

**Gaseous emissions  
under elevated CO<sub>2</sub>**

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# Trace gas fluxes of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O in a permanent grassland soil exposed to elevated CO<sub>2</sub> in the Giessen FACE study

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## Abstract

Long-term field observations showed that N<sub>2</sub>O fluxes were not significantly affected by elevated CO<sub>2</sub> shortly after N application in the Giessen Free Air Carbon dioxide Enrichment (FACE) study. To further investigate this unexpected result a <sup>15</sup>N tracer study was carried out under controlled conditions where in parallel treatments either the NH<sub>4</sub><sup>+</sup> pool (<sup>15</sup>NH<sub>4</sub>NO<sub>3</sub>) or the NO<sub>3</sub><sup>-</sup> pool (NH<sub>4</sub><sup>15</sup>NO<sub>3</sub>) was enriched with <sup>15</sup>N. Fluxes of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O as well as the <sup>15</sup>N enrichment of the N<sub>2</sub>O were measured. Denitrifying Enzyme Activity (DEA), total denitrification (N<sub>2</sub> + N<sub>2</sub>O) and N<sub>2</sub>-to-N<sub>2</sub>O ratios were quantified in separate experiments. Over the 57 day incubation, N<sub>2</sub>O fluxes averaged 0.090 ng N<sub>2</sub>O-N g<sup>-1</sup> h<sup>-1</sup> under ambient and 0.083 ng N<sub>2</sub>O-N g<sup>-1</sup> h<sup>-1</sup> under elevated CO<sub>2</sub> (not significantly different). Based on the <sup>15</sup>N enrichments of the N<sub>2</sub>O the N<sub>2</sub>O production processes were identified by a two-source model. Results showed that N<sub>2</sub>O must have also been produced by a third source – possibly related to organic N transformation – which was stimulated by elevated CO<sub>2</sub>. Soil CO<sub>2</sub> fluxes were approximately 20% higher under elevated CO<sub>2</sub> than soil from ambient but the differences were not significant. CH<sub>4</sub> oxidation rates were on average -1.75 ng CH<sub>4</sub>-C g<sup>-1</sup> h<sup>-1</sup> in the elevated and -1.17 ng CH<sub>4</sub>-C g<sup>-1</sup> h<sup>-1</sup> in the ambient indicating that elevated CO<sub>2</sub> increased the CH<sub>4</sub> oxidation by 49% compared to ambient CO<sub>2</sub>. N fertilization increased CH<sub>4</sub> oxidation by 3-fold in both CO<sub>2</sub> treatments CO<sub>2</sub> did not have any significant effect on DEA while total denitrification and N<sub>2</sub>-to-N<sub>2</sub>O ratios increased by 36 and 33%, respectively. The results indicate that shortly after N application elevated CO<sub>2</sub> must have stimulated both the N<sub>2</sub>O production and reduction to N<sub>2</sub> to explain the increased N<sub>2</sub>-to-N<sub>2</sub>O ratio and at the same time explain the non-responsiveness of the N<sub>2</sub>O emissions. Thus, the observed variation of the CO<sub>2</sub> effect on N<sub>2</sub>O emissions throughout the year is possibly related to the dynamics of the N<sub>2</sub>O reductase activity.

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## 1 Introduction

The level of earth's atmospheric carbon dioxide ( $\text{CO}_2$ ) concentration has risen from  $\sim 280 \mu\text{L L}^{-1}$  at the start of the industrial revolution to greater than  $385 \mu\text{L L}^{-1}$  today, and is expected to exceed  $700 \mu\text{L L}^{-1}$  by the end of this century (Intergovernmental Panel on Climate Change, 2007). Elevated atmospheric  $\text{CO}_2$  increases the plant productivity and aboveground biomass resulting in a substantial allocation of carbon (C) to belowground that may lead to a general increase in C inputs in soil. This additional C is likely to fuel belowground microbial processes and may alter both C and N cycling in soil. Any change in C and N flow and transformation will affect the soil-atmosphere exchange of biogenic trace gases. Accumulation of radiatively active gases in the atmosphere could alter the earth's atmosphere energy balance, and has been linked to recent warming trends in global climate (Watson et al., 1992; IPCC, 2007; Smith et al., 2010). Although  $\text{CO}_2$  is by far the most abundant greenhouse gas,  $\text{N}_2\text{O}$  and  $\text{CH}_4$  are important atmospheric trace gases because of their unique radiative properties and their long residence time in the atmosphere resulting in stratospheric ozone depletion and global warming potential of 296 and 21 times that of  $\text{CO}_2$ , respectively (IPCC, 2007). In addition,  $\text{N}_2\text{O}$  and  $\text{CH}_4$  participate in other atmospheric reactions (e.g. stratospheric ozone depletion) of global environmental significance. Their concentration in the atmosphere is continuously rising and since the pre-industrial era it has increased by 15 and 145%, respectively (Watson et al., 1992; Houghton et al., 1996; IPCC, 2007).

Soil plays a major role in the global accounting of C not only due to large amount of C stored in soil, but also since soil contribution to the annual flux of  $\text{CO}_2$  to the atmosphere is 10 times that contributed by fossil fuel burning (Post et al., 1990). Fluxes of  $\text{CO}_2$  in grassland ecosystems under elevated  $\text{CO}_2$  varied from a 10% decline to a 162% increase with a mean response of 51% increase (Zak et al., 2000). Reich et al. (2001) found a 13% greater  $\text{CO}_2$  fluxes per unit mass under elevated atmospheric  $\text{CO}_2$ . Similarly, Smith et al. (2010) reported that seasonal soil  $\text{CO}_2$  flux in an arable soil was significantly greater under elevated  $\text{CO}_2$  being in the range of 15% to 50% compare to ambient  $\text{CO}_2$ .

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In addition to soil CO<sub>2</sub> flux, elevated atmospheric CO<sub>2</sub> can affect other greenhouse and reactive trace gases i.e. CH<sub>4</sub> and N<sub>2</sub>O and studies so far provide contradictory results. Ineson et al. (1998) measured fluxes of N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> from soils under ambient and elevated CO<sub>2</sub> at the Swiss FACE experiment in plots of *Lolium perenne* and reported increased N<sub>2</sub>O emissions by 27% under elevated CO<sub>2</sub> while ambient plots oxidized consistently more CH<sub>4</sub> than the elevated plots indicating that elevated CO<sub>2</sub> may result in the inhibition of CH<sub>4</sub> oxidation. Cheng et al. (2006) reported a 58% increase in CH<sub>4</sub> flux from rice paddies under elevated CO<sub>2</sub>. This increase was attributed to greater root exudates and numbers of tillers, resulting in more surface area for the release of CH<sub>4</sub> to the atmosphere (Ziska et al., 1998; Inubushi et al., 2003). In another study, Arnon and Bohlen (1998) and Baggs et al. (2003a) reported that both N<sub>2</sub>O and CO<sub>2</sub> fluxes under elevated CO<sub>2</sub> were 2–3 times higher than those observed in ambient CO<sub>2</sub>. This increase was attributed to increased belowground C allocation in elevated CO<sub>2</sub> providing energy for denitrifiers or that there is increased O<sub>2</sub> consumption under elevated CO<sub>2</sub>. However, Mosier et al. (2002) conducted an open-top-chamber CO<sub>2</sub> enrichment study in the Colorado shortgrass steppe and reported that even though both C<sub>3</sub> and C<sub>4</sub> plant biomass increased and soil moisture content was typically higher under elevated CO<sub>2</sub>, none of the trace gas fluxes were significantly altered by CO<sub>2</sub> enrichment over the 43 months period of observation. Similarly, N<sub>2</sub>O fluxes was not affected by elevated CO<sub>2</sub> in a paddy, arable and grassland fields (Cheng et al., 2006; Smith et al., 2010; Dijkstra et al., 2010). However, Kettunen et al. (2006) showed that elevated CO<sub>2</sub> increased both N<sub>2</sub>O flux from soil and soil water content.

