N_2O Emissions and Inorganic N Release Following Incorporation of Crop Residue and/ or Inorganic N Fertiliser into Soil

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Abstract

Nitrous oxide emissions are usually increased following incorporation of crop residues or inorganic N fertiliser into soil, but the effect of combining these inputs at different proportions on N dynamics and N_2O emissions has yet to be adequately examined. The interactive effect of combining crop residues barley (*Hordereum vulgare)* and clover (*Trifolium pretense)* and inorganic N fertiliser (NH_4NO_3) on N_2O emission and mineral N dynamics under controlled laboratory conditions is reported. Emissions of N_2O were significantly higher from soils amended with the low C:N ratio clover residues compared to the high C:N ratio barley residue treatments and was further increased, following combined application of crop residues and inorganic N fertiliser. Furthermore, the magnitude of emission was influenced by the proportions at which the residue-N and the fertiliser-N were combined with the 75:25 fertiliser:clover treatment emitting the highest ($P < 0.05$) amount of 65 mg N_2O-N m^{-2} 30 d^{-1}. Incorporation of sole clover residues resulted in net N mineralization and addition of sole barley residues led to a net N immobilization. However, combined application of either residue with inorganic N fertiliser resulted in net N mineralisation. The results from the study demonstrated that whilst there is the potential for N_2O emission to be controlled through varying ratios of residue:fertiliser input, the magnitude and direction of interactions between these N sources vary between different species as a result of their different qualities. This relationship should be verified under field conditions.

Introduction

N_2O emissions are mainly driven by soil mineral N availability because mineral N is required for nitrification and denitrification, the main processes responsible for soil N_2O production (Baggs *et al.,* 2000; Firestone & Davidson, 1989). In sub-Saharan Africa (SSA) inorganic fertiliser use is often limited by lack of capital and unreliable supply. Therefore, organic resources such as crop residues are the preferred alternative N sources for resource-poor farmers in SSA. Available organic N resources are often low in quality and when applied alone may not supply adequate amounts of nutrients for plant growth (Gentile *et al.,* 2008). Consequently, the integrated nutrient management, which optimises the use of both organic and inorganic N sources, is recommended as a better alternative to sole crop residue use in SSA (Kimani *et al.*, 2003).

Emissions of N_2O from soil have been shown to increase after addition of inorganic N fertiliser (Baggs *et al.,* 2000; Duxbury & McConnaughey, 1986) or after the addition of organic N sources such as crop residues (Huang *et al.,* 2004; Toma & Hatano, 2007; Miller *et al.,* 2008). Crop residues may supply easily mineralisable N as potential inorganic N source and organic C, which enhances nitrifier and denitrifier activity, and increases oxygen consumption in the soil,

thereby, creating optimal conditions for N_2O production through nitrification or denitrification (Velthof *et al.,* 2002). However, the magnitude of N_2O emission from soils amended with crop residues is reported to vary depending on the chemical composition such as C:N ratio of the residues (Millar & Baggs, 2004; Millar *et al.,* 2004) because C:N ratios of organic materials influence the rates of N mineralisation, nitrification and subsequent denitrification (Mubarak *et al.,* 2001; De Neve *et al.,* 2004).

The C:N ratio of plant material incorporated into soil is an important determinant not only of the magnitude of inorganic N dynamics but also for N_2O emissions (Millar & Baggs, 2004; Millar *et al.,* 2004; Huang *et al.,* 2004; Toma & Hatano, 2007). N_2O production has been found to be high following incorporation of crop residues with low C:N ratio rather than those with high C:N ratio (Baggs *et al.,* 2000, Millar *et al.,* 2004; Huang *et al.,* 2004; Gentile *et al.,* 2008) due to promotion of N mineralisation, resulting in high NH_4^+ availability for nitrification and organic C release to promote denitrification in the presence of NO_3^- (Lemke *et al.,* 1999; Baggs *et al.,* 2000; 2006). In contrast, addition of high C:N ratio residues might decrease N available for nitrification and denitrification through stimulating microbial N immobilisation, thereby, lowering N_2O production at least in the short term.

Azam *et al.* (1985) reported that combined application of *Sesbania acuelata* residues and ammonium sulphate lowered total losses of fertiliser N by up to 30% due to increased mineralisation of *Sesbania* N. Additionally, Baggs *et al.* (2003) found that combined application of ^{15}N- labeled fertiliser and bean residues resulted in higher or lower emissions, depending on cultivation technique, when compared to the sum of N_2O from single applications. Such interactions have important implications for mitigating N_2O emissions from agricultural soils because combined application of fertiliser and crop residue has the potential to stimulate microbial-driven N cycling *via* mineralisation, nitrification and denitrification, thereby, enhancing N_2O emission (Granli & Bockman, 1994). Zou *et al.* (2005) reported increased N_2O emission after addition of rapeseed cake with N fertiliser, but a combined application of wheat straw and N fertiliser resulted in low N_2O emission. The latter observation was consistent with the findings of Gentile *et al.* (2008), who stated that the interactive effect of combining fertiliser with crop residues on mineral N changed from negative to positive with increasing residue quality.

The strength of the effect of residue quality on N_2O emission following combined application of crop residues and inorganic N fertiliser is expected to vary depending on the ratio of inorganic N to organic N incorporated, but this has yet to be verified (Garcia -Ruiz & Baggs, 2007). An improved understanding of the controls of N_2O emission and of the interactive effect of combining crop residue and inorganic fertiliser-N on N_2O emission and inorganic N dynamics is, therefore, critical. Such knowledge will enable the determination of the optimal combinations for maximum N use efficiency and their potential impact on atmospheric N_2O loading. In view of this a laboratory experiment was conducted under controlled environmental conditions to

examine the effects of combined applications of low C:N clover or high C:N barley residues with inorganic N fertiliser (NH_4NO_3) at different proportions (100:0, 75:25, 50:50, 25:75 and 0:100; residue: fertiliser), respectively, on soil mineral N dynamics and N_2O emission under controlled laboratory conditions.

Materials and methods

Soil

Soil (0–15 cm depth) was sampled from an arable field at the Savannah Agricultural Research Institute, Tamale, Ghana in February, 2008. This soil is Nyankpala series; reddish brown, sandy loam (72.5% silt,10% clay, 17.5% sand, 1.1% organic C, 0.07% total N, *p*H (H_2O) 6.1, bulk density 1.03 g cm^{-3}), classified as a Ferric Luvisol (FAO, 1998). The soil was mixed thoroughly, air-dried and sieved through a 2-mm mesh prior to establishment of the experiment.

