Quantifying nitric oxide emissions under rice-wheat cropping systems

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Abstract

Urea deep placement (UDP) increases nitrogen use efficiency (NUE) and crop yields while reducing nitrogen (N) losses to the environment. However, studies on its environmental impacts on nitric oxide (NO) emissions are still limited. Therefore, we conducted a greenhouse experiment to quantify the NO emissions from a rice-wheat system. NO emissions were measured from three N fertilizer treatments – control (no N), UDP, and broadcast prilled urea (PU) – using an automated gas sampling and analysis system continuously for a rice-wheat cropping cycle. In rice, UDP was tested under two water regimes – continuous flooding (CF) and alternate wetting and drying (AWD). Fertilizer treatments had significant effects ($p<0.05$) on NO emissions. UDP with AWD irrigation increased NO emissions (3.41g N ha^{-1}) ($p<0.05$) by 2.5-times compared to UDP with CF (1.35g N ha^{-1}). But emissions were similar between UDP and broadcast PU under the CF water regime. In wheat, the application of N fertilizer – regardless of application methods – increased NO emissions (615g N ha^{-1}, average across application methods) by 10-times over control (62.52 g N ha^{-1}). However, emissions were not significantly ($P>0.05$) different among the treatments. Fertilizer induced emission factors (EFs) were not affected by N placement methods in either rice or wheat. On average, EFs in the rice were very low (<0.002%) compared to the wheat (0.5%). This study reveals that (regardless of treatments), the contribution of rice (<4 g N ha^{-1}) on total annual NO emissions (433 g N ha^{-1}) was very small (<0.5%) compared to emissions from wheat.

Key words: nitric oxide emissions, nitrogen use efficiency, fertilizer deep placement, rice-wheat system

Capsule: Contribution of rice cultivation on annual nitric oxide emissions is negligible compared to wheat, and N fertilizer placement in wheat had no significant effects on emissions.

1. Introduction

Nitric oxide (NO), an environmental pollutant, is highly reactive in the atmosphere. It participates in photochemical reactions in the troposphere that produce ozone (Davidson et al., 2000). NO, by its oxidation products, also contributes to the formation of acid rain. The major sources of NO in the atmosphere are fossil fuel combustion, biomass burning, lightning and emissions by soil microbes (Pilegaard, 2015). Since NO is both produced and consumed in soils during the microbial processes of nitrification and denitrification (Firestone and Davidson, 1989; Davidson et al., 2000), agricultural soils are an important source of NO, among others.

In nitrification, ammonium is oxidized via nitrite (NO_2^-) to nitrate (NO_3^-), and NO is produced during the first step. The primary regulating factors of nitrification are ammonium content (NH_4^+-N) and oxygen (O_2) supplies in the soils. During nitrification, NO emissions appear at a low soil water-filled pore space (WFPS) of around 25% (Bouwman et al., 2002). On the other hand, denitrification is the stepwise reduction of NO_3^- to nitrogen (N_2) in the absence of O_2. The NO is the obligate product of the denitrification process. The most important regulating factors for denitrification in the soils are carbon, inorganic nitrogen (N) and O_2 concentration. The degree of soil aeration and O_2 content determines whether nitrification or denitrification prevails in the soils. Therefore, crop management practices – mainly N fertilization and irrigation management practices – influence patterns and magnitudes of NO emissions by affecting N availability, soil moisture content and O_2 status. In addition, NO emissions are also affected by N and organic matter content in the soils, soil pH and temperature (Pilegaard, 2015). Due to the complex interactions among these factors, large temporal and spatial variations of NO emissions are usually observed in cropland soils. Nevertheless, most of the previous studies demonstrated that nitrification is the dominant process for NO production in a soil (Laville et al., 2011).

The NO emissions from agricultural soils have been studied in numerous experiments both in the field and in the laboratory, often together with nitrous oxide (N_2O). Reported measurement results show large spatial and temporal variations, probably due to differences in environment, crops and management (Cui et al., 2012; Yan et al., 2015). Spatial variability not only exists across sites and climates but also within a field with similar crop management and agro-climate. Previous studies reported coefficient of variations of up to 200% (Laville et al., 2011; Medinets et al., 2016). Therefore, quantification of annual NO emissions from agricultural soils remains a major challenge, and they are estimated with high uncertainty. Moreover, the differences in measurement methodology are also responsible for the large variations on reported emissions. For example, extrapolation of the results of the discrete measurements done at weekly or biweekly intervals may either over or underestimate total emissions compared to the results of continuous measurements. Fluxes estimated from the continuous measurements are more reliable because it includes all the temporal variations (Medinets et al., 2016; Recio et al., 2019). Therefore, more intensive measurements are needed to get season, site- and crop-specific emission factors.

As N availability is one of the major drivers of nitrification and denitrification, together with soil moisture content, its sources, amount, method and time of application may affect NO emissions from soils (Liu et al., 2016). Though N fertilizers are critical for crop production, its use is associated with environmental pollution, including greenhouse gas (GHG) emissions. This is because more than 50% of applied N is not utilized by crops and is lost to the environment (Ladha et al., 2005) through different mechanisms, including ammonia (NH_3) volatilization and

N_2O and NO emissions (Rochette et al., 2013; Gaihre et al., 2015). These losses increase with increasing N rate following a non-linear exponential trend, particularly when availability of inorganic N exceeds crop N demand (Zhao et al., 2015). Similarly, methods of application have significant effects on emissions. Generally, incorporating N fertilizers into sub-surface soils and/or placing it in concentrated bands instead of traditional broadcast application in the soil surface are considered a sustainable fertilizer management practice, as it reduces N losses and increases crop yields. It is reported that deep placement of urea (granular or briquetted), commonly called urea deep placement (UDP) reduces N losses up to 35% and increases rice yield up to 20% compared to conventional broadcast application (Savant and Stangel, 1990; Huda et al., 2016, Miah et al., 2016). Therefore, UDP increases N use efficiency (NUE) by minimizing N losses from surface runoff and NH_3 volatilization as the applied N (ammonium) is protected from nitrification/denitrification in anaerobic soil layers.