A significant increase of N<sub>2</sub>O emissions under elevated atmospheric CO<sub>2</sub> has been observed in the Giessen FACE study (Kammann et al., 2008). The more than 9-year data set allowed for the first time the investigation of different time periods throughout the year. Unexpectedly, the N<sub>2</sub>O stimulation in this N limited grassland ecosystems occurred throughout the vegetation period when mineral N supply was limited, while in the period following N application no significant difference in N<sub>2</sub>O emissions was detected. Differences in N cycling and/or stimulation of different microbial groups under

elevated CO<sub>2</sub> were made responsible for the observed results. A <sup>15</sup>N tracing study with soil taken from the Giessen FACE study showed that under elevated CO<sub>2</sub> the turnover of N changed towards a higher N cycling speed (Müller et al., 2009). To explain the CO<sub>2</sub> response on N<sub>2</sub>O it is particularly important to study in detail the periods following N fertilizer application because these are times when high N<sub>2</sub>O emissions occur. Thus the objective of this study was to identify the effect of CO<sub>2</sub> on N<sub>2</sub>O emissions and identify the processes of N<sub>2</sub>O production as well as the effect on the N<sub>2</sub>-to-N<sub>2</sub>O ratios.

## 2 Material and methods

### 2.1 Site description

The grassland site (Environmental Monitoring Climate Impact Research Station) is located 50°32'N and 8°41.3'E at an elevation of 172 m a.s.l. near Giessen, Germany. The semi-natural non-grazed grassland has been managed extensively as a meadow for at least 50 years, fertilized with 50–80 kg N ha<sup>-1</sup> annum<sup>-1</sup> as calcium ammonium nitrate and mown twice per year. The annual mean precipitation and temperature (last 35 years) are 644 mm and 9.9 °C. The vegetation, an *Arrhenatheretum elatioris* Br.Bl. *Filipendula ulmaria* sub-community, is dominated by 12 grass species, 2 legumes and 15 non-leguminous herbs. The soil is classified as Stagnofluvic Gleysol on loamy-sandy sediments over clay (Kammann et al., 1998). In May 1998, the long-term Giessen FACE system was established (Jäger et al., 2003).

### 2.2 Soil sampling and experimental set-up

Soil for the experiments reported here was sampled from the top 12 cm of the old grassland soil (organic C 6.6; pH 6.2). The soil was taken from the ambient and elevated FACE rings where also soil had been sampled for the <sup>15</sup>N tracing study described by Müller et al. (2009) (see this publication for more details). Fresh soil was sieved

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(5 mm) and sub-samples were taken for determining initial gravimetric moisture content at 105 °C for 24 h. The soil was stored for a week at 4 °C before the start of the incubation experiment. A set of twelve jars (Weck®) was arranged according to the treatments: (i) two soils i.e. elevated CO<sub>2</sub> soil and ambient soil; (ii) two N sources i.e. <sup>15</sup>NH<sub>4</sub>NO<sub>3</sub> or NH<sub>4</sub><sup>15</sup>NO<sub>3</sub> (60 atom%) with three repetitions per treatment. Soil portions of 200 g (fresh wt. equivalent) were weighed out and filled into each jar. The soil was adjusted to a water content of 0.40 g H<sub>2</sub>O g<sup>-1</sup> dry soil with distilled water and incubated for a week at 20 °C prior to fertilizer application. Both the soils (either from plots under elevated or ambient CO<sub>2</sub>) were labelled with <sup>15</sup>N at a rate of 100 µg N g<sup>-1</sup> fresh soil in 10.5 mL per jar using a seven-needle applicator to assure an even distribution of the applied N in soil. The resulting water content was on average 0.45 g H<sub>2</sub>O g<sup>-1</sup> dry soil. The jars were covered with parafilm that was perforated with a needle to facilitate gas exchange and incubated at 20 °C. Samples were weighed at regular intervals during the incubation; water loss under present experimental set-up was almost negligible (~0.2 mL).

### 2.3 Gas samplings and measurements

In total, 13 gas samplings were carried out at day 0 (shortly after N application) and 1, 2, 4, 9, 14, 18, 24, 29, 35, 39, 48 and 57 days after N application. Four samplings were carried out (3, 4, 5, 7 days) before fertilizer application (control). Gas samples were analyzed on a gas chromatograph equipped with ECD (N<sub>2</sub>O, CO<sub>2</sub>) and FID (O<sub>2</sub>, CH<sub>4</sub>) detector by standard gas chromatographic method (Mosier and Mack, 1980). The gas chromatograph (Shimadzu 14a) was equipped with a <sup>63</sup>Ni-electron capture detector ECD for N<sub>2</sub>O and CO<sub>2</sub> (oven, valve and detector temperatures were operated at 65, 100 and 280 °C) and flame ionization detector (FID) for O<sub>2</sub> and CH<sub>4</sub> estimation. The <sup>15</sup>N excess in N<sub>2</sub>O was determined in separate samples by isotope-ratio mass spectrometry (Stevens et al., 1993). The procedure assumes that N<sub>2</sub>O is produced either via nitrification (NH<sub>4</sub><sup>+</sup> oxidation) and/or denitrification (NO<sub>3</sub><sup>-</sup> reduction). A negative

value would indicate that the enrichment of the  $\text{N}_2\text{O}$  is lower than the enrichment of the  $\text{NH}_4^+$  and the  $\text{NO}_3^-$  pool. Thus providing an indication that  $\text{N}_2\text{O}$  was produced by a third process that is not associated with the turnover of  $\text{NH}_4^+$  and/or  $\text{NO}_3^-$ .

