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ORIGINAL ARTICLE

Does incorporation of cowpea-maize residue mixes influence nitrous oxide emission and mineral nitrogen release in a tropical luvisol?

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Abstract In the face of climate change, quantification of the emission of nitrous oxide from soils in relation to sufficient N availability for crop uptake has assumed much significance. This study used the ^{15}N stable isotope technique, under controlled laboratory conditions, to quantify the interactive effect on and relative contributions of the component species to N_2O emission and mineral N dynamics in a tropical luvisol incorporated with different rates of cowpea-maize residue mixtures. The results show that increasing the maize residue proportion in the mixture significantly decreases N_2O emission compared to the sole cowpea incorporation but increases mineral N concentration compared to sole maize residue incorporation. It is concluded that mixing low C:N ratio cowpea residue with high C:N ratio maize residue has potential for N management in tropical legume-cereal intercropping systems with the view to minimizing N_2O emission while making N available for crop uptake.

Keywords Nitrous oxide emission · Mineral N · Cowpea-maize residue · ^{15}N stable isotope

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Introduction

Arable crop production systems account for a fourth of global nitrous oxide (N_2O) emissions (Mosier et al. 1998). Nutrient management in cropping systems has therefore, become critical not only to sustainable food supply but also agro-environmental management that mitigates the emission of greenhouse gases. Grain legumes are considered appropriate resources for soil fertility replenishment on smallholder farms due to their capacity to fix atmospheric N_2 in addition to direct food provision (Snapp and Silim 2002; Ojiem 2006). Cowpea (*Vigna unguiculata*), which is an acid tolerant and drought tolerant tropical legume (John et al. 1992) has an efficient atmospheric N_2 fixing capacity, high biomass N accumulation (Franzluebbers et al. 1994) and is highly compatible with maize

(*Zea mays*) in intercropping systems commonly practised by smallholder farmers throughout the tropics (Sakala et al. 2000). As a result, cowpea has a great potential for soil fertility management in tropical agricultural systems.

However, the low C:N ratio cowpea might decompose rapidly, resulting in a rapid residue N mineralisation, which may be lost through leaching or as N_2O through nitrification and denitrification (Weier et al. 1993; Baggs et al. 2001; Millar and Baggs 2004), the two key N_2O producing processes. Therefore, it is imperative that management strategies are identified that could ensure synchrony between N release from cowpea residues and uptake by subsequent crops while minimizing N_2O emissions. Mixing residues of different C:N ratios can increase temporary N immobilisation and prolong N mineralisation (Handayanto et al. 1997; Schwendener et al. 2005; Vityakon et al. 2000) and alter N_2O emission (Kaewpradit et al. 2008). The high C:N ratio cereal residue can provide large amounts of labile C to enhance microbial activity, immobilisation of inorganic residue and/or soil- N and lower N_2O emission compared to sole incorporation of low C:N ratio legume residues (Handayanto et al. 1997; Vityakon et al. 2000). This interactive effect is also expected to vary with varying ratios of the component residues. The interactive effect can be the weighted mean of single components or a synergistic or antagonistic non-additive effect, which is observed only when large amounts of reactive, soluble C or polyphenols are present in one of the residues (Handayanto et al. 1997).

Kaewpradit et al. (2008) and Vityakon et al. (2000) observed that mixing groundnut and rice residues delayed N mineralisation for up to 8 weeks after incorporation, attributing it to microbial immobilisation of groundnut residue N stimulated by high organic C release from the rice residue. Eagle et al. (2000) stated that maize residue also has the potential to retard N mineralisation when mixed with high N residues. Although these studies examined the interactions between component species, to date, no study has exploited the potential of the ^{15}N stable isotope technique to quantify the relative contributions of the component species to N_2O emitted and mineral N concentration. Therefore, this experiment used the ^{15}N stable isotope technique, under controlled laboratory conditions, to: (1) quantify N_2O emission and mineral N dynamics following the addition of different rates of cowpea-maize mixtures and (2) quantify the interactive effect and relative contributions of cowpea and maize to N_2O emission and mineral N dynamics.