In addition to N fertilizer management, water management plays a significant role in NO emissions from crop fields (Cui et al., 2012). For example, rice cultivation under continuously flooded conditions emits less NO due to a reduction of NO to N_2 during denitrification. In contrast, alternate wetting and drying (AWD) irrigation (keeping fields dry for some time until the next irrigation) triggers considerable NO emissions (Cui et al., 2012). This is because intermittent soil drying and wetting enhances the transport of gases in the deeper soil layer, which may affect NO emissions directly due to increased nitrification (Pilegaard, 2015; Medinets et al., 2015). Therefore, the adoption of AWD irrigation, with the addition of N fertilizer, either as broadcast or deep placement, may increase NO emissions due to an increased conversion of soil NH_4^+ to NO_3^- through nitrification and subsequent denitrification of NO_3^-. However, studies on the effects of UDP on NO emissions are still few, particularly in flooded rice fields under different irrigation regimes. Few studies from rice and wheat cultivation show variable results (Cui et al., 2012; Huang and Li, 2014). Therefore, this study was conducted to quantify the NO emissions from two crop-growing periods (rice-wheat) using an automated closed chamber technique with the following specific objectives:

- To quantify NO emissions from rice-wheat systems under different N-fertilizer placement methods and water regimes.
- To determine the influence of nitrogen fertilizer placement methods on the dynamics of NO emissions.
- To compare total seasonal N loss as NO emissions between broadcast urea and UDP.

2. Materials and Methods

2.1. Experimental design and treatments

The pot experiments were conducted in a greenhouse at International Fertilizer Development Center (IFDC), Muscle Shoals, Alabama, USA, from March 2013 to June 2014. The following treatments were tested for both rice and wheat:

- Control (N0): 0 kg N ha^{-1}
- Broadcast PU: Urea was broadcast applied at 105 and 110 kg N ha^{-1} for rice and wheat, respectively, at 2-3 equal splits.
- UDP: Urea briquettes were deep-placed as a single application between two rows of plants at 20 cm distance.

For rice, there were two UDP treatments, one under continuous flooding (UDP-CF) and another under alternate wetting and drying irrigation (UDP-AWD). The AWD plots were irrigated when water depth reached 15 cm below the soil surface. Though we continued two UDP treatments (UDP-CF and UDP-AWD) for wheat, irrigation management was similar for all treatments. These four treatment combinations were arranged in a randomized complete block design with three replications. The treatment randomization done for rice was continued for wheat.

2.2. Handling of plants and soils

Twelve wooden experimental plots (length: 130 cm, breadth: 40 cm and height: 28 cm) were filled up with 140 kg of soil. The soil (Crowley silt loam, fine, smectitic thermic Typic Albaqualfs) was collected from Louisiana, USA (Soil Survey Staff, 2014) (latitude: 30°25’25.5288” N, longitude: 92°23’7.1916” W) (Table 1). For rice cultivation, the soil was puddled thoroughly, and triple superphosphate (0-46-0) for phosphorus (P) and muriate of potash (0-0-60) for potassium (K) were applied as basal application one day before the transplanting of rice seedlings. Sensors for temperature and water potential and aluminum base for the GHG chamber were installed after basal fertilization (described later). Rice seedlings (*Oryza sativa* L. cv. Pusa) (25 days old) were transplanted at 20 x 20 cm in each plot on 26 April 2013.The N fertilizers were applied at 105 kg ha^{-1}. Urea was broadcast applied in two equal splits, one week after transplanting and at maximum tillering stage. For UDP, urea briquettes of 2.35 g were deep-placed (7 cm) as a single application at 20 cm distance between two rows of rice (5 briquettes per plot) seven days after transplanting.

The experimental plots (except AWD plots) were maintained continuously flooded until one week before harvesting the rice plants. Plots under AWD conditions were irrigated following safe AWD principles. To monitor floodwater depth in AWD plots, a 25 cm long, 10 cm diameter PVC pipe, perforated up to 15 cm, was inserted 15 cm into the soil, perforated side down, leaving 10 cm above the ground. Soils inside the pipe were removed to make a hole up to 15 cm. Water depth inside the PVC pipes was monitored every day after transplanting, and plots were irrigated when water depth in AWD pipes were 12-15 cm below the soil surface.

2.3. Measurement of NO emissions

NO emissions were measured continuously with fully automated gas sampling and analysis systems from March 2013 to June 2014, covering two cropping seasons (rice-wheat). Measurements for each treatment were done from three replicate chambers. Twelve Plexiglass chambers were installed over an aluminum base before rice transplanting. A detail of the chamber's installation, gas sampling and analysis system has already been described (Gaihre et al. 2015, 2017). In brief, the automated GHG measurement system consisted of four components: (i) automated gas chambers with compressed air-driven lids, (ii) an automated gas sampling unit, (iii) an online gas analysis system and (iv) an opening/closing control and a data-logging unit. Twelve Plexiglass chambers (118.8 cm x 12.5 cm x 31.2 cm length, breadth and height, respectively) were fixed on aluminum bases. Each chamber was installed in a plot between two rows of rice that covered a surface area of 0.148 m^2 and headspace volume of 0.0578 m^3 (57.8 L). Each chamber was equipped with a DC fan for mixing air during gas sampling and sensors for air temperature and water potential. Moreover, four soil temperature sensors were installed at 5 cm depth for four plots.

Each chamber was connected to a gas analyzer (described later) to obtain on-site measurements of NO. Air samples from each chamber were taken six times at eight-minute (min) intervals (0, 8, 16, 24, 32 and 40 min) which resulted in a chamber closing time of 40 min. Each chamber was sampled every three hours, which allowed calculations of eight fluxes per day. There were three sets of four chambers, one set equaling one replication, and four chambers were sampled in a one-hour cycle. The three-hour sequence consisted of three, one-hour sequences that were identical, except the first hour applied to chambers 1-4 (Rep 1), the second hour applied to chambers 5-8 (Rep 2) and the third hour applied to chambers 9-12 (Rep 3).

Air samples collected from the chambers were passed to the analyzers using a Teflon tube with ¼ inch diameter via a 13-port sample manifold (equipped with solenoid valve, i.e., KIP valves). Out of 13 valves in a sample manifold, 12 were used for air samples that came from the respective 12 chambers. The last one was used for the calibration gases (i.e., connected to calibrator). Each sample valve in the manifold was controlled by a datalogger (Campbell Scientific, CR3000) via a 16-port (channel) relay controller (SDMCD16 AC/DC Relay Controller). Air samples were filtered and dried before passing to the respective analyzers.

The NO concentration of the air sample was measured by a Teledyne API (Advanced Pollution Instrumentation, USA) T200 Nitrogen Oxide analyzer. The T200 uses a chemiluminescense detection principle. It measures the amount of NO present in a gas by detecting the chemiluminescense that occurs when NO is exposed to ozone (O_3). It can analyze NO concentration up to 20 parts per million (ppm) with a lower detection limit of 0.4 parts per billion (ppb).

