Type of contribution: Research paper

Date of preparation: 21/6/2016

Title: The effect of temperature and moisture on the source of N_2O and contributions from ammonia oxidizers in an agricultural soil

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Submitted to: *Biology and Fertility Soils*

ABSTRACT

In recent years, identification of the microbial sources responsible for soil N_2O production has substantially advanced with the development of isotope enrichment techniques, selective inhibitors, mathematical models, and the discoveries of specific N-cycling functional genes. However, little information is available to effectively quantify the N_2O produced from different microbial pathways (e.g. nitrification and denitrification). Here, a ^{15}N-tracing incubation experiment was conducted under controlled laboratory conditions [50%, 70% and 85% water-filled pore space (WFPS) at 25°C and 35°C]. Nitrification was the main contributor to N_2O production. At 50%, 70% and 85% WFPS, nitrification contributed 87%, 80% and 53% of total N_2O production, respectively, at 25°C, and 86%, 74% and 33% at 35°C. The proportion of nitrified N as N_2O (P_{N2O}) increased with temperature and moisture, except for 85% WFPS, when P_{N2O} was lower at 35°C than at 25°C. Ammonia-oxidizing archaea (AOA) were the dominant ammonia oxidizers, but both AOA and ammonia-oxidizing bacteria (AOB) were related to N_2O emitted from nitrification. AOA and AOB abundance was significantly influenced by soil moisture, more so than temperature, and decreased with increasing moisture content. These findings can be used to develop better models for simulating N_2O from nitrification to inform soil management practices for improving N use efficiency.

Keywords Nitrification, ammonia-oxidizing archaea, ammonia-oxidizing bacteria, ^{15}N isotope technique, model

Introduction

Nitrous oxide (N_2O) is a trace greenhouse gas that contributes to global warming and stratospheric ozone depletion. Soils are the largest source of N_2O, accounting for approximately 65% of the anthropogenic atmospheric loading of N_2O (IPCC 2007). N_2O is generated through several microbiological processes in soils including nitrification, denitrification, dissimilatory nitrate reduction to ammonium (DNRA) and nitrifier denitrification (Wrage et al. 2005; Li et al. 2014; Hu et al. 2015), though the primary N_2O sources are believed to be nitrification and denitrification. Ammonia oxidation, the first step of nitrification catalyzed by the *amo*A gene encoding the ammonia monooxygenase (AMO) enzyme, is performed by two distinct types of nitrifiers: ammonia-oxidizing bacteria (AOB) (Purkhold et al. 2000) and ammonia-oxidizing archaea (AOA) (Brochier-Armanet et al. 2008; Watanabe et al. 2011). Ammonia oxidation is the rate-limiting step of the nitrification process and thus is critical for nitrification-derived N_2O emissions. Denitrification is the process in which nitrate (NO_3^-) is reduced to N_2 under anaerobic conditions by denitrifiers, and N_2O is an intermediate.

There have been many studies to investigate and distinguish the N_2O production pathways by using stable isotope (^{15}N and ^{18}O) tracer technique (Wrage et al. 2005). Some of these studies used selective inhibitors (e.g. Bateman and Baggs 2005), and mathematical modelling (Müller et al. 2014). However, each methodology was used alone cannot provide a precise clarification of the pathways, and the microbial mechanisms and the relative contribution of each pathway are poorly understood as well (Hu et al. 2015).

Furthermore, there are multiple factors regulating N_2O emissions from soils, such as agricultural practices, climatic conditions and soil properties (Mørkved et al. 2007; Livesley

et al. 2008; Butterbach-Bahl et al. 2013; Yamamoto et al. 2014), adding uncertainty in predicting N_2O production and consumption pathways in complex soil environments.

Soil water content and temperature are the predominant factors regulating N_2O production and the contribution of nitrification and denitrification to N_2O emission from soils (Cheng et al. 2014; Hu et al. 2015). It was reported that N_2O emitted from fields amended with N fertilizer was affected mainly by soil moisture conditions (Zheng et al. 2000; Huang et al. 2004). Increasing N_2O emissions with increasing temperature from 10°C to 15°C indicated that N_2O production was sensitive to soil temperature (Lang et al. 2011). Allen et al. (2010) showed that N_2O emissions were higher during wet and hot months than in cool and dry months. A higher temperature was favourable for nitrification within a certain range (25°C to 35°C) (Haynes 1986). Generally, the rate of N_2O production is low below 40% water-filled pore space (WFPS), but increases rapidly from around 50% to 65% WFPS in the absence of other limiting factors, such as NH_4^+ supply (Dalal et al. 2003; Bateman and Baggs 2005; Mathieu et al. 2006.) It is a common belief that nitrification is the principal source of N_2O in aerobic conditions while denitrification the predominant contributor to N_2O production in anaerobic conditions (Mathieu et al. 2006). It has been reported that nitrification could contribute around 80% of total N_2O emissions depending on soil temperature and moisture (Godde and Conrad 1999). It is usually considered that the maximum N_2O production from denitrification and/or nitrification will occur when soil moisture content falls within 55-85% WFPS (Granli and Bøeckman 1994). A higher soil water content stimulates the reduction of N_2O to N_2 in denitrification, thus the ratio of N_2/N_2O increases with soil moisture content above 75% WFPS (Davidson 1992; Weier et al. 1993; Saggar et al. 2013). The effect of a single factor, temperature or moisture, on nitrification and denitrification sourced N_2O emissions has been well documented (Liu et al.

2016). However, limited information is available on the interaction of these factors regulating N_2O pathways and the correlations between nitrification-derived N_2O and nitrifiers under different environmental conditions.

There is emerging evidence that the soil microbial communities (AOA and AOB) play a vital role in determining the consumption and production of N_2O (Di et al. 2009; Jia and Conrad 2009; Leininger et al. 2006; Mertens et al. 2009; Offre et al. 2009; Tourna et al. 2008; Zhang et al. 2012; Akiyama et al. 2014). However, there are some controversial conclusions on the contributions of AOA and AOB in nitrification. Di et al. (2010) demonstrated that N_2O flux was associated with the dynamics of AOB in N-rich grassland soils. Jia and Conrad (2009) reported that AOB was more active in ammonia oxidation than AOA in agricultural soils even though the AOA populations were much more abundant than the AOB populations. However Andert et al. (2011) did not observe a significant relationship between AOA or AOB abundance and N_2O emission in boreal peat soils. Therefore, more research is required, particularly under variable conditions, to improve our understanding of possible impacts on AOA and AOB abundance dynamics and N_2O production in agricultural soils.

The objectives of this study were: 1) to investigate how soil moisture and temperature affect the contribution of nitrification and denitrification to N_2O emissions and the abundance of AOA and AOB, and 2) to explore the relationship between N_2O emission and AOA and AOB abundance.

Materials and methods

Site description and soil sampling

Surface soil (0-10 cm) was collected from the Victorian Department of Economic Development, Jobs, Transport and Resources research farm 9 km south of Hamilton, Victoria, Australia (38.32° S, 142.07° E). The study site is in a high rainfall zone (688 mm per annum) and subjected to two land management practices: cropping and pasture. Previous studies at the site found that high N_2O emissions occurred when the soil was converted from pasture to cropping (Officer et al. 2008, 2012). We collected soil from the cropping system after harvest (January 2012) when wheat-stubble covered the soil surface. The soil is classified as a Chromosol (Isbell 1996), with an acidic gravelly loam topsoil, and contained 0.52% total N, 5.2% organic C, 19% clay, 38% silt and 43% sand. The CEC was 9.42 meq/100g and the soil pH (H_2O) was 4.5. The original exchangeable NH_4^+-N and NO_3^--N were 13 and 93 mg kg^{-1} soil, respectively.

Soil incubations

Design of soil microcosms

Collected soil was air-dried and remaining roots and leaves were removed with tweezers. The soil was then ground and sieved (< 2 mm) prior to establishment of the microcosm incubation. Subsamples were taken to determine gravimetric moisture content and for chemical analyses. Replicated samples of soil (60g oven-dry equivalent) were placed into 500 ml incubation vials. Distilled water was added to soil to just under the final moisture content (50%, 70% and 85% WFPS) and the microcosms were pre-incubated at 25°C and 35°C for 3 weeks to stabilise the soil microbial communities and prevent priming effects associated with wetting events. After pre-incubation, 2 ml solution were added to each incubation vessel to reach the targeted soil moisture contents. The treatments contained 100 mg N kg^{-1} as exchangeable NH_4^+-N and 50 mg N kg^{-1} as NO_3^--N, which were added to the soil as 1) $^{15}NH_4Cl$ (10 atom%

^{15}N) + KNO_3 and 2) NH_4Cl + $K^{15}NO_3$ (10 atom% ^{15}N). The soils were incubated for 3 weeks under 50%, 70% and 85% WFPS at 25°C and 35°C. The soil samples were aerated by removing the caps for 30 min and the headspace was flushed with fresh air every 3 days and water was replenished every 3 days.