Materials and methods

Soils

Soil samples from the Guinea Savannah agro-ecological zone of Ghana were collected for the study. The soils were air-dried, sieved and packed to a bulk density of 1.23 gcm^{-3} in 500 ml Kilner jars. The soils were pre-incubated at 45°C for 7 days prior to addition of the residues to re-initiate microbial activity after storage, and to minimise changes in soil water filled pore space (WFPS) at the start of the experiment. WFPS was calculated based on soil volumetric water content, bulk density and a particle size of 2.3 gcm^{-3}.

Crop residues

Maize and cowpea residues were chosen as crop residues because of their varying N content and C:N ratios and the widespread use of these species as intercrop or multi-crop species in subsistence farming in the tropics. The cowpea and maize were grown in vermiculite in a greenhouse at the University of Aberdeen. One-third of the plants were ^{15}N-labelled by supplying them with 100–400 ml of 0.5 mM $^{14}NH_4$ $^{15}NO_3$ (10.1 atom % excess ^{15}N) when necessary, while the remainder received a solution at natural abundance. Harvesting was done after 7 weeks. Subsamples of the maize and cowpea leaves were dried at 45°C for the determination of dry matter (%), and then milled (<1 mm) for further laboratory analyses. Total C and N contents were determined on a 0.5 g dry subsample through dry combustion using a Metler-Toledo AG 2455 C/N auto analyser. Lignin content was determined in an Ankom 220 fibre analyser (Acid detergent fibre) and the total extractable polyphenol was measured (Table 1) using Folin-ciolcateau reagent in a method adapted from Anderson and Ingram (1993).

Experimental setup

Two experiments were conducted to quantify the effects of incorporating different ratios of cowpea-maize

Table 1 Biochemical characteristics of residues used in the study

Residue	TEP (%)	ADL (%)	Total N (%)	Total C (%)	Atom % ^{15}N (%)
Cowpea	1.28	7.21	3.4	39.6	4.86
Maize	1.14	7.36	0.92	42.1	4.32

TEP Total extractable polyphenol, *ADL* Acid detergent lignin

residue mixes on mineral N release and N_2O emission (using unlabelled residues) and to quantify the interactive effects (using ^{15}N labelled residues).

Quantification of N_2O emission and N dynamics using unlabelled residues

Laboratory microcosm incubation was set up with 100 g of soil in 500 ml Kilner jars (a 500 cm^3 glass jar with a gas tight lid) using a completely randomised design. Unlabelled cowpea and maize residues were incorporated to each soil at different proportional ratios of 100:0, 75:25, 50:50 and 25:75 and 0:100, maize:cowpea on a biomass basis at a rate of 4 t ha^{-1}. In addition, the control had no residue incorporation. Each of these six treatments was replicated 4 times for gas sampling and a further 3 times for destructive soil sampling. The incubation was carried out in the dark at 21°C for 30 days. The soil was brought to 60% WFPS at the start of incubation (Day 0). Parton et al. (1996) suggested that at 60% WFPS, neither the diffusion of substrates nor the diffusion of oxygen is limited, indicating that WFPS of 60% probably offers the optimum conditions whereby both nitrification and denitrification significantly contribute to N_2O production (Davidson et al. 1991).

Quantification of labelled N_2O emission and mineral N concentrations

In the second experiment, $^{15}N_2O$ emission and labelled mineral N concentrations were determined after addition of ^{15}N-labelled cowpea or ^{15}N-labelled maize residues to the soil. Here, each of the cowpea and maize residues was applied at a rate of 4 t ha^{-1} solely, or in combination with the other. Where both cowpea and maize were incorporated, unlabelled residues of each species was combined with labelled residues of the other. Thus, where the two residues were added together, the total quantity of residue incorporated was 8 t ha^{-1} to enable the determination of whether the interactive effect between the component residues was additive or not. The treatments applied were:

