The impact of atmospheric N deposition and N fertilizer type on soil nitric oxide and nitrous oxide fluxes from agricultural and forest Eutric Regosols

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Abstract
Agricultural and forest soils with low organic C content and high alkalinity were studied over 17 days to investigate the potential response of the atmospheric pollutant nitric oxide (NO) and the greenhouse gas nitrous oxide (N2O) on (1) increased N deposition rates to forest soil; (2) different fertilizer types to agricultural soil and (3) a simulated rain event to forest and agricultural soils. Cumulative forest soil NO emissions (148–350 ng NO-N g⁻¹) were ~ 4 times larger than N2O emissions (37–69 ng N2O-N g⁻¹). Contrary, agricultural soil NO emissions (21–376 ng NO-N g⁻¹) were ~ 16 times smaller than N2O emissions (45–8491 ng N2O-N g⁻¹). Increasing N deposition rates 10 fold to 30 kg N ha⁻¹ yr⁻¹, doubled soil NO emissions and NO₃⁻ concentrations. As such high N deposition rates are not atypical in China, more attention should be paid on forest soil NO research. Comparing the fertilizers urea, ammonium nitrate, and urea coated with the urease inhibitor ‘Agrotain®,’ demonstrated that the inhibitor significantly reduced NO and N2O emissions. This is an unintended, not well-known benefit, because the primary function of Agrotain® is to reduce emissions of the atmospheric pollutant ammonia. Simulating a climate change event, a large rainfall after drought, increased soil NO and N2O emissions from both agricultural and forest soils. Such pulses of emissions can contribute significantly to annual NO and N2O emissions, but currently do not receive adequate attention amongst the measurement and modeling communities.

Keywords Atmospheric N deposition · Ammonium nitrate · Urea · Urease inhibitor · Pulsing effect

Introduction
The industrialization of mineral N fertilizer production contributes immensely to global food security, but also shares responsibility for a series of environmental pollution issues. The N use efficiency of crops is rather poor, with a global average of 0.4% in 2010 (Zhang et al. 2015). Excess N fertilizer is largely converted through microbial and chemical reactions to environmentally damaging compounds such as nitrate (NO₃⁻), nitric oxide (NO) and nitrous oxide (N₂O). Surplus N is an acute problem in China. Between 1961 and 2012 China’s total fertilizer N input has increased by 490% and the N surplus by more than 10 times, from 3.3 Mt in 1961 to 38 Mt in 2012 (Yuan and Peng 2017). Consequently, many natural ecosystems, especially forests in China, experience high atmospheric N deposition rates and commonly exceed critical loads of sensitive ecosystems (Liu et al. 2011). Annual wet deposition rates have increased from 13 kg N ha⁻¹ yr⁻¹ in the 1980s to 21 kg N ha⁻¹ yr⁻¹ in the 2000 (Liu et al. 2013), and forest ecosystems are changing from naturally N-limited to N-saturated systems. This can lead to negative impacts such as soil acidification and changes in the species composition of flora and fauna (Bobbink et al. 2010).

Modern agricultural strives towards maximum productivity to feed our growing population, whilst also reducing the environmental burden of N fertilizer additions. A proportion of the N fertilizer applied is inevitably lost to the atmosphere as NO, N₂O and N₂ (Zhu et al. 2013) and NH₃ (Yan et al. 2011), or leached to the waters as NO₃⁻ and dissolved organic N compounds (Shan et al. 2015). The ratio of these loss products...
and their rates depend on the amount of N fertilizer applied, soil properties and climatic conditions (Zhang et al. 2014). Agricultural ecosystems contribute to about 60% of the global anthropogenic emissions of the greenhouse gas N$_2$O (IPCC 2013), and can also be an important source of soil NO emissions in rural areas (Almaraz et al. 2018). N research tends to focus on N$_2$O, NH$_3$ and NO$_3^-$ and especially in relation to fertilizer application, whereas the loss of NO from soils is not sufficiently researched. The reason for this is that soil is a small source of NO$_x$ compared to the main source, fossil fuel combustion. Nitric oxide is a highly reactive air pollutant in the troposphere, and contributes to O$_3$ production and acid rain (Hertel et al. 2012). It has been estimated that soils in China contribute only to 4% of the total annual NO$_x$ loss to the atmosphere (Gu et al. 2012). However, with the ongoing clean-up of NO$_x$ combustion sources soil NO emissions are becoming increasingly more important as a source of atmospheric ozone in rural areas (Almaraz et al. 2018).

The N input from atmospheric deposition is relatively small compared to N fertilizer application rates (Chen et al. 2014; Liu et al. 2013), even in regions with very large atmospheric N deposition rates. For example, at Yanting research station in the Sichuan Basin, where we collected the soils for this study, the average annual atmospheric bulk N deposition rate for the Sichuan Basin, where we collected the soils for this study, deposition rates. For example, at Yanting research station in Liu et al. 2013), even in regions with very large atmospheric N deposition rates (Chen et al. 2014; Pfab et al. 2011; Yao et al. 2017). The rates of these emissions are largely determined by soil moisture, soil texture and bulk density, which control the oxygen concentrations (Davidson et al. 2000). In addition, soil pH is of importance as it influences the efficiency of nitrification and the ratio of denitrification products (N$_2$O and N$_2$H$_4$). High soil moisture contents tend to favor N$_2$O emissions, whereas the opposite is the case for NO emissions (Skiba et al. 1992). Precipitation rate and frequency plays an important role on NO and N$_2$O emission rates. A large rainfall onto dry soil can trigger a pulse of NO and/or N$_2$O emissions, even from soils with low mineral N contents. However, effects of such events are poorly understood. They are not uncommon, and can contribute significantly to the overall annual NO and N$_2$O emission budget (Dick et al. 2006; Medinet et al. 2016a; Sanchez-Martín et al. 2008).

The focus of this study is to provide new data of soil NO and N$_2$O fluxes from an alkaline Regosol, supporting two different ecosystems, a forest and agricultural field, which are adjacent to each other and experience the same climate. By conducting controlled environment laboratory studies, the impact of atmospheric N deposition, N fertilizer type, and the pulsing effect (rewetting dry soil) on NO and N$_2$O emissions will be addressed simultaneously. Our hypothesis is that investigating NO and N$_2$O emissions from low N (deposition) and high N (fertilization) systems under stable soil moisture conditions, varying soil moisture conditions (pulsing effect) and varying N rates from a forest and agricultural ecosystems will provide insight into the relative importance of NO or N$_2$O emissions of the scenarios to be investigated.