The NO analyzer was calibrated weekly using the Teledyne T700 Dynamic Dilution Calibrator. NO fluxes were calculated from the slope of the linear increase or decrease in concentration of respective gases against the chamber closure time (Gaihre et al., 2015). The slope (ppb min^{-1}) is then corrected for air temperature, atmospheric pressure and the ratio of chamber volume to surface area using the following formula to determine the emission rate.

Emission rate (μg NO-N or N_2O-N m^{-2} h^{-1}) =

$$\frac{\text{ppb min}^{-1} \times V \times MW \times 60}{[0.08206 \times (273+T)\ ^0K] \times A \times 1000} \quad \text{------------------------------------ (1)}$$

Where,

V is the volume of the gas chamber in L (57.8)

MW is the molecular weight of the respective gas in ng $nmol^{-1}$ (NO-N: 14, N_2O-N: 28)

60 is conversion factor for time (min h^{-1})

0.08206 is the gas law constant (L atm mol^{-1} $^0K^{-1}$)

T is the temperature inside the chamber (°C)

A is the area covered by chamber (m^2, 0.146) and

1000 is conversion factor for mass (ng μg^{-1})

An emission event was considered significant when the slope was significant at $p<0.05$. Cumulative seasonal total emissions (g NO-N) were calculated by summing the hourly emission rates. Direct NO emission factors (EF_d%) of applied N fertilizer were calculated by using the following equation:

$$EF_d\ \% = [EF-E0]\ 100/N\ Rate \quad \text{----------------- (2)}$$

Where EF (kg N ha^{-1}) is the cumulative NO flux from the N-fertilized treatment, E0 (kg N ha^{-1}) is the cumulative NO emission from the control treatment, and N Rate (kg N ha^{-1}) is the amount of N applied in the N fertilized treatment.

2.4. Data analysis

The effects of N treatment (T) and day (D) on NO emission rates were analyzed with a generalized linear mixed model (GLIMMIX) with repeated measures and with ‘day’ as the time factor. The treatments were handled as fixed effects and day as a random effect. Analysis of Variance (ANOVA) for the cumulative emissions, NUE and grain yields was performed with SAS 9.3, using GLIMMIX Models. Treatment was considered as fixed effect and error term was considered as random effect for each response variable and crop. Mean comparison was done with LSD values at the 5% level.

3. Results

3.1. Soil moisture and temperature

Daily soil moisture content and temperature (air and soil) for rice (March-October) and wheat (November-May) crop cycles are presented in Figs. 1 and 2, respectively. In rice (Fig. 1) except under AWD treatment, soil moisture potential was within ±10 Kpa as it was continuously flooded. Under AWD treatment, soil moisture dropped up to -90 Kpa during the drying period. Daily air and soil temperatures ranged from 14-29°C. Contrary to rice, soil moisture potential in wheat (Fig. 2) was relatively low (-40 to -200 Kpa) throughout the season. During the plants’ reproductive stage, fertilized plots were drier than control plot, probably due to increased water uptake by the plants from fertilized plots. As with rice, temperatures (air and soil) ranged from 12 to 29°C.

3.2. Dynamics of fluxes

Nitric oxide fluxes during both rice and wheat growing seasons are displayed in Figs. 3 and 4, respectively. N treatment and day had an interaction effect on emissions (Table 2), emission peaks were observed in both the rice and wheat crop cycles when dry soils were wetted and/or after fertilizer application. In rice, emission peaks appeared three days after the addition of water in the dry soils (March 19, 2013) (Fig. 3). Plots were kept fallow around a month (March 19-April 25) and water was added regularly at two to three days interval. Some emission peaks were observed during this period from all the treatments, particularly after irrigation and basal fertilization. After rice transplanting, the emission peaks varied with fertilizer treatments and irrigation regimes. Occasional emission peaks were observed in UDP plots during the drying period. The magnitudes of those peaks decreased gradually with subsequent drying. On the other hand, emission peaks from broadcast urea treatment (PU) were mostly negligible (<10 µg m^{-2} d^{-1}) even after urea topdressing.

In wheat growing season, as in rice growing season (Fig. 4), NO fluxes varied widely with fertilizer treatments. The highest emission peak was observed in UDP, which was almost double (2500 µg m^{-2} d^{-1}) that of the broadcast urea treatment. The majority of emission peaks were observed during a two-month period (January-February) when soil moisture potential was from -40 Kpa to -70 Kpa. Overall, NO emissions were higher during the wheat season compared to rice season. NO fluxes ranged up to 2500 µg m^{-2} d^{-1} during the wheat season while it ranged up to 65 µg N m^{-2} d^{-1} during the rice season.

3.3. Cumulative emissions and direct emission factor (EF) of NO

Cumulative NO emissions, regardless of treatments, ranged from 0.50 to 3.41 g N ha^{-1} during the *rice* season and 62.52 to 626.43 g N ha^{-1} during the *wheat* season (Table 3). In rice, fertilizer treatments had significant effects on emissions. The treatment UDP with AWD irrigation increased NO emissions ($p<0.05$) by 682% and 252% compared to broadcast urea and UDP-CF, respectively. Emissions from UDP-CF and broadcast urea were similar to the control. In wheat, although application of N fertilizer – regardless of application methods – increased NO emissions by approximately 850% to 900% over control, the increases were not significantly different ($P>0.05$) among N sources. Cumulative NO emissions were similar between UDP and broadcast urea treatments.

The direct NO EF of the applied N fertilizers were very low (0.0002% to -0.005%) in rice, and there was no significant difference between UDP and broadcast urea treatments. On the other hand, direct emissions factors in wheat were relatively large (0.5%) compared to rice ($p<0.05$). However, they were similar between UDP and urea broadcast treatments.

The application of N fertilizer significantly increased grain yields for both rice and wheat. In rice, the effect of UDP on grain yield varied with the irrigation regime (Table 3). UDP with CF irrigation increased grain yield by 26% compared to broadcast PU. In wheat, UDP increased grain yield by 9% compared to broadcast PU.

4. Discussion

The NO emissions estimated, using continuous measurements, are more reliable than discrete measurement done in weekly or bi-weekly intervals, because it minimizes uncertainties associated with temporal variations. We estimated cumulative NO emissions throughout the rice and wheat cycle, taking one measurement (0900-1200h) every week, which is a standard practice for GHG sampling from rice fields (Minamikawa et al., 2015). The cumulative emissions were different between the two estimates in both rice and wheat. For the weekly rice measurements, the cumulative emissions were overestimated by 34-62%, particularly in fertilized treatments with a single measurement, compared with continuous measurements (8 measurements) made every day. For wheat, the cumulative emissions were overestimated by 22% in the UDP treatment and underestimated by 7% in the broadcast PU treatment.