Gas sampling and analysis

Gas samples (20 ml) for N_2O and CO_2 analysis were taken from the headspace of the vials on 0, 4, 7, 12, 15 and 21 days after fertilizer application. Before each gas collection, the vials were opened, flushed with ambient air to ensure ambient N_2O and CO_2 concentrations in the headspace. The vials were sealed with gas collection caps and gas samples (20 ml) were taken using gastight syringes at 0, 8, 24, 48 and 72 hours after vial closure, to determine the N_2O and CO_2 flux, with each sample transferred into a pre-evacuated 12 ml exetainer (Exetainer®, Labco Ltd., Lampeter, Ceredigion, UK). The 20 ml gas samples were analyzed for N_2O and CO_2 by gas chromatography (Agilent 7890A) using an ECD (N_2O) and TCD (CO_2) detector, respectively. A single 70 ml gas samples was collected and injected into a 60 ml evacuated vial for ^{15}N-N_2O by Isotope Ratio Mass Spectrometry (IRMS) (Hydra 20–20, SerCon, Crewe, UK) on days 0, 4, 7 and 15 following flux sample collection (72 hours).

Soil Sampling and analysis

Soils were destructively sampled for soil mineral N analysis on days 0, 7, 15 and 21 and for ^{15}N on days 0, 7, 15 immediately after gas sampling. Two grams of soil was also collected at each sampling time for DNA extraction. Soil (50 g) was shaken with 250 ml 2M KCl for 1 h at 200 rpm at room temperature, and the extracts were filtered through a Whatman 42 qualitative filter paper and analysed for mineral N (exchangeable NH_4^+ and NO_3^-), using a

segmented-flow analyzer (Skalar, SAN++), and ^{15}N abundance in mineral N. The ^{15}N enrichment of exchangeable NH_4^+ and NO_3^- was determined by a micro-diffusion method as described by Saghir et al. (1993), with the modification that an acidified filter paper disc was used instead of the petri dish of acid to absorb NH_3, and analysed by the IRMS (Hydra 20–20, SerCon, Crewe, UK).

Soil DNA extraction and quantitative PCR analysis

The PowerSoil DNA Isolation kit (MO BIO Laboratories Inc., Carlsbad, CA, USA) was used for DNA extraction, following the manufacturer's instructions, of soil samples collected on days 0, 7, and 15. The quantity and quality of the DNA extracted was assessed using a Nanodrop spectrophotometer (NanoDrop Technologies, Wilmington, DE, USA). The *amo*A gene copy numbers were quantified from triplicate samples using quantitative PCR (qPCR) with the universal primer sets to target AOA (Francis et al. 2005) and AOB (Rotthauwe et al. 1997). Each AOA *amo*A qPCR reaction was performed in a 20 µl volume containing 10 µl SensiFAST SYBR green (Bio-Rad Laboratories, USA), 0.5 µM of each primer and 2 µl of 10-fold dilution DNA template (1-10 ng). Amplification conditions were as follows: 95°C for 3 mins, 40 cycles of 5 s at 95°C, 30 s at 60°C, and 45 s at 72°C. Each AOB *amo*A qPCR reaction was performed in a 10 µl volume containing 5 µl iTaq Universal SYBR Green Supermix (Bio-Rad Laboratories, USA), 0.6 µM of each primer and 2 µl of 10-fold dilution DNA template (1-10 ng). Amplification conditions were the same as the AOA qPCR assay. A known copy number of plasmid DNA for AOA or AOB was used to create a standard curve. For all assays, qPCR efficiency was 90-100% and r^2 was 0.96-0.99.

Calculations

N_2O fluxes were calculated according to the following equation (Lan et al. 2013):

$$F=\rho \times \frac{V}{A} \times \frac{\Delta c}{\Delta t} \times \frac{273}{273+T} \qquad (1)$$

where F is the gas flux in μg N_2O-N m^2 d^{-1}, ρ is the density of N_2O under the standard state (kg m^{-3}), V is the volume of the head space (m^3), A is the area of the vial (m^2), $\frac{\Delta c}{\Delta t}$ is the change in gas concentration (*c)* per unit of time (*t*) in ppb d^{-1}, and T is the air temperature within the vessel (°K).

The gross nitrification rate (*n*) was determined by the ^{15}N dilution technique (Kirkham and Bartholomew 1954; Barraclough and Puri 1995).

The relative contributions of denitrification (Cd) and nitrification (Cn) to N_2O production were calculated using the method of Stevens et al. (1997). Briefly, if there is only one denitrifying pool of NO_3, simultaneous nitrification and denitrification can be confirmed by examining the distribution of ^{15}N atoms within the N_2O molecules, particularly in the treatment pair where NO_3 is labelled. When the NH_4 pool is at natural abundance and the NO_3 pool is enriched with ^{15}N, nitrification will produce N_2O at natural abundance while denitrification will produce N_2O of the same enrichment as the NO_3 pool from which it was derived. The relative contributions of two processes can be calculated following the equations:

$$Cd = (a_{N2O} - a_{NH4}) / (a_{NO3} - a_{NH4}) \qquad (2)$$

$$Cn = 1 - Cd \qquad (3)$$

where a_{N2O} is the ^{15}N atom% enrichment of N_2O, a_{NO3} is the ^{15}N atom% enrichment in NO_3^- pool, and a_{NH4} is the ^{15}N atom% enrichment in NH_4^+ pool. Based on Stevens et al. (1997), the relative contributions of nitrification and denitrification to N_2O emission were calculated from the ^{15}N-NO_3 treatment as follows;

N_2O production from nitrification (N_2O_n) was calculated as:

$$N_2O_n = Cn \times N_2O_T \qquad (4)$$

where N_2O_T is the total N_2O emission

N_2O production from denitrification (N_2O_d) was calculated as:

$$N_2O_d = Cd \times N_2O_T \quad (5)$$

The proportion of nitrified N emitted as N_2O (P_{N2O}) was calculated as:

$$P_{N2O} = N_2O_n / n \quad (6)$$

Statistical analyses

Data were analysed using SPSS 19 (IBM, USA) and means were compared using one-way ANOVA between treatments to test the variance with a level of significance of $P < 0.05$. Significant differences in soil properties and microbial gene abundance levels over time and between treatments were examined by ANOVA. Relationships between measures were assessed by correlation analysis, using Pearson's r if data were normally distributed and Spearman's rho if data were not normally distributed (normality assessed by Shapiro-Wilk's W), in both Stata12/SE (StataCorp, USA) and the statistical software package PAST (v2.17; Hammer et al. 2001).

Results

N_2O emission under different environmental conditions

There was no significant difference ($P > 0.05$) in N_2O produced between the $^{15}NH_4^+$ and $^{15}NO_3^-$ treatments throughout the incubation period under any conditions (Figure 1). N_2O production rates increased over the first 7 days and then decreased before stabilising. N_2O production reached a peak flux on day 4 at 70% and 85% WFPS at 25°C, and on day 3 at 35°C for all moisture treatments (Figure 1). The largest N_2O peak (48.92 mg N_2O kg^{-1} d^{-1}) was detected at 85% WFPS and 25°C. A significantly ($P < 0.05$) higher level of N_2O was

emitted at each temperature at 70% or 85% WFPS than 50% WFPS. The N_2O production rates were significantly higher ($P < 0.05$) when the soil temperature was 35°C compared to 25°C, except for the 85% WFPS treatments (Figure 1).

Sources of N_2O under different environmental conditions

The ^{15}N enrichment of the N_2O pool consistently remained between the ^{15}N enrichment of the NH_4^+ and NO_3^- pools under all conditions (Figures 2 and 3), suggesting that N_2O was produced by both nitrification and denitrification. In the $^{15}NH_4Cl + KNO_3$ treatment, the enrichment of the $^{15}NO_3^-$ pool increased during the incubation due to nitrification (Figure 2). In the $NH_4Cl + K^{15}NO_3$ treatment, the enrichment of the $^{15}NH_4^+$ pool remained close to natural abundance throughout the incubation period and ^{15}N abundance in the NO_3^- pool decreased due to dilution by $^{14}NO_3^-$ from nitrification (Figure 3).