## 2.4 Denitrification Enzyme Activity (DEA)

5 A set of twelve flasks (Brand) per sampling date (total of 8 sets) was arranged according to the treatments: (i) two soils i.e. elevated  $\text{CO}_2$  soil and ambient soil; (ii) two  $\text{C}_2\text{H}_2$  levels ( $-\text{C}_2\text{H}_2$ ;  $+\text{C}_2\text{H}_2$ ) with three repetitions per treatment. Prior to DEA analysis, twenty grams of soil at a moisture content of 41% (vol/vol) was pre-incubated at  $20^\circ\text{C}$  for 7 days after adding  $100\ \mu\text{g}\ \text{N}\ \text{g}^{-1}$  fresh soil (as  $\text{NH}_4\text{NO}_3$ ) following experiment

10 1. DEA was carried out in 250 mL flasks (Brand) with a septum fitted in the lid for gas sampling, using an anaerobic slurry technique as described by Müller et al. (2002). At the start of the assay 50 mL of a nitrate-glucose solution were applied to each flask resulting in concentrations of  $50\ \mu\text{g}\ \text{NO}_3^- \text{N}\ \text{g}^{-1}$  (as  $\text{KNO}_3$ ) and  $300\ \mu\text{g}\ \text{C}\ \text{g}^{-1}$  soil (as glucose). The bottles were immediately closed, evacuated and the headspace flushed

15 (to atmosphere pressure) with pure  $\text{N}_2$  with a double needle. Each evacuation and/or flushing lasted for 2 min and the internal atmosphere did not contain detectable oxygen, as occasionally confirmed by gas chromatography. In  $\text{C}_2\text{H}_2$  treated flasks, 10% of headspace gas was removed and replaced by adding 10 mL of  $\text{C}_2\text{H}_2$  with a syringe and internal pressure was equilibrated to atmospheric pressure. The samples were placed

20 at  $20^\circ\text{C}$  on a rotary shaker at 120 rpm for a total of 40 min. The headspace atmosphere was removed (first sample) with 60 mL gas-tight syringes at 20 min. The extracted gas after the first sample was replaced by the same amount of  $\text{N}_2$ . Following continuous shaking, a second sample was taken after 40 min. Gas samples were analysed for  $\text{O}_2$ ,  $\text{CH}_4$ ,  $\text{CO}_2$ , and  $\text{N}_2\text{O}$  on a gas chromatograph (GC) equipped with an FID and ECD detector (Mosier and Mack, 1980). DEA was calculated as the difference in  $\text{N}_2\text{O}$  concentration increase during a 20 min incubation (40-20 min), accounting for bottles, soil, media and water volume. The concentrations of the sampling were adjusted for dissolved gas in soil solution using the Bunsen coefficient (Moraghan and Buresh, 1977).

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## 2.5 Statistical analysis

Statistical analysis was carried out with Sigmaplot in combination with Sigmastat (version 3.1, SPSS, Inc.).

## 3 Results

### 3.1 Effect of elevated atmospheric CO<sub>2</sub> on CO<sub>2</sub> emissions

Soil carbon dioxide fluxes before N application were 1.00–1.47  $\mu\text{g CO}_2\text{-C g}^{-1}$  under ambient and 1.13–1.42 under elevated CO<sub>2</sub> (Fig. 1). During 7 days samplings (average), the fluxes were 1.22 and 1.27  $\mu\text{g CO}_2\text{-C g}^{-1}$  in ambient and elevated CO<sub>2</sub> soils, respectively showing a non-significant response (3.6%) of elevated CO<sub>2</sub>. Application of N fertilizer did not alter the CO<sub>2</sub> fluxes in both the soils: The maximum fluxes occurred during the first 14 days and thereafter CO<sub>2</sub> fluxes continuously decreased with incubation time. Over 57 days' sampling, CO<sub>2</sub> fluxes were on average 0.77  $\mu\text{g CO}_2\text{-C g}^{-1}$  and 0.93  $\mu\text{g CO}_2\text{-C g}^{-1}$  in ambient and elevated CO<sub>2</sub> soil, respectively indicating approximately 20% higher soil CO<sub>2</sub> emissions under elevated CO<sub>2</sub> than soil from ambient CO<sub>2</sub> but the differences were not significantly different ( $p > 0.05$ ).

### 3.2 Effect of elevated atmospheric CO<sub>2</sub> on CH<sub>4</sub> fluxes

Net CH<sub>4</sub> oxidation was observed in all samplings before and after N application (Fig. 1). The CH<sub>4</sub> oxidation rates before N application were -0.29 to -0.34  $\eta\text{g CH}_4\text{-C g}^{-1} \text{h}^{-1}$  in ambient and -0.46 to -0.76  $\eta\text{g CH}_4\text{-C g}^{-1} \text{h}^{-1}$  in elevated CO<sub>2</sub> soil indicating about a 22% higher oxidation rate in soil that had been under elevated CO<sub>2</sub>. After N application, the rate of CH<sub>4</sub> oxidation increased from -0.21 to -3.1  $\eta\text{g CH}_4\text{-C g}^{-1} \text{h}^{-1}$  in ambient and -0.45 to -4.26  $\eta\text{g CH}_4\text{-C g}^{-1} \text{h}^{-1}$  in elevated CO<sub>2</sub>. Maximum oxidation rates were observed 1 day after fertilizer application and occurred at constant rates till

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18–24 days of incubation. During this period the oxidation rates in the ambient control were  $-1.19$  to  $-3.07 \text{ } \eta\text{g CH}_4\text{-C g}^{-1} \text{ h}^{-1}$  while in elevated  $\text{CO}_2$  the rates were  $-1.79$  to  $-4.18 \text{ } \eta\text{g CH}_4\text{-C g}^{-1} \text{ h}^{-1}$ . After day 24, the oxidation potential of soil decreased consistently to background level till the end of the incubation. On average over the incubation time,  $\text{CH}_4$  oxidation rates before N application were  $-0.40 \text{ } \eta\text{g CH}_4\text{-C g}^{-1} \text{ h}^{-1}$  and became  $-1.46 \text{ } \eta\text{g CH}_4\text{-C g}^{-1} \text{ h}^{-1}$  after N application indicating a substantial increase in  $\text{CH}_4$  oxidation with N fertilization. Average rates over sampling dates revealed that  $\text{CH}_4$  oxidation in elevated  $\text{CO}_2$  soil was  $-1.75 \text{ } \eta\text{g CH}_4\text{-C g}^{-1} \text{ h}^{-1}$  while the  $\text{CH}_4$  oxidation in the ambient soil was  $-1.17 \text{ } \eta\text{g CH}_4\text{-C g}^{-1} \text{ h}^{-1}$  indicating a 49% higher  $\text{CH}_4$  oxidation under elevated compared to ambient  $\text{CO}_2$ .

### 3.3 Effect of elevated atmospheric $\text{CO}_2$ on $\text{N}_2\text{O}$ emissions

In the week before fertilizer N application  $\text{N}_2\text{O}$  emissions were  $0.019 \text{ } \eta\text{g N}_2\text{O-N g}^{-1} \text{ h}^{-1}$  in the ambient and  $0.023 \text{ } \eta\text{g N}_2\text{O-N g}^{-1} \text{ h}^{-1}$  in the elevated  $\text{CO}_2$  soils (Fig. 2).  $\text{N}_2\text{O}$  fluxes did not show any consistent pattern with time. Likewise,  $\text{N}_2\text{O}$  fluxes did not differ between elevated  $\text{CO}_2$  and ambient treatments and both showed similar fluxes i.e.  $0.019$  and  $0.023 \text{ } \eta\text{g N}_2\text{O-N g}^{-1} \text{ h}^{-1}$  (average). After N application the fluxes rates increased substantially and reached  $0.280$  and  $0.240 \text{ } \eta\text{g N}_2\text{O-N g}^{-1} \text{ h}^{-1}$  at day 0. Over the 57 days,  $\text{N}_2\text{O}$  fluxes averaged  $\eta\text{g N}_2\text{O-N g}^{-1} \text{ h}^{-1}$  in ambient and  $0.083 \text{ } \eta\text{g N}_2\text{O-N g}^{-1} \text{ h}^{-1}$  in elevated  $\text{CO}_2$  (not significantly different) resulted in a 3- to 4-fold increase after N application. The highest fluxes of  $0.281$  and  $0.240 \text{ } \eta\text{g N}_2\text{O-N g}^{-1} \text{ h}^{-1}$  were measured from ambient and elevated  $\text{CO}_2$  treatments, respectively just after N application (day 0). The increase in emissions was short-lived (3–4 days) with fluxes returning to “background” levels 30 days after N application.