Emissions of NO appear sporadic and event specific (interact with time, Table 2), such as after N fertilizer application, drying of wet soils and re-wetting of dry soils. Therefore, at least daily measurements of NO emissions are needed during such periods to get a reliable estimate of their annual emissions. There are still few studies on NO emissions from the rice-wheat system, particularly with the continuous measurement approach. Therefore, we quantified NO emissions from a rice-wheat system as affected by N placement methods.

NO emissions are controlled by several factors, including N fertilizer and water regime (Medinets et al., 2015). Optimum use of N fertilizer, i.e. right source, right rate, right time and right method (4R of nutrient stewardship) (Johnston and Bruulsema, 2014), not only increases NUE and crop yields, but also reduces emissions of N_2O and NO. For example, deep placement of N fertilizers into the soils, instead of uniform surface broadcast, reduces losses which in turn increase plant uptake and NUE (Savant and Stangel, 1990; Rochette et al., 2013). Previous studies reported that the increase in NUE was much higher in lowland rice (Rochette et al., 2013) compared to upland crops (Agyin-Birikorang et al., 2018). In lowland rice fields (flooded paddy soils), when urea is incorporated at 7-10 cm depth, NH_4^+-N concentrates in the anaerobic soil layer which reduces its movement to the soil surface or in floodwater (Savant and Stangel, 1990;

Kapoor et al., 2008; Rochette et al., 2013; Huda et al., 2016). This results in a reduction of potential nitrification/denitrification losses and, thus, NO emissions (Akiyama et al., 2010). Contrary to UDP, when urea is applied uniformly, such as in a broadcast method, it is dissolved in water immediately. The exposed NH_4^+-N in the soil's surface and in floodwater is subjected to losses through different mechanisms, including nitrification/denitrification producing N_2O and NO and NH_3 volatilization (Gaihre et al., 2015; Rochette et al., 2013). UDP in lowland rice cultivations increases NUE and grain yields while reducing N losses to the environment as NH_3 volatilization, surface runoff and emissions of N_2O and NO. However, experiment settings in the greenhouse are different than those under field conditions because of differences in environmental parameters. The magnitude of N losses could be different compared to fields, as there were no losses associated with surface runoff and leaching.

However, in this study, UDP with continuous flooding irrigation (UDP-CF) had no significant effects on NO emissions when compared to the broadcast method (Table 3). These results are in agreement with our previous field studies (Gaihre et al., 2015; 2017). On the other hand, UDP with AWD irrigation significantly increased NO emissions (2.5 times) compared to UDP-CF treatment. In the UDP plot, AWD irrigation triggered more emission peaks, particularly during dry episodes (Fig. 3), which resulted in significantly higher cumulative emissions compared to broadcast PU. With the drying of the plot, the NH_4^+ retained from the sub-surface layer might be exposed to nitrification, resulting in greater NO emissions. Higher NO emissions under AWD conditions has also been reported in previous studies (Zhou et al., 2010).

Nonetheless, the magnitudes of seasonal total emissions were very low in the rice-growing period (<4 g N ha^{-1} $season^{-1}$). In continuously flooded soils, denitrification dominates, and much of the NO is consumed before it can leave the soil (Firestone and Davidson, 1989). For rice fields, there are very few studies that measure NO emissions. Our results are in agreement with Zhou et al. (2010) – they observed a very small amount of NO emissions during flooded rice, compared with the emissions during the wheat growing season and the fallow period. Significant NO fluxes were observed during mid-season drainage that accounted for 85% of the total NO emissions (Fig. 3). Similarly, in this study, AWD induced pulse emissions contributed about 60% to the seasonal cumulative emissions.

In the wheat-growing season, despite the huge NO emission peaks in the UDP plot (Fig. 4), the contributions of fertilizer-induced NO emission peaks to seasonal total emissions were not sufficient enough to result in a significant difference from broadcast PU. This is because NO emission peaks after topdressing of PU were higher during the *wheat* season compared with the *rice* season. Nevertheless, fertilized plots (UDP and broadcast) increased emissions by ~10-fold compared to the emissions from control (without N fertilizer) (Table 3). These results confirm the higher variability of emissions within a field, indicating that the spatial variability of NO emissions is likely to be greater than the temporal variability. Therefore, the increase in the number of replicates (spatial measurement) may be more important than the increase in frequency of temporal measurement. Temporal variability could be minimized by adjusting sampling time to determine average emissions (Laville et al., 2011). Higher emission from fertilized plots could be associated with continuous substrate (NH_4) availability for nitrification and optimum soil moisture (-40 Kpa to -70 Kpa) (Fig. 2). Since UDP reduced N losses from NH_3 volatilization – the main pathway of N loss – it retained more N in the soil which subjected it to nitrification and, thus, NO emissions. Similarly, for broadcast urea treatment, N was applied at two equal splits with optimum soil moisture, which sustained nitrification for about two months (Jan-Feb). Therefore, both UDP and broadcast urea produced similar NO emissions (Table 3).

Moreover, this study reveals that (regardless of treatments) with similar N inputs, the contribution of rice on total annual NO emissions was very small (<0.5%) compared to emissions from wheat.

However, fertilizer induced EFs were not affected by N placement methods in either rice or wheat. In rice, EFs were very low (<0.002%) when compared to 0.7% of applied N (global mean) (Bouwman et al., 2002) and 0.04% from rice fields in China (Huang and Li, 2014). However, our previous study conducted under field conditions showed similar results (Gaihre et al., 2015; 2017). These results confirm that NO emissions from continuously flooded rice fields are negligible under current rates and methods of N applications. On the other hand, EFs for wheat were much higher (~0.5%) compared to rice (<0.002%), but in agreement with previous studies (Hou et al., 2010; Liu et al., 2011). As discussed above, higher N loss as NO emissions from wheat could be associated with sustained nitrification due to a continuous availability of N and optimum soil moisture. Given the lower magnitude of NO emissions from rice (regardless of application methods), and since there were no significant effects on emissions from wheat, the selection of N application methods could be determined by considering other benefits, including grain yields, increased NUE and reduced N losses, such as ammonia volatilization and N_2O emissions (Gaihre et al., 2015; Huda et al., 2016; Rochette et al., 2013).

