a large amount of water. With the increasing water scarcity in most rice-growing countries, there is a need for increasing water use efficiency. Therefore, a water-saving irrigation, alternate wetting and drying (AWD) is developed to save water, which also mitigates greenhouse gas methane emissions from rice farming [12,13]. While adopting AWD irrigation, irrigation is intermittently applied at a certain interval, particularly when soil water drops 10–15 cm below the surface. However, previous studies reported that AWD irrigation may increase N_2O emissions due to increased microbial nitrification and subsequent denitrification [14–17]. In contrast, rice cultivation with continuous flooding (CF) irrigation may emit less N_2O due to a complete denitrification of N_2O to N_2. However, studies on the effects of UDP on N_2O emissions and N use efficiency of irrigated rice, particularly comparing water-saving AWD irrigation with conventional continuous flooding, are still few and the results are not consistent [12,13,18]. Moreover, studies on the impacts of UDP on wheat yield, NUE, and emissions are lacking. Therefore, a greenhouse experiment was conducted to determine the effects of UDP on N_2O emissions, NUE, and grain yields of rice and wheat as affected by different irrigation regimes (rice).

2. Materials and Methods

2.1. Experimental Set-Up

A greenhouse study (temperature and humidity were not controlled) was conducted at the International Fertilizer Development Center (IFDC), Muscle Shoals, AL, USA. The study was designed in wooden boxes (L: 130 cm, W: 40 cm, and H: 28 cm) containing 140 kg of soil (Crowley silt loam, fine, smectitic thermic Typic Albaqualfs) collected from Louisiana, USA (30°25′ N, longitude: 92°23′ W). The soil had 1.78 g kg^{-1} organic matter, pH 6.84, 0.98 g kg^{-1} total N, 17.30 mg kg^{-1} available P, and 11.1 cmolc kg^{-1} available K. The detailed soil properties are presented in [19].

Three N fertilizer treatments were (i) control (N0, 0 kg N ha^{-1}), (ii) broadcast prilled urea, and (iii) UDP. These treatments were arranged in a randomized complete block design with three replications (a total of 12 experimental boxes). N rates in N fertilizer treatments for rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) were 105 and 110 kg N ha^{-1}, respectively. These N application rates were considered optimal for the crop's yield potential. There were two irrigation regimes in rice—continuous flooding and AWD for UDP treatment. The remaining two treatments were tested only under CF. For AWD boxes, irrigation was intermittently applied when the water depth dropped 10–15 cm below the surface, following the safe AWD principle [20]. In wheat, the irrigation regime (as needed, 2–4 L per box at 2–4 days interval) was similar for all the treatments. The soil moisture potential was continuously measured in each box using a moisture sensor (Soil Metric Potential Sensor, Model 253-L, Watermark 200, Campbell Scientific, Inc., Logan, UT, USA). Sensors for moisture and soil temperatures were horizontally placed in 5–7 cm depth.

The rate of nitrogen fertilizer in experimental boxes was applied as per treatment. For PU treatment, urea was applied through the broadcast method, the first with split application (50% of N) at 7 days after the transplanting of rice seedlings and the second with 50% at the maximum tillering stage. For UDP, prilled urea was physically compressed to make briquettes of 2.35 g. Then the briquettes were deep-placed at 7 cm and properly covered by soils. A total of five briquettes were deep-placed in each box at a 20 cm distance between two rows of rice seven days after transplanting. All other agronomic practices were similar in all treatments.

After harvesting the rice, wheat was planted following the same treatment and experimental design. Wheat seeds were sown (22 November 2013) in a line at 20 cm × 10 cm spacing, which accommodated 12 plants in a row and 24 plants in each box. Urea (PU) was applied by broadcasting in two splits: 50% of N was applied two weeks and another 50% two months after seeding. UDP was placed in 7 cm below the soil surface following a similar practice as in rice two weeks after the seeding. Details of field preparation, transplanting of rice, and crop management for rice and wheat are described elsewhere [19].

After harvesting the wheat on 18 June 2014, soil samples (0–15 cm) were collected from each box and analyzed for mineral N (ammonium and NO_3^-–N) and soil pH. Soil samples were separately collected from inside and outside the GHG chambers. Analysis for mineral N and pH was performed following a standard protocol.

2.2. Grain Yield, N Uptake, and Nitrogen Use Efficiency

Crops were harvested at physiological maturity and then threshed and cleaned, and the grain moisture content was determined. The grain yield was corrected to 14% moisture content. The nitrogen contents of grain and straw samples were analyzed to determine the total N uptake and NUE by plants. The different components of NUE were calculated using the following formulas.