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### 3.4 $^{15}\text{N}$ enrichment of the $\text{N}_2\text{O}$

The  $^{15}\text{N}$  enrichment of the  $\text{N}_2\text{O}$  in the soil increased one day after N fertilizer application together with the increase in  $\text{N}_2\text{O}$  concentrations (Fig. 3). Ten days after fertilizer N application, the enrichment of the  $\text{N}_2\text{O}$  was close to the enrichment in the applied N, indicating that the observed  $\text{N}_2\text{O}$  originated from the applied fertilizer. Comparing the  $^{15}\text{N}$  enrichments in the  $\text{N}_2\text{O}$  from the ambient and elevated  $\text{CO}_2$  soils, no significant difference was observed between the two soils labeled either with  $\text{NH}_4^{15}\text{NO}_3$  or  $^{15}\text{NH}_4\text{NO}_3$ . The  $^{15}\text{N}$  enrichment of the  $\text{N}_2\text{O}$  in the treatments where  $\text{NO}_3^-$  was labelled, were relatively higher than the treatment where  $\text{NH}_4^+$  was labeled. The contribution of denitrification for  $\text{N}_2\text{O}$  production estimated by the 2-pool model of Stevens et al. (1997) indicated on day 1 after  $^{15}\text{N}$  application a contribution of 16 and 32% under ambient and elevated  $\text{CO}_2$  respectively. Negative values after 15 days showed that apart from  $\text{N}_2\text{O}$  contribution related to  $\text{NH}_4^+$  and  $\text{NO}_3^-$  turnover a third process must have been in operation which was responsible for a dilution of the  $^{15}\text{N}$   $\text{N}_2\text{O}$  abundance below the  $^{15}\text{N}$  abundance of  $\text{NH}_4^+$  and  $\text{NO}_3^-$ .

### 3.5 Denitrification enzyme activity, total denitrification and ratio of $\text{N}_2$ -to- $\text{N}_2\text{O}$

The measurement of denitrification enzyme activity (DEA) by measuring  $\text{N}_2\text{O}$  emissions during short incubation periods (anaerobic), total denitrification ( $\text{N}_2\text{O} + \text{N}_2$ ) and  $\text{N}_2/\text{N}_2\text{O}$  ratios was carried-out from both  $\text{CO}_2$  treatments (Fig. 4). Before N application, one measurement was taken and DEA rates were 0.137 in ambient and 0.172  $\mu\text{g N}_2\text{O-N g}^{-1} \text{h}^{-1}$  in elevated  $\text{CO}_2$  soil while total denitrification ( $\text{N}_2\text{O} + \text{N}_2$ ) was 0.456 in ambient and 0.514  $\mu\text{g N}_2\text{O-N g}^{-1} \text{h}^{-1}$  in elevated  $\text{CO}_2$  soil. The  $\text{N}_2/\text{N}_2\text{O}$  ratios were 3.33 for ambient and 2.99 for elevated  $\text{CO}_2$  treatment. After N application, DEA rates (both  $\text{N}_2\text{O}$  and  $\text{N}_2\text{O} + \text{N}_2$ ) increased in the first two samplings (day 0 and 1) but thereafter the rates continuously declined over time. DEA rates ( $\text{N}_2\text{O}$  fluxes) in the elevated  $\text{CO}_2$  treatment

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were on average (20 days incubation) 16% higher ( $0.149$  vs.  $0.128 \mu\text{g N}_2\text{O-N g}^{-1} \text{h}^{-1}$ ) than  $\text{N}_2\text{O}$  fluxes in the ambient  $\text{CO}_2$  treatment. But the values of both treatments across different sampling days were not-significantly different. Total denitrification rates ( $\text{N}_2\text{O} + \text{N}_2$ ) indicated significantly higher fluxes (36%) in elevated  $\text{CO}_2$  treatment than in ambient  $\text{CO}_2$  ( $P \leq 0.05$ ). Similarly, the  $\text{N}_2$  production was consistently higher under elevated  $\text{CO}_2$  treatment and on average 54% higher than the  $\text{N}_2$  production in the ambient  $\text{CO}_2$  treatment (Fig. 5). The  $\text{N}_2/\text{N}_2\text{O}$  ratio was 1.02 in the ambient and 1.36 in the elevated  $\text{CO}_2$  treatment showing a 33% higher ratio under elevated  $\text{CO}_2$ . Contribution of  $d$  ( $\text{NO}_3^-$  reduction) to total  $\text{N}_2\text{O}$  production at ambient and elevated  $\text{CO}_2$  is shown in Fig. 5. Results indicated that shortly after N application  $\text{N}_2\text{O}$  production and reduction to  $\text{N}_2$  substantially increased both in ambient and elevated  $\text{CO}_2$  and the emissions decreased sharply with time. Elevated  $\text{CO}_2$  stimulated both the  $\text{N}_2\text{O}$  production and reduction to  $\text{N}_2$  compared to ambient  $\text{CO}_2$ .

## 4 Discussion

### 4.1 $\text{CO}_2$ production and methane oxidation

Over the 57-day period of observation,  $\text{CO}_2$  flux averaged 0.77 in ambient and  $0.93 \mu\text{g N}_2\text{O-N g}^{-1} \text{h}^{-1}$  in elevated  $\text{CO}_2$  treatment showing a 20% increase in  $\text{CO}_2$  fluxes under elevated atmospheric  $\text{CO}_2$ . But the differences between the two soils were non-significant suggesting that  $\text{CO}_2$  flux was not affected by elevated atmospheric  $\text{CO}_2$ . The observed effect from the soil having 25% high  $\text{CO}_2$  concentration and under  $\text{CO}_2$  enrichment for the last 6 years was unexpected since the amount of C entering the soil is generally considered to be higher because of higher rhizodeposition and microbial activity. Although soil from both ambient and elevated  $\text{CO}_2$  treatments was incubated under similar conditions, yet the pre-existing organic fractions and microbial differences may have had a substantial effect on  $\text{CO}_2$  emissions which was not the case in the present study. This is not in agreement with the previous observations

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where CO<sub>2</sub> fluxes under elevated CO<sub>2</sub> were significantly higher compared to ambient CO<sub>2</sub> (Hungate et al., 1997; Arnone and Bohlen, 1998; Ambus and Robertson, 1999; Reich et al., 2001; Smith et al., 2010). However, there are reports showing that ecosystem respiration (CO<sub>2</sub> flux) was not affected by elevated CO<sub>2</sub> (Ineson et al., 1998; Mosier et al., 2003). Hu et al. (2001) suggested that in the long term, soil microbial decomposition is slowed under elevated CO<sub>2</sub> because of N limitation and CO<sub>2</sub> production is either not affected or limited. In our study there was no difference in N supply because equal amount of N fertilizer was applied in both the soils. Both the soils had shown similar CO<sub>2</sub> production potential indicating that it is not the N limiting factor affecting the CO<sub>2</sub> production in elevated CO<sub>2</sub> soils but some other unknown control factors.

