Soil Use and Management

Soil Use and Management, December 2010, **26,** 412–424 doi: 10.1111/j.1475-2743.2010.00293.x

Do combined applications of crop residues and inorganic fertilizer lower emission of N_2O from soil?

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Abstract

Emissions of N_2O were measured following addition of ^{15}N-labelled residues of tropical plant species [*Vigna unguiculata* (cowpea), *Mucuna pruriens* and *Leucaena leucocephala*] to a Ferric Luvisol from Ghana at a rate of 100 mg N/kg soil under controlled environment conditions. Residues were also applied in different ratio combinations with inorganic N fertilizer, at a total rate of 100 mg N/kg soil. N_2O emissions were increased after addition of residues, and further increased with combined (ratio) applications of residues and inorganic N fertilizer. However, ^{15}N-N_2O production was low and short-lived in all treatments, suggesting that most of the measured N_2O-N was derived from the applied fertilizer or native soil mineral N pools. There was no consistent trend in magnitude of emissions with increasing proportion of inorganic fertilizer in the application. The positive interactive effect between residue- and fertilizer-N sources was most pronounced in the 25:75 *Leucaena*:fertilizer and cowpea:fertilizer treatments where 1082 and 1130 mg N_2O-N/g residue were emitted over 30 days. N_2O ($\log_e$) emission from all residue amended treatments was positively correlated with the residue C:N ratio, and negatively correlated with residue polyphenol content, polyphenol:N ratio and (lignin + polyphenol):N ratio, indicating the role of residue chemical composition in regulating emissions even when combined with inorganic fertilizer. The positive interactive effect in our treatments suggests that it is unlikely that combined applications of residues and inorganic fertilizer can lower N_2O emissions unless the residue is of very low quality promoting strong immobilisation of soil mineral N.

Keywords: Nitrous oxide, crop residues, inorganic fertilizer, residue quality, stable isotopes, tropical soil

Introduction

Integrated soil fertility management aims to optimize the use of a range of local suitable resource inputs for sustainable crop production (Kimani *et al.*, 2003). One example is the combined application of plant or crop residues with inorganic fertilizer which is thought to better optimize N use-efficiency, either through promoting temporary immobilisation of inorganic fertilizer N or by improving soil organic matter content, and thereby offering the potential to lower losses of N (Kirchmann & Thorvaldsson, 2000; Vanlauwe *et al.*, 2001). Such an integrated approach is essential in much of sub-Saharan Africa where a decrease in soil fertility is often also coupled with low availability or affordability of inorganic fertilizers and low quantities of N-rich crop residues. However, there is evidence that combined applications of crop residues and inorganic fertilizer may have an interactive effect on N release and on emissions of the greenhouse gas nitrous oxide (N_2O), the magnitude and direction of which is thought to depend on the chemical composition, or quality, of the organic inputs (Garcia-Ruiz & Baggs, 2007; Gentile *et al.*, 2008), and therefore also on the ratio of inorganic-to-organic N applied (Garcia-Ruiz & Baggs, 2007).

Addition of plant material or inorganic N-based fertilizers to soil typically increase N_2O emissions, with emission factors based on the quantity of N applied (Eichner, 1990; Baggs *et al.*, 2000; Millar *et al.*, 2004; Novoa & Tejeda, 2006; Snyder *et al.*, 2007). The emission factor from plant material is harder to predict because of the role of the chemical composition of this material (Novoa & Tejeda, 2006). Agricultural soils are a major source of atmospheric N_2O, contributing to global warming and the destruction of stratospheric ozone (Solomon *et al.*, 2007; Ravishankara

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Received March 2010; accepted after revision July 2010

et al., 2009), with the contribution of tropical soils, currently thought to be ca. 20–50%, anticipated to increase with continuing application of inorganic fertilizers. In tropical systems this also represents a crucial lowering in N-use efficiency in often N-limited cropping systems.

The chemical composition of residues added to soil has been shown to be important in regulating the magnitude of N_2O emissions, both in temperate (Baggs *et al*., 2000; Harrison *et al*., 2002; Baggs *et al*., 2003) and tropical agricultural systems (Millar *et al*., 2004; Gentile *et al*., 2008), and after addition of temperate and tropical species under controlled environment conditions (Millar & Baggs, 2004, 2005; Huang *et al*., 2004; Garcia-Ruiz & Baggs, 2007). We have previously demonstrated strong negative relationships between N_2O emission and residue C-to-N ratio in tropical agroforestry systems (Millar *et al*., 2004) and with residue lignin content and (lignin + polyphenol)-to-N ratio after applying tropical agroforestry residues and olive crop weed residues to soil under controlled environment conditions (Millar & Baggs, 2004; Garcia-Ruiz & Baggs, 2007). The latter relationship was attributed to lower N release when the residue contains > 15% lignin and/or > 3–4% total extractable polyphenol content (Palm *et al*., 2001; Constantinides & Fownes, 1994). The threshold for N mineralization is generally accepted to be above 1.7–1.8% N, with temporary immobilisation after addition of material with lower N contents (Melillo *et al*., 1982; Constantinides & Fownes, 1994; Seneviratne, 2000). Combined application of inorganic fertilizer-N with residues may overcome such immobilisation, and such an integrated approach will also lower fertilizer-N requirements through N supply from the residues, thereby holding the potential to regulate N release for crop uptake, whilst minimizing detrimental effects on the environment. However, little is known of the extent to which these different N sources interact in soil, nor the nature or underlying mechanisms of any interaction (Garcia-Ruiz & Baggs, 2007; Gentile *et al*., 2008), but are likely to be strongly influenced by the chemical composition of the residue.

Here, we report a controlled environment experiment, the objective of which was to determine the optimum combination of residue-to-fertilizer N to increase N release from the residue, but to also lower N_2O emission after addition of leguminous tropical species to a tropical Ferric Luvisol. Applied residues ranged in their chemical compositions, and were ^{15}N-labelled to enable the influence of lignin and polyphenol contents of the residue N to be determined, to quantify the contribution of this residue ^{15}N to measured mineral N pools and N_2O production, and to enable a better understanding of any interaction between the two N sources. The hypothesis was that the extent of interaction would depend on the chemical composition of the residue applied, with a high residue-to-fertilizer ratio only being able to lower soil N availability and N_2O emissions after addition of these high N leguminous residues if they also have high lignin and high polyphenol contents, and conversely greater N availability and potential for N_2O loss with a low residue-to-fertilizer ratio where the residue has a high N content and lower lignin and polyphenol contents.

Materials and methods

Soil

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

Experimental set-up

A laboratory soil microcosm experiment was established in 500 mL Kilner jars to each of which 100 g of the sieved soil was added and packed to a bulk density of 1.23 g/cm^3. 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 minimize changes in soil WFPS at the start of the experiment. WFPS was calculated based on the soil volumetric water content, bulk density and a particle size density of 2.65 g/cm^3, and was achieved by applying an appropriate volume of distilled H_2O using a pipette and mixing thoroughly. Fertilizer (NH_4NO_3) and ^{15}N-labelled residues (leaf material, chopped to 3–5 mm) of cowpea (*Vigna unguiculata*), *Mucuna* (*Mucuna pruriens*) and *Leucaena* (*Leucaena leucocephala*) were mixed in to the soil on day 0 in the following treatments of residue-to-fertilizer ratio: 100:0, 75:25, 50:50, 25:75, 0:100 at a rate of 100 mg N/kg soil per treatment. A control treatment was also included which had no residue or fertilizer addition, but this soil was disturbed in the same way as the other treatments when the target WFPS was established. Each treatment was replicated three times for gas sampling and a further three times for destructive soil sampling. Three days prior to residue and fertilizer 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.

^{15}N-labelling of plant species

Seedlings of *L. leucocephala*, *M. pruriens*, and *V. unguiculata* were grown in vermiculite for 6 months in a greenhouse at the University of Aberdeen. Nodulation of the leguminous species was prevented by previous addition of 1% sodium hypochlorite solution to the pots, after Millar & Baggs

(2004). The seedlings were fed regularly with a 5 mM $^{14}NH_4{}^{15}NO_3$ solution (10 atom percent excess ^{15}N) at a rate of 200 to 400 mL per pot per day depending on plant demand. Other macro and micro nutrients were provided in a nutrient solution adapted from Yoshida *et al.* (1976). The leaves were harvested after 6 months, oven dried at 40 °C and their chemical composition determined as described below. The atom percent excess ^{15}N of the leaves was determined using a SerCon 20/20 isotope ratio mass spectrometer (SerCon Ltd, Crewe, UK) (Table 1).