- Agronomic efficiency of N (AEN) = (GYN − GY0)/(FN − FN0), kg grain yield increase per kg N applied
- Recovery efficiency of N (RE) = (UNN − UN0)/(FN − FN0), kg N uptake per kg N applied

where GYN = total grain yield when N applied, FN = total N fertilizer applied, FN0 = control, without N, GY0 = total grain yield without N application, UNN = total N uptake in N application treatment, and UN0 = total N uptake without N application treatment.

2.3. Gas Sampling and Measurement of N_2O Emissions

Gas samples were collected using an automated closed-chamber technique and then analyzed to determine N_2O emissions. The measurements were conducted for two cropping seasons (rice–wheat) from March 2013 to June 2014. Gas sampling for N_2O measurement was performed using an automated continuous measurement system as described earlier [21]. A closed chamber with a head space volume of 0.0578 m^3 (118.8 cm $\times$ 12.5 cm $\times$ 31.2 cm; 57.8 L) was installed in each box between two rows of crops. For each gas sampling time, a chamber was closed for 40 min, and six gas samples were collected at 8 min intervals (0, 8, 16, 24, 32, and 40 min). Gas sampling was repeated from the same chambers (boxes) every three hours, resulting in an estimate of eight fluxes per day.

The mixing ratio of N_2O was determined using a T320U Gas Filter Correlation Analyzer (Teledyne Advanced Pollution Instrumentation, API, San Diego, CA, USA), which uses an infrared radiation (IR) absorption principle. T320U can analyze N_2O concentration up to 200 ppm, with a lower detection limit of <10 ppb. The minimum detection limit of the flux was 10 μg m^2 h^{-1} based on the chamber volume, area, and closure time. The analyzer was checked with N_2O standard gas every week and calibrated.

Emission rates of N_2O were estimated using the linear regression of the gas mixing ratio against the chamber closure time. The linear regression curve gives the slope, i.e., ppb min^{-1}, which is converted to emission rate as mg N_2O–N h^{-1} using the ideal gas law [21]. As gas sampling was performed at a three-hour interval, the emission rate between two measured points was calculated through the linear interpolation of two emission rates. Hourly emission rates were summed up to obtain the daily emission rate, then the daily emission rates were summed up to obtain the seasonal total emissions (g N_2O–N). Cumulative emissions were then expressed as CO_2 equivalent emission using the global warming potential (GWP) value of N_2O [22]. Yield-scaled emission was measured by dividing cumulative emissions by grain yields and was expressed as g N_2O–N per ton of yield.

After estimating the seasonal total emissions, the direct emission factor (% of applied N lost as N_2O emissions) was determined as follows:

$$EFd\ (\%) = [N_2O(tr) - N_2O(cr)] \times 100/N\ Rate(tr)$$

where N_2O(cr) and N_2O(tr) are the seasonal total N_2O emissions (kg N ha^{-1}) from control and N applied box, respectively, and N Rate(tr) is the N applied (kg N ha^{-1}) to treatment t.

2.4. Data Analysis

The analysis of variance (ANOVA) for grain yield, NUE, cumulative emissions, emission factor, and global warming potential was conducted with SAS 9.3 using generalized linear mixed models. Before performing the ANOVA, the data were tested for normality and homogeneity of variance, and they were found normally distributed. A post hoc analysis for significant response variables was carried out for mean grouping with the least significant difference (LSD) test at a 5% probability level.

3. Results

3.1. Soil Moisture and Temperature

Temperatures (air and soil) in both rice- and wheat-growing periods ranged from 12 to 29 °C. The details of soil and air temperatures are presented in Figure 1.