Experimental set-up

The laboratory soil microcosm experiment was established in 500 ml Kilner jars to each of which 100 g of the sieved soil was added. The soil was pre-incubated at 45% water filled pore space (WFPS) for 7 days prior to the start of the experiment to re-initiate microbial activity after dry storage, and to minimise changes in soil WFPS at the start of the experiment. Fertiliser (NH_4NO_3) and milled (< 2 mm) residues of clover (*Trifolium pratense*) and barley straw (*Hordereum vulgare*) were applied to the soil on day 0 in the following treatments of residue N-to-fertiliser N ratio: 100:0, 75:25, 50:50, 25:75, 0:100 at a rate of 100 mg N kg^{-1} soil per treatment. The treatments applied were based on the percentage N content of the residues. A control treatment (no residue, no fertiliser) was also included. Each treatment was replicated three times for gas sampling and a further three times for destructive soil sampling. After residue and fertiliser addition on day 0, soil in all treatments and the control was wetted to 60% WFPS and maintained at this WFPS on a weight basis for the duration of the experiment. The experiment was conducted at 21 °C in the dark for 30 days.

Chemical composition of the plant residues

Dried leaf residues were ground (< 1 mm) in a rotary mill and analysed for total N, organic C, lignin and total extractable polyphenol contents (Table 1). Lignin content was determined in an Ankom 220 fibre analyser (acid detergent fibre). Total extractable polyphenol content was

TABLE 1

Biochemical characteristics of the crop residues used in the experiment

Residue	*Organic C (%)*	*Total N (%)*	*C:N ratio*	*ADL[1] (%)*	*TEP[2] (%)*
Clover	37.4	4.2	9.0	3.5	1.0
Barley	40.8	0.7	58.3	9.0	2.4

[1] ADL = Acid detergent lignin

[2] TEP = Total extractable polyphenol

measured using Folin-Ciocalteu reagent in a method adapted from Anderson & Ingram (1993). Organic C and total N contents were determined using a Metler Toledo AG 2455 C/N autoanaylser.

Gas sampling and analysis

Gas samples for N_2O and CO_2 analysis were collected from the Kilner jar headspaces on day 0 immediately prior to addition of fertiliser and residues, and on days 1, 2, 3, 7, 14 and 30 after addition. The gas samples were taken through a gas sampling port in the Kilner jars at 0, 30 and 60 min after their closure and stored in pre-evacuated 12 ml gas vials (Labco, UK.). N_2O concentration was determined on a Perkin Elmer autosystem gas chromatograph, fitted with an electron capture detector, and CO_2 concentration was determined using a Chrompack CP9001 gas chromatograph, fitted with a methaniser and flame ionisation detector. Oven and detector temperatures were 50 and 250 ^{o}C, respectively. The increase in N_2O concentration during the 60 min headspace closure period was used to calculate a daily flux of N_2O from the soil. Total N_2O and CO_2 emissions over specified periods were calculated by linear interpolation between daily fluxes.

Soil mineral N analyses

Soil was destructively sampled from three additional replicates on days 0 (prior to fertiliser and residue addition), 1, 3, 7, 14 and 30. Sub-samples (40 g) of the fresh soil were extracted with 1 *M* KCl at a soil to extractant ratio of 1:5 and filtered through Whatmann No.1 filter paper. NH_4^+-N and NO_3^- -N concentrations in the extracts were determined colorimetrically by continuous flow analysis on an FIA star 5010 analyser, fitted with a cadmium column.

Statistical analysis

All data were analysed using the Minitab 15.0 statistical package. Data were tested for normality and log-transformed where appropriate (Parkin & Robinson, 1993) prior to analysis of variance. Turkey's HSD test was used to detect significant differences between means of the measured variables.

Results

Total N_2O and total CO_2 emissions

Total N_2O emitted over the 30 days after the addition of crop residues (clover and barley) and, or N fertiliser ($NH_4 NO_3$) were higher ($P < 0.05$) compared to emission from the unamended soil. Total N_2O emitted from the sole crop residue or sole fertiliser amended treatments varied from 33.2 –15.2 mg N_2O- N m^{-2} 30 d^{-1} (Table 2), whilst total emissions varied from 65.3 to 27.8 mg N_2O-N m^{-2} 30 d^{-1} in the combined crop residues and N fertiliser treatments, with the 25: 75 clover:fertiliser treatment emitting the highest ($P < 0.05$) N_2O over the 30 days. Total N_2O emitted over the 30 days in the combined clover residue and N fertiliser treatments, except the 75:25 clover: fertiliser treatment, were greater ($P < 0.05$) than from the sole clover and sole fertiliser applications. In contrast, there was no significant difference between the total N_2O emitted from the 25:75 and 50:50 barley:fertiliser treatments and the sole fertiliser treatment.

Total CO_2 emissions from the sole crop residues or fertiliser treatments varied from 39.3 to 22.3 g CO_2- C m^{-2} 30 d^{-1} and were significantly higher ($P < 0.05$) than total CO_2 emitted from the control (15.0 g CO_2- C m^{-2} 30 d^{-1}), with the 100:0 clover:fertiliser treatment emitting the highest ($P < 0.05$) total

TABLE 2

Total N_2O and total CO_2 emissions (Mean ± 1 s.e.m.) following addition of residues and residue:fertiliser combinations to soil. Different superscripts following values in the same columns represent significant difference at $P < 0.05$