Chemical composition of the plant residues

Dried leaf residues were ground (< 1 mm) in a rotary mill and analyzed for total N, total C, lignin and total extractable polyphenol contents (Table 1). Lignin content was determined in an Ankom 220 fiber analyser (acid detergent fibre). Total extractable polyphenol content was measured using Folin-Ciocalteu reagent in a method adapted from Anderson & Ingram (1993). Total C and total N contents were determined using a Metler Toledo AG 2455 C/N autoanalyser.

Gas sampling and analysis

Gas samples for N_2O and CO_2 analysis were collected from the Kilner jar headspaces on day 0, 2 h prior to addition of fertilizer and residues, and on days 1, 2, 3, 5, 7, 10, 14 and 30 after addition. Kilner jars were closed for an hour during gas sampling. The gas samples were taken through a gas sampling port in the Kilner jar lids 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 ionization detector. Oven and detector temperatures were 50 °C and 250 °C, respectively. The increase in N_2O concentration during the 60 min headspace closure period was used to calculate by linear interpolation 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.

Samples (120 mL) for ^{15}N-N_2O determination were taken after 60 min closure of the headspace, and an equal volume of air was replaced to the headspace. Samples were stored in helium-flushed and pre-evacuated 120 mL gas-tight glass bottles (Supelco, UK) and the ^{15}N-enrichment of the N_2O molecule determined on a SerCon 20/20 isotope ratio mass spectrometer following condensing and cryofocusing of the sample in an ANCA TGII gas module (SerCon Ltd). ^{15}N-enrichments of the gas fluxes were calculated from the atom percent excess of samples, taking into account the atom percent excess of the residues applied.

Soil mineral N and total organic carbon analyses

Soil was destructively sampled from three additional replicates per sampling date on days 0 (prior to fertilizer and residue addition), 1, 3, 7, 14 and 30. Subsamples (40 g) of the fresh soil were extracted in 1 M KCl at a soil-to-extractant ratio of 1-to-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. The ^{15}N-enrichments of $NH_4{}^+$ and $NO_3{}^-$ were determined by diffusion methodology (Brooks *et al.*, 1989) and analysis on the SerCon 20/20 isotope ratio mass spectrometer. Water extractable C (cold water) was quantified in soil sampled on days 0, 1, 7 and 30. A 10-g (air-dried basis) subsample was shaken in 40 mL deionised water for 2 h, and filtered through Whatmann no. 42 filter paper. Further filtration of the extract was undertaken with a 0.45-μL micropore filter. Concentration of C in the supernatant liquid was determined using a total organic carbon analyzer (TOC-5000A, Shimadzu).

Statistical analysis

Data obtained in the study were subjected to statistical analysis using the MINITAB 15 statistical package. Tukey's HSD (Honestly Significant Difference) method was used for means' comparison.

Results

Emissions of $^{14+15}N$-N_2O and C-CO_2

Emissions of $^{14+15}N$-N_2O and CO_2 over the 30-day experimental period were increased ($P < 0.001$) after

Table 1 Chemical composition of the tropical residues applied in this experiment

Treatment	N (%)	C (%)	C-to-N ratio	ADL (%)	TEP (%)	Atom % ^{15}N excess
Leucaena leucocephala	6.1	41.7	6.8	8.3	4.6	4.50
Mucuna pruriens	4.3	39.8	9.2	10.1	2.2	4.28
Vigna unguiculata	3.4	39.6	11.7	7.2	1.3	4.08

ADL, acid detergent lignin; TEP, total extractable polyphenols.

combined addition of residues and fertilizer-N, compared to measured emission from the control (Tables 2 and 3). Between 51 and 87% of the total N_2O or CO_2 measured throughout the 30-day experiment was emitted in the first 7 days after addition. Of the 100:0 residue:fertilizer treatments, the cowpea:fertilizer treatment resulted in the highest N_2O and CO_2 emissions (37.2 mg N_2O-N/m^2 per 30 days; 14.5 g CO_2-C/m^2 per 30 days; $P < 0.05$). This emission of N_2O was increased ($P < 0.05$), but CO_2 emission lowered ($P < 0.05$), when the cowpea residue was combined with fertilizer-N, with 63.1 mg N_2O-N/m^2 per 30 days emitted from the 50:50 cowpea:fertilizer treatment, 87% of which was emitted in the first 7 days. Emissions of both N_2O and CO_2 were low from the fertilizer only treatment (0:100 residue:fertilizer; 18.5 mg N_2O-N/m^2 per 30 days; 4.7 g CO_2-C/m^2 per 30 days). Increasing the proportion of fertilizer-N combined with the residues had no consistent effect on emissions between the different residue species, but emissions of both N_2O and CO_2 were lower ($P < 0.05$) from the 75:25 ratio of all residues than from the 25:50 and 50:50 residue:fertilizer combinations. Total N_2O ($\log_e$) and CO_2 ($\log_e$) emitted by 30 days were positively correlated in the 25:75, 50:50 and 75:25 residue:fertilizer treatments ($r = 0.93$; $P < 0.05$; Figure 1). N_2O ($\log_e$) emission over the 30-day experiment from all residue-amended treatments was positively correlated with residue C:N ratio ($r = 0.63$; $P < 0.05$), and negatively correlated with residue polyphenol content ($r = -0.59$; $P < 0.05$), polyphenol:N ratio ($r = -0.61$; $P < 0.05$) and (lignin + polyphenol):N ratio ($r = -0.61$; $P < 0.05$) (Figure 1).

N_2O fluxes were temporarily increased ($P < 0.01$) compared to the control after addition of residues, with peak fluxes measured from all residue treatments on day 1 (Figure 2). Maximum fluxes of 24 and 20 mg N_2O-N/m^2/day ($P < 0.05$) were measured from the 50:50 cowpea:fertilizer and 50:50 *Mucuna*:fertilizer treatments, respectively, on day 1. In contrast, addition of fertilizer on its own (0:100 residue:fertilizer treatment) only raised emissions compared to the unamended control on days 1 and 7. The trend was for an exponential decrease in CO_2 fluxes from all treatments with time after addition of residues and fertilizer (Figure 3). The highest CO_2 flux of 1.6 g CO_2-C/m^2/day was measured in both the 50:50 and 75:25 cowpea:fertilizer treatments on day 0. Both N_2O and CO_2 fluxes from the residue only treatments (100:0 residue:fertilizer) decreased the least rapidly after day 1, and after day 10 were the only treatments for which CO_2 fluxes remained higher ($P < 0.05$) than from the control. N_2O and CO_2 fluxes from the 50:50 and 100:0 cowpea:fertilizer treatments were positively correlated ($r = 0.54$ and 0.63 for the 50:50 and 100:0 treatments, respectively; $P < 0.05$).

^{15}N-N_2O emissions

Combining residues with fertilizer addition increased ($P < 0.001$) the total ^{15}N-N_2O emitted over the first 7 days

Table 2 Total emissions of N_2O (mg N/m^2 and mg N per g residue) and ^{15}N-N_2O (μg ^{15}N/m^2) after addition of residues and fertilizer to soil