Total N_2O emission ($N_2O_d + N_2O_n$) increased with temperature and moisture except for 85% WFPS. At 85% WFPS there was higher total N_2O production at 25°C than at 35°C, suggesting an interactive effect of temperature and moisture on the relative contribution of nitrification and denitrification to N_2O emission (Table 1). The contribution of nitrification (Cn) to N_2O production decreased with increasing temperature and moisture, while the contribution of denitrification (Cd) was the reverse (Table 1). Nitrification contributed more to N_2O emission than denitrification when soil moisture content was 50% and 70% WFPS. At the first incubation week under 85% WFPS, the contribution of denitrification was approximately equal to (35^oC) or less than (25^oC) that from nitrification. On average across all sample days, nitrification was responsible for 87.2%, 79.8% and 52.9% of the N_2O production at 50%, 70%, 85% WFPS respectively at 25°C, and for 86.3%, 73.9% and 33.1% of total N_2O production at 50%, 70%, 85% WFPS respectively at 35°C. N_2O from

nitrification (N_2O_n) increased as the soil moisture content increased from 50% to 85% WFPS, with the greatest production detected at 25°C and 85% WFPS in the first week.

The percentage of nitrified N emitted as N_2O (P_{N2O}) decreased over the incubation time regardless of soil moisture and temperature (Table 1). For the period of day 7 to day 15, P_{N2O} at 50% and 70% WFPS at 25°C (0.0012% and 0.106%, respectively) were lower than those at 50% and 70% WFPS at 35°C (0.0068% and 0.663%, respectively). However, at 85% WFPS, P_{N2O} was higher when the soil temperature was 25°C (0.614%) compared to 35°C (0.0901%).

The dynamics of ammonia oxidizer populations

The abundance of both AOA and AOB responded to the changes in soil temperature and moisture over the incubation period after the application of the treatments (Figure 4). At day 0, at the same soil moisture content, AOA *amo*A gene copies were higher at 35°C compared to 25°C, but AOB *amo*A gene copies were higher at 25°C than at 35°C. Before incubation commencement at day 0 the initial abundances of archaeal and bacterial nitrifiers were greater under higher WFPS conditions (85%) but there were no statistically significant differences. Following application of fertilizers, both AOA and AOB *amoA* gene abundance significantly increased ($P < 0.05$), with the greatest increase observed for AOB. Over the incubation period AOA *amo*A gene copy numbers increased from day 0 to 7 and then declined for the remaining period, whereas AOB *amo*A gene copy numbers increased continually over the incubation period from day 0 to 15 (Figure 4).

Soil moisture had a significant ($P < 0.05$) influence on AOA and AOB abundance (Figure 4). After the treatments were applied, AOA *amo*A gene copy numbers declined as WFPS

increased. There was a modest effect of temperature on the abundance of AOA and AOB populations with a similar pattern of change in AOA and AOB *amo*A gene copies observed at 25°C and 35°C.

Correlation between nitrification-sourced N_2O and AOA and AOB populations

There was a significant correlation between AOA-*amo*A gene abundance and nitrification-sourced N_2O regardless fertilizer addition or not ($P < 0.05$) (Table 2). Before the fertilizer application, there was no significant relationship between nitrification-derived N_2O and AOB-*amo*A gene copies. However, after fertilizer application, AOB-*amo*A gene copies showed a strong significant relationship with N_2O production through nitrification (N_2On) ($P < 0.001$). AOA and AOB abundances had a strong significant correlation with NO_3^- concentration suggesting both AOA and AOB were responsible for nitrification.

Discussion

Source of N_2O

From both previous studies and the current study, soil water content and temperature were the predominant factors regulating N_2O emission from soils. Kool et al. (2010) found that emitted N_2O was mainly related to soil moisture conditions. An increase in soil water content due to irrigation and rainfall can stimulate nitrification and denitrification (Hu et al. 2014), and also can promote N_2O production (Hofstra and Bouwman 2005). The increase in gross nitrification rate (n) with soil moisture content (Table 1) is consistent with previous studies (Maag and Vinther 1996; Garrido et al. 2002). In N fertilizer amended soil, N_2O emission has been found to be highly correlated with WFPS, with the highest emission under around 70% WFPS levels, which was attributed to a combination of nitrification (35–53%), and

denitrification (only 2–9%) (Huang et al. 2014). In sandy loam soils, when moisture status was sub-optimal for denitrification (50% and 70% WFPS), nitrification was the significant contributor (around 29%) to N_2O emissions (Kool et al. 2011), but in wetter soils (-0.1 kPa) nitrification contributed less than 3% (Webster and Hopkins 1996). Well et al. (2008) revealed that 88% of total N_2O emission was attributed to nitrification at 45% WFPS. This suggests that favourable conditions for N_2O production from nitrification occur within the range of 30% to 70%, whereas denitrification dominates N_2O production in wet soils with >80–90% WFPS (Braker and Conrad 2011; Huang et al. 2014), which is consistent with our observation that nitrification was the main source of N_2O production at 50% and 70% WFPS (Table 1) and denitrification dominated N_2O production at 85% WFPS soils. At 35°C, and 70% and 85% WFPS the peak N_2O flux occurred 3 days after N was applied, while at 25°C, and 70% and 85% WFPS the peak N_2O flux occurred at day 4 (Figure 1), suggesting increasing soil temperature can promote N_2O emission.

Soil water content and temperature not only determine the availability of O_2, but also influence transport of nutrients within the soil matrix and the metabolic activity of microbial cells (Hu et al. 2014), which could confound the relationships between soil temperature and WFPS and rates of N_2O emissions (Hu et al. 2015). The effect of WFPS on the relative contributions of nitrification and denitrification to N_2O emissions is much more complex due to the heterogeneity of the soil environment where both anaerobic and aerobic conditions can exist within the soil at the same time, and cannot be as clearly depicted as changes in O_2 concentrations with changing moisture content (WFPS) (Hu et al. 2015).

This is likely due to the effect of soil moisture content on the growth of nitrifiers. When soil moisture content was 85% WFPS, N_2O_n was higher at 25°C than at 35°C. It is also

possible that the supply of NO_3^- became limiting for denitrification during the first few days under 25°C and 85% WFPS (gross nitrification rate was lower than that of 35°C) (Ciarlo et al. 2008; Harris et al. 2013). But we hypothesis that denitrification was driven to N_2 in the 35°C 85% WFPS treatment. This can be supported by the total N_2O production being reduced by around 90% during the second incubation week compared to the first week incubation at 35°C 85% WFPS (Table 1).

Dalal et al. (2003) reported that when soil moisture content was above 80-90% WFPS, both N_2O and N_2 production occurred. The N_2O:N_2 ratio has often been found to decrease with increasing soil water content (Colbourn and Dowdell 1984; Davidson 1992; Rudaz et al. 1999), particularly when the soil water content exceeds 75% WFPS (Davidson 1992; Weier et al. 1993). Likewise, the measured N_2O:N_2 ratio was highest ($\geqslant$1) under dry conditions during summer and early autumn when denitrification was relatively inactive in a study on three pasture soils in New Zealand (Ruz-Jerez et al. 1994). Friedl et al. (2016) revealed that N_2 emissions exceeded N_2O emissions by a factor of 8 ± 1 at 80% WFPS and a factor of 17 ± 2 at 100% WFPS. In our study, the average proportion of nitrified N as N_2O (P_{N2O}) was 0.007% to 0.7% at 35°C across the three moisture contents, which is higher than the range of 0.02% to 0.2% reported in previous studies in agricultural soils under aerobic conditions (Tortoso and Hutchinson 1990; Magg and Vinther 1996; Garrido et al. 2002; Zhu et al. 2011). However, Khalil et al. (2004) demonstrated a higher ratio of 0.16% to 1.48% when O_2 concentration was reduced from 20.4 to 0.76 kPa. The P_{N2O} in our study varied significantly with temperature and moisture. Higher temperature increased P_{N2O}, except at 85% WFPS, which was also noted by Goodroad and Keeney (1984). This suggests that models such as DNDC (Li et al. 2000) and CENTURY (Mathieu et al. 2006), which use fixed ratios to estimate P_{N2O}, may not accurately simulate the relative contribution of nitrification and

denitrification to N_2O production.