**Materials and methods**

### Site description and soil collection

Soils were collected from the Yanting Agro-ecological Experimental Station for Purple Soils (31°16' N, 105°28' E), which is part of the Chinese Ecosystem Research Network (CERN), Chinese Academy of Sciences, in the center of the Sichuan Basin. The climate is a subtropical monsoon climate, and alkaline Eutric Regosols (locally known as purple soils) occupy 300,000 km$^2$ in this region (Wang et al. 2015b). Soils were collected from an agricultural and a forest soil in February, 2016. The agricultural soil originates from a field cropped with wheat, which was sown in October 2015, and fertilized with ammonium carbonate (NH$_4$HCO$_3$) at a rate of 130 kg N ha$^{-1}$ yr$^{-1}$ by broadcast at sowing stage. The soil is of loamy texture with a sand, silt, and clay content of 27.1%, 51.6% and 22.3%, respectively. The average annual bulk N deposition rate to this agricultural area was 23 kg N ha$^{-1}$ yr$^{-1}$ in the period 2008–2013 (Song et al. 2017). Other soil properties are shown in Table 1.

The forest soil was collected from a cypress (Cypressus funebris) plantation forest, and only 3 km away from the agricultural field. The forest was planted approximately 40 years ago, has never received N fertilizer and is representative of plantation forests throughout the central Sichuan Basin. The forest soil is also a purple soil, with a sand, silt, and clay content of 46.5%, 35.8% and 17.7%, respectively. The average annual N deposition rate to this agricultural area was 3 kg N ha$^{-1}$ yr$^{-1}$ in the period 2008–2013 (Song et al. 2017). Other soil properties are shown in Table 1.

Soil was collected randomly from the top 15 cm soil layer of the wheat field and forest. The soil was air-dried in the laboratory, then passed through a 2-mm sieve, and transported by air to the UK Centre for Ecology and Hydrology, Edinburgh, Scotland, where the experiments were conducted.

### Soil manipulation studies

Three incubation experiments, measuring fluxes of NO, N$_2$O, and KCl extractable soil NH$_4^+$ and NO$_3^-$ concentrations were carried out over a 17 day period.

**Experiment I** The impact of N deposition rate on forest soil was tested, with application rates equivalent to 0 kg N ha$^{-1}$ (control), 3 kg N ha$^{-1}$ (low N) and 30 kg N ha$^{-1}$ (high N), applied in the form of NH$_4$NO$_3$. 

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\[ \text{N fertilization} \]
Experiment 2 The impact of different N fertilizer types on NO and N₂O fluxes from the agricultural soil was investigated. The fertilizer application rate was equivalent to 150 kg N ha⁻¹, which is approximately 0.04 mg N g⁻¹ soil, assuming a soil depth of 0.25 m and a bulk density of 1.5 g cm⁻³. Applying the same principles to the atmospheric N deposition rates (experiment 1) converts the 3 and 30 kg N ha⁻¹ rates to 0.0008 and 0.008 mg N g⁻¹, respectively. The tested fertilizers were: ammonium nitrate (NH₄NO₃), urea, urea coated with the urease inhibitor Agrotain® DRI-MAXX (UI) and no fertilizer (control). The active ingredient of Agrotain® is N-(n-butyl)-thiophosphoric triamide (NBPT; CAS #94317–64-3) 60%, and the inactive ingredients are formaldehyde polymer and pigment, 40%. It is a dry N stabilizer developed by Koch Agronomic Services (2020). A previous study found that the influence of Agrotain® on soil N concentration and N gas emission occurred within approximately two weeks after fertilizer application (Cowan et al. 2019).

Experiment 3 The impact of simulating a ‘pulsing effect’ on NO and N₂O fluxes was investigated for both the agricultural and forest soils. Dry soils were wetted with a weak solution of 0.008 mg NH₄NO₃ g⁻¹, simulating a low atmospheric N deposition event.

The experiments were carried out using clear Perspex cores (20 cm height × 5 cm diameter), which were sealed at the base, and during flux measurements, also at the top with a rubber bung. Close to the top of the cores 5-mm inlet and outlet silicon ports were fitted and equipped with three way taps; the outlet hole was 5 cm above the inlet hole (Sanchez-Martin et al. 2008). Aliquots of 180 g of soil were placed into the cores and compressed to adjust to the field bulk density, which was 1.56 g cm⁻³ for the agricultural soil and 1.42 g cm⁻³ for the forest soil. The headspace above the soil was on average 0.34 l. For the ‘N deposition to forest’ (experiment 1) and ‘fertilizer to an arable crop’ (experiment 2), a pre-incubation was necessary to avoid the interference of pulses of large NO and N₂O emissions, which are typically observed when wetting dry soil (Dick et al. 2006). The dried soils were therefore brought to a water content of 50% WFPS (water filled pore space) for forest soil and 45% WFPS for agricultural soil, representing the saturated water capacity (Wang et al. 2015a). They were placed in an incubator at a constant temperature of 25 °C for 10 days, and were mixed daily. At the end of the pre-incubation period the soils had lost on average of 9.2 ± 1.6 ml of water from the forest soils and 8.5 ± 0.9 ml from the agricultural soils. This water was replaced with a solution of fertilizer dissolved in deionized water to exactly provide N deposition rates of 3 or 30 kg N ha⁻¹ in experiment 1 and a fertilization rate of 150 kg N ha⁻¹ soil in experiment 2. The soil moisture content was maintained throughout the experimental period by daily reweighing the cores and replacing weight loss with deionized water, after the flux measurements were made.

For experiment 3 dry forest and dry agricultural soils (180 g) were placed into cores and were wetted to field capacity with a solution of NH₄NO₃ simulating a low N deposition rate of 3 kg N ha⁻¹, and then were left to dry out naturally over the next 17 days. The cores were reweighed daily to monitor weight loss, as a proxy for changes in soil moisture. The conversion from weight loss to soil moisture throughout the 17 day study period was inferred from the gravimetric moisture content measured at the start and end of the incubation period, by drying at 105 °C for 24 h. For all three experiments, each lasting 17 days, fluxes were measured on 9 occasions, daily in the first week, and then at 2 to 3 day intervals. All treatments were replicated 3 times.