	$^{14+15}N$-N_2O emission (mg N/m^2)		^{15}N-N_2O emission (μg ^{15}N/m^2)	$^{14+15}N$-N_2O emission (mg N per g residue)	
Treatment	7 days	30 days	7 days	7 days	30 days
Leucaena leucocephala					
25:75 residue:fertilizer	20.3 ($\pm$1.6)^{b}	26.4 ($\pm$2.1)^{b}	74 ($\pm$2)^{i}	753 ($\pm$63)^{b}	1082 ($\pm$66)^{a}
50:50 residue:fertilizer	21.9 ($\pm$1.5)^{b}	29.0 ($\pm$2.2)^{c}	127 ($\pm$1)^{h}	416 ($\pm$29)^{c}	606 ($\pm$37)^{b}
75:25 residue:fertilizer	9.7 ($\pm$0.4)^{d}	15.8 ($\pm$0.8)^{d}	230 ($\pm$2)^{g}	78 ($\pm$1.2)^{f}	189 ($\pm$0.7)^{d}
100:0 residue:fertilizer	11.4 ($\pm$1.1)^{d}	16.3 ($\pm$1.5)^{d}	27 ($\pm$1)^{j}	78 ($\pm$10)^{f}	147 ($\pm$10)^{e}
Mucuna pruriens					
25:75 residue:fertilizer	23.0 ($\pm$2.7)^{b}	29.7 ($\pm$3.0)^{b}	1823 ($\pm$13)^{c}	490 ($\pm$66)^{a}	691 ($\pm$63)^{b}
50:50 residue:fertilizer	31.3 ($\pm$1.2)^{b}	37.3 ($\pm$1.6)^{b}	1012 ($\pm$2)^{e}	357 ($\pm$12)^{d}	448 ($\pm$12)^{c}
75:25 residue:fertilizer	16.0 ($\pm$2.7)^{c}	22.4 ($\pm$3.1)^{c}	1549 ($\pm$76)^{d}	131 ($\pm$28)^{e}	215 ($\pm$29)^{d}
100:0 residue:fertilizer	13.8 ($\pm$1.0)^{d}	18.9 ($\pm$1.5)^{d}	109 ($\pm$3)^{h}	78 ($\pm$6.4)^{f}	130 ($\pm$6.7)^{e}
Vigna unguiculata (cowpea)					
25:75 residue:fertilizer	32.2 ($\pm$3.6)^{b}	45.8 ($\pm$4.3)^{b}	1456 ($\pm$21)^{d}	931 ($\pm$91)^{a}	1130 ($\pm$97)^{a}
50:50 residue:fertilizer	54.7 ($\pm$1.0)^{a}	63.1 ($\pm$11)^{a}	6618 ($\pm$72)^{a}	675 ($\pm$131)^{b}	799 ($\pm$136)^{b}
75:25 residue:fertilizer	23.6 ($\pm$3.7)^{b}	29.9 ($\pm$4.1)^{b}	3301 ($\pm$16)^{b}	168 ($\pm$31)^{e}	232 ($\pm$31)^{d}
100:0 residue:fertilizer	30.9 ($\pm$2.2)^{b}	37.2 ($\pm$2.9)^{c}	884 ($\pm$17)^{f}	176 ($\pm$13)^{e}	224 ($\pm$15)^{d}
0:100 residue:fertilizer	4.9 ($\pm$0.3)^{e}	18.5 ($\pm$1.1)^{d}			
Control	5.0 ($\pm$0.3)^{e}	17.2 ($\pm$1.1)^{d}			

Different superscript letters within a column indicate significant differences between treatments at $P < 0.05$.

Table 3 Total emissions of CO_2 (g C/m^2 and g C per g residue) after addition of residues and fertilizer to soil

Treatment	CO_2 emission (g C/m^2)		CO_2 emission (g C per g residue)	
	7 days	30 days	7 days	30 days
Leucaena leucocephala				
25:75 residue:fertilizer	4.1 (±0.2)^{c}	6.7 (±0.6)^{c}	102 (±16)^{a}	120 (±7.6)^{a}
50:50 residue:fertilizer	4.0 (±1.2)^{c}	6.2 (±0.3)^{c}	49 (±8.5)^{c}	47 (±10)^{d}
75:25 residue:fertilizer	2.7 (±0.1)^{f}	4.8 (±0.2)^{e}	11 (±6.6)^{e}	8 (±7.7)^{f}
100:0 residue:fertilizer	4.3 (±0.3)^{c}	10.6 (±0.6)^{b}	28 (±3.2)^{d}	77 (±1.9)^{c}
Mucuna pruriens				
25:75 residue:fertilizer	3.8 (±0.2)^{e}	7.0 (±0.4)^{c}	60 (±1.4)^{b}	72 (±2.5)^{c}
50:50 residue:fertilizer	3.7 (±0.1)^{e}	6.4 (±0.1)^{c}	49 (±3.3)^{c}	76 (±3.6)^{c}
75:25 residue:fertilizer	3.0 (±0.1)^{d}	5.9 (±0.3)^{d}	46 (±3.5)^{c}	66 (±4.3)^{c}
100:0 residue:fertilizer	5.2 (±0.4)^{b}	11.4 (±0.7)^{b}	46 (±0.8)^{c}	91 (±0.1)^{b}
Vigna unguiculata (cowpea)				
25:75 residue:fertilizer	4.3 (±0.5)^{c}	6.9 (±0.8)^{c}	47 (±8.5)^{c}	74 (±8.8)^{c}
50:50 residue:fertilizer	5.7 (±0.3)^{b}	9.9 (±0.4)^{b}	22 (±6.3)^{c}	29 (±7.7)^{e}
75:25 residue:fertilizer	6.0 (±0.2)^{b}	9.8 (±0.3)^{b}	8 (±3.5)^{e}	15 (±3.6)^{f}
100:0 residue:fertilizer	7.3 (±0.4)^{a}	14.5 (±0.7)^{a}	21 (±0.9)^{d}	49 (±0.3)^{d}
0:100 residue:fertilizer	2.1 (±0.2)^{f}	4.7 (±0.3)^{e}		
Control	2.1 (±0.5)^{f}	4.3 (±0.7)^{e}		

Different superscript letters within a column indicate significant differences between treatments at $P < 0.05$.

compared to emissions from the residue only (100:0 residue:fertilizer) treatments (Table 2). The highest ($P < 0.001$) emission of 6.6 mg ^{15}N-N_2O/m^2/7 days was emitted from the 50:50 cowpea:fertilizer treatment. Emissions from all *Mucuna* and cowpea treatments were greater ($P < 0.05$) than from the corresponding *Leucaena* treatments. Much of this higher emission was due to the fluxes on day 1, with 5.1 and 3.3 mg ^{15}N-N_2O/m^2/day measured from the 50:50 *Mucuna*:fertilizer and cowpea:fertilizer treatments, respectively (Figure 4). Emission of ^{15}N-N_2O ($\log_e$) over the first 7 days from all treatments was negatively correlated with residue polyphenol content ($r = -0.78$; $P < 0.05$), N content ($r = -0.77$; $P < 0.05$), polyphenol:N ($r = -0.77$; $P < 0.05$), and (lignin + polyphenol):N ($r = -0.57$; $P < 0.05$), and positively correlated with residue C:N ratio ($r = 0.73$; $P < 0.05$) and lignin:N ratio ($r = 0.70$; $P < 0.05$).

Concentrations of soil mineral N

Available soil NH_4^+ concentrations increased after residue and fertilizer addition, with the highest ($P < 0.05$) concentrations in the 100:0 cowpea:fertilizer and *Leucaena*:fertilizer treatments (Figure 5). ^{15}N-NH_4^+ concentrations in these treatments on day 14 (7.4 and 8.8 mg ^{15}N-NH_4^+/kg soil, cowpea and *Leucaena*, respectively) accounted for 30% and 26% of the $^{14+15}N$-NH_4^+ concentrations. Fertilizer addition maintained concentrations between 41 and 53 mg NH_4^+/kg soil during the experiment, and by the end of the experiment (day 30) concentrations remained high in the cowpea and *Leucaena* 100:0 residue:fertilizer treatments and in the *Mucuna* 25:75 and 50:50 treatments. NH_4^+ concentrations in the 50:50 *Mucuna*:fertilizer, 50:50 cowpea:fertilizer and 100:0 *Leucaena*:fertilizer treatments were strongly negatively correlated with CO_2 fluxes ($r = -0.93$ for each of these treatments; $P < 0.05$).

The trend was for increasing NO_3^- concentrations after addition of residues, both solely and in combination with fertilizer (Figure 6). The highest ($P < 0.005$) concentration of 117 mg NO_3^--N/kg soil was measured in the 50:50 *Leucaena*:fertilizer treatment on day 30, with the residue-derived ^{15}N only contributing to 16% of this $^{14+15}N$-NO_3^- pool. On this day concentrations in the 75:25 *Mucuna*:fertilizer and cowpea:fertilizer treatments were greater ($P < 0.05$) than in the other *Mucuna* and cowpea treatments. Also on this day 50% (9 mg ^{15}N-NO_3^-/kg soil) of the $^{14+15}N$-NO_3^- pool in the 100:0 cowpea:fertilizer treatment was derived from the ^{15}N-residue. NO_3^- concentrations in the *Mucuna* and cowpea treatments were negatively correlated with CO_2 fluxes ($r = -0.5$ to -0.64, varying with residue:fertilizer ratio; $P < 0.05$), and the NO_3^- concentrations in the 100:0 *Mucuna*:fertilizer treatment were negatively correlated with N_2O fluxes ($r = -0.67$; $P < 0.05$).