AOA and AOB

AOA were the predominant ammonia oxidizers (Figure 4) in the acidic soil, which is consistent with other research (Schleper et al. 2005; Zhang et al. 2012). The activity of nitrification enzymes, including AMO, can vary with environmental conditions (Niklaus et al. 2001; Zak et al. 2000). Several studies have reported significant increases in AOA and AOB abundance in response to N fertilization (Mendum et al. 1999; Hermansson and Lindgren 2001; Okano et al. 2004), which is consistent with our observations. Soil moisture and temperature have also been found to affect N_2O emission by nitrification indirectly through changes in the abundance of ammonia oxidizers (Avrahami and Bohannan 2009; Szukics et al. 2010). However compared to soil moisture, we found soil temperature only had a modest effect on the abundance of AOB (Figure 4), in agreement with the results in Horz et al. (2004). At day 0 the initial abundances of archaeal and bacterial nitrifiers were greater under higher WFPS conditions (85%). The population dynamic had changed however 7 days after fertilizer application with the greatest *amo*A copy numbers observed at 50% WFPS for both AOA and AOB. Our results demonstrated that increasing moisture content decreased AOA and AOB abundance. This may be attributed to a reduction in oxygen (O_2) availability in the soil. However, previous studies showed that the effect of soil moisture content on AOB abundance could be positive or negative. Hastings et al. (2000) found that elevation of soil moisture increased AOB abundance by reducing water stress. Belser (1979) indicated that further increases in soil moisture can decrease abundance of nitrifiers due to decreased diffusion of O_2 into the soil. Another possibility is that elevated CO_2 due to increasing moisture and temperature altered the competition for resource substrates between AOA, AOB and heterotrophic microbes (Horz et al. 2004) and therefore both AOA and AOB abundance

decreased.

Before application of fertilizers, only AOA abundance were significantly related with N_2O_n emission but after N was applied, both AOA and AOB played an important role (Table 2). It suggests that AOA may be particularly adapted to unfavourable and low fertility environments (Schauss et al. 2009; Di et al. 2009), while AOB require high nutrient availability conditions to flourish (Di et al. 2009). Therefore, the present study demonstrated that AOB was only playing a limited role in N_2O emissions depending on N conditions. Di et al. (2010) reported that the total N_2O emissions from grazed grasslands rich in NH_4^+ were significantly related to the *amo*A gene copy numbers from the AOB community. This suggests that the AOB were responsible for N_2O emissions from the N-rich soils, which is in agreement with our study. However, Andert et al. (2011) found that there was no relationship between the abundance of AOB and AOA communities and N_2O emissions from a peat soil. Therefore, future study needs to be done with wide range of soils.

We measured the *amoA* gene abundance at different conditions based on soil DNA, giving insights into community size and potential contribution to activity, however, measurements of active community based on soil RNA are highly desirable in future studies. It is not possible to accurately determine the relative contribution of AOA and AOB to N_2O emissions, because the assumptions were made that all AOA and AOB produced the same yield of N_2O per unit of ammonia oxidized. However, a large body of previous literature stated that this was not the case (Stieglmeier et al. 2014). Furthermore, the interpretation of the relative contributions of AOA and AOB to N_2O emissions cannot be made clearly and the underlying mechanism may need to be studied further using more advanced molecular techniques. 1-octyne, a recently reported AOB selective inhibitor, can be used to separate

AOA-related N_2O and AOB-related N_2O and specifically inhibited AOB growth, activity and N_2O production (Hink et al. 2016). Therefore, it is essential to make use of AOA or AOB selective inhibitor to give an explicit interpretation on the relative role on nitrification-sourced N_2O.

Conclusion

We have identified that soil water, temperature, and their interaction significantly affect N_2O emissions, P_{N2O}, and AOA and AOB abundance. Soil temperature and moisture decreased the contribution of nitrification to N_2O emission. Nitrification occurred even at 85% WFPS in this study. Compared to soil temperature, soil moisture had a significant influence on the abundances of AOA and AOB population. In our study, a significant relationship was found between both AOA and AOB populations and N_2O emitted from nitrification. Our study provides information on the variable contributions of nitrification and denitrification to N_2O emissions. This information can be used to inform appropriate N_2O mitigation strategies and improve the model simulation of N_2O emissions. Further work needs to be done for validation of these findings under field conditions to account for the heterogeneity that exists and for expression of the functional genes which are involved in N_2O consumption and production.

Acknowledgements

The authors would like to acknowledge the financial support by Incitec Pivot, the 424 Australian Government Department of Agriculture through the Grains Research and 425 Development Corporation, and Australian Research Council (DE150100870, DP160101028).

References

Akiyama H, Morimoto S, Tago K, Hoshino YT, Nagaoka K, Yamasaki M, Karasawa T, Takenaka M, Hayatsu M (2014) Relationships between ammonia oxidizers and N_2O and CH_4 fluxes in agricultural fields with different soil types. Soil Sci Plant Nutri 60: 520–529

Allen D, Kingston G, Rennenberg H, Dalal RC, Schmidt S (2010) Effect of nitrogen fertilizer management and waterlogging on nitrous oxide emission from subtropical sugarcane soils. Agric Ecosyst Environ 136: 209–217

Andert J, Wessén E, Börjesson G, Hallin S (2011) Temporal changes in abundance and composition of ammonia-oxidizing bacterial and archaeal communities in a drained peat soil in relation to N_2O emissions. J Soils Sediments 11: 1399–1407

Avrahami S, Bohannan BJM (2009) N_2O emission rates in a California meadow soil are influenced by fertilizer level, soil moisture and the community structure of ammonia-oxidizing bacteria. Glob Chang Biol 15: 643–655

Barraclough D, Puri G (1995) The use of ^{15}N pool dilution and enrichment to separate the heterotrophic and autotrophic pathways of nitrification. Soil Biol Biochem 27: 17–22

Bateman EJ, Baggs EM (2005) Contributions of nitrification and denitrification to N_2O emission from soils at different water-filled pore space. Biol Fertil Soils 41: 379–388

Belser LW (1979) Population ecology of nitrifying bacteria. Annu Rev Microbiol 33: 309–333

Braker G, Conrad R (2011) Diversity, structure, and size of N_2O producing microbial communities in soils–what matters for their functioning? Adv Appl Microbiol 75: 33–70

Brochier-Armanet C, Boussau B, Gribaldo S, Forterre P (2008) Mesophilic crenarchaeota: proposal for a third archaeal phylum, the thaumarchaeota. Nat Rev Microbiol 6: 245–252

Butterbach-Bahl K, Baggs EM, Dannenmann M, Kiese R, Zechmeister-Boltenstern S (2013) Nitrous oxide emissions from soils: how well do we understand the processes and their controls?. Philos Trans R Soc B 368: 20130122

Ciarlo E, Conti M, Bartoloni N, Rubio G (2008) Soil N_2O emissions and $N_2O/(N_2O+N_2)$ ratio as affected by different fertilization practices and soil moisture. Biol Fertil Soils 44: 991–995

Cheng Y, Wang J, Wang SQ, Zhang JB, Cai ZC (2014) Effects of soil moisture on gross N transformations and N_2O emission in acid subtropical forest soils. Biol Fertil Soils 50: 1099–1108

Colbourn P, Dowdell RJ (1984) Dnitrification in field soils. Plant Soil 76: 213–226

Dalal RC, Wang W, Robertson GP, Parton WJ (2003) Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. Soil Res 41: 165–195

Davidson EA (1992) Sources of nitric oxide and nitrous oxide following wetting of dry soil. Soil Sci Soc Am J 56: 95–102

Di HJ, Cameron KC, Shen JP, Winefield C, O'Callaghan M, Bowatte S, He JZ (2009) Nitrification driven by bacteria and not archaea in nitrogen-rich grassland soils. Nat Geosci 2: 621–624

Di HJ, Cameron KC, Sherlock RR, Shen JP, He JZ, Winefield C (2010) Nitrous oxide emissions from grazed grassland as affected by a nitrification inhibitor, dicyandiamide, and relationships with ammonia-oxidizing bacteria and archaea. J Soils Sediments 10: 943–954

Francis CA, Roberts KJ, Beman JM, Santoro AE, Oakley BB (2005) Ubiquity and diversity of ammonia-oxidizing archaea in water columns and sediments of the ocean. Proc Natl Acad Sci U.S.A. 102: 14683–14688

Friedl J, Scheer C, Rowlings DW, McIntosh HV, Strazzabosco A, Warner DI, Grace PR (2016)