Soil mineral N concentrations were measured from separate cores, in order not to disturb the soil profile of the flux cores, described above. These cores were treated the same as the flux measurement cores, regarding N and water additions and incubation temperature. Due to limited amount of soil, aliquots of only 100 g of each soil were placed into polyethylene cups of similar dimensions to the Perspex cores used for the flux measurements, and there were 3 replicates for each treatment. To avoid too much disturbance, the soil sampling

| Ecosystem | Total annual precipitation a (mm) | Average annual air temperature a (°C) | Vegetation | Fertilizer application rate (kg N ha⁻¹ yr⁻¹) | Atmospheric N deposition rateb (kg N ha⁻¹ yr⁻¹) | Soil Texture | pH (H₂O)c | Soil bulk densityd (g m⁻³) | Soil organic Cc (g kg⁻¹) | Total N contentf (g kg⁻¹) |
|-----------|---------------------------------|--------------------------------------|------------|---------------------------------------------|------------------------------------------------|--------------|----------|--------------------------|--------------------------|--------------------------|
| Forest    | 863                             | 16.7                                 | Cypress    | 0                                           | 15                                              | loamy        | 8.3 ± 0.03 | 1.4 ± 0.1                | 21.0 ± 5.3                | 1.6 ± 0.2                |
| Agricultural | 826                           | 17.3                                 | Wheat      | 130                                         | 23                                              | loamy        | 8.5 ± 0.05 | 1.6 ± 0.8                | 12.3 ± 0.4                | 0.9 ± 0.1                |

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aPrecipitation and temperature are 10 years (2008–2017) averages (http://yga.cern.ac.cn/)

bN deposition rates are for the period 2008–2013 (Song et al. 2017)

cValues are from this study and based on 6 replica

dData for soil bulk density from Wang et al. (2015a)

eData for soil organic C and total N from Wang et al. (2017)
frequency was reduced to 5 occasions in experiment 1 and 3, and to 4 occasions in experiment 2. The soil moisture content was maintained throughout the experimental period by daily reweighing the cores and replacing weight loss with deionized water, after the flux measurements were made. 

All three experiments were carried out at 25 °C, which is the average air temperature of the Yanling area for the months of June to September. On the first day the applications of the N and control treatments were staggered in time, in order to observe the immediate response (approximately 0.5 h after application) in NO, N₂O fluxes. On all subsequent measurement days, samples for N₂O analysis were collected within 1 h from all treatments and before starting with the NO flux measurements, which took between 20 and 30 min for each core. Cores were weighed, and adjusted for water loss (experiment 1 & 2) at the end of the day. The soil samples for NH₄⁺, NO₃ analysis were always collected after adjusting the soil moisture content.

NO and N₂O fluxes measurements

NO fluxes were measured from the soil cores using a gas flow-through system, as described in detail by Dick et al. (2006). Ambient air, filtered through charcoal and aluminum/KMnO₄ to remove O₃ and NOₓ, was passed over the headspace of the core into the chemiluminescence analyzer (flow rate 40 ml min⁻¹) to measure NO by using a chemiluminescent analyzer (42C NO-NO₂-NOx, Thermo Environmental Instruments Inc., Franklin, MA, USA) and O₃ using a UV photometric O₃ analyzer (49C Thermo Environmental Instruments Inc., Franklin, MA, USA). As the NOₓ and O₃ analyzer each require a flow rate of 1.1 min⁻¹, additional filtered air was supplied. The NOₓ and O₃ analyzers were calibrated against a zero air standard before starting this study. Ozone concentrations were only measured to ensure that concentrations were sufficiently low (on average 2.2 ppb) to avoid reactions with NOₓ. The flow rates through the core and into the analyzer were monitored using mass flow meters (Aera FC 7700C; Advanced Energy Industries Inc., Fort Collins, CO, USA). NO and O₃ concentrations, air temperature and flow rates were recorded at 10 s intervals using a 21x data logger (Campbell Scientific, Shropshire, UK). Typically, measurements from each core lasted approximately 30 min and until the NO concentration recorded was steady. These measurements were interspersed with NO concentration measurements from empty control cores, in order to take into account reactions with chamber walls and lids. The NO flux (ng N g⁻¹ h⁻¹) was calculated as the product of the flow rate of the air stream through the repacked soil core, the increase in NO concentration above the control (empty core) and the dilution rate, by supplying additional air to the analyzer, divided by the soil dry weight (180 g).

N₂O fluxes were always measured within 4 h after measuring the NO fluxes. The cores were sealed with a rubber bung for a period of 20 min, and air samples were extracted from the headspace at time 0, 10 and 20 min, using 10 ml syringes fitted with a luer lock. The extracted gas samples were stored in syringes until analysis of N₂O concentrations within 5 h. Previous tests using standard N₂O concentrations showed that over this time N₂O concentrations remained stable (Drewer, pers. com.). N₂O concentrations were analyzed by gas chromatography using an Agilent Technology 7890B GC system, fitted with an electron capture detector (ECD) (Drewer et al. 2020). The N₂O flux was calculated as the product of the increase in N₂O concentrations above ambient laboratory air and volume of the headspace in the repacked soil core, divided by the time the core was sealed and the soil dry weight in the core.

Soil nutrient analysis

The soil organic matter content was measured using the standard method of loss on ignition (Rowell 1994). To determine soil exchangeable NH₄⁺ and NO₃⁻ content, 15 g of soil were extracted with 50 ml of 1 M KCl solution for 1 h at 100 rpm on an orbital shaker (Stuart Orbital Shaker SSL1 Barloworld Scientific Ltd.). The extract was filtered through Whatman No 42 filter paper and frozen until analysis. Concentrations of exchangeable NH₄⁺ and NO₃⁻ were analyzed by colorimetric methods (Harwood and Huysr 1970; Henriksen and Selmer-Olsen 1970) using the SEAL AQ2 discrete analyzer. Moisture contents were calculated from the weight difference between the wet and oven dried soils.

Statistical analysis

Statistical analyses including multiple comparison were performed using the SPSS software package, version 14.0 (SPSS Inc., Chicago, IL). Pearson correlations, linear regression analyses and significance were evaluated using a significance level (p) of 0.05. Cumulative flux data were interpolated using LOESS smoothing in R. Daily interpolated values were calculated, even when there were no flux measurements and then summed to obtain the cumulative fluxes (Table 2).