Throughout the course of experiment, net CH<sub>4</sub> oxidation was observed in all samplings before and after N application. In both the cases, CH<sub>4</sub> oxidation potential was significantly greater in the elevated CO<sub>2</sub> (49%) than the ambient CO<sub>2</sub>. These results were in contrast to studies where either reduced CH<sub>4</sub> emissions (Ineson et al., 1998; Cheng et al., 2006) more oxidation in ambient than elevated CO<sub>2</sub> soil (Mosier et al., 2003), or no effect of elevated CO<sub>2</sub> on CH<sub>4</sub> oxidation was observed (Mosier et al., 2002; Smith et al., 2011). Most of these studies were conducted under field conditions where two possibilities may tend to increase CH<sub>4</sub> production and decrease CH<sub>4</sub> oxidation (i) increased soil moisture under elevated CO<sub>2</sub> constrain and slow down the diffusive CH<sub>4</sub> (and O<sub>2</sub>) transport from the atmosphere to the water- film covered microbial population and therefore inhibit CH<sub>4</sub> oxidation (Dorr et al., 1993), (ii) inorganic N pools tended to be higher in the elevated CO<sub>2</sub> soil than in the ambient CO<sub>2</sub> soil. The higher concentration of either NH<sub>4</sub><sup>+</sup> or NO<sub>3</sub><sup>-</sup> may inhibit CH<sub>4</sub> oxidation (Stendler et al., 1989; Reay and Nedwell, 2004). We provided similar atmospheric conditions to both ambient and elevated CO<sub>2</sub> soils in the laboratory and oxidation of CH<sub>4</sub> throughout the experiment supported the idea that evidently the mechanism responsible for inhibiting CH<sub>4</sub> oxidation in response to elevated CO<sub>2</sub> in the field was not operative under laboratory conditions. Reduced CH<sub>4</sub> oxidation in response to elevated CO<sub>2</sub> soil generally linked to lower diffusion rates. However, under field conditions in the same study site,

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Kammann et al. (2001) explained that moisture level does not play major role on CH<sub>4</sub> oxidation/production but the depth of the CH<sub>4</sub> producing horizon in combination with the duration of sub-surface CH<sub>4</sub> production contribute to the overall CH<sub>4</sub> oxidation rate at the soil surface, conditions which are not present under laboratory conditions.

5 Average of both -N and +N soils over time indicated oxidation rates of -0.4  $\eta\text{g CH}_4\text{-C g}^{-1}\text{ h}^{-1}$  in control (-N) and -1.46  $\eta\text{g CH}_4\text{-C g}^{-1}\text{ h}^{-1}$  in N added (+N) soil indicating a 3-fold increase in CH<sub>4</sub> oxidation following N application. These results are in contrast to earlier findings that the application of NH<sub>4</sub><sup>+</sup> reduced CH<sub>4</sub> oxidation rates almost immediately (forest soils, Steudler et al., 1989; short-grass steppe, Mosier et al., 1991; 10 Laboratory incubations, Hütsch, 1998; Tlustos et al., 1998; Ullah et al., 2008). They attribute this delay to suppression in the population growth of methane oxidizers and to an inhibition of de-novo enzyme synthesis. Kammann et al. (2001) found no relationship between the N fertilizer and CH<sub>4</sub> oxidation rates during field study of the same site. The high oxidation rates by N addition in the present study might be that 15 after 6–7 years of FACE establishment, it is unlikely to have any inhibitory effect by elevated CO<sub>2</sub> (Kammann et al., 2001). Most of the researchers reported inhibition of CH<sub>4</sub> oxidation by NH<sub>4</sub><sup>+</sup> not by NO<sub>3</sub><sup>-</sup> and accumulation of NO<sub>3</sub><sup>-</sup> after nitrification might slow down the inhibitory effect of N fertilizer. Steudler et al. (1989) reported that nitrification is responsible for CH<sub>4</sub> oxidation and nitrifying bacteria including the dominant 20 soil ammonium-oxidizing bacterium *Nitrosomonas europaea*, have the ability to oxidize CH<sub>4</sub>. The hypothesis of higher CH<sub>4</sub> oxidation by nitrification could not be justified in our study. We in our mineral N study found significantly more accumulation of NO<sub>3</sub><sup>-</sup> in ambient than elevated CO<sub>2</sub> while CH<sub>4</sub> oxidation were 49% higher under elevated CO<sub>2</sub>. Reay and Nadwell (2004) found a differential reduction in CH<sub>4</sub> oxidation by NO<sub>3</sub><sup>-</sup>, 25 rather than NH<sub>4</sub><sup>+</sup>. Therefore, the kinetics of CH<sub>4</sub> oxidation/production is complex and their dependence on soil N status or moisture remains an area of some controversy.

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## 4.2 N<sub>2</sub>O emission

Results of the previous study on the Giessen FACE site indicated significant increase in N<sub>2</sub>O emissions throughout the vegetation period when mineral N supply was limited, while in the period following N application no significant difference in N<sub>2</sub>O emissions was detected (Kammann et al., 2008). However, estimation of N<sub>2</sub>O emission was only one time period in the Kammann et al. (2008) study. Moreover, <sup>15</sup>N tracing study showed that the N turnover changed towards a higher N cycling speed under elevated CO<sub>2</sub> (Müller et al., 2009). To explain the CO<sub>2</sub> response of N<sub>2</sub>O it is particularly important to study in detail the periods following N fertilizer application because these are times when high N<sub>2</sub>O emissions occur. The experimental conditions resemble the period after N fertilizer application. Kammann et al. (2008) showed that N<sub>2</sub>O emissions from field observations of the Giessen FACE study were not significantly different during the period following N application which is in line with the results from this laboratory incubation.

Long-term incubation studies in the present investigation indicated a substantial increase in N<sub>2</sub>O emissions after fertilizer N application. Results indicated that N<sub>2</sub>O emissions in both the treatments (ambient and elevated) appeared to be limited by available N as fluxes in N fertilized soils increased 3-to 4-fold. Application of fertilizer N would have had a direct influence on N<sub>2</sub>O production by provision of N for both nitrification and denitrification. The two processes can occur simultaneously and produce N<sub>2</sub>O in ecosystem (Abbasi and Adams, 2000a, b). Emissions of N<sub>2</sub>O have previously been shown to increase after application of inorganic fertilizer (e.g. Mosier, 1994; Clayton et al., 1997; Abbasi and Adams, 2000b). However, the magnitude of emissions varies depending on type, method and timing of inorganic fertilizer application, soil temperature, moisture content, soil type (Baggs et al., 2003a; Khalil et al., 2009; Sistani et al., 2010). Calculations of the contribution that denitrification had on the total N<sub>2</sub>O gas carried out according to Stevens et al. (1997). Results showed that the contribution of denitrification was higher under elevated CO<sub>2</sub>. Furthermore results showed that

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apart from nitrification and denitrification a third source for N<sub>2</sub>O, which was not related to NH<sub>4</sub><sup>+</sup> and/or NO<sub>3</sub><sup>-</sup> turnover, must have been active. A recent study on the effect of CO<sub>2</sub> on N cycling showed that oxidation of organic N may be an important process for N<sub>2</sub>O production in permanent grassland soils (Rütting et al., 2010). They showed that denitrification increased from 4.7 to 8%. A similar trend was observed in our study. Stimulation of denitrification and N<sub>2</sub>-to-N<sub>2</sub>O ratios was also observed from the soil incubation studies. However, apart from CO<sub>2</sub> the magnitude of emissions varies depending on type and timing of inorganic fertilizer application, soil temperature, moisture content, soil type which will vary throughout the year (Baggs et al., 2003a; Kammann et al., 2008).