Denitrification losses from an intensively managed sub-tropical pasture – Impact of soil moisture on the partitioning of N_2 and N_2O emissions. Soil Biol Biochem 92: 58–66

Garrido F, Henault C, Gaillard H, Perez S, Germon JC (2002) N_2O and NO emissions by agricultural soils with low hydraulic potentials. Soil Biol Biochem 34: 559–575

Godde M, Conrad R (1999) Immediate and adaptational temperature effects on nitric oxide production and nitrous oxide release from nitrification and denitrification in two soils. Biol Fertil Soils 30: 33–40

Goodroad L, Keeney D (1984) Nitrous oxide production in aerobic soils under varying pH, temperature and water content. Soil Biol Biochem 16: 39–43

Granli T, Bøeckman OC (1994) Nitrous oxide from agriculture. Nor J Agric Sci 12: 128

Hammer Ø, Harper DAT, Ryan PD (2001) PAST: paleontological statistics software package for education and data analysis. Palaeontol Electron 4: 9

Harris RH, Officer SJ, Hill PA, Armstrong RD, Fogarty KM, Zollinger RP, Phelan AJ, Partington DL (2013) Can nitrogen fertiliser and nitrification inhibitor management influence N2O losses from high rainfall cropping systems in South Eastern Australia? Nutri Cycl Agroecosyst 95: 269–285

Hastings R, Butler C, Singleton I, Saunders J, McCarthy A (2000) Analysis of ammonia-oxidizing bacteria populations in acidic forest soil during conditions of moisture limitation. Lett Appl Microbiol 30: 14–18

Haynes R (1986) Nitrification. In Mineral Nitrogen in the Plant-Soil System Haynes RS(Ed). Academic Press; London. pp. 127–165

Hermansson A, Lindgren PE (2001) Quantification of ammonia-oxidizing bacteria in arable soil by real-time PCR. Appl Environ Microbiol 67: 972–976

Hink L, Nicol GW, Prosser JI (2016) Archaea produce lower yields of N_2O than bacteria during aerobic ammonia oxidation in soil. Environ Microbiol doi: 10.1111/1462-

2920.13282

Hofstra N, Bouwman AF (2005) Denitrification in agricultural soils: Summarizing published data and estimating global annual rates. Nutri Cycl Agroecosyst 72: 267–78

Horz HP, Horz A, Barbrook CB, Field BJM, Bohannan (2004) Ammonia-oxidizing bacteria respond to multifactorial global change. Proc Natl Acad Sci U.S.A. 101: 15136–15141

Hu HW, Macdonald CA, Trivedi P (2014) Water addition regulates the metabolic activity of ammonia oxidizers responding to environmental perturbations in dry sub-humid ecosystems. Environ Microbiol 17: 444–61

Hu HW, Chen DL, He JZ (2015) Microbial regulation of terrestrial nitrous oxide formation: understanding the biological pathways for prediction of emission rates. FEMS Microbiol Rev Doi: http://dx.doi.org/10.1093/femsre/fuv021

Huang Y, Zou J, Zheng X, Wang Y, Xu X (2004) Nitrous oxide emissions as influenced by amendment of plant residues with different C: N ratios. Soil Biol Biochem 36: 973-981

Huang T, Gao B, Hu XK (2014) Ammonia-oxidation as an engine to generate nitrous oxide in an intensively managed calcareous Fluvo-aquic soil. Sci Rep 4: 3950

Hungate BA, Jaeger CH, Gamara G, Chapin FS, Field CB (2000) Soil microbiota in two annual grasslands: responses to elevated atmospheric CO_2. Oecologia 124: 589–598

IPCC. Climate change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, (Ed). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2007

Isbell RF (1996) The Australian Soil Classification, Revised Ed (CSIRO Publishing: Melbourne) http://www.publish.csiro.au/pid/3529.htm

Jia Z, Conrad R (2009) Bacteria rather than Archaea dominate microbial ammonia oxidation in an agricultural soil. Environ Microbiol 11: 1658-1671

Khalil K, Mary B, Renault P (2004) Nitrous oxide production by nitrification and denitrification in soil aggregates as affected by O_2 concentration. Soil Biol Biochem 36: 687–699

Kirkham D, Bartholomew WV (1954) Equations for following nutrient transformations in soil utilizing tracer data. Soil Sci Soc Am J 18: 33–34

Kool DM, Dolfing J, Wrage N (2011) Nitrifier denitrification as a distinct and significant source of nitrous oxide from soil. Soil Biol Biochem 43: 174–8

Kool DM, Wrage N, Zechmeister-Boltenstern S (2010) Nitrifier denitrification can be a source of N_2O from soil: A revised approach to the dual-isotope labelling method. Eur J Soil Sci 61: 759–72

Lan T, Han Y, Roelcke M, Nieder R, Cai ZC (2013) Processes leading to N_2O and NO emissions from two different Chinese soils under different soil moisture contents. Plant Soil 371: 611–627

Lang M, Cai Z, Chang SX (2011) Effects of land use type and incubation temperature on greenhouse gas emissions from Chinese and Canadian soils. J Soils Sediments 11: 15–24

Li C, Aber J, Stange F, Butterbach-Bahl K, Papen H (2000) A process-oriented model of N_2O and NO emissions from forest soils: 1. Model development. J Geophys Res 105: 4369–4384

Li P, Lang M (2014) Gross nitrogen transformations and related N_2O emissions in uncultivated and cultivated black soil. Biol Fertil Soils 50: 197–206

Liu R, Hu HW, Suter H, Hayden HL, He JZ, Mele P, Chen DL (2016) Nitrification is a primary driver of nitrous oxide production in laboratory microcosms from different land-use soils. Front Microbiol 7: 1373

Livesley S, Kiese R, Graham J, Weston C, Butterbach-Bahl K, Arndt S (2008) Trace gas flux

and the influence of short-term soil water and temperature dynamics in Australian sheep grazed pastures of differing productivity. Plant Soil 309: 89–103

Leininger S, Urich T, Schloter M, Schwzrk L, Qi J, Nicol G, Prosser J, Schuster S, Schleper C (2006) Archaea predominate among ammonia-oxidizing prokaryotes in soils. Nature 442: 806–809

Maag M, Vinther FP (1996) Nitrous oxide emission by nitrification and denitrification in different soil types and at different soil moisture contents and temperatures. Appl Soil Ecol 4: 5–14

Mathieu O, Hénault C, Lévêque J, Baujard E, Milloux MJ, Andreux F (2006) Quantifying the contribution of nitrification and denitrification to the nitrous oxide flux using ^{15}N tracers. Environ Pollut 144: 933–940

Mendum T, Sockett R, Hirsch P (1999) Use of molecular and isotopic techniques to monitor the response of autotrophic ammonia-oxidizing populations of the beta subdivision of the class proteobacteria in arable soils to nitrogen fertilizer. Appl Environ Microbiol 65: 4155–4162

Mertens J, Broos K, Wakelin SA, Kowalchuk GA, Springael D, Smolders E (2009) Bacteria, not archaea, restore nitrification in a zinc-contaminated soil. ISME J 3: 916–923

Mørkved PT, Dörsch P, Bakken LR (2007) The N_2O product ratio of nitrification and its dependence on long-term changes in soil pH. Soil Biol Biochem 39: 2048–2057

Müller C, Laughlin RJ, Spott O, Rütting T (2014) Quantification of N_2O emission pathways via a ^{15}N tracing model. Soil Biol Biochem 72: 44–54

Niklaus PA, Kandeler E, Leadley PW, Schmid B, Tscherko D, Korner C (2001) A link between plant diversity, elevated CO_2 and soil nitrate. Oecologia 127: 540–548

Officer S, Kearney G, Kelly K, Graham J (2012) Large nitrous oxide emissions after conversion from pasture to cropping in temperate south eastern Australia. Paper

presented at the SSA-NZSSS Conference, Hobart, pp 2–7 December

Officer .J, Phillips F, Armstrong R, Kelly K (2008) Nitrous oxide emissions from dry-land wheat in south-eastern Australia. In: Proceedings of the 14th Australian Agronomy Conference. Australian Society of Agronomy, Adelaide http://www.survey.regional.org.au/au/asa/

Offre P, Prosser JI, Nicol GW (2009) Growth of ammonia–oxidizing archaea in soil microcosms is inhibited by acetylene. FEMS Microbiol Ecol 70: 99–108