Results

The impact of low and high atmospheric N deposition rates on N fluxes and soil mineral N concentrations in forest soil

NO and N₂O fluxes Nitric oxide emissions from the high N treatment were significantly (p<0.01) higher than for the other two treatments during the first 5 days, and emissions peaked
Table 2 Summary of soil NO and N₂O fluxes and KCl exchangeable NH₄⁺-N and NO₃⁻-N content. Experiment 1: N application rates are equivalent to an atmospheric N deposition rate of 3 kg N ha⁻¹ (Low N) and 30 kg N ha⁻¹ (High N). Experiment 2: N fertilizer applications are equivalent to 150 kg N ha⁻¹. Nitrogen was not applied to the controls in experiments 1 & 2. Experiment 3: The pulsing experiment received a low rate of N (3 kg N ha⁻¹) applied to dry soil.

| Treatments       | NO Average flux | N₂O Cumulative emission | N₂O Average concentrations | NH₄⁺-N Average concentrations | NO₃⁻-N Average concentrations |
|------------------|-----------------|--------------------------|----------------------------|-------------------------------|-------------------------------|
|                  | ng N g⁻¹ h⁻¹    | ng N g⁻¹                 | µg N g⁻¹                   |                               |                               |
| Control          | 0.5 ± 0.4 a      | 0.1 ± 0.0 d               | 11.1 ± 1.4 a               | 19.6 ± 6.23 a                 |                               |
|                  | (0.1–1.4)        | (0.0–0.2)                 | (0.0–6.0)                  | (10.4–32.5)                   |                               |
| Low N            | 0.6 ± 0.5 a      | 0.2 ± 0.1 b               | 18.8 ± 2.7 a               | 22.8 ± 7.0 a                  |                               |
|                  | (0.1–1.5)        | (0.0–0.4)                 | (42.2–94.1)                | (8.3–34.9)                    |                               |
| High N           | 1.2 ± 0.9 b      | 0.2 ± 0.2 b               | 349.6 ± 59.3 b             | 54.8 ± 21.8 b                 |                               |
|                  | (0.1–2.7)        | (0.0–0.8)                 | (287.7–406.0)              | (22.7–105.0)                  |                               |
|                  |                  |                          |                            |                               |                               |
| Control          | 0.1 ± 0.1 a      | 0.1 ± 0.1 a               | 20.9 ± 8.0 a               | 18.3 ± 4.9 a                  |                               |
|                  | (0.0–0.6)        | (0.0–0.3)                 | (13.9–29.6)                | (11.4–25.6)                   |                               |
| NH₄NO₃           | 0.9 ± 1.0 a      | 15.6 ± 12.8 c             | 227.2 ± 48.7 c             | 254.4 ± 106.7 b               |                               |
|                  | (0.0–2.8)        | (0.1–35.4)                | (419.6–6224.4)             | (92.4–430.7)                  |                               |
| Urea             | 1.3 ± 1.4 c      | 22.2 ± 20.9 c             | 375.6 ± 18.8 c             | 214.3 ± 84.3 b                |                               |
|                  | (0.0–3.9)        | (0.0–7.02)                | (464.6–14,080.1)           | (104.6–329.6)                 |                               |
| Urea + Agrotain  | 0.5 ± 0.2 b      | 6.2 ± 5.5 b               | 158.1 ± 11.9 b             | 258.0 ± 79.8 b                |                               |
|                  | (0.0–1.0)        | (0.0–17.9)                | (145.5–169.2)              | (119.5–384.9)                 |                               |
| Agricultural soil| 0.4 ± 0.5 a      | 0.5 ± 1.0 a               | 111.9 ± 17.6 a             | 16.0 ± 6.6 a                  |                               |
|                  | (0.0–1.7)        | (0.0–3.6)                 | (92.0–125.3)               | (8.4–27.7)                    |                               |
| Forest soil      | 0.7 ± 0.5 b      | 0.1 ± 0.1 a               | 308.3 ± 51.2 b             | 15.2 ± 5.5 a                  |                               |
|                  | (0.2–2.1)        | (0.0–0.3)                 | (249.2–339.9)              | (4.9–24.8)                    |                               |

Data shown are average/cumulative ± standard deviation (n = 4) of fluxes / concentrations over the 17 days incubation periods, with minimum and maximum values shown in brackets.

Different letters across the columns for each experiment indicate a significant difference between treatments at P < 0.05.

on day 3 followed by a significant (p<0.01) decrease of about 75% by day 8 (Fig. 1a). Thereafter fluxes were not significantly different from the control and low N treatments. Generally, NO emissions from the control and low N treatments were not significantly different from each other and followed similar emission trends throughout the 17 day measurement period (Table 2, Fig. 1a). For both NO emissions peaked immediately after N addition, and then declined to significantly (p<0.01) smaller emissions on day 4 (control) and day 5 (low N). Overall average NO fluxes were 0.5 ± 0.4, 0.6 ± 0.5 and 1.2 ± 0.9 ng NO-N g⁻¹ h⁻¹ for the zero N control, the low N deposition and high N deposition treatments, respectively; and cumulative emissions ranged from 148 to 350 ng N g⁻¹ (Table 2).

Control core N₂O emissions did not change significantly during the 17 day study period, and average emission rates of 0.10 ± 0.03 ng N₂O-N g⁻¹ h⁻¹ were significantly lower (p<0.05) than for the low and high N deposition rates (0.2 ± 0.2 ng N₂O g⁻¹ h⁻¹) (Table 2). For the low N treatment a significant 26-fold increase in N₂O emissions was observed on day 2, which then remained at a relatively stable value of about 0.2 ± 0.1 ng N₂O-N g⁻¹ h⁻¹. For the high N treatment, a significant 2-fold increase (p<0.01) in N₂O emission occurred between day 1 and 2 and continued to increase until day 5. Thereafter N₂O declined to the rates of the control and low N treatment, with no significant differences between them (Fig. 1b). Cumulative soil N₂O emissions ranged from 37 to 69 ng N g⁻¹ (Table 2).

Soil mineral N concentrations Forest soil exchangeable NH₄⁺ concentrations remained low during the incubation period. Average concentrations ranged from 1.1 to 2.0 µg NH₄⁺-N g⁻¹, and there were no significant differences between treatments or with time (Fig. 2c). Contrary soil NO₃⁻ concentrations were one order of magnitude higher than exchangeable NH₄⁺ concentrations (p<0.01). NO₃⁻ contents in the low N
treatment and control cores were not significantly different from each other, and did not change significantly with time. Average concentrations were 19.6 and 22.8 μg N O\textsubscript{3}− N g\textsuperscript{−1}. For the high N deposition rate soil NO\textsubscript{3}− concentrations were about 2.5 times larger than the control, 2 days after N application. They decreased with time until day 12, and then rose again on the last measurement day 17 (Fig. 2d). Apart from day 12, NO\textsubscript{3}− concentrations were significantly (p<0.01) larger than the control and low N treatment.