Treatments	*Total N_2O (mg N_2O-N m^{-2})*		*Total CO_2 (g CO_2-C m^{-2})*	
	7d	*30d*	*7d*	*30d*
Combined residue and fertiliser				
25:75 barley : fertiliser	17.43 ± 0.68^{c}	33.62 ± 0.96^{c}	18.31 ± 3.85^{b}	30.31 ± 4.72^{b}
50:50 barley : fertiliser	11.25 ± 0.39^{d}	31.08 ± 0.98^{c}	15.93 ± 0.61^{c}	33.62 ± 0.72^{b}
75:25 barley : fertiliser	7.75 ± 0.17^{d}	27.84 ± 0.25^{d}	13.78 ± 2.4^{c}	21.76 ± 0.9^{c}
25:75 clover : fertiliser	36.95 ± 1.80^{a}	65.31 ± 2.79^{a}	28.66 ± 3.07^{a}	48.8 ± 4.98^{a}
50:50 clover : fertiliser	22.44 ± 0.59^{b}	44.77 ± 2.12^{b}	22.78 ± 0.55^{a}	41.32 ± 0.64^{a}
75:25 clover : fertiliser	15.56 ± 0.66^{c}	29.37 ± 0.94^{c}	18.26 ± 0.73^{b}	32.33 ± 3.1^{b}
Sole residue or fertiliser				
100:0 barley : fertiliser	5.49 ± 0.45^{d}	15.22 ± 0.69^{d}	6.06 ± 0.08^{d}	22.28 ± 1.38^{c}
100:0 clover : fertiliser	15.9 ± 1.35^{c}	33.2 ± 1.03^{c}	19.88 ± 0.91^{b}	39.34 ± 1.45^{a}
0:100 residue : fertiliser	9.07 ± 0.49^{c}	21.63 ± 0.53^{d}	13.11 ± 0.32^{c}	31.26 ± 1.25^{b}
Control	6.04 ± 0.39^{d}	8.99 ± 0.06^{e}	6.66 ± 0.26^{d}	15.02 ± 0.94^{d}

CO_2 (Table 2). In the combined residue and fertiliser treatments, total CO_2 emissions ranged from 48.8 to 21.7 g CO_2 -C m^{-2} $d^{-1}$and, although there was no significant difference between total CO_2 emissions from the 25:75 and 50: 50 clover:fertiliser treatments, these were higher ($P < 0.05$) than that emitted from the 75: 25 clover:fertiliser treatment. Total N_2O emitted over the 30 days from the sole residue and, or fertiliser treatments were strongly positively correlated with total CO_2 emitted over the same period ($r = 0.87$, $P < 0.05$) (Fig. 1).

Daily N_2O fluxes

N_2O fluxes varied between the treatments from day 1 to day 7, but by day 14 N_2O fluxes in all the treatments had returned to 'background' levels (Fig. 2ab). N_2O fluxes peaked on day 1 in all the treatments, with the sole clover amended treatment emitting the highest flux of 4.7 mg N_2O- N m^{-2} d^{-1} ($P < 0.05$). In the combined clover and fertiliser amended treatments, peak N_2O fluxes ranged from 8.2 to 17.1 mg N_2O- N m^{-2} d^{-1} for the same period, and were significantly higher ($P < 0.05$) than those in the barley:fertiliser amended treatments (2.0–7.9 mg N_2O-N m^{-2} day $^{-1}$). Peak N_2O fluxes in the combined clover and fertiliser treatments increased with increasing fertiliser concentration in the ascending order 75:25 > 50:50 > 25:75, clover: fertiliser, but there was no significant difference between the peak N_2O fluxes from the 75:25 and 50:50 barley:fertiliser treatments . N_2O fluxes from the combined clover and fertiliser treatments between days 0 and 3 were higher ($P < 0.05$) than fluxes from the sole clover treatments. In

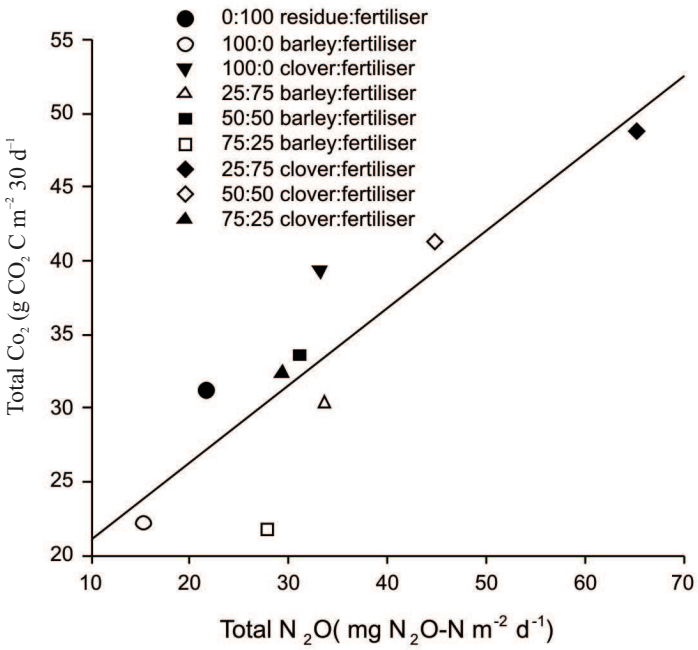

Fig. 1. Correlations between total N_2O emissions and total CO_2 emissions following addition of residues and residue:fertiliser combinations to soil

contrast, only the 25:75 barley:fertiliser amended treatment emitted significantly higher N_2O fluxes ($P < 0.05$) than the sole barley treatment between days 0 and 2.

Daily CO_2 fluxes

The patterns of daily CO_2 fluxes were similar to that observed for the daily N_2O fluxes, with peak fluxes occurring on day 1 in most treatments (Fig. 2cd). In the sole fertiliser or sole residue amended treatments, the highest CO_2 flux (6.7 g CO_2-C m^{-2} day^{-1}, $P < 0.05$) was measured from the sole clover (Fig. 2c) whilst the 25:75 clover: fertiliser treatment emitted the highest daily CO_2 flux (7.6 g CO_2- C m^{-2} day^{-1}, $P < 0.05$) in the combined residue and fertiliser treatments (Fig. 2d). By day 14, daily CO_2 fluxes from all the combined crop residue and fertiliser amended treatments had returned to 'background' levels, whilst it took up to day 30 for fluxes in the sole fertiliser or sole residue amended soils to return to background fluxes (Fig. 2c).