5. Conclusions

This study quantified the NO emissions from two N placement methods in a rice-wheat system using an automated continuous measurement system. Total seasonal emissions were estimated from eight daily flux measurements. These intensive measurements count all sub-diurnal variability, which helps to reduce uncertainties of cumulative estimate. In rice, NO emissions between UDP and broadcast urea treatments were similar under continuous flooding irrigation. But UDP with AWD irrigation produced more NO emission peaks, resulting in 2.5-fold higher ($p<0.05$) seasonal total emissions compared to UDP-CF. Nevertheless, magnitudes of emissions were very low to negligible (<4 g N ha^{-1} $season^{-1}$) with N loss as NO less than 0.001%. On the other hand, during wheat cultivation, N loss as NO emissions was up to 626 g N ha^{-1} $season^{-1}$ which is much higher than from rice. This loss (in wheat) is equivalent to about 0.5% of the applied N. NO emissions from fertilized plots were 10 times higher than the unfertilized plot. Despite the huge increase in emissions, the differences among the treatments were below statistical significance.

These results confirm that water regime is one of the main driving factors for NO emissions. N loss as NO emissions from rice cultivation increase when the irrigation regime is switched from continuous flooding to AWD. For wheat, the overall N loss as NO is higher compared to rice. Nevertheless, these losses are very minimal (<1% of applied N) from an agronomic perspective, and adoption of UDP should be decided based on the effects on grain yields and NUE.

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List of Tables

Table 1. Physicochemical properties of soil used in the experiment

Soil property	Results
pH-H_2O	6.84
Organic matter (g kg^{-1})	1.78
Total N (g kg^{-1})	0.98
NH_4^+ (mg kg^{-1})	4.67
NO_3^- (mg kg^{-1})	7.66
Pi (mg kg^{-1})	17.30
Available P-Olsen (mg kg^{-1})	11.1
Available K ($cmol_c$ kg^{-1})	0.15
Ca ($cmol_c$ kg^{-1})	6.66
Mg ($cmol_c$ kg^{-1})	1.22
Na ($cmol_c$ kg^{-1})	0.15
CEC ($cmol_c$ kg^{-1})	8.18
Fe (mg kg^{-1})	13.40
S (mg kg^{-1})	5.44
B (mg kg^{-1})	0.51
Cu (mg kg^{-1})	0.46
Al (mg kg^{-1})	0.60
Particle size (%)	
Sand	23.6
Silt	57.8
Clay	18.6
Texture class	Silt loam

Table 2. Effects of two factors (N treatment [T] and day[D]) on nitric oxide (NO) emissions in rice and wheat by the analysis of variance with repeated measures using the SAS mixed procedure

Effect	DF	Denominator DF	*F*	*P*
Rice				
N Treatment (T)	3	63.6	11.11	<0.0001
Day	202	737.8	2.87	<0.0001
T × Day	606	960.7	1.53	<0.0001
Wheat				
N Treatment (T)	2	682.3	6.04	0.0025
Day	244	984.7	1.3	0.0037
T × Day	488	815.9	1.2	0.01

Table 3. Seasonal cumulative emissions of NO (g N ha^{-1}) and direct emission factor of NO (EF-NO-N, %) for different treatments in rice and wheat

Crop	N treatments	Grain yields		NO emissions		EF-NO-N	
		kg ha^{-1}		g N ha^{-1}		%, w/w	
Rice	Control	5614 (292)	c	1.15 (0.34)	a	-	
	UDP-CF	9224 (292)	a	1.35 (0.75)	a	0.0002 (0.0007)	a
	Broadcast	7311 (638)	b	0.50 (0.12)	a	-0.0005 (0.0003)	a
ANOVA (Pr> F)		0.0039		0.5029		0.3102	
Rice	UDP-CF	9224 (292)	a	1.35 (0.75)	b	0.0002 (0.0007)	a
	UDP-AWD	6963 (198)	b	3.41(0.99)	a	0.0017 (0.0010)	a
ANOVA (Pr>F)		0.0321		0.04901		0.1176	
Wheat	Control	897 (37)	b	62.52 (28.86)	a	-	
	UDP	2956 (87)	a	604.00 (258.82)	a	0.4923 (0.3910)	a
	Broadcast	2706 (90)	a	626.43 (416.30)	a	0.5126 (0.3600)	a
ANOVA (Pr> F)		0.0001		0.5452		0.8053	

UDP = urea deep placement, CF = continuous flooding, AWD = alternate wetting and drying, number in parenthesis indicates standard error

Figure Captions

Fig. 1. Daily average of soil moisture and air and soil temperatures at different treatments during rice-growing season

Fig. 2. Daily average of soil moisture and air and soil temperatures at different treatments during wheat-growing season

Fig. 3. Seasonal variations of NO fluxes under different fertilizer treatments during rice growing season

Fig. 4. Seasonal variations of NO fluxes under different fertilizer treatments during wheat growing season

Fig. 5. Relationship between NO fluxes and soil moisture potential during whole wheat-growing period under fertilized treatments (n=414)

Fig. 1.

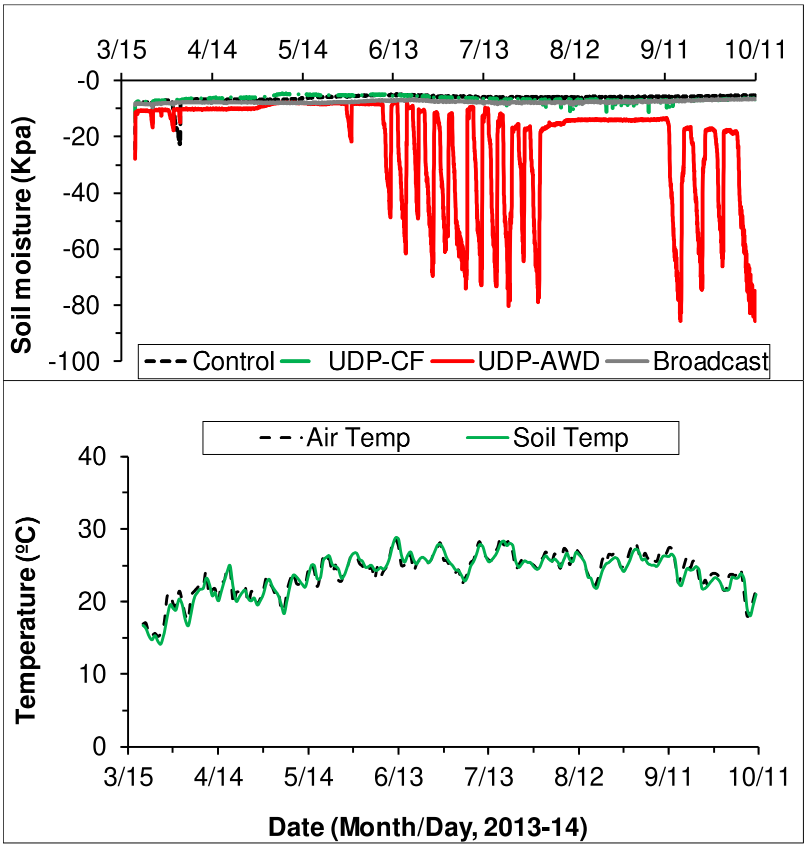

3/15
4/14
5/14
6/13
7/13
8/12
9/11
10/11
-0
-20
-40
-60
-80
-100
Soil moisture (Kpa)
Control
UDP-CF
UDP-AWD
Broadcast
Air Temp
Soil Temp
40
30
20
10
0
Temperature (ºC)
3/15
4/14
5/14
6/13
7/13
8/12
9/11
10/11
Date (Month/Day, 2013-14)

Fig. 2.