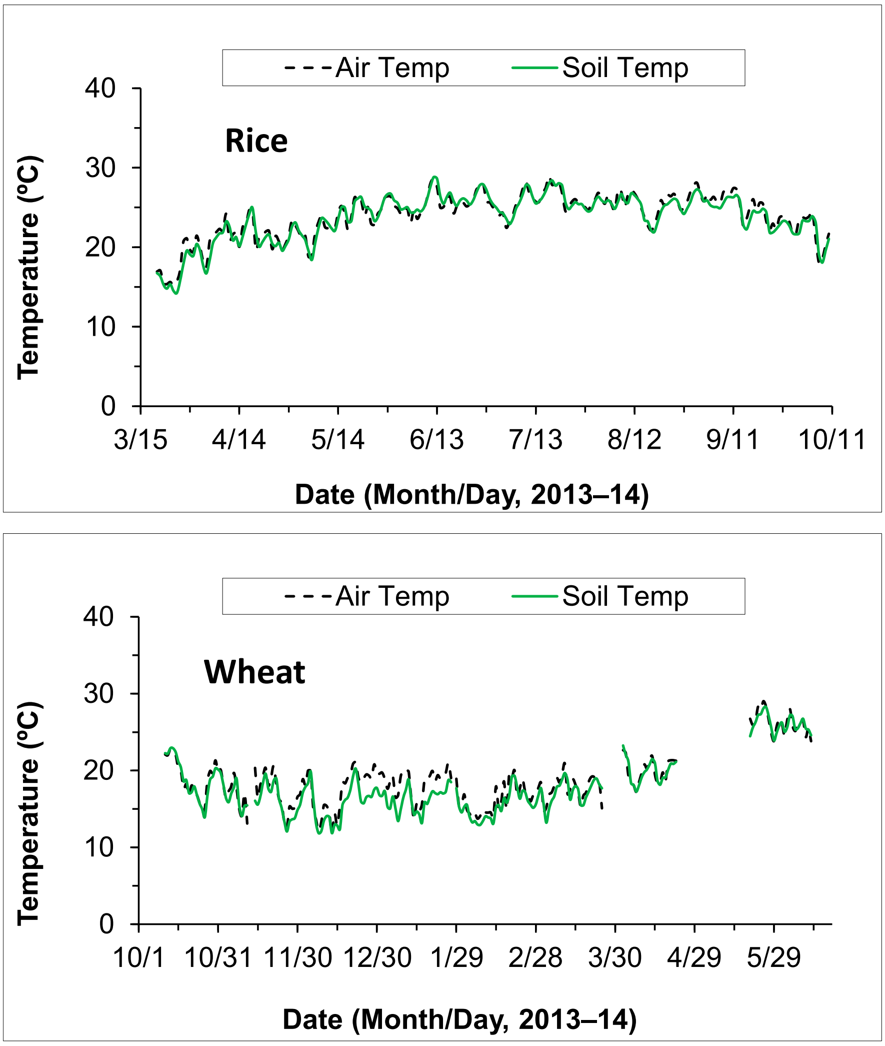

Figure 1. Daily average of air and soil temperatures during rice- and wheat-growing season [19].

Soil moisture potential in all experimental boxes during the rice-growing season (except under the AWD treatment) remained within ±10 kPa, while it dropped to −90 kPa during the drying episodes of AWD (Figure 2). There were 14 drying episodes in AWD boxes. During the wheat-growing season, all boxes were dry, and the soil moisture potential ranged from −40 to −200 kPa throughout the season (Figure 3). Boxes were much drier (~−200 kPa) during the plants' reproductive stage compared with the vegetative stage (~100 kPa).