1. ^{15}N-labelled maize (4 t ha^{-1})
2. ^{15}N-labelled cowpea (4 t ha^{-1})
3. ^{15}N-labelled maize (4 t ha^{-1}) + unlabelled cowpea (4 t ha^{-1})
4. ^{15}N-labelled cowpea (4 t ha^{-1}) + unlabelled maize (4 t ha^{-1})
5. Control (no residue incorporation)

Sampling and analysis

Gas sampling and analysis

Gas sampling and analysis were done following the procedures described in Millar and Baggs (2004) and Garcia-Ruiz and Baggs (2007). Gas samples for N_2O and CO_2 analysis were collected from the Kilner jar headspaces on day 0, (6 h after addition of fertiliser 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 ionisation detector. Oven and detector temperatures were 50 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 $^{15}N_2O$ 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, Crewe, UK). ^{15}N-enrichments of the gas fluxes were calculated from the atom % excess of samples, taking into account the atom % excess of the residues applied.

Destructive soil sampling and analysis

The soils were destructively sampled on days 0, 1, 3, 7, 14, and 30. Subsamples (40 g) from each treatment were extracted with 1 M KCl (extraction ratio: 1:5) and extracts were analysed for NH_4^+ and NO_3^- concentrations colorimetrically by continuous flow analysis on a FIA star 5,010 autoanalyser fitted with a cadmium column. The ^{15}N atom % of the NO_3^- and NH_4^+ was determined by diffusion methodology (Brooks et al. 1989) and analysed on a SerCon 20/20 isotope ratio mass spectrometer.

Water extractable carbon

Water extractable carbon (WEC) was quantified in soil sampled on days 0, 1, 7, 14 and 30. To extract the WEC, 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 WEC in the supernatant liquid was determined using a total organic carbon analyser (TOC-5000A, Shimadzu).

Calculations

Net N_2O emission from residue amended treatments (mixed or single) was calculated using the 'difference method' as shown below:

$$\text{Net } N_2O = \left(\text{Total } N_2O_{\text{residue}} - \text{Total } N_2O_{\text{control}}\right) / \text{residue N applied } \left(\text{mg kg}^{-1}\text{soil}\right)$$

where Total N_2O_{residue} denotes total N_2O production from the residue amended soil and Total N_2O_{control} denotes total N_2O production from the control soil.

Where maize and cowpea residues were applied as a mixture, residue N was calculated as weighted average N of the two species. The interactive effect of mixing cowpea and maize residues on $^{15}N_2O$ emission and labelled mineral N concentrations were calculated as follows:

$$\text{Interactive Effect (I.E.)} = \left({}^{15}\text{N cowpea}_{\text{combined}} - {}^{15}\text{ N cowpea}_{\text{single}}\right) + \left({}^{15}\text{N maize}_{\text{combined}} - {}^{15}\text{ N maize}_{\text{single}}\right)$$

where ^{15}N maize$_{\text{combined}}$ denotes ^{15}N-labelled maize (4 t ha^{-1}) + unlabelled cowpea (4 t ha^{-1}), ^{15}N cowpea$_{\text{combined}}$ denotes ^{15}N-labelled cowpea (4 t ha^{-1}) + unlabelled maize (4 t ha^{-1}), ^{15}N maize $_{\text{single}}$ denotes ^{15}N-labelled maize only (4 t ha^{-1}), and ^{15}N cowpea$_{\text{single}}$ denotes ^{15}N-labelled cowpea only (4 t ha).

Statistical analysis

All data were analysed using the Minitab 15 statistical package. ANOVA was carried out using the measured values of $^{14+15}N_2O$, $^{15}N_2O$, mineral N (NH_4^+ and NO_3) and WEC. Significant difference was tested using pooled standard error of the difference (SED) and Turkey's HSD at 0.05 significance level. Pearson correlation analyses were carried out to establish relationships if any, between crop residue C:N ratio and total N_2O and CO_2 productions, and between WEC and mineral N concentrations, and CO_2 and N_2O fluxes.