Water extractable C

Water extractable C decreased in all treatments with time after addition of residues and fertilizer. Concentrations in treatments to which residue had been applied were greater ($P < 0.05$) than in the fertilizer only (0:100) treatment and in

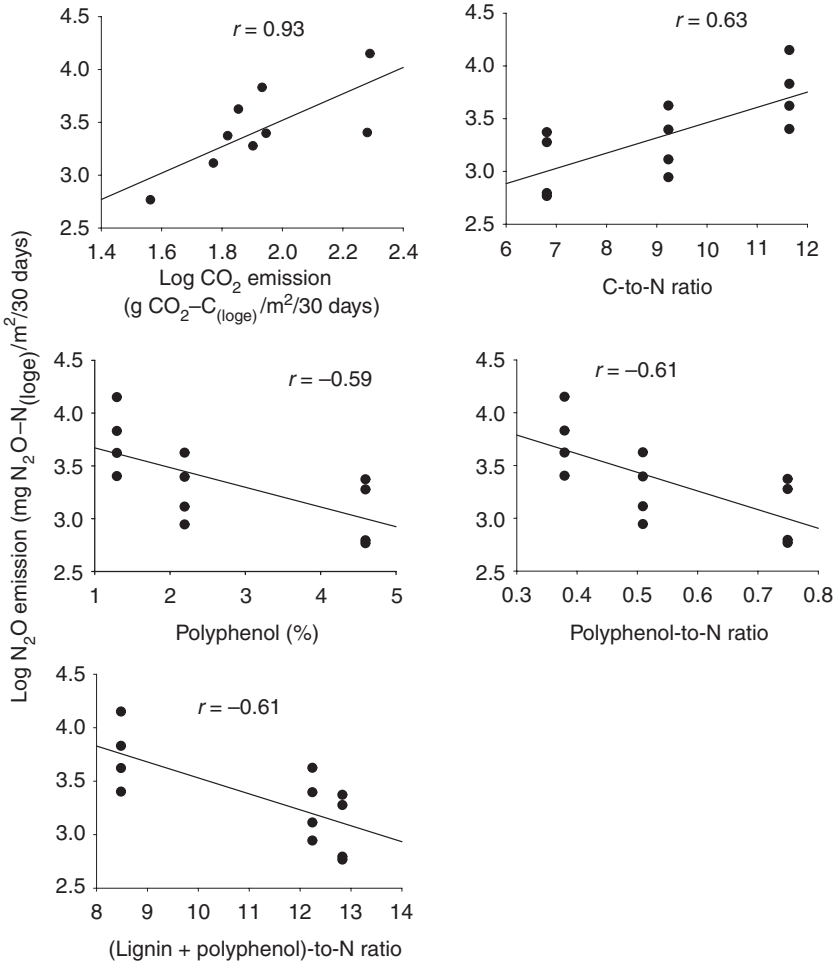

Figure 1 Correlations between N_2O emissions (log_e) and CO_2 emissions (log_e), residue C-to-N ratio, polyphenol content, polyphenol-to-N ratio and (lignin + polyphenol)-to-N ratio.

the control (Figure 7). The highest concentration of 357 mg C/kg soil was in the 100:0 cowpea:fertilizer treatment on day 0, but had fallen to 149 mg C/kg soil by day 1. Concentrations in the 100:0 *Leucaena*:fertilizer and 100:0 *Mucuna*:fertilizer treatments on day 7 were greater ($P < 0.05$) than in the other ratio treatments for these residues. C concentrations were negatively correlated with $^{15}N\text{-}NO_3^-$ concentrations in all the residue treatments ($r = -0.51$ to -0.88; $P < 0.05$), and with $^{15}N\text{-}NH_4^+$ concentrations in the *Leucaena* and *Mucuna* treatments ($r = -0.61$ to -0.99; $P < 0.05$), and positively correlated with CO_2 emissions from all residue treatments ($r = 0.71$ to 0.97; $P < 0.05$).

Discussion

Residue addition and the influence of residue chemical composition

As hypothesized, and in accordance with several other studies (e.g. Baggs *et al*., 2000; Velthof *et al*., 2002; Millar *et al*., 2004; Toma & Hatano, 2007), N_2O fluxes were raised after addition of residues (100:0 residue:fertilizer) to soil, with greater magnitude than fluxes measured from the unamended control soil. This increase in emission was short-lived, and the positive correlation between N_2O and CO_2 fluxes in the cowpea (100:0 cowpea:fertilizer) treatment, suggests that the immediate increase in N_2O flux after addition of this residue resulted from a direct stimulation of microbial activity (Azam *et al*., 2002). Addition of residues to soil would also have resulted in an increase in sub-oxic microsites within the soil structure (Tiedje *et al*., 1984), which along with the provision of residue-C and -N would have created ideal conditions for the stimulation of N_2O-genic processes such as denitrification or nitrate ammonification. Alternatively, release of residue-N may have increased ammonia oxidation in more oxic microsites. Any stimulation in microbial activity in the 100:0 residue:fertilizer treatments was longer-lived than in the fertilizer treatments as exemplified by the more gradual decrease in CO_2 fluxes after residue addition. The negative correlation between CO_2 fluxes and NO_3^- concentrations in the *Mucuna* and cowpea treatments, and between N_2O fluxes and NO_3^- concentrations in the 100:0 *Mucuna*:fertilizer treatment may be indicative of NO_3^- reduction during

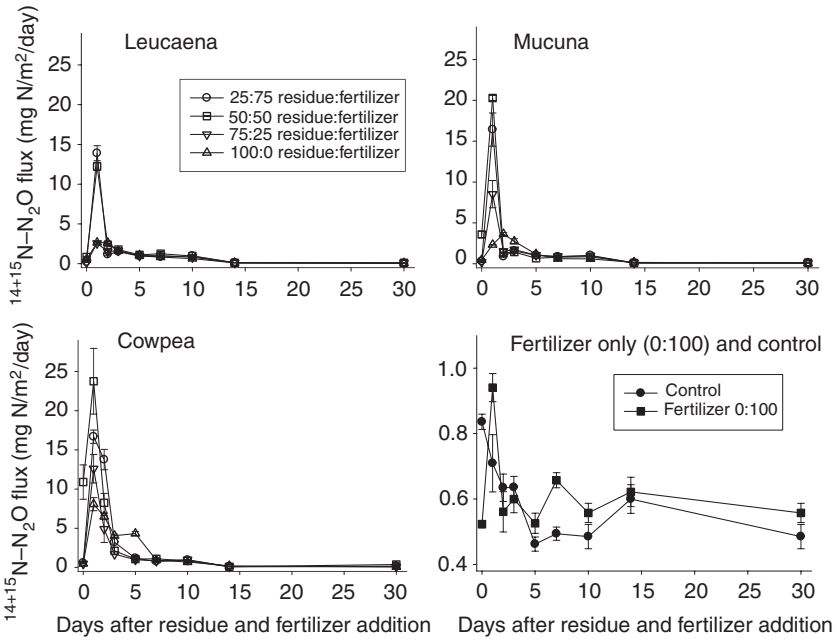

Figure 2 Daily fluxes of N_2O following addition of residues and residue:fertilizer combinations to soil. Error bars represent ± one standard error of the mean.