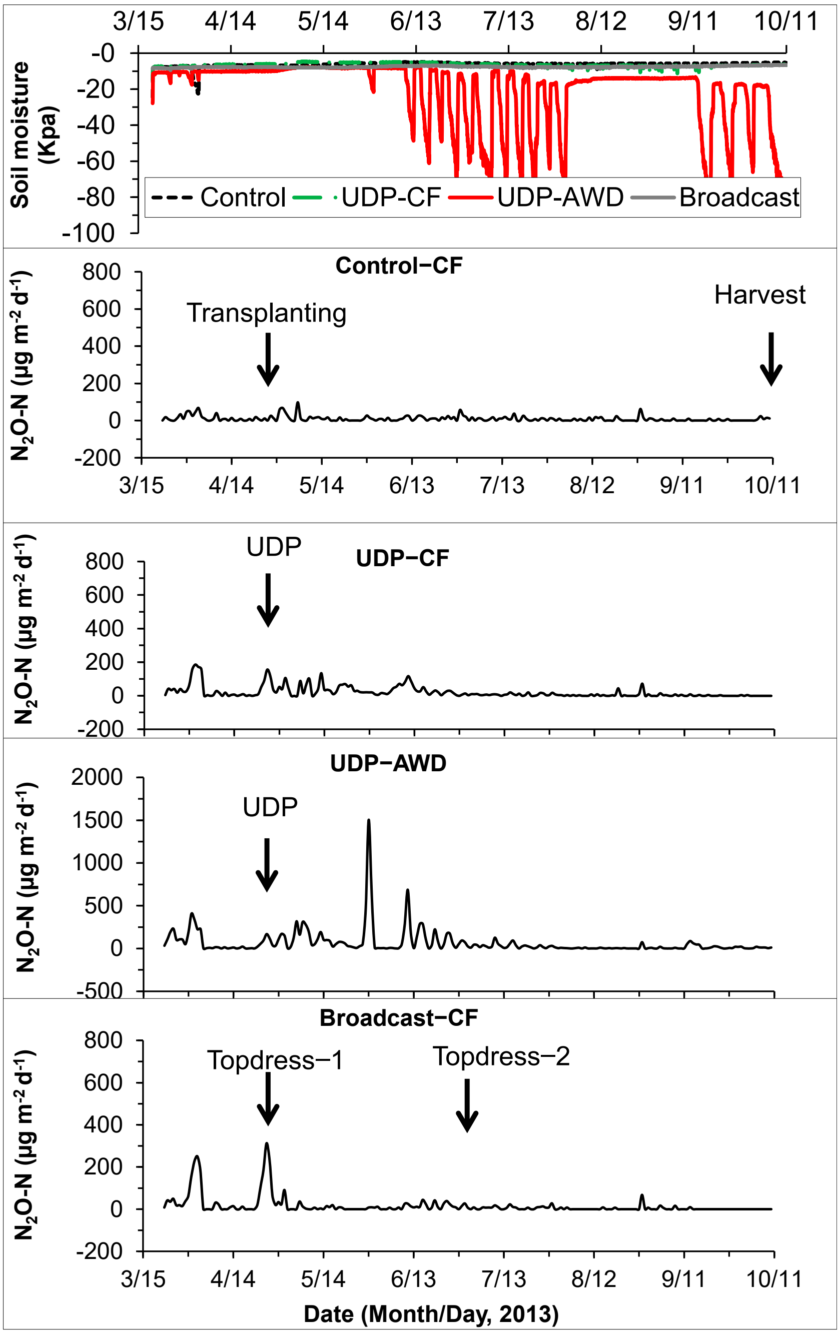

Figure 2. Seasonal variations of N_2O fluxes and soil moisture content under different fertilizer treatments during rice-growing season. UDP, CF, and AWD represent urea deep placement, continuous flooding, and alternate wetting and drying, respectively (*n* = 3).