Okano Y, Hristova KR, Leutenegger CM, Jackson LE, Denison RF, Gebreyesus B, Lebauer D, Scow KM (2004) Appl Environ Microbiol 70: 1008–1016

Purkhold U, Pommerening-Roser A, Juretschko S (2000) Phylogeny of all recognized species of ammonia oxidizers based on comparative 16S rRNA and amoA sequence analysis: implications for molecular diversity surveys. Appl Environ Microbiol 66: 5368–5382

Rotthauwe JH, Witzel KP, Liesack W (1997) The ammonia monooxygenase structural gene amoA as a functional marker: molecular fine-scale analysis of natural ammonia-oxidizing populations. Environ Microbiol 63: 4704–4712

Rudaz AO, Walti E, Lehmann P, Fuhrer J (1999) Temporal variation in N_2O and N_2 fluxes from a permanent pasture in Switzerland in relation to management, soil water content and soil temperature. Agric Ecosyst Environ 73: 83–91

Ru-Jerez BE, White RE, Roger ball P (1994) Long-term measurement of denitrification in three contrasting pastures grazed by sheep. Soil Biol Biochem 26: 29–39

Saggar S, Jha N, Deslippe J, Bolan NS, Luo J, Giltrap DL, Kim DG, Zaman M, Tillman RW (2013) Denitrification and N_2O:N_2 production in temperate grasslands: Processes, measurements, modelling and mitigating negative impacts. Sci Total Environ 465: 173–195

Saghir NS, Mulvancy RL, Azam F (1993) Determination of nitrogen by microdiffusion in

mason jars. I. Inorganic nitrogen in soil extracts. Commun Soil Sci Plant Anal 24: 1745–1762

Schauss K, Focks A, Leininger S, Kotzerke A, Heuer H, Thiele-Bruhn S, Sharma S, Berndt-Michael W, Michael M, Smalla K, Munch JC, Amelung W, Kaupenjohann M, Schloter M, Schleper C (2009) Dynamics and functional relevance of ammonia-oxidizing archaea in two agricultural soils. Environ Microbiol 11: 446–456

Schleper C, Jurgens G, Jonuscheit M (2005) Genomic studies of uncultivated archaea. Nat Rev Microbiol 3: 479–488

Schuster M, Conrad R (1992) Metabolism of nitric oxide and nitrous oxide during nitrification and denitrification in soil at different incubation conditions. FEMS Microbiol Ecol 10: 133–143

Stevens RJ, Laughlin RJ, Burns LC, Arah JRM, Hood RC (1997) Measuring the contributions of nitrification and denitrification to the flux of nitrous oxide from soil. Soil Biol Biochem 29: 139–151

Stieglmeier M, Mooshammer M, Kitzler B (2014) Aerobic nitrous oxide production through N-nitrosating hybrid formation in ammonia-oxidizing archaea. ISME 8: 1135–1146

Szukics U, Abell GCJ, Hodl V, Mitter B, Sessitsch A, Hackl E, Zechmeister-Boltenstern S (2010) Nitrifiers and denitrifiers respond rapidly to changed moisture and increasing temperature in a pristine forest soil. FEMS Microbiol Ecol 395–406

Tortoso AC, Hutchinson GL (1990) Contributions of autotrophic and heterotrophic nitrifiers to soil NO and N_2O emissions. Appl Environm Microbiol 56: 1799–1805

Tourna M, Freitag TE, Nicol GW, Prosser JI (2008) Growth, activity and temperature responses of ammonia‐oxidizing archaea and bacteria in soil microcosms. Environ Microbiol 10: 1357–1364

Watanabe T, Lee CG, Murase J, Asakawa S, Kimura M (2011) Carbon flow into ammonia-

oxidizing bacteria and archaea during decomposition of ^{13}C-labeled plant residues in soil. Soil Sci Plant Nutri 57: 775–785

Webster EA, Hopkins DW (1996) Contributions from different microbial processes to N_2O emission from soil under different moisture regimes. Biol Fertil Soils 22: 331–5

Weier K, Doran J, Power J, Walters DT (1993) Denitrification and the dinitrogen/nitrous oxide ratio as affected by soil water, available carbon, and nitrate. Soil Sci Soc Am J 57: 66–72

Well R, Flessa H, Lu X (2008) Isotopologue ratios of N_2O emitted from microcosms with NH_4^+ fertilized arable soils under conditions favoring nitrification. Soil Biol Biochem 40: 2416–26

Wrage N, Groenigen JW, Oenema O, Baggs EM (2005) A novel dual‐isotope labelling method for distinguishing between soil sources of N_2O. Rapid Commun Mass Spectrom 19: 3298–3306

Yamamoto A, Akiyama H, Naokawa T, Miyazaki Y, Honda Y, Sano Y, Nakajima Y, Yagi K (2014) Lime-nitrogen application affects nitrification, denitrification, and N_2O emission in an acidic tea soil. Biol Fertil Soils 50: 53–62

Zak DR, Pregitzer KS, Curtis PS, Holmes WE (2000) Atmospheric CO_2 and the composition and function of soil microbial communities. Ecol Appl 10: 47–59

Zhang LM, Hu HW, Shen JP, He JZ (2012) Ammonia-oxidizing archaea have more important role than ammonia-oxidizing bacteria in ammonia oxidation of strongly acidic soils. ISME J 6: 1032–1045

Zheng X, Wang M, Wang Y, Shen R, Ji G, Li J, Jin J, Li L (2000) Impacts of soil moisture on nitrous oxide emission from croplands: a case study on the rice-based agro-ecosystem in Southeast China. Chemosphere-Glob Chang Sci 2: 207–224

Zhu TB, Zhang JB, Cai ZC (2011) The contribution of nitrogen transformation processes to total N_2O emissions from soils used for intensive vegetable cultivation. Plant Soil 343: 313–327

Figure 1 N_2O production rate from the two treatments under different incubation conditions: 25°C + 50% WFPS (a), 25°C + 70% WFPS (b), 25°C + 85% WFPS (c), 35°C + 50% WFPS (d), 35°C + 70% WFPS (e), and 35°C + 85% WFPS (f). Error bars are the standard deviation of four replicates.

Figure 2 ^{15}N enrichment of N_2O, NH_4^+ and NO_3^- in the ^{15}N labelled NH_4^+ treatment during the incubation. a, b and c represent 50%, 70% and 85% WFPS at 25°C, respectively. d, e and f represent 50%, 70% and 85% WFPS at 35°C, respectively. Error bars are the standard deviation of four replicates.

Figure 3 ^{15}N enrichment of N_2O, NH_4^+ and NO_3^- in the ^{15}N labelled NO_3^- treatment during the incubation. a, b and c represent 50%, 70% and 85% WFPS at 25°C, respectively. d, e and f represent 50%, 70% and 85% WFPS at 35°C, respectively. Error bars are the standard deviation of four replicates.

Figure 4 AOA and AOB *amo*A gene copy numbers in $^{15}NH_4$ treatment at 25°C and 35°C during the incubation period. Error bars are the standard deviation of four replicates.