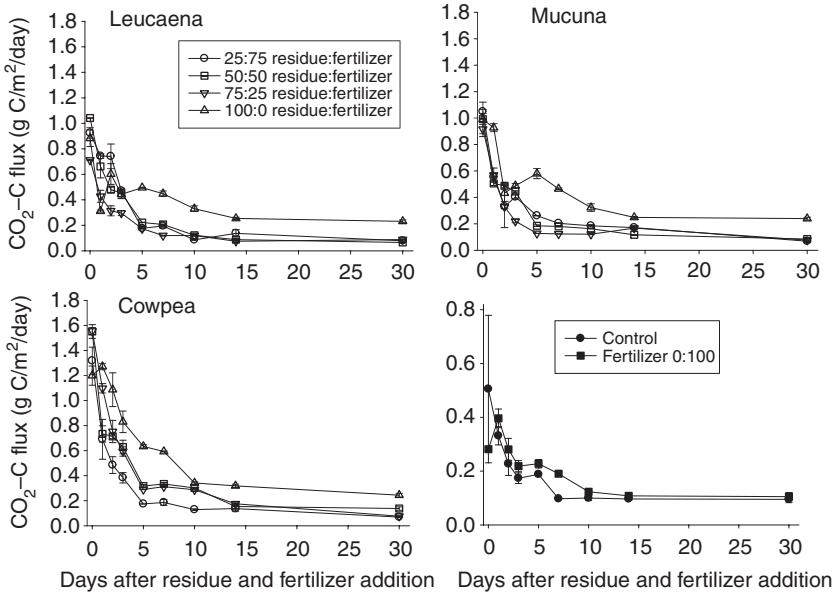

Figure 3 Daily fluxes of CO_2 following addition of residues and residue:fertilizer combinations to soil. Error bars represent ± one standard error of the mean.

denitrification. This is supported by the negative correlations between total organic C and $^{15}N\text{-}NO_3^-$ concentrations in all the residue treatments. Water extractable C concentrations were highest in the 100:0 cowpea:fertilizer treatment which was attributed to solubilization of more C in the low lignin, low polyphenol cowpea residue compared to the relatively higher lignin *Mucuna* and higher polyphenol *Leucaena* residues. This may account for the higher $^{15}N\text{-}N_2O$ (7 days) and $^{14+15}N\text{-}N_2O$ emission from this cowpea treatment than from the *Leucaena* and *Mucuna* 100:0 treatments.

Measurement of $^{15}N\text{-}N_2O$ fluxes and ^{15}N-enrichment of soil mineral N pools enabled us to determine the fate of applied ^{15}N-labelled residues, and to quantify the contribution of this residue-^{15}N to N_2O emissions. Over the 30-day experiment 9.9% (442 μg $^{15}N\text{-}N_2O$/kg soil), 1.1% (54 μg $^{15}N\text{-}N_2O$/kg soil) and 0.3% (13 μg $^{15}N\text{-}N_2O$/kg soil) of the ^{15}N applied in the cowpea, *Mucuna* and *Leucaena* (all 100:0 residue:fertilizer) treatments, respectively, was emitted as $^{15}N\text{-}N_2O$. Only up to 2.9% of N_2O emission was enriched in ^{15}N, meaning that a significant proportion of the measured

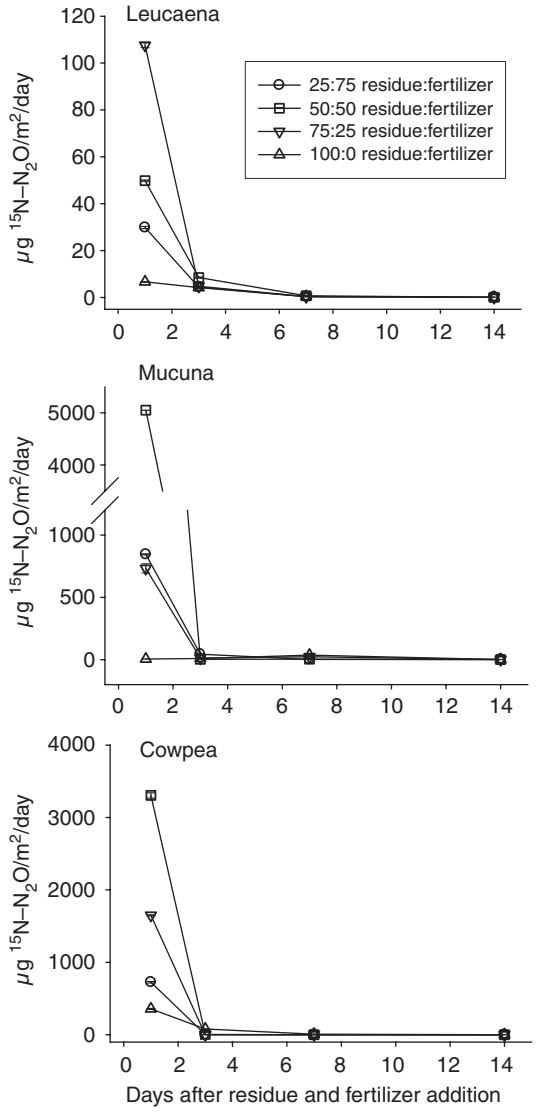

Figure 4 Daily fluxes of ^{15}N-N_2O following addition of residues and residue:fertilizer combinations to soil. Error bars represent ± one standard error of the mean.

$^{14+15}N$-N_2O emission was derived from unlabelled residue N, native soil mineral N, or a priming of N release from soil organic matter. Recovery of applied ^{15}N was greater as mineral N than as N_2O in the *Mucuna* and *Leucaena* treatments, with 2.4% and 1.2% of applied ^{15}N recovered as ^{15}N-NO_3^- on day 14 in these treatments, and 1.4% and 8.5% recovered as ^{15}N-NH_4^+. Conversely, in the cowpea treatment proportionally more applied ^{15}N was recovered as ^{15}N-N_2O (9.9%), with 6.3 and 8.3% of ^{15}N applied recovered as ^{15}N-NH_4^+ and ^{15}N-NO_3^-, respectively, at day 14.

Total N_2O emission at 30 days was positively correlated with residue C-to-N ratio in the 100:0 residue:fertilizer treatments ($r = 0.97$; $P < 0.05$). Although this is in agreement with data of Millar & Baggs (2004), it is against the generally accepted negative relationship in which N_2O emissions increase with greater residue-N content (Kaiser *et al*., 1998; Baggs *et al*., 2000; Akiyama & Tsurata, 2003; Millar *et al*., 2004; Toma & Hatano, 2007). Our result may reflect that C was limiting in this system for denitrification of available NO_3^-, or that release of N from the residues was slow. N_2O emission from the 100:0 residue:fertilizer treatments was negatively correlated with residue polyphenol ($r = -0.87$; $P < 0.05$) and lignin ($r = -0.6$; $P < 0.05$) contents, and polyphenol:N ($r = -0.91$; $P < 0.05$) and (lignin + polyphenol):N ($r = -0.99$; $P < 0.05$) ratios. The lower (lignin + polyphenol):N ratio of the cowpea coupled with its higher C:N ratio compared to the other residues may account for emission from the 100:0 cowpea:fertilizer treatment (374 mg N_2O-N/m^2/30 days, 2.5 g N_2O-N/m^2/kg biomass/30 days) being greater than that emitted from the 100:0 *Mucuna* and *Leucaena* treatments. Lignin and polyphenol contents are known to delay N release from the residue, either by forming recalcitrant N compounds, or binding to soil microbial enzymes (Baldwin *et al*., 1983; Mole & Waterman, 1986), thereby lowering the substrate availability for N_2O-genic processes. Millar & Baggs (2004) also showed a strong relationship between N_2O emission and the (lignin + polyphenol):N ratio of agroforestry residues when combining their data with that of Baggs *et al*. (2001). However, here our residue lignin of all three species, and polyphenol contents of *Mucuna* and cowpea were below the thresholds generally accepted to lower N release; >15% lignin and/or >3–4% total extractable polyphenol content (Constantinides & Fownes, 1994; Palm & Rowland, 1997).