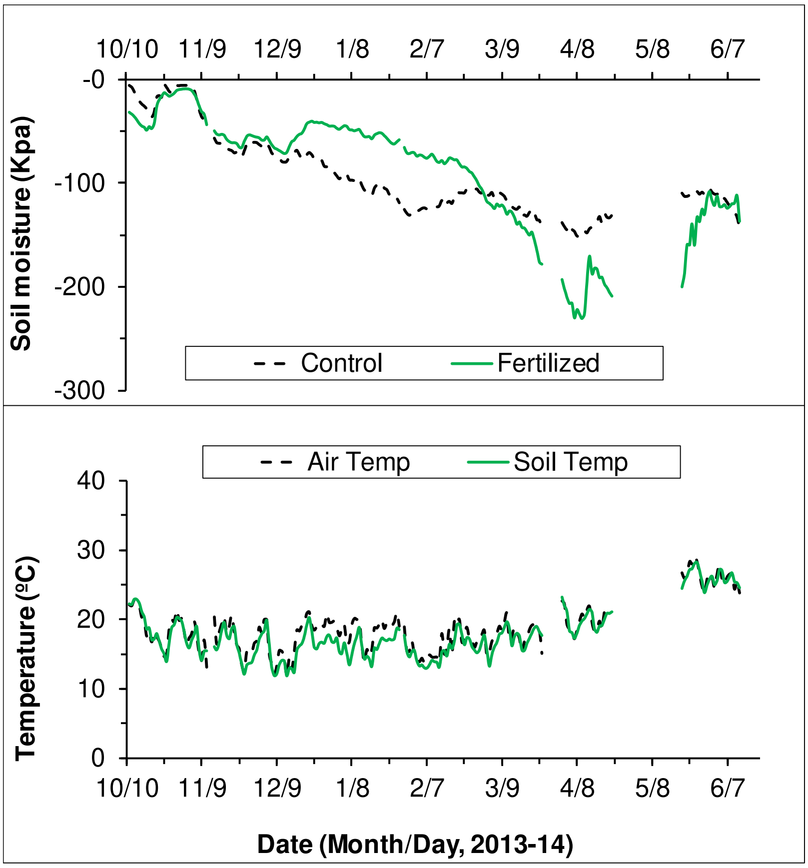

10/10
11/9
12/9
1/8
2/7
3/9
4/8
5/8
6/7
-0
-100
-200
-300
Soil moisture (Kpa)
Control
Fertilized
Air Temp
Soil Temp
40
30
20
10
0
Temperature (ºC)
Date (Month/Day, 2013-14)

Fig. 3.