The effect of different N fertilizer types on soil N fluxes and soil mineral N concentrations in agricultural soil

NO and N\textsubscript{2}O fluxes Soil NO emissions were significantly (p<0.01) higher from the N fertilized cores compared to the zero N control. Average fluxes measured during the 17 day period were 0.1 ± 0.1, 0.9 ± 1.0, 1.3 ± 1.4, and 0.5 ± 0.2 ng NO-N g\textsuperscript{−1} h\textsuperscript{−1} for the control, NH\textsubscript{4}NO\textsubscript{3}, urea, and UI,
respectively, with cumulative NO fluxes ranging from 21 to 376 ng N g⁻¹ (Table 2). Overall, there was no significant difference between NH₄NO₃ and urea applications (p>0.05), and both were significantly (p<0.01) higher than the UI treatment. For all N treatments significant increases (p<0.01) in NO emissions were measured by day 2. For NH₄NO₃, NO emissions peaked on day 2 (2.6 ± 0.2 ng NO-N g⁻¹ h⁻¹), at rates about ten times higher than NO emissions from the control, and thereafter declined significantly (p<0.01) to zero by day 8 and not significantly different from the control. For the urea application, NO emissions plateaued at 3.0 ± 0.7 ng NO-N g⁻¹ h⁻¹ from the 3rd to the 5th day. For UI, peak NO emissions occurred the day after fertilizer application (0.7 ± 0.0 ng NO-N g⁻¹ h⁻¹) and were about 70% lower that the peak NO emissions for NH₄NO₃ and urea. A significant decreasing trend occurred from the 4th day onwards (Fig. 2a).

Soil N₂O emissions followed a very similar pattern to NO emissions. N₂O fluxes from the zero N control were significantly smaller (p<0.01) than for the N fertilizer treatments, and average fluxes were 0.1 ± 0.1, 15.6 ± 12.8, 22.2 ± 20.9, and 6.2 ± 5.5 ng N₂O-N g⁻¹ h⁻¹ for the control, NH₄NO₃, urea and UI, respectively, and cumulative N₂O emissions ranged from 45 to 8492 ng N g⁻¹ (Table 2). Differences were not significant (p>0.05) between NH₄NO₃ and urea, but both were significantly (p<0.01) larger than UI. The response of increased N₂O fluxes after NH₄NO₃ application was faster than for the urea application, as also observed for soil NO emissions. By the second day, NH₄NO₃ induced N₂O emissions had increased significantly (p<0.01) from 0.1 ng N₂O-N g⁻¹ h⁻¹ to 29.9 ng N₂O-N g⁻¹ h⁻¹, and further significantly (p<0.01) increased to a peak emission of 32.7 ng N₂O-N g⁻¹ h⁻¹ on the 3rd day. Thereafter emissions declined steadily, and were not significantly different from the control by day 8 (p>0.05). For urea, a significant increase was observed on the 3rd day and peak emissions (45.0 ng N₂O-N g⁻¹ h⁻¹) were achieved on the 4th day after urea application, and remained high until day 8. Thereafter emissions declined significantly (p<0.01), and were statistically the same as the control on the 12th and 17th day (p>0.05). For UI, a small significant (p<0.01) increase of N₂O emission was observed from 0.0 ng N₂O-N g⁻¹ h⁻¹ (day 1) to 9.9 ng N₂O-N g⁻¹ h⁻¹ (day 5) and then returned to same rates as for the control plots (Fig. 2b).

**Soil mineral N concentrations** Average soil exchangeable NH₄⁺ concentrations ranged from 0.3–0.7 μg g⁻¹ during the incubation period, and did not show significant differences between treatments and with time, except that the exchangeable NH₄⁺ concentration in the urea treatment was significantly (p<0.01) higher than the control on the 2nd day after fertilization application (Table 2, Fig. 2c). Soil NO₃⁻ concentrations from fertilized cores were more than 2 orders of magnitude higher than soil exchangeable NH₄⁺ concentrations and for the control soil NO₃⁻ concentrations were around 10 fold higher than soil exchangeable NH₄⁺ concentrations. Average NO₃⁻ concentrations in the control cores were about 18.3 ± 4.9 μg NO₃⁻ N g⁻¹, whereas N fertilizer application had increased NO₃⁻ concentrations to 254.4 ± 106.6, 214.3 ± 84.3, 258.0 ± 79.8 μg NO₃⁻ N g⁻¹ for the NH₄NO₃, urea and urea with Agrotain® treatment, respectively. However, there were no statistical significant differences with time and fertilizer type (p>0.05) (Fig. 2d).

**The impact of the pulsing effect on N fluxes and soil mineral N concentrations from forest and agricultural soils**

**NO and N₂O fluxes** At the start of the experiment, the WFPS was adjusted to the saturated soil moisture content in the forest (50%) and in the agricultural field (45%). During the incubation period, the WFPS decreased at a relatively constant rate in both soils. Differences between the soil moisture of the forest and agricultural soil were maintained throughout the study. At the end of the incubation period, the WFPS of the forest and agricultural soil had decreased to 15% and 10%, respectively (Fig. 3e).

The response of NO flux to the pulsing effect was faster in the agricultural soil compared to the forest soil. In the forest soil, NO emissions increased significantly (p<0.01) until the 3rd day of incubation, and further increased significantly to the peak NO emission of 1.8 ng NO-N g⁻¹ h⁻¹ on the 8th day of incubation, after which emissions decreased. For the agricultural soil, NO emissions increased immediately after water addition on the first day, and increased significantly (p<0.01) to peak NO emissions (1.37 ng NO-N g⁻¹ h⁻¹) on the second day of incubation. Significant decreasing trends were observed from the 3rd day onwards (Fig. 3a).

The pulsing effect significantly stimulated N₂O emissions for both, the forest and agricultural soil, and followed a similar trend. N₂O emissions peaked on day two, and was significantly (p<0.01) higher for the agricultural soil compared to the forest soil (2.84 ng N₂O-N g⁻¹ h⁻¹ for agricultural, and 0.28 ng N₂O-N g⁻¹ h⁻¹ for the forest). Thereafter N₂O emissions from the forest and agricultural soils significantly decreased, and on the 5th (agricultural soil) and 8th (forest soil) day N₂O emissions had returned to those on day 1 (Fig. 3b). Cumulative soil NO and N₂O emissions from the agricultural (112 ng NO-N g⁻¹, 97 ng N₂O-N g⁻¹) and forest (308 ng NO-N g⁻¹, 32 ng N₂O-N g⁻¹) soils were within the range of fluxes measured in experiment 1.