Results

N_2O Emission

Daily $^{14+15}N_2O$ emission

Total N_2O emissions over the 30 days from all the treatments were significantly higher ($P < 0.05$) than those from the control. The 100:0 and 75:25 cowpea:maize treatments recorded the highest total emissions of 13.4 and 13.27 mg N m^{-2} d^{-1}, respectively, which were significantly different ($P < 0.05$) from the rest of the treatments. This is followed by the 25:75 treatment (8.76 mg N m^{-2} d^{-1}), which is also significantly different ($P < 0.05$) from the remaining treatments. The control recorded the least emission

(4.56 mg N m^{-2} d^{-1}). Regarding daily emissions, however, the 75:25 and 100:0 cowpea:maize treatments recorded the maximum values of 4.55 and 4.38 mg N m^{-2} d^{-1}, respectively on day 1, which differed significantly ($P < 0.05$) from the other treatments. The least daily emission (0.14 mg N m^{-2} d^{-1}) was observed in the control. Figure 1 shows the temporal profile of emissions for the treatments.

Daily fluxes from 100:0 to 75:25 cowpea:maize treatments peaked on day 1 while emissions from the 25:75 and the 50:50 treatments peaked on days 2 and 3, respectively (Fig. 1). The rest of the treatments did not show any particular patterns of peaks and dips. By day 7, emissions from all the treatments had returned to background levels but even that decreased slightly by day 30.

Daily $^{15}N_2O$ emission

Total $^{15}N_2O$ emissions measured over 14 days ranged from 11.74 (sole maize treatment) to 189.60 (labelled cowpea treatment) μg ^{15}N m^{-2} d^{-1}. The labelled maize treatment recorded the second highest value of 127.82 μg ^{15}N m^{-2} d^{-1}. These were significantly higher than the unlabelled treatments. The maximum daily fluxes ranged from 2.78 (unlabelled maize treatment) to 107.30 (labelled cowpea treatment) μg ^{15}N m^{-2} d^{-1}. The least daily flux of 1.45 μg ^{15}N m^{-2} d^{-1} was measured from the labelled maize treatment. Figure 2 shows the temporal profile of the $^{15}N_2O$ emission. Apart from the sole maize treatment which had no characteristic feature, all other treatments peaked on day 1 and decreased sharply until day 7. By day 14, all treatments were close to zero emissions.

In the ^{15}N-labelled cowpea + unlabelled maize treatment, the contribution of the cowpea ^{15}N to the total $^{14+15}N_2O$ was 53% lower than when it was applied alone. In contrast, the contribution of the maize ^{15}N to $^{14+15}N_2O$ production was fivefold higher in the unlabelled cowpea + ^{15}N-labelled maize treatment than from the sole ^{15}N-maize treatment.

Carbon dioxide emission

The gross total CO_2 emission over the 30 days period was 88.19 g C m^{-2} 30 d^{-1}. The total values ranged from 5.4 (control) to 28.51 (75:25 cowpea:maize treatment) g C m^{-2} 30 d^{-1}. The highest maximum daily emissions were recorded from the 75:25 treatment (7.58) and 100:0 treatment (4.83) which were significantly different ($P < 0.05$) from the other treatments. However, the lowest emission (0 g C m^{-2} d^{-1}) was recorded from the 100:0 cowpea:maize treatment on day 0. The temporal profile of the CO_2 emissions is presented in Fig. 3. CO_2 emission was significantly higher ($P < 0.05$) in the 75:25 treatment from days 1 to 5, reaching a peak on day 2. The 50:50, 25:75 and 0:100 treatments peaked on day 1 while the 100:0 peaked on day 3. From day 7 to day 30, the emission from all treatments did not vary significantly.