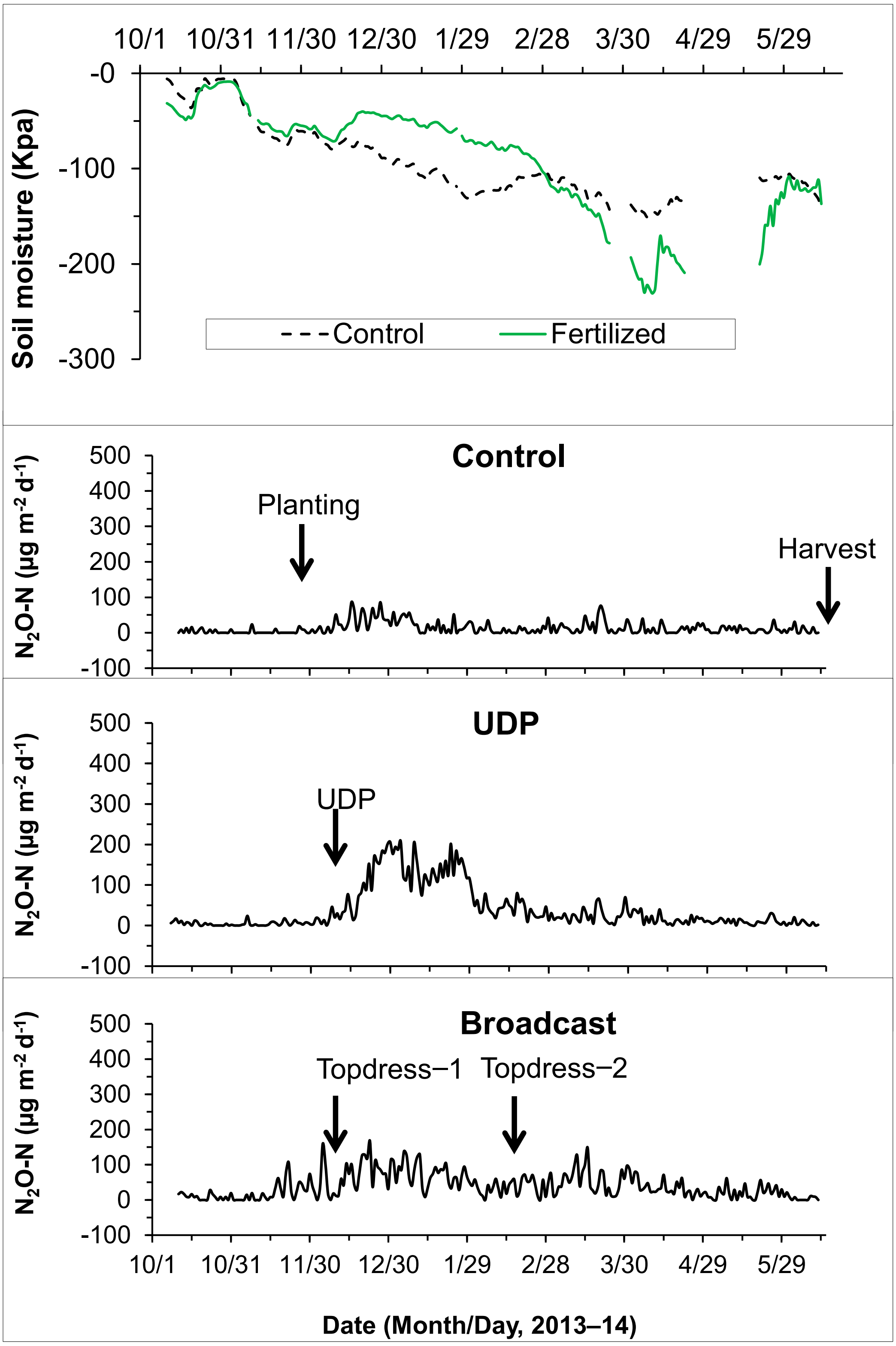

Figure 3. Seasonal variations of N_2O fluxes under different fertilizer treatments and soil moisture content during wheat-growing season. UDP represents urea deep placement (n = 3).

3.2. Effects on Inorganic Soil Nitrogen (NH_4 and NO_3)

The fertilizer placement affected ($p < 0.05$) the NH_4^+ and NO_3^- content in the soils after two continuous cropping seasons (Table 1). The UDP treatment produced significantly higher NH_4^+–N compared with broadcast urea inside the chamber, while the amount was higher in PU than UDP outside the chamber. Due to this variability, the average residual NH_4^+–N, which includes inside and outside the chamber, was not statistically different between PU and UDP. The average NO_3^-–N content was significantly lower in UDP than PU. In the PU treatment, the higher inorganic N (ammonium and nitrate) content observed outside the chamber reflects uniform N application throughout the box. Soil pH was not different between treatments or locations, i.e., inside and outside the chambers. Likewise, the higher soil NH_4^+–N content inside the chamber with UDP is attributed to the deep placement of N, which occurred only inside the chamber. Moreover, as expected, the outside soil N content was similar to the control (Table 1).

Table 1. Soil ammonium (NH_4^+–N), nitrate (NO_3^-–N), and pH at different positions of experimental pots (inside and outside of the chamber) after two continuous cropping seasons (rice–wheat). Means (± standard error) within a column followed by same letters are not significantly different by LSD at 0.05 level.

Treatments	NH_4^+–N (mg/kg Dry Soil)			NO_3^-–N (mg/kg Dry Soil)			pH		
	Inside	Outside	Average	Inside	Outside	Average	Inside	Outside	Average
Control	3.67 ± 0.06 b	4.01 ± 0.16 b	3.84 ± 0.05 b	1.67 ± 0.18 b	1.40 ± 0.14 b	1.54 ± 0.14 b	6.56 ± 0.12 a	6.47 ± 0.06 a	6.50 ± 0.04 a
UDP	6.76 ± 0.65 a	4.21 ± 0.16 b	5.49 ± 0.36 a	1.64 ± 0.52 b	1.24 ± 0.24 b	1.44 ± 0.37 b	6.73 ± 0.13 a	6.41 ± 0.07 a	6.51 ± 0.08 a
Broadcast	4.78 ± 0.46 b	5.05 ± 0.36 a	4.91 ± 0.39 a	3.24 ± 0.59 a	2.24 ± 0.42 a	2.74 ± 0.50 a	6.44 ± 0.17 a	6.35 ± 0.06 a	6.38 ± 0.03 a

3.3. *Temporal Variations in N_2O Fluxes*

Overall N_2O emission showed high temporal variations. In rice, N_2O emissions were stimulated, and some peaks appeared when soil was irrigated on March 19 before rice transplanting (Figure 2). Both N fertilizer application and AWD affected emissions. The UDP-AWD treatment produced more prominent emission peaks, particularly when the plots were dry, while the peaks were negligible in the UDP-CF and broadcast treatments.