Combined application of residue and fertilizer

Application of residues and fertilizer increased the total N_2O emitted compared to the sum of sole applications of residue and fertilizer (100:0 and 0:100 residue:fertilizer treatments), by up to 114% (25:75 *Mucuna*:fertilizer treatment) indicating a positive interactive effect on emissions. This, coupled with the lack of difference in N_2O emission between the 0:100 residue:fertilizer treatment and unamended control, suggests that the combined addition in part alleviated any limitation on N_2O production in the sole treatments. Previously this has been attributed to the greater C availability from residues driving dissimilatory reduction of NO_3^- (denitrification or nitrate ammonification) (de Catanzaro & Beauchamp, 1985; Sarkodie-Addo *et al*., 2003). However, here water extractable C was not significantly correlated with daily N_2O fluxes, suggesting that whilst microbial activity was increased (exemplified by increased CO_2 fluxes, and strong positive correlation between water extractable C and CO_2), residue C was not solely responsible for stimulating N_2O production. It is possible that ammonia oxidation was contributing to N_2O production in our soil, as has previously been demonstrated for the 60% WFPS at which the soil was maintained here

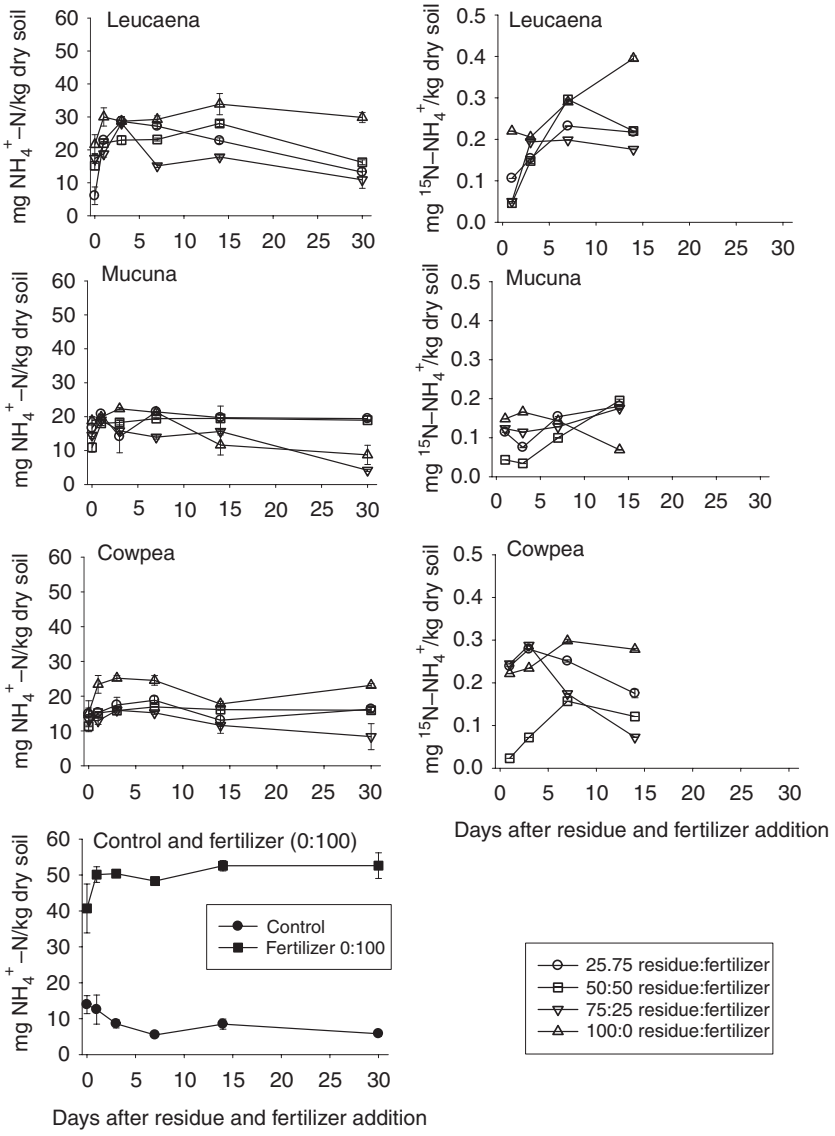

Figure 5 Concentrations of available soil NH_4^+ and ^{15}N-NH_4^+ following addition of residues and residue:fertilizer combinations to soil. Error bars represent ±one standard error of the mean.

(Bateman & Baggs, 2005), which as an autotrophic process would account for the lack of relationship between water extractable C or CO_2 and N_2O production. The increase in NO_3^- concentrations over time were also indicative of nitrification. The nature of such interactive effects on the microbial source of N_2O requires further investigation, for example by adopting an isotopomer approach for source partitioning the N_2O (Baggs, 2008) and a ^{15}N pool dilution approach for quantifying gross nitrification rates (Davidson *et al*., 1991).

Increasing the proportion of fertilizer-N applied with *Leucaena* and *Mucuna* residues increased emission of N_2O (30 days) when expressed on a per residue biomass basis, with greater emissions from the 25:75 residue:fertilizer than from the 50:50 or 75:25 treatments, but this trend was not reflected in the ^{15}N-N_2O emission over the first 7 days. To our knowledge this is the first study investigating interactions between residue and fertilizer-N addition on N_2O production where the residues were ^{15}N-labelled, and demonstrates that increasing the proportion of fertilizer-N applied with residues does not consistently increase or decrease the contribution of residue-^{15}N to N_2O production. ^{15}N-N_2O production only accounted for up to 2.9% of the total $^{14+15}N$-N_2O emitted after residue addition, suggesting that the N substrates for ammonia oxidation or nitrate reduction were predominantly from native soil N pools or the applied fertilizer-N.

The interactive effect between residue- and fertilizer-N sources was most pronounced in the *Leucaena*:fertilizer treatments where total $^{14+15}N$-N_2O emission (mg N/m^2/g residue/30 days) from the 25:75 *Leucaena*:fertilizer treatment was 13 times greater than the emission from the 100:0 *Leucaena*:fertilizer treatment. The contribution of

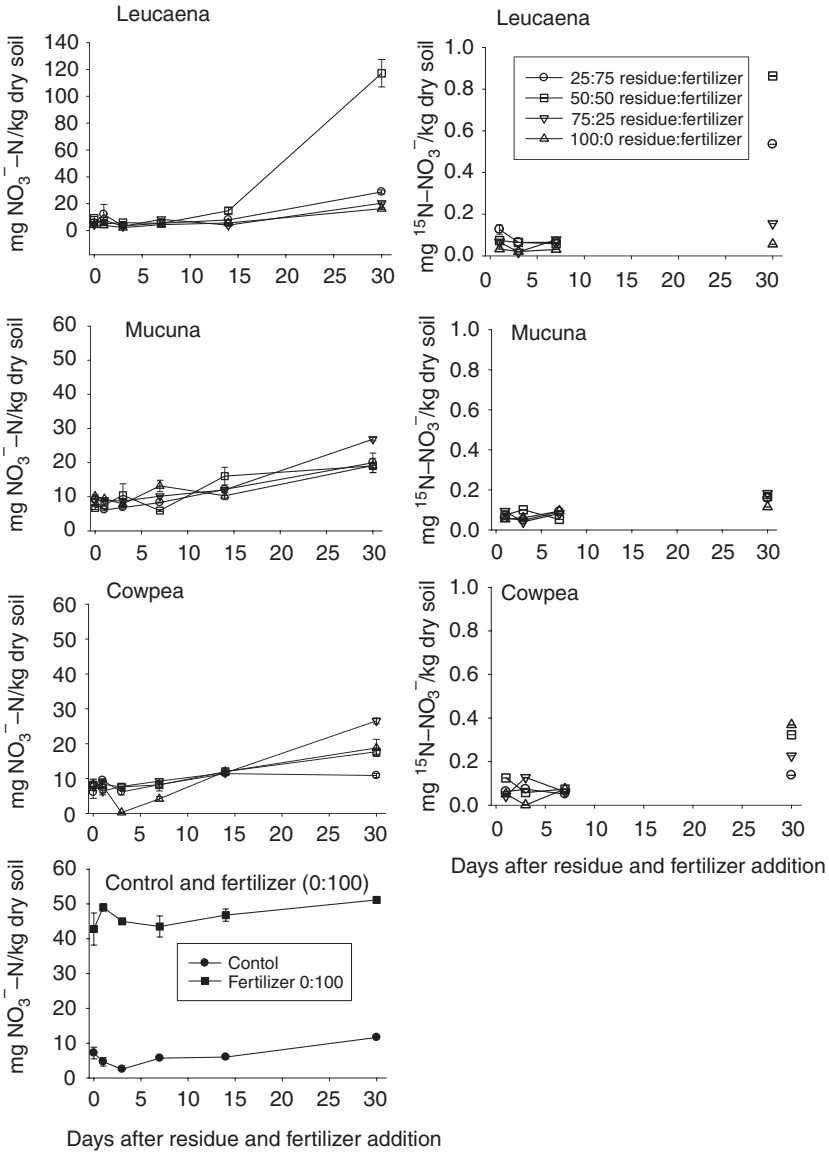

Figure 6 Concentrations of available soil NO_3^- and ^{15}N-NO_3^- following addition of residues and residue:fertilizer combinations to soil. Error bars represent ± one standard error of the mean.

residue-derived ^{15}N to total N_2O emitted was also increased with joint residue and fertilizer application, and resulted in up to 10-fold greater recovery of applied ^{15}N as ^{15}N-N_2O. This was most marked in the 50:50 cowpea:fertilizer treatment where ^{15}N-N_2O accounted for 88% of the total recovered ^{15}N (N_2O, NH_4^+ and NO_3^- pools). Total recovery of applied ^{15}N increased with the proportion of fertilizer-N in the combined application of residues and fertilizer. This suggests that application of fertilizer increased mineralization of ^{15}N from the residues, and further increased its utilization in N_2O-genic processes.