**Soil mineral N concentrations** Forest soil exchangeable NH₄⁺ concentrations were much higher during the first 8 days compared to the agricultural soil and significantly decreased thereafter (p<0.01). In contrast, exchangeable NH₄⁺ concentrations of the agricultural soil increased significantly (p<0.01) in the second week only (Fig. 3c). Soil NO₃⁻ concentrations first
showed a significant increasing trend, peaked on day 5 and thereafter declined in both, the forest and agricultural soils (Fig. 3d).

**Discussion**

The results of this paper have provided interesting observations on soil NO and N\textsubscript{2}O emissions from an alkaline Regosol supporting a forest and agricultural system within around 500 m from each other. Both ecosystems received N as atmospheric N deposition to the forest, at a relatively low rate of 30 kg N ha\textsuperscript{-1} yr\textsuperscript{-1} compared to N fertilization (150 kg N ha\textsuperscript{-1} yr\textsuperscript{-1}) to agricultural soils. This N input increases soil N availability and thereby provides substrates for nitrification; and the product of nitrification, NO\textsubscript{3}\textsuperscript{-}, provides substrates for denitrification (Freedman et al. 2016). Both processes can lead to the production and emission of NO and N\textsubscript{2}O.

**Drivers of soil NO and N\textsubscript{2}O emissions**

In the present study much more NO than N\textsubscript{2}O was emitted from the forest soil in the N deposition experiment 1, whereas the opposite was the case for the agricultural soil in the N fertilization experiment 2. Over the 17-day measurement period, cumulative fluxes of NO were on average 4 times larger than of N\textsubscript{2}O for the forest soil (experiment 1), whereas about 16 times more N\textsubscript{2}O than NO was emitted from the agricultural soil (experiment 2) (Table 2). Interestingly, in the pulsing experiment (experiment 3) NO emissions dominated in both the agricultural and forest soils, with 5 times more NO emissions compared to N\textsubscript{2}O emissions. The reason for this difference to experiments 1 and 2 is related to differences in the soil moisture content. In experiment 1 and 2 the soil moisture content was kept at a constant WFPS prior to adding N, in order to avoid the pulsing effect. Contrary, the aim of experiment 3 was to study the pulsing effect, i.e. dry soils were wetted to the same WFPS as in experiments 1 and 2, but then left to dry out (Fig. 3). Thus we may infer that the
pulsing effect can contribute significantly to NO and N₂O emissions from fertilized soils, and should be accounted for in measurements and models.

Many physical and chemical properties influence NO and N₂O emission, by providing conditions that promote either nitrification or denitrification, such as soil C and P content, pH, soil texture, temperature and soil water (Mehnaz et al. 2018). Of these parameters, soil water, often expressed as WFPS, is a key driver in determining the redox potential and thereby oxygen availability (Werner et al. 2007). WFPS is a function of the soil moisture content and the soil bulk density and thereby influences the relative proportions of N₂O and NO emissions (Ludwig et al. 2001). Based on measurements from different ecosystems, Davidson (2000) created a simple model stating that soil NO emissions occur at lower soil WFPS (range 10–60%) than N₂O (range 40–80%). There are of course variations with ecosystems. For example, van Dijk and Meixner (2001) observed maximum NO emission at a WFPS of 27% for a tropical forest soil; and Schindlbacher et al. (2004) reported a maximum N₂O emission at a WFPS of 80% in the temperate boreal forest in Europe. In our pulsing experiment, NO and N₂O emissions from the agricultural soil both peaked on the second day at a soil water content of about 43% (Fig. 3). This supports the Davidson (2000) model, that probably both processes, nitrification and denitrification could be responsible for the emissions. In the pulsing experiment, NO and N₂O emissions increased exponentially with WFPS (Fig. 4 exp. 3d). Contrary, in the forest soil the relationship of WFPS with N₂O was linear but bell shaped for NO (Fig. 4 exp. 3e).

It is reassuring that our observations agree with other laboratory and field studies across the globe. For example, a meta-study by Liu et al. (2017) has shown that on average forests across the global climate zones have larger NO than N₂O emissions; and a review of fertilized agricultural soils, has shown that N₂O emissions prevail over NO emissions (Bouwman et al. 2002). Similarly, lower N₂O emission fluxes from the forest soil and higher N₂O emission fluxes from a cropland were also observed in field studies at the Yanting research station (Zhou et al. 2019).

**Atmospheric N deposition to forests**

Field measurements from European forests have demonstrated a strong relationship of soil NO emissions with atmospheric N deposition rates, but not for N₂O, because NO was positively correlated with the nitrification process while N₂O was correlated with soil pH and their C/N ratio (Pilegaard et al. 2006). Unlike in this European study (Pilegaard et al. 2006; Schindlbacher et al. 2004) we observed a significant correlation of soil NO and N₂O emissions with each other (Fig. 4 exp. 1a), but only soil NO emissions significantly increased under simulated high N deposition rates (30 kg N ha⁻¹) (Fig. 1). Atmospheric N deposition has increased substantially in southwest China. For example, over a 6 year period (2008–2013) the bulk wet deposition of N had increased from 17 kg N ha⁻¹ yr⁻¹ to 25 kg N ha⁻¹ yr⁻¹ in the Sichuan province, where our soils originate from (Song et al. 2017). The higher N deposition rate may alleviate short-term nutritional constraints in N limited ecosystems and may increase C sequestration in the above and below ground woody biomass (Schulte-Uebbing and de Vries 2018). However, once such ecosystems reach N saturation further N additions can lead to increased N losses, such as higher NO₃⁻ leaching rates, and increased NO and N₂O emissions (Galloway et al. 2004; Peterjohn et al. 1998). In our study, simulated atmospheric N deposition to the forest soils increased soil NO₃⁻ concentrations, which significantly correlated with NO and N₂O emissions (Fig. 4, exp. 1b, c).

Atmospheric N deposition stimulates N₂O and NO production in the same manner as N fertilizer application, albeit at much lower rates. The molecule NO₃⁻ is the endpoint of the nitrification pathway, and the starting point of denitrification. It is tempting to speculate that the presence of large NO₃⁻ concentrations are an indication of N₂O production by denitrification. However, this may not be the case. The processes nitrification and denitrification occur simultaneously in different microsites within the soil (Dong et al. 2018). Sophisticated isotopic labelling studies have identified many different processes (Butterbach-Bahl et al. 2013), but without isotopic labels it is impossible to identify whether large NO₃⁻ concentration rate are indicative of soil N₂O production by nitrification or denitrification in this study.