The N_2O emission peaks showed a consistent trend during the wheat-growing season (Figure 3). These emissions were sustained for almost two months (Dec–Jan) with emission peaks of up to 260 μg m^{-2} d^{-1} in the UDP treatment. In broadcast urea, emission peaks appeared after each irrigation and topdressing of urea and reached up to 167 μg m^{-2} d^{-1}.

3.4. *Seasonal Total N_2O Emissions and Emission Factor (EF)*

In rice, fertilizer placement had significant effects on the seasonal total emissions (Table 2). Deep-placed urea under AWD irrigation increased N_2O emissions by 4.6-fold compared with UDP under CF irrigation. In contrast, under CF irrigation, deep-placed urea produced emissions similar to those of broadcast urea. The seasonal total emissions ranged from 14.9 to 85.3 g N ha^{-1} during the rice-growing season. In wheat, the seasonal total emissions ranged from 30.5 g N ha^{-1} to 91.0 g N ha^{-1}, and fertilizer placement had no significant effects on emissions. Although the application of N fertilizer either as PU or UDP increased N_2O emissions by 134% to 198% relative to the control, this increase was not significant ($p > 0.05$). The effects on GWP of N_2O (CO_2 eq. emissions) followed the same pattern as the cumulative emissions.

The UDP-AWD treatment (rice) had higher emission intensity (7. 67 g N t^{-1} grain) compared with that of the broadcast and UDP-CF treatments (<3 g N t^{-1}), but this effect was statistically similar ($p > 0.05$). Similarly, fertilizer application methods had no significant ($p > 0.05$) effects on emission intensity in wheat.

In rice, the emission factor (EF) for UDP-AWD (0.0656%) was higher ($p < 0.05$) than that for broadcast urea and UDP-CF treatments. As with cumulative emissions, the EF of UDP-CF was similar to that for the broadcast urea treatment. In wheat, fertilizer placement had no significant effect on the EF. Nevertheless, fertilizer-induced EF was very low (<0.06%) in both rice and wheat, ranging from 0.0011% to 0.0656% in rice and 0.051% to 0.055% in wheat.

Table 2. Seasonal cumulative emissions of N_2O (g N ha^{-1}), global warning potential (CO_2 eq), yield-scaled emissions, and direct emission factors of N_2O (EF-N_2O–N, %) in control, urea deep placement (UDP), and broadcast urea (*n* = 3).

Crop	N Treatments	N_2O Emissions			EF N_2O–N
		g N ha^{-1}	kg CO_2 eq. ha^{-1}	g N t^{-1} grain	%, *w*/*w*
Rice	Control-CF	13.90 b	6.38 b	2.51	-
	UDP-CF	15.33 b	6.38 b	1.67	0.0011 b
	UDP-AWD	85.28 a	35.51 a	7.67	0.0657 a
	Broadcast-CF	14.93 b	6.22 b	2.11	0.0008 b
ANOVA (Pr > F)		0.0037	0.0037	0.0844	0.0183
Wheat	Control	30.50	12.70	33.28	-
	UDP	71.40	29.73	24.40	0.0510
	Broadcast	91.00	37.89	32.88	0.0550
ANOVA (Pr > F)		0.7673	0.7673	0.8864	0.6704

Within a column, means followed by identical letters are not significantly different by LSD at the 0.05 level; CF, continuous flooding; AWD = alternate wetting and drying.

3.5. Effects on Grain Yields and Nitrogen Use Efficiency (NUE)

N fertilization—regardless of the application method—increased yields for both rice (except in UDP-AWD) and wheat compared with the control. UDP-CF increased grain yields by 26% compared with PU-CF, while UDP-AWD had similar yield with PU-CF and control-CF (Table 3). In wheat, UDP produced higher yields (9%) than PU, but this difference was not significant ($p > 0.05$). Deep placement significantly increased the total N uptake and NUE (RE) in both rice (under CF) and wheat compared with the broadcast application of urea. UDP increased NUE (RE) by up to 53% in wheat and up to 80% in rice compared with 36% and 40%, respectively, in the case of PU. However, agronomic efficiency (AE) was not affected by fertilizer treatments in either rice or wheat.