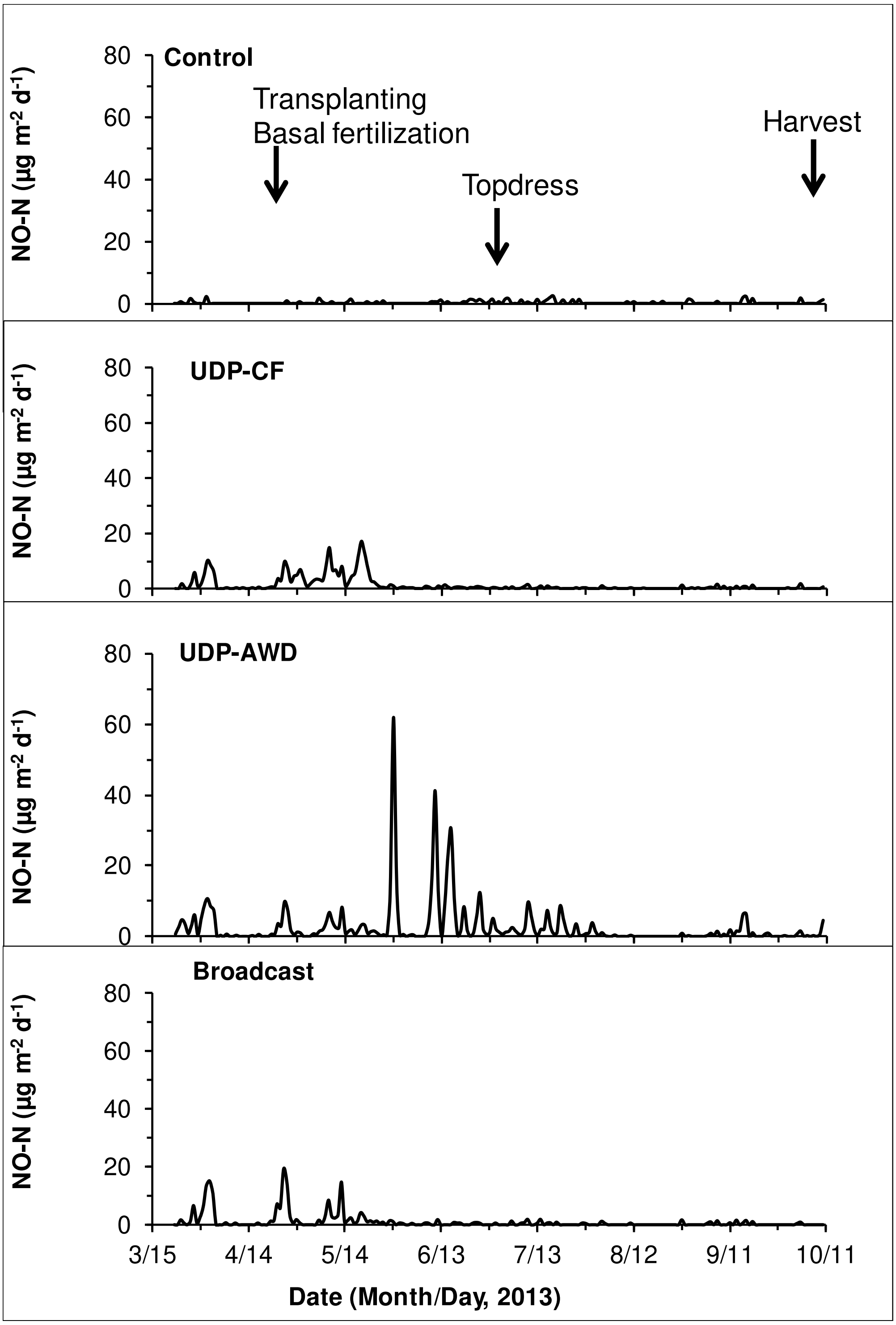

Control
Transplanting
Basal fertilization
Harvest
Topdress
UDP-CF
UDP-AWD
Broadcast
NO-N (μg m-2 d-1)
80
60
40
20
0
3/15
4/14
5/14
6/13
7/13
8/12
9/11
10/11
Date (Month/Day, 2013)

Fig. 4.

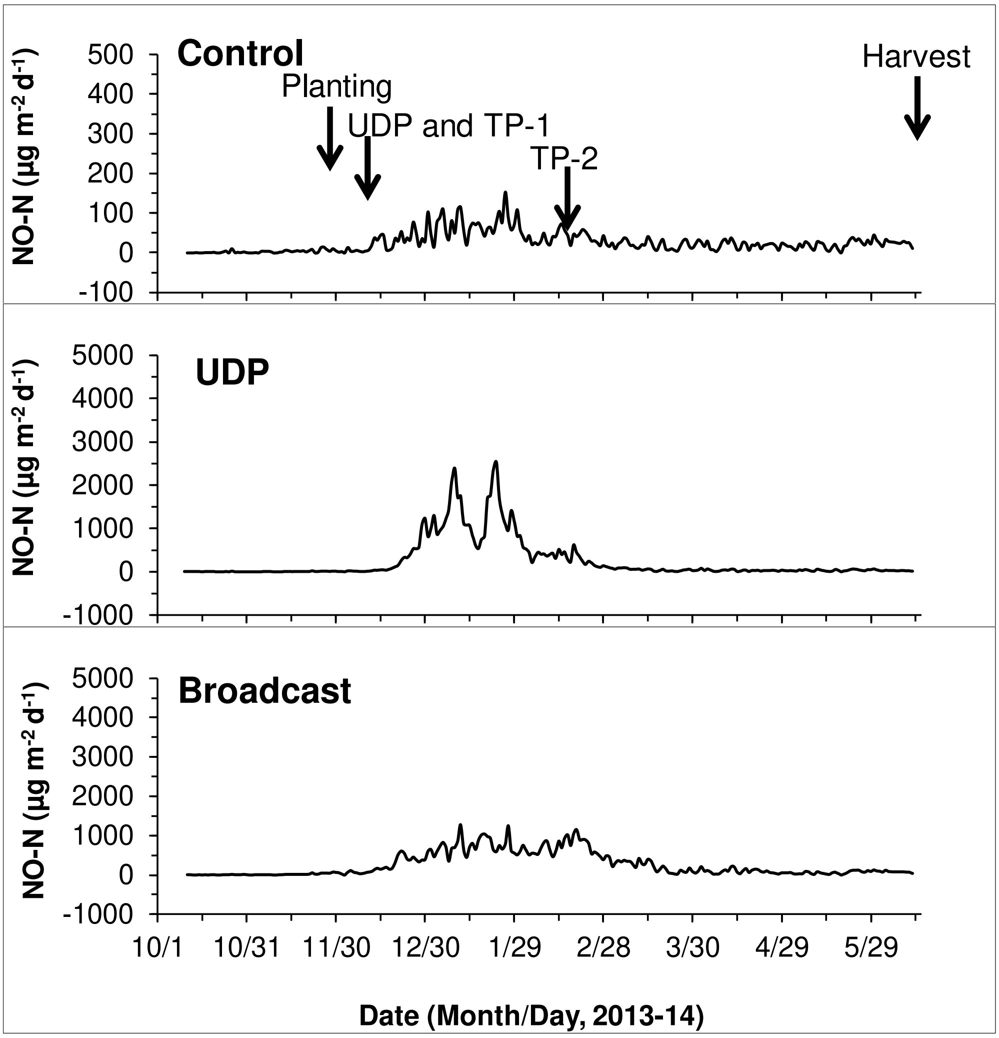
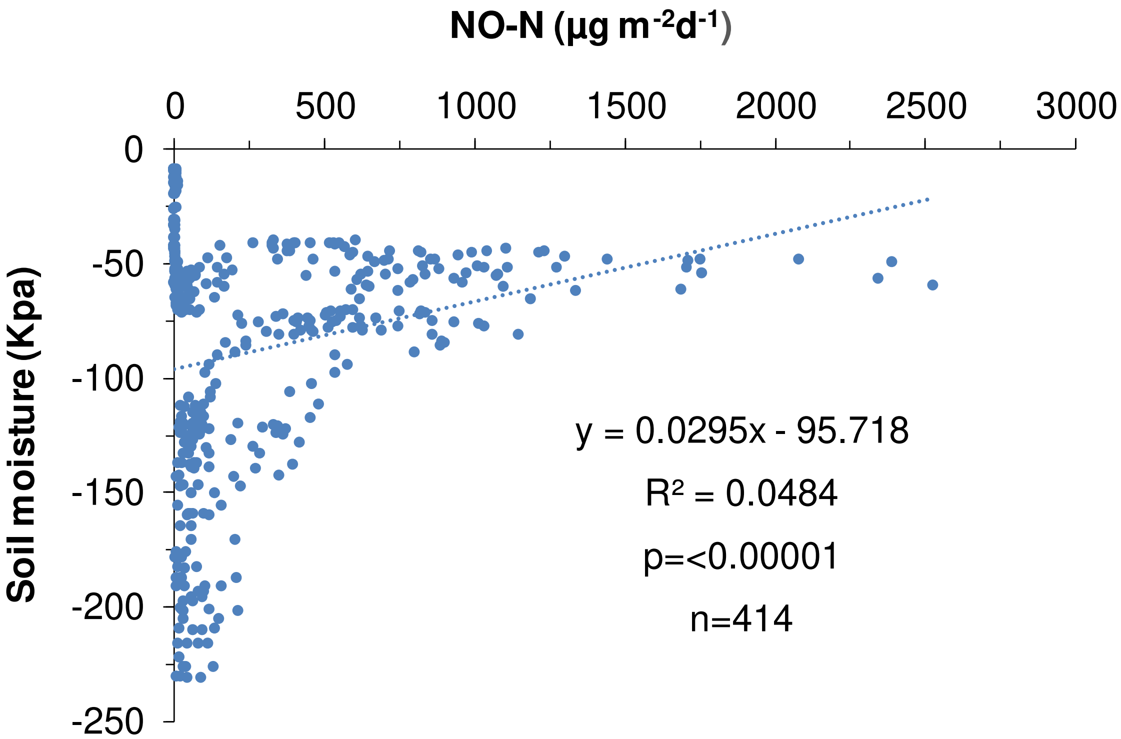
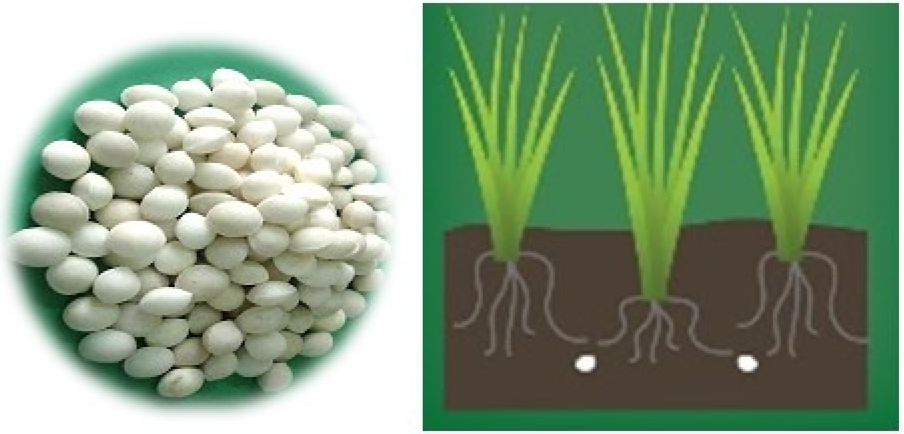