Soil mineral N

At the start of the experiment (day 0) , NH_4^+ - N concentrations in sole fertiliser and sole clover amended soils were significantly higher ($P < 0.05$) than in the control, but NH_4^+ - N concentration in the sole barley amended treatment was not significantly different from the control treatment (Fig. 3ab). In the sole residue or sole fertiliser treatments, NH_4^+ concentrations differed significantly ($P <$ 0.05) between sampling days, with the

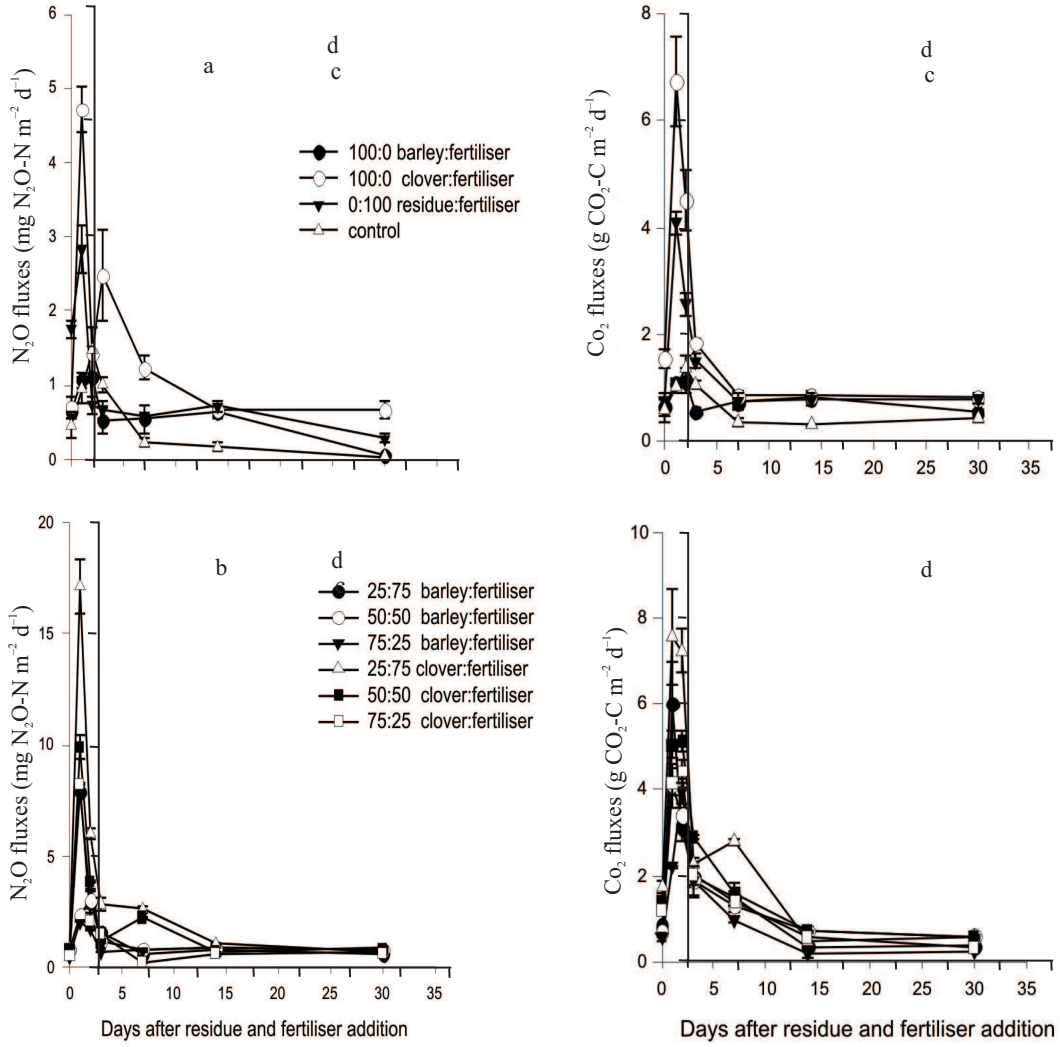

Fig. 2. Daily a and c N_2O and b and d daily CO_2 fluxes following addition of residues and residue:fertiliser combinations to soils. Error bars represent ± one standard error of the mean.

highest concentration of 29.2 mg N kg^{-1} soil ($P < 0.05$) occurring on day 1 in the sole fertiliser. In the combined residue and fertiliser treatments the highest NH_4^+ concentration (40 mg NH_4^+- N kg^{-1} soil, $P < 0.05$) was measured on day 0 in the 25: 75 clover:fertiliser treatment, but this was not significantly different from that measured on the same day in the 25:75 barley: fertiliser amended treatment (35.9 mg NH_4^+- N kg soil). By day 30, NH_4^+ concentrations in all the combined crop residue and fertiliser treatments had declined to less than 3 mg NH_4^+-N kg^{-1} soil (Fig. 3c).

No_3^- concentrations between days 3 and day 30, in the sole clover and the sole fertiliser amended treatments, were higher ($P < 0.05$) than in the control (Fig. 3cd). The NO_3^- -N concentration of 48 mg NO_3^--N kg^{-1} soil ($P < 0.05$) measured on day 30 in the sole fertiliser treatment was the highest for the sole residue or sole fertilizer treatments throughout the 30 days (Fig. 3b). Higher ($P < 0.05$) No_3^- -N concentrations were measured by day 30 in combined barley or clover and fertiliser treatments than in the control or in the corresponding single clover or single barley treatments. NO_3^- -N concentrations in the combined barley and fertiliser treatments ranged between 15.4-27.9 mg NO_3^- -N kg^{-1}