Emission of ^{15}N-N_2O, indicative of the contribution of residue-^{15}N to N_2O emission, was lower in all the *Leucaena* residue treatments than the *Mucuna* and cowpea treatments. The *Leucaena* residues had a higher polyphenol content (4.6%) than the other residues, which was at the threshold thought to influence N release (Constantinides & Fownes, 1994; Palm & Rowland, 1997), and to lower N_2O production (Millar & Baggs, 2004). However, there was no discernable influence on soil NH_4^+ or NO_3^- concentrations, and recoveries of applied ^{15}N as ^{15}N-NO_3^- in the 25:75 and 50:50 *Leucaena*:fertilizer treatments (46 and 37% of ^{15}N applied) were higher than in the other residue treatments. Residue polyphenol and N contents, and (lignin + polyphenol):N ratio still exerted an effect on N_2O ($\log_e$) emission in the combined residue and fertilizer treatments (Figure 1), but were less strong than where the residues were applied alone ($r = -0.87$ for polyphenol content; $r = -0.90$ for N content; $r = -0.99$ for (lignin + polyphenol):N; $P < 0.05$), reflecting the contribution of applied fertilizer N as a substrate for N_2O producing processes, with the higher mineral N contents of soil resulting from immediate availability of fertilizer-N possibly

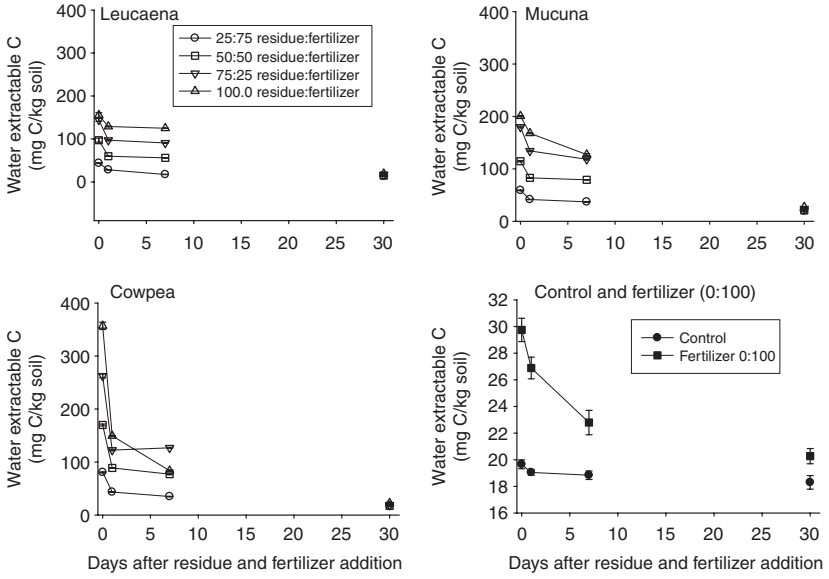

Figure 7 Concentrations of water extractable C following addition of residues and residue:fertilizer combinations to soil. Error bars represent ±one standard error of the mean.

dampening the influence of residue composition over this 30 days experiment, and a lower quantity of residues applied.

Does the combined application of residues and fertilizer-N hold the potential for regulation of N_2O production?

Our results demonstrate that whilst there is the potential for N_2O emission to be controlled through varying ratios of residue:fertilizer input, the magnitude and direction of interactions between these N sources varies between different species as a result of their differing qualities. This is in spite of the range in qualities examined here being quite narrow. The potential for regulation may be greater where residues have a high C:N ratio, higher lignin and higher polyphenol contents, as Millar & Baggs (2004) showed that strength of relationship between N_2O emission and these residue characteristics depended on the range of chemical composition being considered. Gentile *et al.* (2008) and Palm *et al.* (2001) have recommended that for the purpose of controlling N release, high quality residues be applied alone, but low and medium quality residues be applied in combination with N fertilizers. Such relationships as we observed here may also be expected to change over time, for instance after the first flush of fertilizer-N has been utilized.

For all residues the lowest N_2O emissions over 30 days were when they were applied alone (100:0 residue:fertilizer), and also resulted in greater NH_4^+ availability. Combined application with fertilizer did not significantly lower NH_4^+ concentrations compared to the control, indicative that strong immobilisation of soil N did not occur, but raised N_2O emissions. Whilst these results confirm the positive interactive effect on N_2O emission following a 50:50 residue:fertilizer application by Sarkodie-Addo *et al.* (2003), it is in contrast to Sakala *et al.* (2000), Vanlauwe *et al.* (2002) and Gentile *et al.* (2008) who report negative interactive effects on soil mineral N, with combined addition of maize and fertilizer-N immobilising the fertilizer-N but stimulating release of the maize-N. The lack of immobilisation of N here may reflect the low C:N ratios of the residues, and the application of residues on an equivalent N basis with a total residue- and fertilizer-N input of 100 mg N/kg soil in each of the treatments.

With combined applications the contribution of residue-derived ^{15}N to measured $^{14+15}N$-N_2O fluxes, and the recovery of applied ^{15}N as ^{15}N-N_2O, increased. For all residues the 75:25 residue:fertilizer treatment resulted in greater NO_3^- availability and least increase in N_2O emission compared to the 100:0 treatments, with N_2O emissions being lower than where proportionally more fertilizer-N was applied, indicating that something was limiting for optimum reduction of NO_3^- to N_2O. Although lower in magnitude, the contribution of residue-^{15}N to N_2O emissions in the 75:25 residue:fertilizer treatments (2–14%) tended to be greater than in the 25:75 treatments (0.4–8%), whereas recovery of applied ^{15}N as ^{15}N-N_2O was greater in the latter. Under our controlled experimental conditions this 75:25 residue:fertilizer ratio would appear to offer the best compromise between release of N for crop uptake, appearing to enhance release of residue-N, and management of N_2O emission. Further studies are required to determine if such relationships hold true under field conditions and in response to varying environmental conditions, particularly in response to rainfall events.

Conclusion

N_2O production was increased after addition of ^{15}N-labelled residues to tropical soil under controlled environmental

conditions, and emissions were further increased when the residues were applied in combination with inorganic N fertilizer. However, there was no consistent trend in magnitude of N_2O production with increasing proportion of inorganic fertilizer in the combined applications, and contribution of residue ^{15}N to measured N_2O emissions was low and short-lived. Correlations confirmed that the magnitude and direction of interaction between N sources was influenced by the chemical composition of the residues, and so varied with residue species. We found no direct evidence that residue C was driving N_2O production, which may either indicate a contribution of ammonia oxidation here, or that soil organic matter C was not limiting for NO_3^- dissimilation. Based on our applications of *Leucaena*, *Mucuna* and cowpea residues, the 75:25 residue:fertilizer ratio at 100 mg N/kg soil is recommended from this study as offering the best compromise between release of N for crop uptake and management of N_2O emission. However, the influence of residue quality is likely to change over time after addition under real field conditions, and with the range of chemical compositions being compared. In order to aid predictions of N_2O emission following addition of different residue species to soil, the biogeochemical and physical effects of residue addition now need to be separated from interactive effects of combined N sources.

Acknowledgements

K. Frimpong was supported by funding from the Ghana Education Trust fund (GETfund), and EM Baggs was supported by an Advanced Research Fellowship from the Natural Environment Research Council [NE/B500666/1]. We express our gratitude to Ken Cruickshank for his assistance with the mineral N analysis, and Janet Woo for analyzing the ^{15}N gas samples. We acknowledge the Scottish Agricultural Science Agency for the licence [IMP/SOIL/2/2008] to import soil from Ghana.

References

Akiyama, H. & Tsurata, H. 2003. Effect of organic matter application on N_2O, NO and NO_2 fluxes from an Anodosol field. *Global Biogeochemical Cycles*, **17,** 1100, doi: 10.1029/2002GB002016.

Anderson, J.M. & Ingram, J.S.I. 1993. Tropical soil biology and fertility. A handbook of methods, 2nd edn. CAB International, Wallingford, UK.