Table 3. Grain yields, aboveground nitrogen uptake, and nitrogen use efficiency across different treatments in rice and wheat (*n* = 3).

Crop	N Treatments	Grain Yields kg ha^{-1}	N Uptake kg N ha^{-1}	AE kg grain kg^{-1} N	RE %, *w*/*w*
Rice	Control-CF	5614 c	161 bc	-	-
	UDP-CF	9224 a	245 a	34.38 a	79.86 a
	UDP-AWD	6963 bc	239 ab	15.42 a	75.26 a
	Broadcast-CF	7311 b	199 bc	16.16 a	35.66 b
ANOVA (Pr > F)		0.0039	0.0002	0.0695	0.0128
Wheat	Control	897 b	22 c	-	-
	UDP	2956 a	82 a	18.72 a	53.37 a
	Broadcast	2706 a	66 b	16.45 a	39.58 b
ANOVA (Pr > F)		0.0001	0.0000	0.2315	0.0046

Within a column, means followed by same letters are not significantly different by LSD at the 0.05 level. AE, agronomic efficiency; RE, recovery efficiency; UDP, urea deep placement; CF, continuous flooding; AWD, alternate wetting and drying.

4. Discussion

Mitigation of nitrous oxide emissions from crop cultivation can be performed by increasing use efficiencies of N fertilizer and water regimes. Increasing NUE not only reduces N losses to the environment but also increases plant uptake and yields. NUE can be increased by synchronizing the N supply with the plant demand, which can be carried out by adopting the 4R's of the nutrient stewardship approach (right source, right rate, right time, and right placement). An effective approach to increasing NUE is sub-surface application or applying fertilizer in the plant's root zone [23]. This increases NUE by increasing the plant N uptake and reduces N losses compared with broadcast application [8,10]. However, the effectiveness of deep placement varies with crops; it is more effective in irrigated lowland rice fields [24] than in other cereal crops [25]. When rice is cultivated with CF irrigation, the deep-placed urea remains in an anaerobic soil layer as NH_4^+–N, and only a negligible amount of N moved into the soil surface compared with PU [10,26]. Due to the absence of oxygen, there is no nitrification and subsequent denitrification. Therefore, deep placement minimized N losses through ammonia emissions, surface run-off, and nitrification and denitrification including N_2O emission reductions [9,10]. Deep placement ensures a continuous N supply that is synchronized with the plant demand. In contrast, the broadcast applied urea immediately dissolves in floodwater. Then the inorganic N on the soil's surface and in floodwater can easily be lost to the environment through ammonia volatilization and nitrification/denitrification with emissions of N_2O and NO [9].

Our results suggest that the impacts of UDP vary with water regimes and crops (Table 2). UDP with CF irrigation had similar emissions as broadcast urea. The reduction of emissions under CF irrigation has already been explained—it increases plant uptake by reducing N losses [11,27]. In contrast, there were increased emissions with UDP-AWD irrigation compared with UDP-CF, which is likely associated with increased nitrification–denitrification caused by the intermittent wetting and drying of soils (Figure 1) resulting in a large emission peak (Figure 2), and a higher cumulative emission than PU and UDP with CF irrigation. As discussed earlier, UDP retains more NH_4^+–N in soils [26], which can be nitrified during the dry period due to increased oxygen supply, and thus higher N_2O emissions. These results confirm that intermittent soil drying and wetting favors both nitrification and denitrification, resulting in greater N_2O emission peaks and cumulative emissions as observed in previous studies [13,16,28,29].

Similarly, in the wheat-growing season, the emissions from the UDP treatment were comparable with the emissions from UDP-AWD in rice (Table 2). Although the application of N fertilizer (either by UDP or broadcast) produced emissions two times higher than the control, this difference was not significant due to large variations among the replicates. Large variability in N_2O emissions occurs at different spatial scales, including across sites, between and within fields, and within a pot in a field; this is due to variations in soils, organic carbon, microbial activities, and the content of soil water and inorganic N, which directly affect N_2O emissions [30,31]. Variations across replications can be expected more in an upland crop (wheat in this study) compared with rice fields, as continuous flooding creates a homogenous environment in the soils. Despite the uniform distribution of soils within a box, the large variability can be explained by the multitude of factors influencing the process of nitrification–denitrification.