Figure 1

25°C

35°C

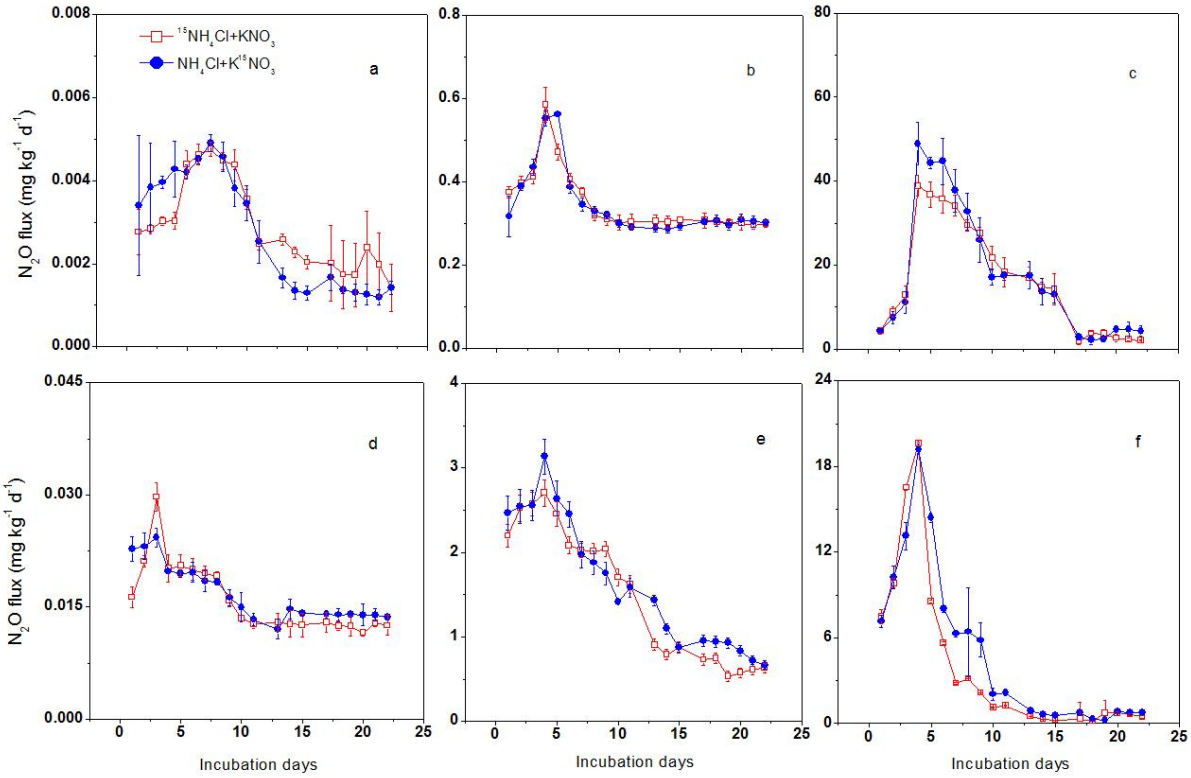

Figure 2

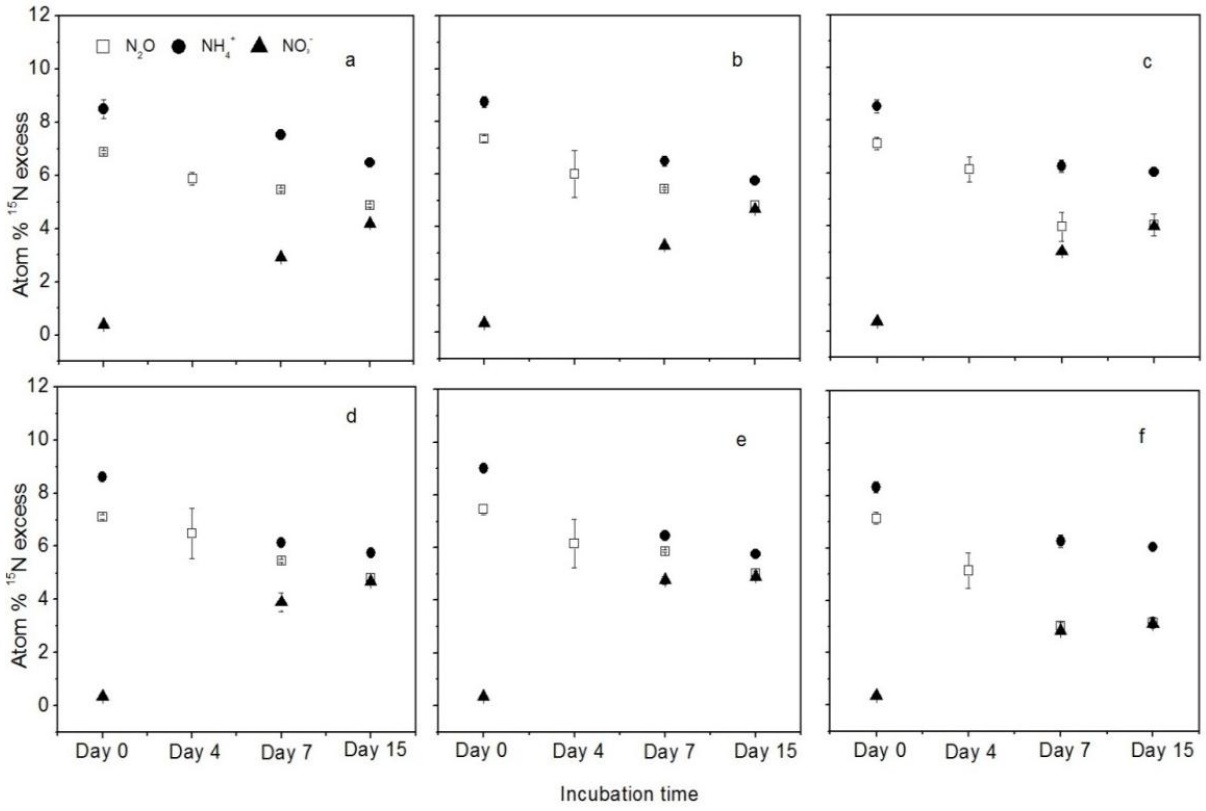
N2O
NH4+
NO3-
a
b
c
d
e
f
Atom % 15N excess
Day 0
Day 4
Day 7
Day 15
Incubation time

Figure 3

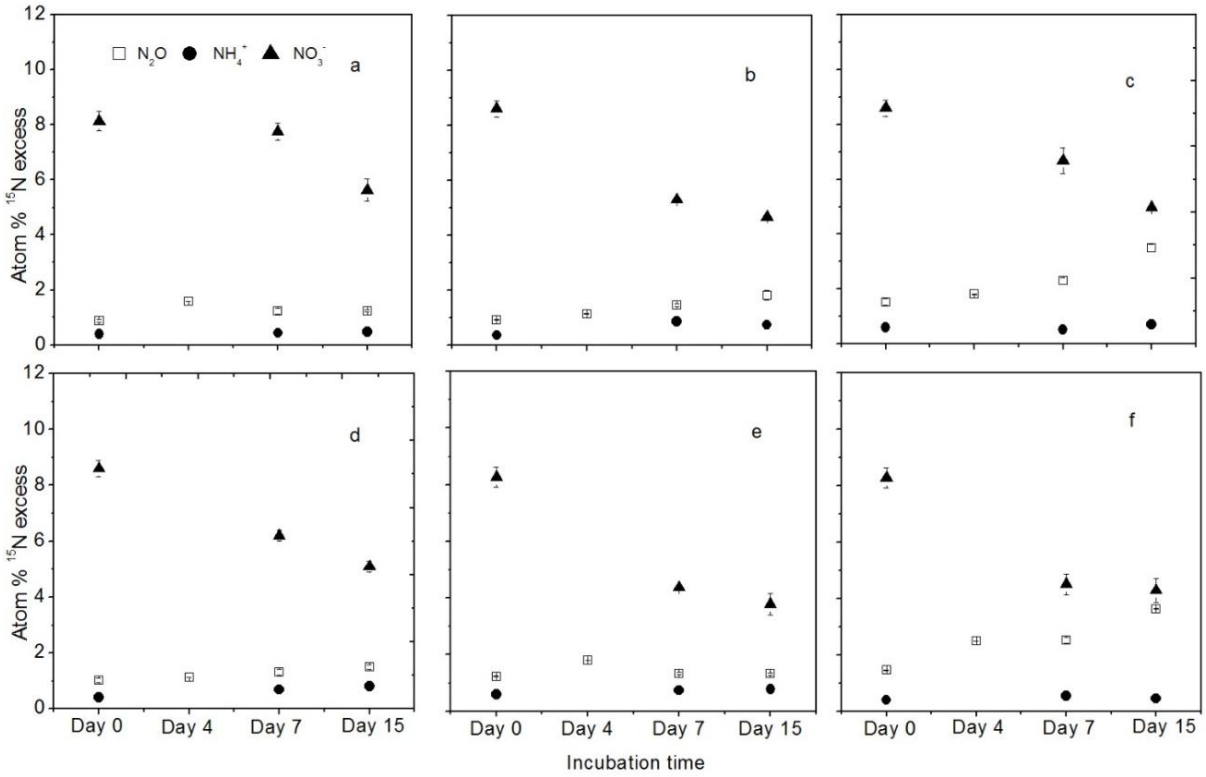
□ N2O ● NH4+ ▲ NO3-
a
b
c
d
e
f
Atom % 15N excess
Atom % 15N excess
0
2
4
6
8
10
12
Day 0
Day 4
Day 7
Day 15
Incubation time