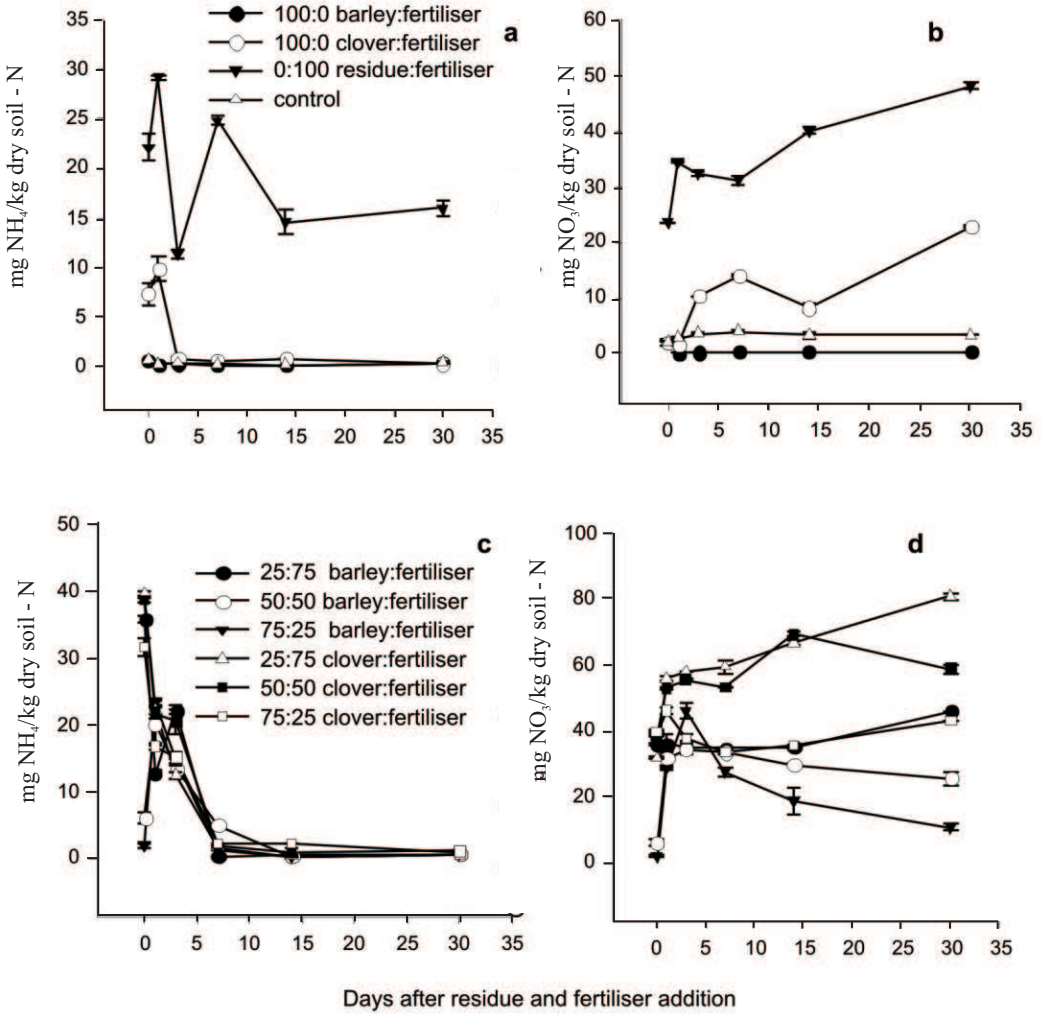

Fig. 3. Concentrations of a and c. soil NH_4^+ and b and d. soil NO_3^- following addition of residues and residue:fertiliser combinations to soil. Error bars represent ± one standard error of the mean.

soil [1], whilst NO_3^- -N concentrations in the combined clover and fertiliser ranged from 45.5 to 50.8 mg N kg^{-1} soil (Fig. 3d).

Net N mineralisation/immobilisation

Incorporation of sole clover residue or sole fertiliser resulted in net N mineralisation, and addition of sole barley residue resulted in net immobilisation throughout the 30 days (Fig. 4a) but net N mineralisation occurred in both the combined barley and fertiliser and combined clover and fertiliser treatments throughout the 30 days (Fig. 4b).

Discussion

Effect of sole incorporation of crop residue or N fertiliser on N_2O and CO_2 emission

Sole addition of the low C:N ratio clover significantly increased both CO_2 and N_2O emission ($P < 0.05$) compared to the control treatment. In agreement with findings from the study, Bernhadt-Riversat (1998) also found that total CO_2 emission was greater in crop residue- amended soils compared to the unamended control. He further explained that residue C served as both energy and C source for heterotrophic microorganisms, enhancing microbial activity and respiration and, hence, CO_2 emission.

In this study higher emphasis was placed on N_2O emission compared to CO_2 emission because N_2O is reported to have an atmospheric residence time of up to 120 years, and a global warming potential (GWP), which is 300 times greater than that of CO_2(IPCC, 2007). However, across all the treatments CO_2 emission and N_2O emission measured were positively correlated (r = 0.81, $P < 0.05$). The positive correlation between CO_2 and N_2O fluxes across all the treatments indicate that increased N_2O emission could be attributed in part to increased microbial activity. N_2O emission from the sole barley treatment was small, with only 15 mg N_2O-N m^{-2} emitted over the 30 days, although organic C availability, which is an important factor driving N_2O emission from denitrification (Paul & Beauchamp, 1989), could have been high in this treatment. Sole addition of fertiliser also resulted in a greater ($P < 0.05$) emission than in the unamended control. Such findings have been previously reported after addition of N fertiliser (Eichner, 1990; Mosier, 1994) and crop residues to soil (Cochran *et al.,* 1997; Huang *et al.,* 2004) due to increased N substrate supply thought to stimulate greater soil N_2O emissions.

As hypothesised, total N_2O emitted from the low C:N ratio clover treatment (33.2 mg N_2O-N m^{-2} 30 d^{-1}) was two-fold higher than from the higher C:N ratio barley residues (15.2 mg N_2O-N m^{-2} 30 d^{-1}), indicating that addition of the low C:N ratio clover residue resulted in rapid mineralisation, N release and, hence, increased substrate N availability (Baggs *et al.,* 2000; Verschot *et al.,* 2006) for nitrification and denitrification and, consequently, enhanced N_2O emission (Baggs *et al.,* 2000; Larsson *et al.,* 1998; Shelp *et al.,* 2000). This is in agreement with Larsson *et al.* (1998), who measured a higher N_2O fluxes after application of high N (2.1–4.3%) plant materials compared to grass mulch with a lower N content (1.2%).

The results showed that the high C:N ratio barley residues also emitted higher ($P < 0.05$) N_2O than the unamended control. The reason for this observation is not clear but it is in