The N<sub>2</sub>O emissions observed before and after N application showed that elevated CO<sub>2</sub> did not show any significant effect on N<sub>2</sub>O fluxes and rates of fluxes (average) were almost similar. Both (elevated and ambient) soils were incubated under similar moisture and temperature condition, so that pre-existing organic fractions and resulting differences in microbial activity and dynamics could have had an effect on N<sub>2</sub>O production. But this was not the case and elevated CO<sub>2</sub> showed no evidence for any significant altered fluxes of N<sub>2</sub>O. In many other investigations, elevated CO<sub>2</sub> increased N<sub>2</sub>O flux rates. Ineson et al. (1998) reported 27% higher N<sub>2</sub>O emissions in grassland exposed to elevated CO<sub>2</sub>. Similarly, in perennial grassland N<sub>2</sub>O fluxes under elevated CO<sub>2</sub> were found double than those observed under ambient CO<sub>2</sub> (Arnone and Bohlen, 1998). Baggs and Blum (2004) reported that response of elevated CO<sub>2</sub> to N<sub>2</sub>O emissions from grass swards depend on the rate of N application. Elevated CO<sub>2</sub> had no significant effect on emissions following low N application rates while N<sub>2</sub>O emissions significantly increased under elevated CO<sub>2</sub> when high rates of N fertilizer were applied to the same grass swards. Observations in the Giessen FACE study are contrary because increasing N<sub>2</sub>O emissions were only observed during times of low N availability. After N fertilizer application N<sub>2</sub>O emissions were not different between ambient and elevated CO<sub>2</sub>. There are reports that elevated CO<sub>2</sub> either did not alter N<sub>2</sub>O fluxes or even lower down (decreased) N<sub>2</sub>O emissions (Hungate et al., 1997; Mosier et al.,

2002, 2003; Welzmilller et al., 2008). The arguments in favor of increased N<sub>2</sub>O emissions under elevated CO<sub>2</sub> are (i) improved soil moisture (ii) increase in C supplies in soil which affect N transformation processes (Ineson et al., 1998; Arnone and Bohlen, 1998; Baggs and Blum, 2004). In contrast, the lower N availability of N in the mineral N pool for soil microbes because of enhance plant uptake and altered N dynamics under elevated CO<sub>2</sub> are responsible for lower N<sub>2</sub>O emissions (Mosier at al., 2003).

Increasing concentration of atmospheric CO<sub>2</sub> is likely to affect the production of N<sub>2</sub>O. Greater above ground biomass production under elevated CO<sub>2</sub> may lead to increase N uptake, reducing the potential for production of N<sub>2</sub>O during nitrification and or denitrification. Alternately, the increased belowground C allocation under elevated CO<sub>2</sub> may increase the potential for denitrification by providing energy for this process. However, the effects of elevated CO<sub>2</sub> on N availability are uncertain, with suggestion of increased availability (Zak et al., 1993), reduced availability of N due to high rate of microbial immobilization of soil N (Diaz et al., 1993; Hartwig et al., 1996) or no significant effect (Gloser et al., 2000). The N<sub>2</sub>O production and its concentration in atmosphere depend more on soil N turnover (mineralization, nitrification, denitrification) (Müller et al., 2009; Rütting et al., 2010). The net and gross nitrification rates even decreased while DEA did not show any significant increase under elevated CO<sub>2</sub>. Therefore, higher fluxes of N<sub>2</sub>O under elevated CO<sub>2</sub> conditions in our experiment were unlikely and the similarity of the N<sub>2</sub>O fluxes from the two soils could be expected. The soil collected from a grassland field exposed to FACE since 1998 and the tendency of soil to respond to elevated CO<sub>2</sub> over 7–8 years of exposure in this FACE experiment may be different to the soil exposed for shorter period of time. In the first 3 years of the FACE study higher N<sub>2</sub>O emissions were observed from the same field exposed to elevated CO<sub>2</sub> (Kammann et al., 2008). Mosier et al. (2002) explained that soil moisture and C, N turnover increased substantially in the earlier stages of CO<sub>2</sub> establishment. But over the long-term, N transformation processes remain unchanged and response to elevated CO<sub>2</sub> becomes limited. A similar, conclusion was also reported by Baggs and Blum (2004). Zak et al. (2003) reported that increased in substrate quantity by elevated CO<sub>2</sub> did

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not alter microbial processes of C and N in soil (e.g. supply and demand of N). Our gaseous measurements suggested that at least trace gases fluxes were not significantly changed by elevated atmospheric CO<sub>2</sub>. Rather than changing N<sub>2</sub>O emissions an effect on the N<sub>2</sub>-to-N<sub>2</sub>O ratio could lead to the same result.

### 5 4.3 Total denitrification and N<sub>2</sub>-to-N<sub>2</sub>O ratio

Denitrification enzyme activity (DEA), total denitrification (N<sub>2</sub> + N<sub>2</sub>O) and the ratio of N<sub>2</sub>-to-N<sub>2</sub>O were determined over a 20-day incubation using an anaerobic slurry technique as described by Müller et al. (2002). DEA was on average 16% higher in the elevated CO<sub>2</sub> than in the ambient treatment but the difference between the two CO<sub>2</sub> treatments was not significant suggesting that elevated CO<sub>2</sub> had only a limited effect on the quantity of active denitrifying enzymes present in the soil. Despite the large potential effects of elevated CO<sub>2</sub> on DEA, our study showed a small response. This small response is attributed to the absence of CO<sub>2</sub> effects on DEA drivers e.g. soil water content and level of CO<sub>2</sub> production. In the same soil under field condition, Kammann et al. (2008) found no change in moisture content. These results were in line with findings of Barnard et al. (2004) who reported very little response of DEA to CO<sub>2</sub> treatment in German grassland soils. However, total denitrification (N<sub>2</sub>O + N<sub>2</sub>) and the ratio of N<sub>2</sub>-to-N<sub>2</sub>O were significantly higher under elevated CO<sub>2</sub>. Total denitrification was 36% higher under elevated CO<sub>2</sub> than the ambient treatment while elevated CO<sub>2</sub> had shown a 33% higher N<sub>2</sub>-to-N<sub>2</sub>O ratio. The ratio under elevated CO<sub>2</sub> (average 1.358) were similar to the ranges typically reported (0.1–40) (Rolston et al., 1976) but lower than the ratios of 345 and 410 measured by Baggs et al. (2003b). Baggs et al. (2003b) found very low N<sub>2</sub>-to-N<sub>2</sub>O ratios till 8 days after fertilizer application and proposed a different lag phases for N<sub>2</sub> and N<sub>2</sub>O production. The ratios in their study increased substantially only in the elevated CO<sub>2</sub> during 8-10 days period and decreased to as low as 0 at day 15 while ambient showed no effect with time. We found different pattern of changes. Both ambient and elevated CO<sub>2</sub> treatments exhibited similar trend and the ratios ranged from 0.77–1.84 in ambient and 1.12–1.72 in the elevated CO<sub>2</sub>. The