**N fertilized agricultural soils**

Most agricultural soils require large amounts of N fertilizers, either in mineral or organic form, to optimize food production. Urea and NH₄NO₃ are amongst the most widely used N fertilizers worldwide, and are the main cause of N₂O, NH₃ and NO emissions. To reduce these emissions chemicals have been developed to slow down the rate of nitrification to NO₃⁻ and the hydrolysis of urea to NH₃. The delay of both processes increases the chance of fertilizer uptake by roots, and thereby reduce NO₃⁻ leaching and N₂O emissions in the case of the nitrification inhibitors. Urease inhibitors combined with urea, such as the commercially available product ‘Agrotain®’ delay the hydrolysis of urea and increase the time available for sufficient rain to fall and move surface applied urea into the soil and thereby reduce NH₃ loss. Smaller soil NH₄⁺ concentrations would lead to reduced nitrification and denitrification rates (Akiyama et al. 2010). The impact of nitrification inhibitors is well researched (Ruser and Schulz 2015), whereas we hardly know if urease inhibitors can have any influence on nitrification and denitrification rates. This laboratory study did not allow us to measure the impact of
fertilizer type on NH$_3$ losses as the small soil cores used were unsuitable for such measurements; besides the focus of this laboratory study lies on the impact of fertilizer type on NO and N$_2$O emissions. However, it is very interesting to observe that Agrotain® decreased NO and N$_2$O emissions significantly, compared to the NH$_4$NO$_3$ and urea fertilizers. There were no significant differences between the NH$_4$NO$_3$ and urea treatments for both, NO and N$_2$O emissions. This suggests that adding Agrotain® to urea may have some beneficial effect reducing emissions of N$_2$O and NO. Similarly, Cowan et al. (2019) and Smith et al. (2012) found that the use of a urease inhibitor in the field can provide some mitigation of N$_2$O emission both in UK crop and grasslands, and Kuang et al. (2019) reported reduced N$_2$O emissions from a laboratory study using a sandy loam from North West China. This was also concluded in a global meta-analysis evaluating a range of enhanced-efficiency fertilizers, including fertilizers with urease inhibitors (Akiyama et al. 2010). The conventional method to reduce soil NO and N$_2$O emissions is adding nitrification inhibitors or controlled-release N fertilizers, which can achieve substantial emission reductions (Liu et al. 2017).

In contrast to the forest soils, agricultural N$_2$O emissions were significantly higher than NO emissions for all three fertilizer treatments (Fig. 2a, b). The occurrence of such high N$_2$O emission in the alkaline agricultural soil could be explained by: 1) excessive N inputs creating an N surplus status which provides more N substrates for microbial N$_2$O production (McSwiney and Robertson 2005); 2) the high NO$_3^-$ content inhibited the reduction of N$_2$O to N$_2$, because of the decreased N$_2$O reductase activity (Senbayram et al. 2012, Kuang et al. 2019). Nitric oxide and N$_2$O fluxes correlated significantly with each other (Fig. 4 exp. 2a), and both correlated significantly with the soil NO$_3^-$ content (Fig. 4 exp. 2b, c), as was also the case for the forest soils. This does not necessarily imply that both gases are products of denitrification. Nitrate concentrations may equally represent the product

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**Fig. 4** Significant correlations between the fluxes and variables measured in experiment 1 (left column), experiment 2, (middle column) and experiment 3 (right column) (a) NO vs N$_2$O fluxes; (b) NO$_3^-$ concentrations vs NO fluxes; (c) NO$_3^-$ concentrations vs N$_2$O fluxes; (d & e) water filled pore space (WFPS) vs NO and N$_2$O fluxes for agricultural (d) and forest (e) soils. Symbols represent averages of 3 replicate soil cores for each measurement date. Experiment 1: control (black squares), low N deposition rate (red triangles), high N deposition rate (blue diamonds). Experiment 2: control (black squares), NH$_4$NO$_3$ (red triangles), urea (blue diamonds), urea with Agrotain® inhibitor, pink circles). Experiment 3: agricultural soils (red triangles) and forest soils (black squares) in a, and NO (black squares) and N$_2$O (red triangles) in d and e.
formation during nitrification as well as the substrate reduct
in denitrification, depending on the redox potential of
individual soil microsites. A recent field study at Yanting
Research Station, investigated soil N2O emissions within
3 weeks after application of an organic fertilizer together with
analysis of functional genes related to nitrification and deni-
trification processes, and concluded that denitrification was
the main source of N2O (Dong et al. 2018).

The pulsing effect

In experiment 1 (forest) and 2 (agriculture), the 10 day pre-
incubation period prior flux measurements was designed to
avoid the pulsing effect, in order not to interfere with the
comparison of N fertilizer types or N deposition rates. The
‘Birch’ effect (Birch 1964) - the surge in microbial activity
after dormancy, triggered by a rain event after prolonged pe-
riods of drought or temperature rise defrosting soil in cool
continental climate regions - leads to pulses of gaseous emis-
Sions, such as CO2, N2O and NO. The timing and rate of these
emission pulses is highly unpredictable, but can be an im-
portant contribution to the overall annual flux, especially in re-
gions that experience seasonal freeze/thaw or wet/dry cycles
(Dick et al. 2001; Medinets et al. 2016b). The water addition
at the start of the pre-incubation period, and prior to the start of
the measurements, would have stimulated nitrification and
denitrification processes and accompanying N2O and NO
emissions in a similar manner to those observed for the puls-
ing effect (experiment 3) (Wei et al. 2017). When the actual
experiments were conducted, the microbial community would
have been sufficiently large to rapidly nitrify the added N,
resulting in the large NO3− concentrations observed in the N
fertilized agricultural soils, but not in the zero N control (Fig.
2d). The same was observed in experiment 1 for the higher rate
of atmospheric N deposition applied to the Cypress forest
soils (Fig. 1d), albeit NO3− accumulation was at a much lower
rate compared to the agricultural soil (Fig. 2d). In contrast, in
the pulsing study, where only a low rate of N, equivalent to
3 kg N ha−1, was applied to dry forest and agricultural soil,
NO3− concentrations increased within the first few days after
application and then slowly declined in a very similar manner
in both soils. Ammonium concentrations remained at back-
ground levels.