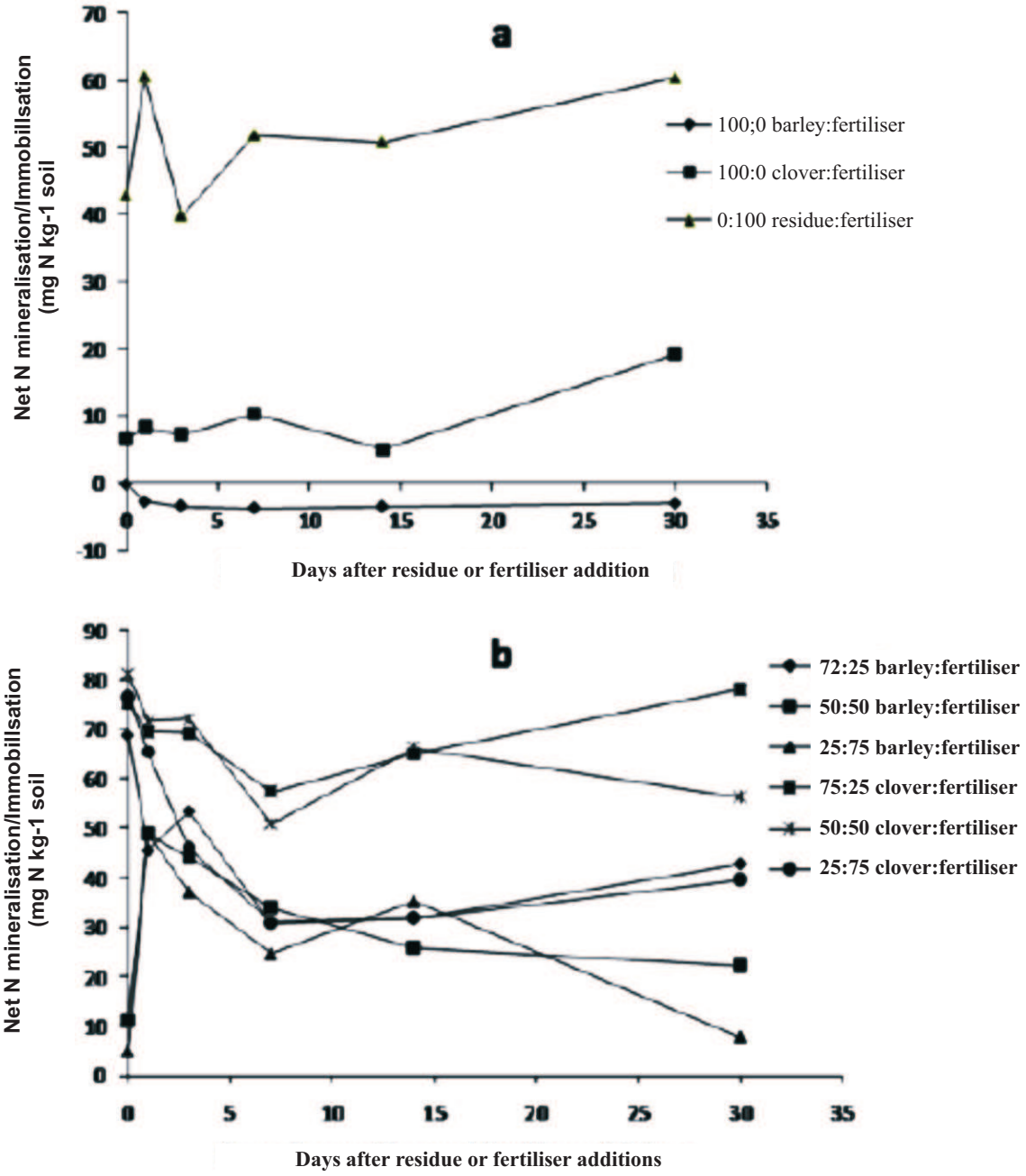

Fig. 4. Net N mineralization or immobilization following addition of residues and residue:fertiliser combinations to soil. Error bars represent ± one standard error of the mean.

agreement with Garcia-Ruiz & Baggs (2007), who found greater N_2O emission in a high C:N ratio (40) olive weed residues (*Ridolfia segetum*) treatment compared to the unamended silty loam soil. High organic C release after the addition of the high C:N ratio barley residues might stimulate microbial growth and activity leading to increased oxygen consumption and creation of anaerobic microsites (Tiedje *et al.,* 1984). Aulakh *et al.* (1991) stated that the release of soluble organic C provides the energy for denitrification. However, given that net N immobilisation occurred immediately after incorporation of the barley residues in this study, it is unlikely that the barley residue N was the source of substrate N that accounted for the N_2O emitted from the sole barley treatment. Thus, soil N might have contributed to the N_2O emitted after barley residue addition to the soil.

N_2O emission from the sole fertiliser treatment was lower ($P < 0.05$) than from the sole clover amended treatment, but this was higher ($P < 0.05$) than from the sole barley treatment, indicating that substrate N supply was still an important factor determining N_2O emissions from fertiliser or crop residues amended soils. Incorporation of barley residues (C:N ratio 58) resulted in a net N immobilisation throughout the 30-day incubation period, whilst addition of the clover (C:N ratio 9) resulted in net N mineralization. Previous authors (e.g. Heal *et al*., 1997; Myers *et al.,* 1994) have stated that the threshold of residue C:N ratio above which net N immobilisation occurs is 20–25. The C:N ratio (58) of the barley residues was higher than this threshold and so was its N content (0.7%) less than the typical threshold (1.7–1.8%) required for immediate net N mineralisation. On the other hand the net content of the clover residue (4.2%) was higher than the threshold value. Net N immobilisation potentially decreased soil N availability and so the low N_2O emissions measured after the addition of barley residues was not unexpected. Baggs *et al.,* 2000 and Millar *et al.,* 2004 have both reported that microbial N immobilisation following the incorporation of high C:N ratio crop residues might be the most important reason for the low NH_4^+ concentration measured in such treatments of the residue.

Influence of combined application of crop residues and N fertiliser on N_2O emission

Combined application of barley or clover residues with N fertiliser resulted in higher ($P < 0.05$) N_2O emission than from the sole residue or sole fertiliser treatments. Total N_2O emitted over the 30 days from the combined barley and fertiliser amended soils were up to 120% higher than that emitted from the barley only treatment, whilst the combined clover and fertiliser treatments, except the 75:25 clover : fertiliser increased N_2O emission by up to 97% compared with the sole clover amended treatments, indicating a positive interactive effect of combining residue-N and fertiliser-N on N_2O emission. This observation agrees with de Catanzaro & Beauchamp (1985) and Sarkodie-Addo *et al.* (2003), who made similar reports, attributing the increased N_2O emission to dissimilatory N reduction stimulated by organic C supply from the residues. In another study, Garcia-Ruiz & Baggs (2007) measured up to 123% increase in N_2O emission following application of *Avena sativa* and *Ridolfia segetum,* and N fertiliser compared to unfertilised residues and fertilised control residue-N.