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maximum ratios in both the treatments were found shortly after N application at day 0. We also considered the long-term measurements proposed by Baggs et al. (2003b) but found no consistent pattern of changes in ratios with time. The constantly higher concentration of  $N_2$  relative to  $N_2O$  throughout the measurements was observed similar to those reported by Welzmler et al. (2008). The higher  $N_2$ -to- $N_2O$  ratios under elevated  $CO_2$  emphasized the need for the consideration of  $N_2$  measurements in the denitrification studies in the future and shows that despite a non significant response to  $N_2O$  total denitrification may be altered. This is supported by a recent microbial study in the Giessen FACE study (Kandeler et al, unpublished results) which strongly indicated a shift towards denitrifier community patterns that could explain an increased  $N_2$ -to- $N_2O$  ration. The results indicate that shortly after N application elevated  $CO_2$  stimulated both the  $N_2O$  production and reduction to  $N_2$  to explain the increased  $N_2$ -to- $N_2O$  ratio. Thus, the observed variation of the  $CO_2$  effect on  $N_2O$  emissions throughout the year is possibly related to the dynamics of the  $N_2O$  reductase activity.

## 5 Conclusions

Most of the studies conducted so far suggesting higher  $N_2O$  emissions under elevated  $CO_2$  while very few reported no response. Over 57 days measurement of trace gas exchange in ambient and elevated  $CO_2$ , we observe no statistically significant  $CO_2$  enrichment effect on fluxes of  $CO_2$  and  $N_2O$ . It is possible that exposure of soil to FACE over long period diminished its enhancing effects on microbial processes including nitrification and denitrification thereby did not show any significant effect on trace gas fluxes. The larger  $CH_4$  oxidation under elevated  $CO_2$  is surprising and shows that potential for  $CH_4$  oxidation may increase under field where reduced net  $CH_4$  uptake was observed under elevated  $CO_2$  previously. Despite several previous studies suggesting N fertilizer to be a key determinant of  $CH_4$  oxidation capacity in soil, our findings suggest that N fertilization do not have any inhibitory effect on  $CH_4$  oxidation rather it increases  $CH_4$  oxidation potential of soil. The understanding of the stimulation of

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population and activity of methanogenics and methanotrophic bacteria is essential to predict the net CH<sub>4</sub> oxidation in terrestrial ecosystem. The higher N<sub>2</sub>-to N<sub>2</sub>O ratios found in our study under elevated CO<sub>2</sub> demonstrate that enzyme dynamics that govern the production and consumption of N<sub>2</sub>O are most likely affected by long-term elevated CO<sub>2</sub> enrichment. Changes in the N cycle and GHG production due to increasing atmospheric CO<sub>2</sub> concentrations are also important to consider in process-based models that try to simulate atmospheric GHG dynamics under climate change. Therefore, while this study does not directly contribute to a better understanding of atmospheric processes, it can elucidate indirectly some of the main drivers of changing GHGs and therefore can contribute to the development of models that are aiming to simulate GHG dynamics in the atmosphere.

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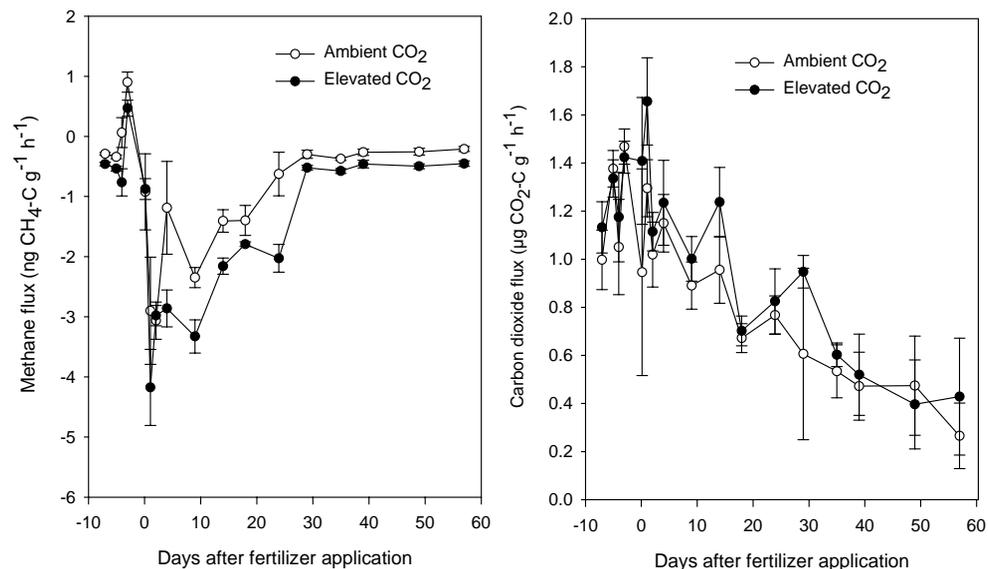
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**Fig. 1.** Daily fluxes of CH<sub>4</sub> ( $\text{ng CH}_4\text{-C g}^{-1} \text{h}^{-1}$ ) and CO<sub>2</sub> ( $\mu\text{g CO}_2\text{-g}^{-1} \text{h}^{-1}$ ) (Avg.  $\pm$  SD) from temperate grassland soil expose to elevated CO<sub>2</sub> and soil without elevated CO<sub>2</sub> treatment i.e. ambient incubated under controlled laboratory conditions following the application of NH<sub>4</sub><sup>15</sup>NO<sub>3</sub> and <sup>15</sup>NH<sub>4</sub>NO<sub>3</sub>.

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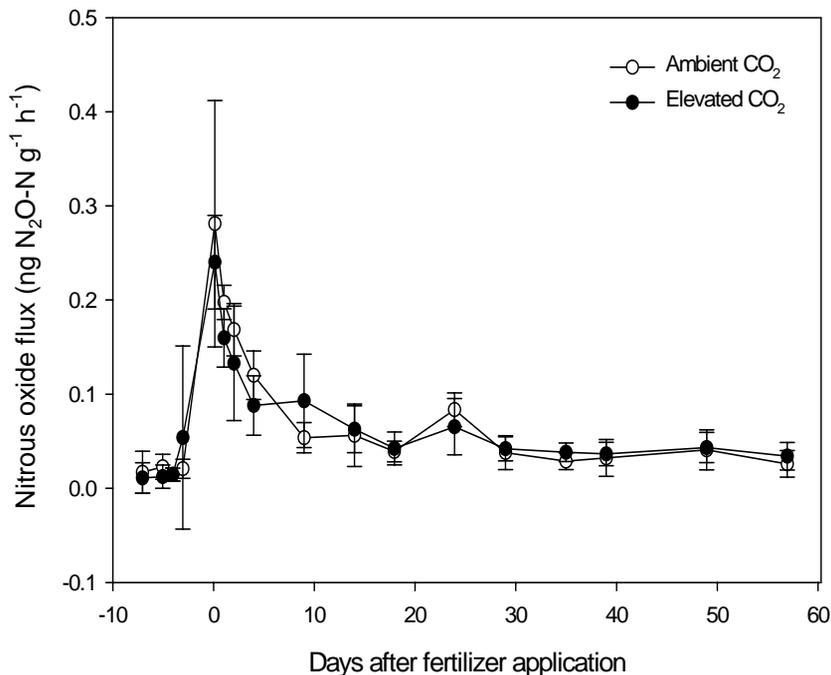
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**Fig. 2.** Daily fluxes of N<sub>2</sub>O ( $\text{ng N}_2\text{O-N g}^{-1} \text{h}^{-1}$ ) (Avg.  $\pm$  SD) from temperate grassland soil exposed to elevated CO<sub>2</sub> and soil without elevated CO<sub>2</sub> treatment i.e. ambient incubated under controlled laboratory conditions following the application of NH<sub>4</sub><sup>15</sup>NO<sub>3</sub> and <sup>15</sup>NH<sub>4</sub>NO<sub>3</sub>.