Figure 4

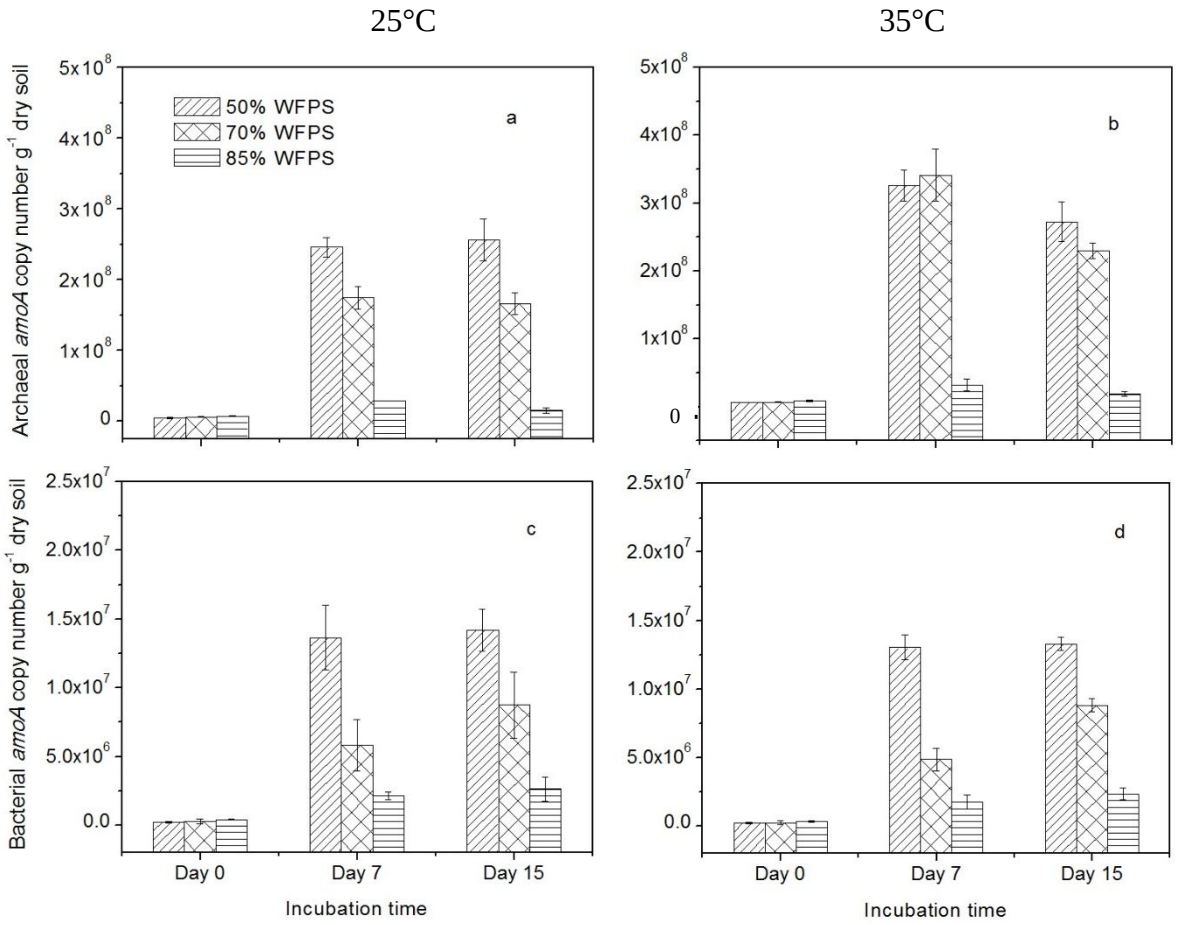
25°C
35°C
50% WFPS
70% WFPS
85% WFPS
a
b
c
d
Archaeal amoA copy number g-1 dry soil
Bacterial amoA copy number g-1 dry soil
5x10^8
4x10^8
3x10^8
2x10^8
1x10^8
0
2.5x10^7
2.0x10^7
1.5x10^7
1.0x10^7
5.0x10^6
0.0
Day 0
Day 7
Day 15
Incubation time

Table 1 Gross nitrification rate, the relative contribution of denitrification (C_d) and nitrification (C_n) to N_2O production, N_2O derived from denitrification (N_2O_d) and nitrification (N_2O_n), and the proportion of N_2O to gross nitrification (P_{N2O}) under the different environmental conditions. Numbers in bracket represent the standard deviation of four replicates.

Temperature	Moisture	Time	Gross nitrification rate mg N kg^{-1} d^{-1}	Relative contribution %		N_2O_d [c] mg N_2O-N kg^{-1} d^{-1}	N_2O_n [d] mg N_2O-N kg^{-1} d^{-1}	P_{N2O} %[e]
				Cd [a]	Cn [b]			
25°C	50%WFPS	d0-d7	1.97 (0.32)	10.68	89.32	0.0002	0.0017	0.0015
				(1.22)	(1.98)	(2.3E5)	(2.3E5)	(0.0004)
		d7-d15	5.26 (1.57)	14.85	85.15	0.0002	0.0013	0.0012
				(1.92)	(3.92)	(3.0E5)	(1.1E5)	(0.0006)
	70%WFPS	d0-d7	8.32 (0.69)	13.08	86.92	0.048	0.317	0.249
				(2.45)	(1.68)	(0.009)	(0.009)	(0.103)
		d7-d15	2.37 (0.24)	27.42	72.58	0.055	0.147	0.106
				(1.89)	(4.64)	(0.004)	(0.004)	(0.012)
	85%WFPS	d0-d7	3.84 (0.78)	29.09	70.91	10.979	26.76	18.101
				(4.050	(6.98)	(1.53)	(1.53)	(5.22)
		d7-d15	6.65 (1.51)	65.21	34.79	1.902	1.036	0.614
				(2.90)	(5.49)	(0.085)	(0.086)	(0.06)
35°C	50%WFPS	d0-d7	5.39 (0.16)	11.14	88.86	0.0024	0.019	0.0161
				(2.11)	(3.46)	(0.0005)	(0.0005)	(0.013)
		d7-d15	3.43 (0.41)	16.13	83.87	0.017	0.0086	0.0068
				(1.24)	(2.37)	(0.001)	(0.0009)	(0.01)
	70%WFPS	d0-d7	7.05 (0.33)	16.21	83.79	0.320	1.952	1.970
				(2.58)	(8.99)	(0.024)	(0.039)	(1.93)
		d7-d15	2.35 (0.76)	18.02	81.98	0.172	0.785	0.663
				(1.93)	(4.51)	(0.018)	(0.014)	(0.27)
	85%WFPS	d0-d7	11.17 (2.24)	50.10	49.90	3.152	3.139	2.343
				(4.20)	(6.78)	(0.264)	(0.109)	(0.19)
		d7-d15	0.97 (0.36)	83.63	16.37	0.624	0.122	0.0901
				(9.11)	(6.24)	(0.068)	(0.028)	(0.07)

[a] The relative contribution by denitrification (Cd) to N_2O production
[b] The relative contribution by nitrification (Cn) to N_2O production
[c] N_2O production from denitrification (N_2O_d)
[d] N_2O production from nitrification (N_2O_n)
[e] The proportion of nitrified N emitted as N_2O (P_{N2O})

Table 2 Correlations between soil mineral N levels, N_2O_n[a] and AOA and AOB abundances.

Time	Factor	AOA (Log number)		AOB (Log number)	
		R	P-Values	R	P-Values
Before fertilizer applied	Exchangeable NH_4^+ concentration	0.454	0.138	0.089	0.779
	NO_3^- concentration	0.217	0.499	0.063	0.846
	N_2O_n	0.615	0.033	0.517	0.085
After fertilizer applied	Exchangeable NH_4^+ concentration	0.623	5.00E-05	0.535	0.008
	NO_3^- concentration	-0.622	5.07E-05	-0.369	0.027
	N_2O_n	0.346	0.038	0.578	0.0002

[a] means N_2O production from nitrification

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Liu, R; Hayden, HL; Suter, H; Hu, H; Lam, SK; He, J; Mele, PM; Chen, D

Title:
The effect of temperature and moisture on the source of N2O and contributions from ammonia oxidizers in an agricultural soil

Date:
2017-01-01

Citation:
Liu, R., Hayden, H. L., Suter, H., Hu, H., Lam, S. K., He, J., Mele, P. M. & Chen, D. (2017). The effect of temperature and moisture on the source of N2O and contributions from ammonia oxidizers in an agricultural soil. BIOLOGY AND FERTILITY OF SOILS, 53 (1), pp.141-152. https://doi.org/10.1007/s00374-016-1167-8.

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