Combined application of crop residues

and N fertiliser also increased inorganic N (NH_4^+ and NO_3^-) concentrations ($P < 0.05$) over concentrations in the sole residue, indicating that, in addition to inorganic N mineralised from the crop residues, the NH_4NO_3 fertiliser potentially provided additional or possibly more readily available substrate N for nitrification and, or denitrification (Duxbury & McConaughey, 1986; Mosier, 1994). However, in this study N_2O emissions in the combined clover and fertiliser treatments were short-lived with up to 59% of the total N_2O measured over the 30 days lost by day 7. This short-lived increase in N_2O emission supports the anaerobic microsites creation concept (Tiedje *et al.,* 1984), whereby the C supply from the incorporated crop residue increased microbial oxygen consumption, which would have created conditions conducive for denitrification in the presence of substrate N, most probably from the accompanying fertiliser- and, or native soil-N (de Catanzaro & Beauchamp, 1985). Therefore, N_2O emission was expected to be lowered after the residue - C was depleted. In this study N_2O fluxes decreased gradually after the temporary flush on day 1, and after day 7 fluxes were less than 2 mg N_2O- N m^{-2} d^{-1} in all treatments, further confirming the above.

Furthermore, the fact that N_2O emission from the 75:25 clover : fertiliser treatment was lower than from the sole clover treatment suggested that increased denitrification probably reduced N_2O to N_2, but this would require further investigation. Total N_2O emission from 25:75 and 50:50 clover:fertiliser treatments were higher ($P < 0.05$) than from the corresponding combined barley and fertiliser treatments indicating that crop residue quality affected N_2O emissions even when they were applied in combination with fertiliser (Garcia-Ruiz *et al.,* 2007, Gentile *et al.,* 2008; Sarkodie-Addo *et al.,* 2003).

In addition to C:N ratio N_2O emission from soils amended with crop residue has often been reported to be influenced by other quality parameters C:N ratio, lignin content, polyphenol content, lignin:N ratio, polyphenol:N ratio and (lignin + polyphenol): N ratio (Garcia - Ruiz & Baggs, 2007; Millar & Baggs, 2004). The lignin and extractable polyphenol contents of the clover and barley residues used in this study were lower than the 15% lignin and 3–4% polyphenol threshold levels proposed in the Organic Resources Database (Palm *et al.,* 2001) to retard residue N mineralisation. The relative contribution of residues and fertilizer to N release and N_2O emissions could not be quantified in this study. However, the use of a stable isotope technique will enable the determination of the contribution of residue-N to N_2O emission when they are applied in combination with N fertiliser. Therefore, the interactive effect of fertiliser N and crop residue N on N_2O emission ought to be further examined with ^{15}N- labelled residues.

Mineral N release after combined application of crop residue and N fertiliser

Combined application of barley or clover residues with N fertiliser promoted immediate release of NH_4^+ - N and NO_3^- - N, but by day 14 NH_4^+ - N concentration had declined considerably in all treatments, whilst NO_3^- - N concentration increased until the end of the incubation, indicative of nitrification. This was in agreement with Jenkinson & Rayner (1985), who attributed the net N mineralisation in combined residue and fertiliser addition to the fertiliser- N,

satisfying the microbial N requirements, and, thereby, increasing the decomposition rate of the residues. In contrast, Bronson *et al.* (1997) and Millar *et al*. (2004) reported low N_2O after combined application of crop residues and N fertiliser, explaining that, where a high C:N crop residue is applied with fertiliser N, microbial immobilisation of the fertiliser N might lower available N substrate for nitrification and denitrification.

Conclusion

The study confirmed the hypothesis that incorporation of high quality (low C:N ratio) clover residues would result in greater N_2O emissions and higher mineral N release than the addition of low quality (high C:N ratio) barley residues and that combined application of crop residues and inorganic N fertiliser would also result in greater N_2O emissions and higher N release than sole application of either crop residues or N fertiliser. Results from this study also indicated that residue C:N ratio influenced the magnitude of N_2O emission but was more pronounced in the sole residue treatments. Thus, C:N ratio, potentially influenced nitrification and denitrification through the regulation of N mineralisation and immobilisation, which are key processes determinining mineral N availability. It is concluded that the interactive effect of combining crop residues and N fertiliser on N_2O emissions was dependent on the residue species and the proportional ratios at which the residues and fertiliser inputs were combined, but there were uncertainties regarding the contribution of residue-N to the N_2O emitted. Therefore, it is recommended that ^{15}N labeled plant materials be used in future studies to allow the quantification of residue-N contribution to N_2O emission and mineral N release.

References

Aulakh M. S., Doran J. W., Walters D. T. and **Powers J. F**. (1991). Legume residue and soil water effects on denitrification in soils of different textures. *Soil Biol. Biochem.* **23**: 1161–1167.

Azam F., Malik K. A. and **Hussain F.** (1985). Microbial biomass and mineralisation – immobilisation of nitrogen in some agricultural soils. *Biol. Fertil. Soils* **2**: 157–163.

Baggs E. M., Chebii, J. and **Ndufa J. K.** (2006). A short-term investigation of trace gas emissions following tillage and no-tillage of agroforestry residues in western Kenya. *Soil Till. Res*. **90**: 69–76.

Baggs E. M., Rees R. M., Smith K. A. and **Vinten A. J. A.** (2000). Nitrous oxide emission from soils after incorporation of crop residues. *Soil Use Mgmt* **16**: 82–87.

Baggs E. M., Stevenson M., Pihlatie M., Roger A., Cook H. and **Cadisch G.** (2003). Nitrous oxide emission following application of residues and fertiliser under zero and conventional tillage. *Pl. Soil* **254**: 361–370.

Bronson K. F., Cassman K. G., Wassman R., Olk D. C., Van Noordwijk M. and **Garity D. P.** (1997). Soil carbon dynamics in different cropping systems in principal ecoregions of Asia. In *Management of carbon sequestration in soil* (R. Lal, J. M. Kimble, R. F. Follet and B. A. Stewart, eds), pp. 35–57. 1. CRC Press. Baxa raton, Florida, USA.

Cochran V. L., Sparrow E. B., Schlentner S. F. and **Knight C. W.** (1997). Long-term tillage and crop residue-management in the subarctic: fluxes of methane and nitrous oxide. *Can. J. Soil Sci.* **77**: 565–570.

de Catanzaro J. B. and **Beauchamp E. G.** (1985). The effect of some carbon substrates on denitrification rates and carbon utilisation in soil. *Biol. Fertil. Soils* **1**: 183–187.

De Neve S., Saez G. S., Daguilar B. C., Sleyel S. and **Hofman G.** (2004). Manipulating N mineralisation from high N crop residues using on and off-farm organic materials. *Soil Biol. Biochem.* **36**: 127–134.

Duxbury J. M. and **McConnaughey P. K.** (1986). Effect of fertiliser sources on denitrification and nitrous oxide emission in a maize filed. *Soil Sci. Soc. Am. J.* **50**: 644–648.