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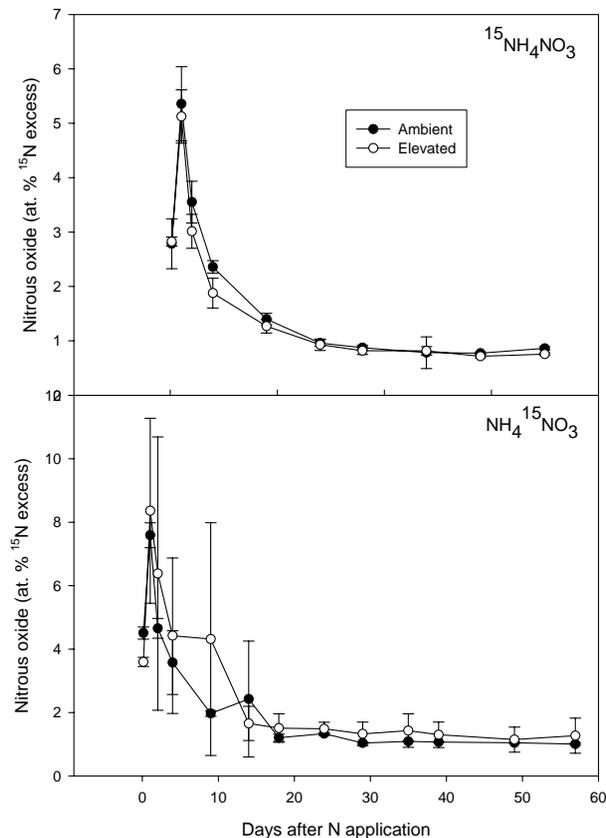
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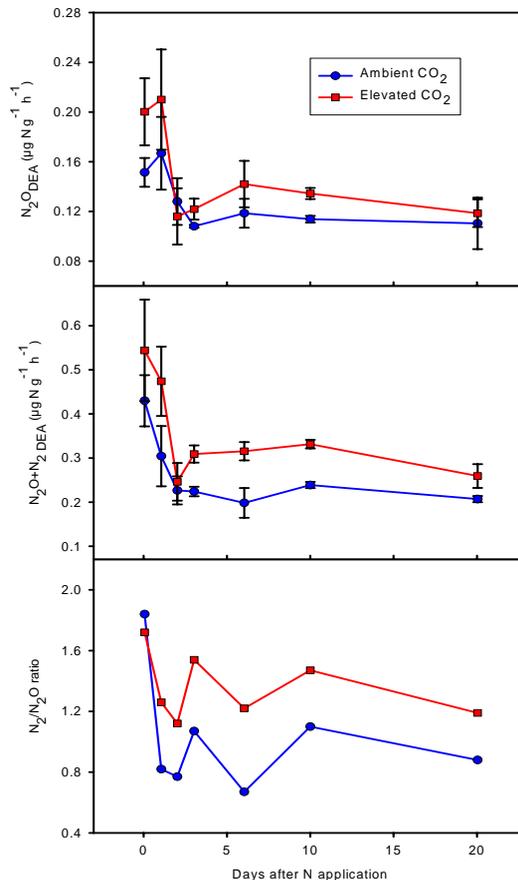
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**Fig. 3.** Nitrous oxide ( $\text{N}_2\text{O}$ ) enrichments (Avg  $\pm$  SD) in a temperate grassland soil expose to elevated  $\text{CO}_2$  and soil without elevated  $\text{CO}_2$  treatment i.e. ambient following N fertilizer application where the nitrate pool ( $\text{NH}_4^{15}\text{NO}_3$ ) and the ammonium pool ( $^{15}\text{NH}_4\text{NO}_3$ ) were labelled with  $^{15}\text{N}$  at 60 atom% excess.

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**Fig. 4.** Emission of N<sub>2</sub>O, total denitrification (N<sub>2</sub>O + N<sub>2</sub>) (µg N g<sup>-1</sup> h<sup>-1</sup>) and N<sub>2</sub>/N<sub>2</sub>O ratio (AVG ±SD) from temperate grassland soil expose to elevated CO<sub>2</sub> and soil without elevated CO<sub>2</sub> treatment i.e. ambient incubated under controlled laboratory conditions following the application of NH<sub>4</sub><sup>15</sup>NO<sub>3</sub> and <sup>15</sup>NH<sub>4</sub>NO<sub>3</sub>.

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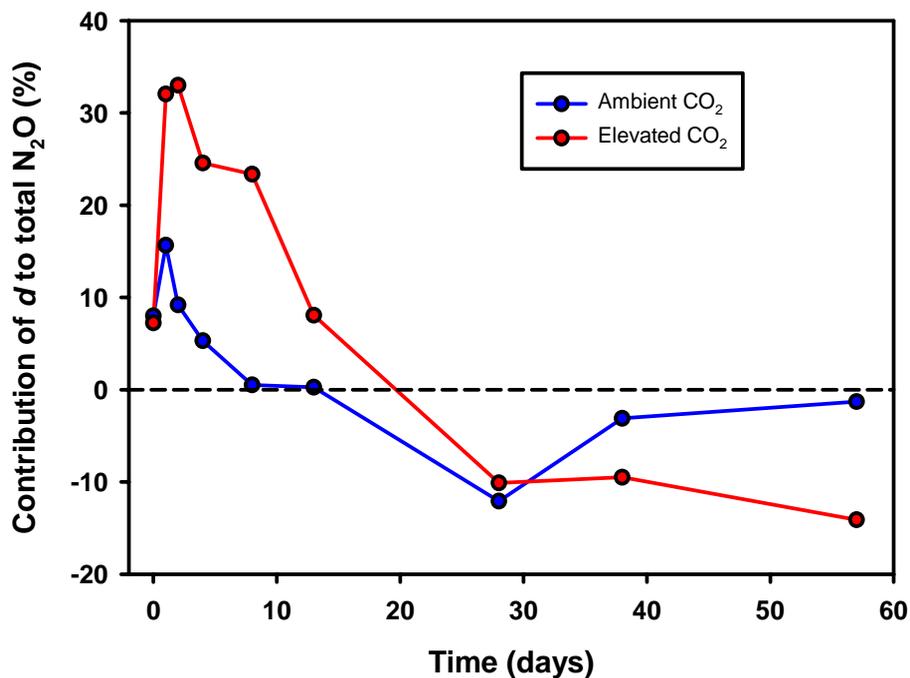
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**Fig. 5.** Contribution of  $d$  (NO<sub>3</sub><sup>-</sup> reduction) to total N<sub>2</sub>O production in grassland soil at ambient and elevated CO<sub>2</sub>.

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