In wheat, similar emissions between UDP and broadcast urea can be due to higher emissions from broadcast application compared with the rice season. These results suggest that upland soils emit more N_2O emissions compared with lowland irrigated soils, regardless of what placement method is used [32,33]. Since all boxes were irrigated to maintain the optimum moisture, fertilized boxes had higher emissions due to continuous substrate availability (NH_4) for nitrification, while UDP retains more N in the sub-surface soils [26], which can be subjected to nitrification and produce higher N_2O emissions. Prilled urea was applied in two equal splits through the broadcast method when soil moisture was at an optimum condition, which facilitated nitrification and was sustained for about two months (December–February) resulting in similar emissions with UDP (Table 2).

The magnitude of the total seasonal emissions was relatively low in both the rice- and wheat-growing seasons, ranging from 15 g N ha^{-1} $season^{-1}$ to 91 g N ha^{-1} $season^{-1}$. Although the fertilizer-induced EF of UDP-AWD in rice was significantly higher than that of UDP-CF and broadcast urea, the total seasonal loss of N through N_2O emissions was relatively low (<0.06% of applied N). On the other hand, in wheat, fertilizer placement had no significant effect on EFs, which ranged from 0.05% to 0.06% of the applied N. These results are supported by previous studies [9]. However, the magnitude of emissions in our study is much lower compared with the default Tier I emission factor of 1% of the applied N [34] and 1.7–2.5% reported from Indo-Gangetic Plains [35]. While emissions from upland crops and rice with AWD irrigation depend on the irrigation regime and moisture content, N_2O emissions can further be mitigated by adopting customized recommended N rates for new products and practices that increase NUE. For example, increasing the depth of N placement from 7–10 cm to 15 cm in wheat [32] and adjusting the water regime (to maintain soil saturation) in rice can be an effective N_2O mitigation strategy.

UDP with CF irrigation increased rice yields and NUE (RE) compared with the conventional urea application method (broadcast). Increased rice yields and NUE with UDP are already well-documented [10,24]. Generally, UDP increases rice yields by 15–20% and saves urea by 25–50% compared with the broadcast application of PU. However, in contrast with previous studies [10,24], UDP had no yield benefits under AWD irrigation. The effects of AWD on grain yields depend on the soil type and intensity and duration of soil drying. Under field conditions with safe AWD irrigation, i.e., applying irrigation when the surface water reaches 10–15 cm below the surface [20], UDP can be equally effective under both CF and AWD irrigation regimes to increase grain yields and NUE [11]. In wheat, although UDP increased grain yields and NUE, the magnitudes of the increase were relatively low when compared with rice. This might be related to the irrigation regime (or moisture content). Generally, as discussed earlier, the effectiveness of UDP in increasing yields and NUE in upland crops is relatively lower than that of lowland rice. In this study, N rates for UDP and broadcast urea were the same; the general recommendation is to apply UDP at lower rates [36] as it increases grain yields and NUE by reducing N losses to the environment [9,10,37]; thus, it can be considered a Climate-Smart fertilizer management practice.

5. Conclusions

This study suggests that the mitigation of nitrous oxide (N_2O) emissions with urea deep placement (UDP) varies with crop and irrigation regime. In rice, UDP with alternate wetting and drying (AWD) irrigation can increase N_2O emissions compared with UDP or PU with continuous flooding (CF). In wheat, N_2O emissions were not affected by N fertilizer application methods. However, irrigated upland crops (e.g., wheat) can emit more N_2O compared with irrigated rice fields, regardless of N placement. This was evident from the similar N_2O emissions in UDP-AWD in rice and UDP in wheat. Nevertheless, the N loss was very minimum (<1% of applied nitrogen) from an agronomic perspective, as losses from other mechanisms may reach up to 50% of applied N. In addition to reducing N_2O emissions, UDP under CF irrigation can increase rice grain yields compared with PU and nitrogen recovery compared with broadcast PU. Thus, UDP, if applied with CF irrigation, can be effective in achieving multiple benefits of the Climate-Smart agriculture—increased yield, nitrogen use efficiency, and reduced GHG emissions from rice—but may increase emissions and reduce yields under water-saving irrigation. More studies with varying intensities of soil drying and fertilizer application are needed across different agroecological regions and soil types to determine the effects on total GHG emissions, fertilizer use efficiency, and change in soil fertility.

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