Eichner M. J. (1990). Nitrous oxide emissions from fertiliser soil: summary of available data. *J. envir Qual.* **19**: 272–280.

FAO. (1998). World Reference Base for Soil Resources No. 84. *World Soil Resources Report.* FAO, Rome, Italy.

Firestone M. K. and **Davidson E. A.** (1989). Microbiological basis of NO and N_2O production and consumption in soil. In *Exchange of trace gases between terrestrial ecosystems and the atmosphere*. (M. O. Andreae and D. S . Schimel, eds), pp. 7–21. John Wiley and Sons Ltd.

Garcia-Ruiz R. and **Baggs E. M.** (2007). N_2O emissions from soil following combined application of fertiliser-N and ground weed residues. *Pl. Soil* **299**: 263–274.

Gentile R., Vanlauwe B., Chivenge P. and **Six J.** (2008). Interactive effects from combining fertiliser and organic residue inputs on nitrogen transformations. *Soil Biol. Biochem*. **40**: 2375–2384.

Granli T. and **Bockman O. C.** (1994). Nitrous oxide from agriculture. *Norw. J. agric. Sci.* (Suppl.) **12**: 1–128.

Heal O. W., Anderson J. M. and **Swift M. J.** (1997). Plant litter quality and decomposition. An historical overview. *In Driven by Nature,*. (G. Cadisch, and Giller, K., eds), pp 3–30. CAB International, Wallingford.

Huang Y., Zou J. W., and **Zheng X. H.** (2004). Nitrous oxide emissions as influenced by amendments of plant residues with different C:N ratios *Soil Boil. Biochem*. **36**: 973–981.

Jenkinson D. S. and **Rayner J. H.** (1985). Interactions between fertilizer nitrogen and soil nitrogen: the so-called 'priming' effect. *J. Soil Sci.* **36**: 425–444.

Kimani S. K., Nandwa S. M., Mugendi D. L., Obanyi S. N., Ojiem J., Murwira H. K. and **Bationo A.** (2003). Principles of integrated soil fertility management. In *Soil Fertility Management in Africa: A Regional Perspective.* (M. P. Gichuru, A. Bationo, M. A. Bekunda, H. C. Goma, P. L. Mafongoya, D. L. Mugendi, H. K. Murwira, S. M. Nandwa, P. Nyathi and M. J. Swift, eds) , pp. 51–72. Academy Science Publishers, Nairobi.

Larsson L., Ferm M., Kasimir-Klemedtsson A. and **Klemedtsson L.** (1998). Ammonia and nitrous oxide emissions from grass and alfalfa mulches. *Nutr. Cycl. Agroecosyst*. **51**: 41–46.

Lemke R. L., Izzaraulde R. C., Nyborg M. and **Solberg E. D.** (1999). Tillage and N source influence soil-emitted nitrous oxide in the Alberta Parkland region. *Can. J. Soil Sci.* **79**: 15–24.

Millar N. and **Baggs E. M.** (2004). The chemical composition or quality of agroforestry residues influences N_2O emissions after their addition to soils. *Soil Biol. Biochem* **36**: 935–943.

Millar N., Ndufa J. K., Cadisch G. and **Baggs E. M.** (2004). Nitrous oxide emissions following incorporation of improved-fallow residues in the humid tropics. *Glob. Biogeochem. Cycl*. **18**: GB 1032, doi: 10.1029/2003GB002114.

Miller M. N., Zebarth B. J., Dandie C. E., Burton D. L., Goyer C. and **Trevors J. C.** (2008). Crop residue influence on denitrification N_2O emission and denitrifier community abundance in soil. *Soil Boil. Biochem*. **40**: 2535–2562.

Mosier A. R. (1994). Nitrous oxide emission from agricultural soils. *Fertil. Res*. **37**: 191–200.

Myers R. K. J., Palm C. C., Cueva E., Gunatileke I. U. N. and **Brossard M.** (1994). The synchronisation of nutrient mineralisation and plant nutrient demand. In *The Biological management of tropical soil fertility*. (P. L. Woomer and M. J. Swift, eds), pp. 81–116. Wiley, Chichester, UK.

Palm C. A. and **Sanchez P. A.** (1991). Nitrogen release from leaves of some tropical legumes as affected by their lignin and polyphenolic contents. *Soil Biol. Biochem*. **23**, 83–88.

Parkin T. B. and **Robinson J. A.** (1993). Statistical evaluation of median estimators for lognormally distributed variables. *Soil Sci. Soc. Am. J.* **57**: 317–323.

Paul, J. W. and **Beauchamp E. G.** (1989). Effects of carbon constituents in manure on denitrification in soil. *Can. J. Soil Sci.* **69**: 49–61.

Sarkodie-Addo J., Lee H. C. and **Baggs E. M.** (2003). Nitrous oxide emissions after application of inorganic fertiliser and incorporation of green manure residues. *Soil Use Mgmt* **19**: 331–339.

Shelp M. J., Beauchamp E. G. and **Thurtell G. W.** (2000). Nitrous oxide emissions from soil amended with glucose, alfalfa, or corn residues. *Communs*

Soil Sci. Pl Anal. **31**: 877–892.

Tiedje J. M., Sextone A. J., Parkin T. B., Revbech N. P. and **Shelton D. R.** (1984). Anaerobic processes in soils. *Pl Soil* **76**: 117–212.

Toma Y. and **Hatano R.** (2007). Effect of crop residue C:N ratio on N_2O emissions from Gray Lowland Soil in Mikasa, Hokkaido, Japan. *Soil Sci. Pl. Nutr.* **53**: 198–205.

Velthof G. L., Kuikman P.J. and **Oenema O.** (2002). Nitrous oxide emission from soils amended with crop residues. *Nutr. Cycl. Agroecosyst*. **62**: 249–261.

Verchot L. V., Hutabarat L., Hairaih K. and **van Noordwijk M.** (2006). Nitrogen availability and soil N2O emission following coversion of forests to coffee in southern *Sumatra. Glob. Biogeochem. Cycl*. **20**: GB4008, doi: 10.1029/2005GB002469.

Zou J., Huang Y., Lu Y., Zheng,X. and **Wang Y.** (2005). Direct emission factor for N_2O from rice winter wheat rotation systems in southeast China. *Atmosph. Envir*. **39**(26): 4755–4765.