Azam, F., Weiske, A. & Benckiser, G. 2002. Nitrification and denitrification as sources of atmospheric nitrous oxide-role of oxidisable carbon and applied nitrogen. *Biology and Fertility of Soils*, **35,** 54–61.

Baggs, E.M. 2008. A review of stable isotope techniques for N_2O source partitioning in soils: recent progress, remaining challenges and future considerations. *Rapid Communications in Mass Spectrometry*, **22,** 1664–1672.

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

Baggs, E.M., Ndufa, J.K. & Cadisch, G. 2001. Effect of residue quality on N_2O emissions from tropical soil. In: *Sustainable management of soil organic matter* (eds R.M. Rees, B.C. Ball, C.O. Campbell & C.A. Watson), pp. 120–125. CABI International, Edinburg.

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

Baldwin, I.T., Olsen, R.K. & Reiners, W.A. 1983. Protein binding phenolics and the inhibition of nitrification in subalpine balsam fir soils. *Soil Biology and Biochemistry*, **15,** 419–423.

Bateman, E.J. & Baggs, E.M. 2005. Contributions of nitrification and denitrification to N_2O emissions from soils at different water-filled pore space. *Biology and Fertility of Soils*, **41,** 379–388.

Brooks, P.D., Stark, J.M. & McInteer, B.B. 1989. Diffusion method to prepare soil extract for automated nitrogen-15 analysis. *Soil Science Society of America Journal*, **53,** 1707–1711.

de Catanzaro, J.B. & Beauchamp, E.G. 1985. The effect of some carbon substrates on denitrification rates and carbon utilisation in soil. *Biology and Fertility of Soils*, **1,** 183–187.

Constantinides, M. & Fownes, J.H. 1994. Nitrogen mineralisation from leaves and litter of tropical plants: relationship to nitrogen, lignin and soluble polyphenol concentrations. *Soil Biology and Biochemistry*, **26,** 49–55.

Davidson, E.A., Hart, S.C., Shanks, C.A. & Firestone, M.K. 1991. Measuring gross nitrogen mineralization, immobilization, and nitrification by ^{15}N isotopic pool dilution in intact soil cores. *Journal of Soil Science*, **42,** 335–349.

Eichner, M.J. 1990. Nitrous oxide emissions from fertiliser soil: summary of available data. *Journal of Environmental Quality*, **19,** 272–280.

FAO. 1998. *World reference base for soil resources No. 84*. World Soil Resources Report. FAO, Rome, Italy.

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

Gentile, R., Vanlauwe, B., Chivenge, P. & Six, J. 2008. Interactive effects from combining fertiliser and organic residue inputs on nitrogen transformations. *Soil Biology and Biochemistry*, **40,** 2375–2384.

Harrison, R., Ellis, S., Cross, R. & Hodgson, J.H. 2002. Emissions of nitrous oxide and nitric oxide associated with the decomposition of arable crop residues on a sandy loam soil in Eastern England. *Agronomie*, **22,** 731–738.

Huang, Y., Zou, J., Zheng, X., Wang, Y. & Xu, X. 2004. Nitrous oxide emissions as influenced by amendments of plant residues with different C: N ratio. *Soil Biology and Biochemistry*, **36,** 973–981.

Kaiser, E.-A., Kohrs, K., Kucke, M., Schnug, E., Heinemeyer, O. & Munch, J.C. 1998. Nitrous oxide release from arable soil: importance of N-fertilisation, crops and temporal variation. *Soil Biology and Biochemistry*, **30,** 1553–1563.

Kimani, S.K., Nandwa, S.M., Mugendi, D.L., Obanyi, S.N., Ojiem, J., Murwira, H.K. & Bationo, A. 2003. Principles of integrated

soil fertility management. In: *Soil fertility management in Africa: a regional perspective* (eds 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 & M.J. Swift), pp. 51–72. Academy Science Publishers, Nairobi.

Kirchmann, H. & Thorvaldsson, G. 2000. Challenging targets for future agriculture. *European Journal of Agronomy*, **12,** 145–161.

Melillo, J.M., Aber, J.D. & Muratore, J.F. 1982. Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. *Ecology*, **63,** 621–626.

Millar, N. & Baggs, E.M. 2004. The chemical composition or, quality of agroforestry residues influence N_2O emissions after their addition to soils. *Soil Biology and Biochemistry*, **36,** 935–943.

Millar, N. & Baggs, E.M. 2005. Relationships between N_2O emissions and water-soluble C and N contents of agroforestry residues after their addition to soil. *Soil Biology and Biochemistry*, **37,** 605–608.

Millar, N., Ndufa, J.K., Cadisch, G. & Baggs, E.M. 2004. Nitrous oxide emissions following incorporation of improved-fallow residues in the humid tropics. *Global Biogeochemical Cycles* **18,** GB 1032, doi: 10.1029/2003GB002114.

Mole, S. & Waterman, P.G. 1986. Tannic acid and proteolytic enzymes. Enzyme inhibition or substrate deprivation? *Phytochemistry*, **26,** 99–102.

Novoa, R.S.A. & Tejeda, H.R. 2006. Evaluation of the N_2O emissions from N in plant residues as affected by environmental and management factors. *Nutrient Cycling in Agroecosystems*, **75,** 29–46.

Palm, C.A. & Rowland, A.P. 1997. A minimum dataset for characterisation of plant quality for decomposition. In: *Driven by nature: plant litter quality and decomposition* (eds G. Cadisch & K.E. Giller), pp. 379–392. CAB International, Wallingford.

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G. & Giller, K.E. 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems and Environments*, **83,** 27–42.

Ravishankara, A.R., Daniel, J.S. & Portmann, R.W. 2009. Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st Century. *Science*, **326,** 123–125.

Sakala, W.D., Cadisch, G. & Giller, K.E. 2000. Interactions between residues of maize and pigeonpea and mineral N fertilisers during decomposition and N mineralisation. *Soil Biology and Biochemistry*, **32,** 679–688.

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

Seneviratne, G. 2000. Litter quality and nitrogen release in tropical agriculture: a synthesis. *Biology and Fertility of Soils*, **31,** 60–64.

Snyder, C.S., Bruulsema, T.W. & Jensen, T.L. 2007. *Greenhouse gas emissions from cropping systems and the influence of fertilizer management: a literature review*. International Plant Nutrition Institute, Norcross, GA, 25 pp.

Solomon, S., Qin, D., Manning, M., Alley, R.B., Berntsen, T., Bindoff, N.L., Chen, Z., Chidthaisong, A., Gregory, J.M., Hegerl, G.C., Heimann, M., Hewitson, B., Hoskins, B.J., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Somerville, R., Stocker, T.F., Whetton, P., Wood, R.A. & Wratt, D. 2007. Technical summary. In: *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller). Cambridge University Press, Cambridge, UK and New York, NY.

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

Toma, Y. & Hatano, R. 2007. Effect of crop residue C:N ratio on N_2O emissions from gray lowland soil in Mikasa, Hokkaido, Japan. *Soil Science and Plant nutrition*, **53,** 198–205.

Vanlauwe, B., Wendt, J. & Diels, J. 2001. Combined application of organic matter and fertiliser. In: *Sustaining soil fertility in West Africa* (eds G. Tian, F. Ishida & J.D.H. Keatinge), pp. 247–279. Soil Science Society of America and American Society of Agronomy, Madison, WI.

Vanlauwe, B., Diels, J., Aihou, K., Iwuafor, E.N.O., Lyasse, O., Sanginga, N. & Merckx, R. 2002. Direct interactions between N fertiliser and organic matter: evidence from trials with ^{15}N-labelled fertiliser. In: *Integrated plant nutrient management in Sub-Saharan Africa: from concept to practice* (eds B. Vanlauwe, J. Diels, N. Sanginga & R. Merckx), pp. 173–184. CAB International, New York.

Velthof, G.L., Knikman, P. & Oenema, O. 2002. Nitrous oxide emission from soils amended with crop residues. *Nutrient Cycling Agroecosystems*, **62,** 249–261.

Yoshida, S., Forno, D.A., Cock, J.H. & Gomez, K.A. 1976. Routine procedure for growing rice plants in culture solution. In: *Laboratory manual for physiological studies of rice* (eds S. Yoshida, D.A. Forno, J.H. Cock & K.A. Gomez), pp. 61–66. 2nd edn. IRRI, Los Baños.