Control
Planting
UDP and TP-1
TP-2
Harvest
UDP
Broadcast
NO-N (µg m-2 d-1)
500
400
300
200
100
0
-100
5000
4000
3000
2000
1000
0
-1000
10/1
10/31
11/30
12/30
1/29
2/28
3/30
4/29
5/29
Date (Month/Day, 2013-14)

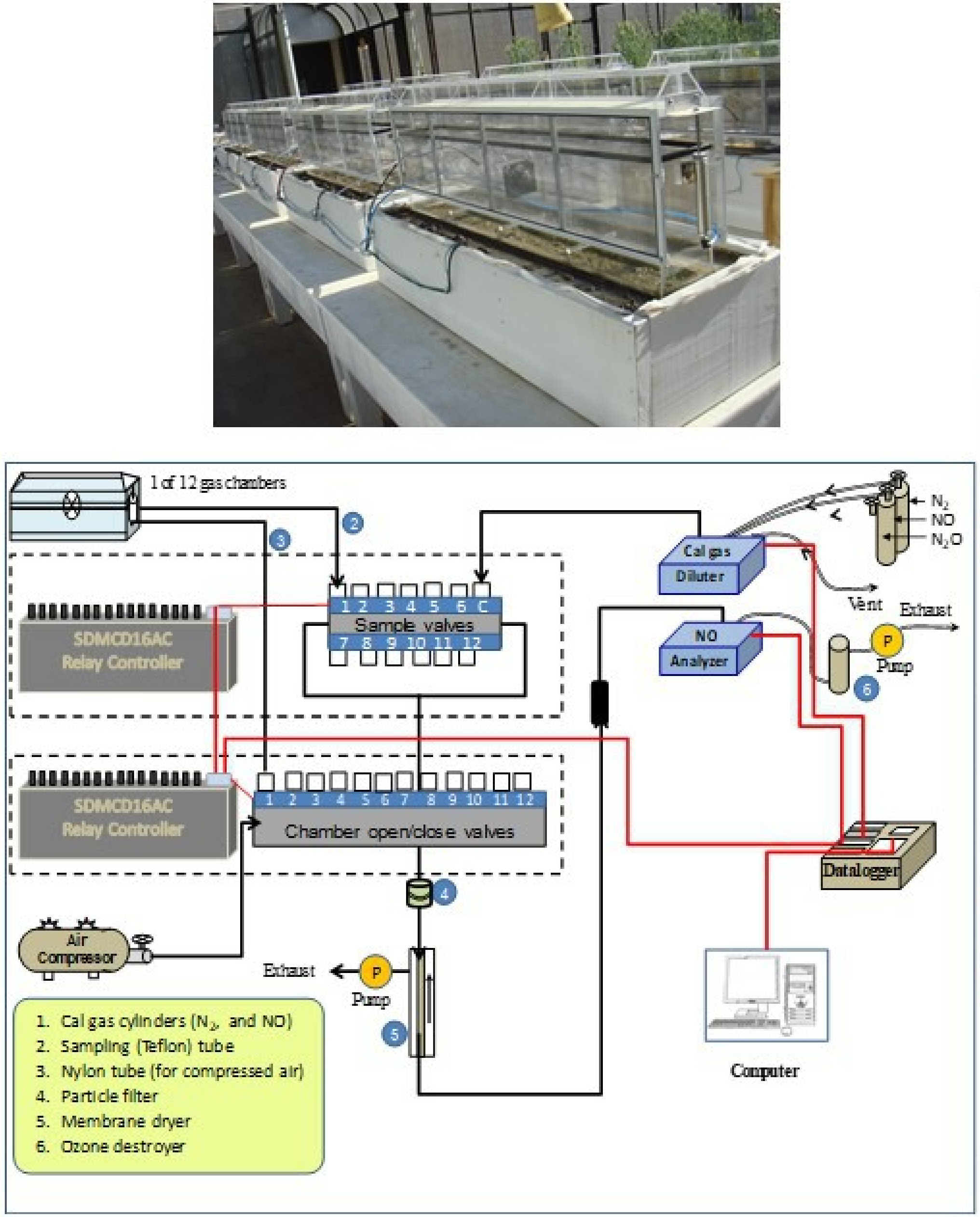
Fig. 5.


NO-N (µg m-2d-1)
0
500
1000
1500
2000
2500
3000
0
-50
-100
-150
-200
-250
Soil moisture (Kpa)
y = 0.0295x - 95.718
R² = 0.0484
p=<0.00001
n=414



Urea briquette deep placement (UDP) at 7-10 cm below soil surface

Conventional broadcast application of prilled urea (PU)



Automated closed chamber system

Cumulative emissions