Previous long-term field studies, conducted at the Yanting
agricultural research station also observed that NO3− is the
dominant form of inorganic N in these purple soils (Wang
et al. 2012, 2015 a,b; Zhou et al. 2012; Zhu et al. 2012). A
15N incubation experiment, also using alkaline soil from
Yanting station, confirmed that the soil NO3− dynamics in this
region appear to be governed by nitrification (Wang et al.
2015b); and, as in our study, promote rapid oxidation of
NH4+ to NO3− (Dong et al. 2018; Wang et al. 2015b; Zhang
et al. 2016a,b). Most of added soil NH4+ transformed to NO3−
within 24 h and soil NO3− concentrations increased sharply
within 48 h because of fast nitrification rates (Wang et al.
2015b). This is also the reason why NO3− concentrations in
relation to exchangeable NH4+ concentrations are disproportionaly larger already at the start of the agricultural
and forests soils in experiment 1 and 2 (Figs. 1, 2, Table 2).

Microbial pathways

Soil NO/N2O emission ratios provide a crude indication of the
prevailing nitrification/ denitrification processes, with ratios
>1 suggestion that nitrification is the main source, and a ratio
of <1 for denitrification (Medinets et al. 2015). This implies
that forest emissions are probably driven by nitrification,
whereas agricultural emissions by denitrification. Although
generally, soil NO emissions are associated with nitrification
processes, denitrification could, under some circumstances
also be a source of soil NO. For example, Loick et al. (2016)
has demonstrated in a He/O2 atmosphere, with 15N labeled
KNO3 and glucose additions that denitrification contributed
to N loss as NO, in addition to the recognized denitrification
products N2O and N2. Abiotic soil NO emissions are mainly
associated with acid soils and are unlikely to occur at signifi-
cant rates in alkaline soils (Medinets et al. 2015). Denitrification is the main pathway for N2O, but N2O is also
a product of nitrification. The relative emission rates depend
largely on the redox potential and soil N availability
(Butterbach-Bahl et al. 2013).

It is not easy to identify the underlying pathways responsible
for the emissions rates, without using isotopic tracers or
studying the gene abundance. However, existing studies with-
in the Sichuan basin on alkaline soil and same climate and
agricultural management, could provide insight into the pro-
cesses responsible for the NO and N2O emissions in our study.
For example, a recent analysis of nitrification and denitrifica-
tion genes and N2O emissions from a wheat/maize field in the
Sichuan basin on alkaline soil, concluded that both nitrifica-
tion and denitrification pathways, with denitrification domi-
nating, contributed to the N2O flux in the first few weeks after
N fertilization when mineral N supply in the soil is high (Dong
et al. 2018). Contrary, when soil mineral N concentration rates
were low, as in our forest soils, nitrification by ammonium
oxidizing archaea and bacteria (AOA, AOB) were mostly
responsible for the N2O flux. AOA and AOB are also responsible
for soil NO emissions (Behrendt et al. 2017). If we assume
that these findings can be translated to our experiment, then
one may speculate that in the forest soil the relatively low rates
of mineral N compared to the agricultural soil would promote
nitrification by AOA and AOB, and possibly AOA would
prevail, due to a larger SOM content (Table 1), compared to
the agricultural soil. The domination of nitrification would
also explain why the forest soil has larger NO emissions than
N2O emissions. The opposite would be the case for the
agricultural soil, were very large soil $\text{NO}_3^-$ concentrations (Table 2) would favor denitrification to $\text{N}_2\text{O}$ and $\text{N}_2$ production. Denitrification to $\text{N}_2$ was not measured in our study, but was measured from the same experimental station at Yanting using the acetylene inhibition method (Dong et al. 2014). They found that overall $\text{N}_2\text{O}$ and $\text{N}_2$ emissions were of similar order of magnitude, possibly due to large $\text{NO}_3^-$ concentrations, which slowed down the reduction of $\text{N}_2\text{O}$ to $\text{N}_2$ (Dong et al. 2018).

The preference of AOA and AOB in soils with low mineral N concentrations (Dong et al. 2018) may be the reason why in experiment 3 (the pulsing experiment) soil NO emissions prevail over soil $\text{N}_2\text{O}$ emissions in both, the agricultural and forest soils. In addition, the rapid declining WFPS would promote nitrification (Fig. 3).

In this paper we have demonstrated contrasting soil NO and $\text{N}_2\text{O}$ fluxes in response to high and low N application rates and soil moisture contents from a forest and agricultural soil. The data highlight the importance of the pulsing effect on soil NO and $\text{N}_2\text{O}$ emissions in both agricultural and forest soils, and presumably also of other natural ecosystems. One can speculate about the possible microbial pathways involved, however to model NO and $\text{N}_2\text{O}$ emissions in relation to N deposition rates and soil moisture changes (including the pulsing effect), it is important to include isotopic tracers and/or genetic markers to ascribe the underlying processes.

Conclusion

The controlled environment laboratory studies have successfully demonstrated the impact of atmospheric N deposition, N fertilizer type, and the pulsing effect (rewetting dry soil) on NO and $\text{N}_2\text{O}$ emissions from an alkaline Regosol, supporting adjacent forest and agricultural ecosystems. Contrasting NO/ $\text{N}_2\text{O}$ emission ratios, with soil NO dominating forest emissions, and $\text{N}_2\text{O}$ being the principal emission source in the agricultural soils, have been observed previously. However, what is interesting in this study is the prevalence of soil NO emissions in forests and of $\text{N}_2\text{O}$ emissions in agricultural soils; and that this is happening in both, the N addition and the pulsing experiments. Overall, soil NO emission rates were not significantly different across the three experiments. Since their impact on atmospheric chemistry is large, one should study not only fertilizer induced agricultural emissions, but focus also on the forest emissions and particularly on hotspot emissions, i.e. a heavy rainfall after drought. Contrary, for $\text{N}_2\text{O}$, the fertilizer induced emission rates dwarf the emission pulses after rewetting. Nitric oxide and $\text{N}_2\text{O}$ emissions increased significantly when fertilized with NH$_4$NO$_3$ and urea, but there was no difference in the flux rates between the two fertilizers. Addition of the urease inhibitor ‘Agrotaín®’ effectively reduced NO and $\text{N}_2\text{O}$ emissions, although it’s main role would be to reduce ammonia emission. The latter was not tested in this study. This observation is interesting, and not well known. Further research is needed to understand the underlying processes of reduced soil NO and $\text{N}_2\text{O}$ emission when the urease inhibitors ‘Agrotaín®’ is applied in the presence and absence of vegetation.

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