Soil mineral nitrogen

Ammonium concentration

The daily values ranged from a minimum of 1.72 (0:100 treatment) to a maximum of 16.82 (100:0

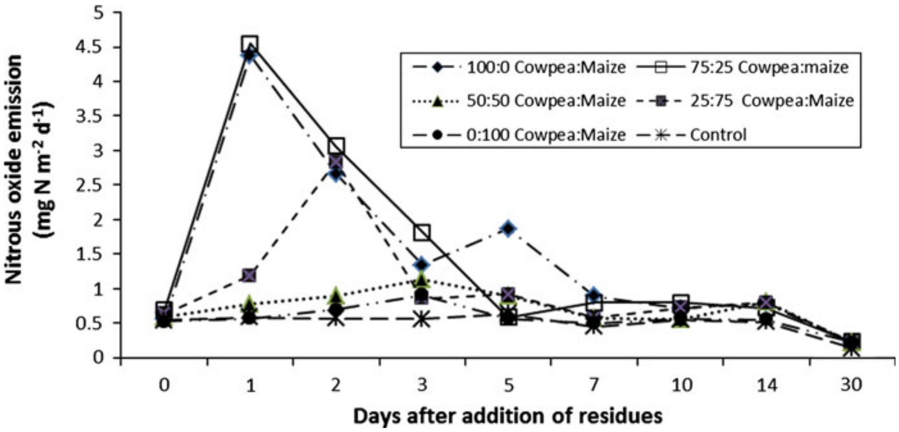


Fig. 1 Effect of cowpea-maize residues (unlabelled) on N_2O emissions in soil

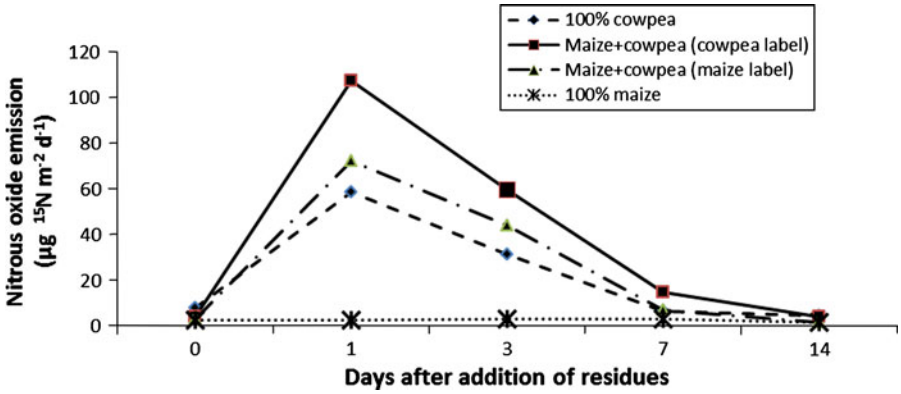


Fig. 2 Relative effect of cowpea-maize residue mixtures on N_2O emissions from soil

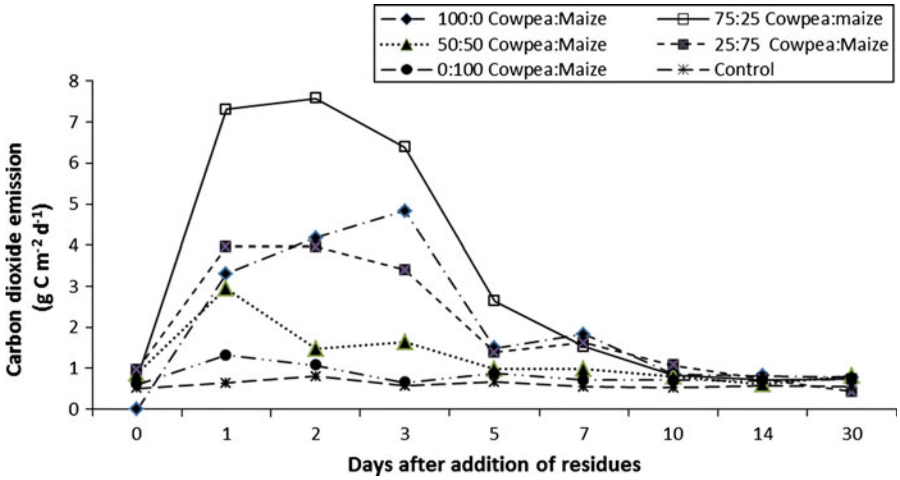


Fig. 3 Effect of addition of cowpea-maize residue mixes on CO_2 emission from soil

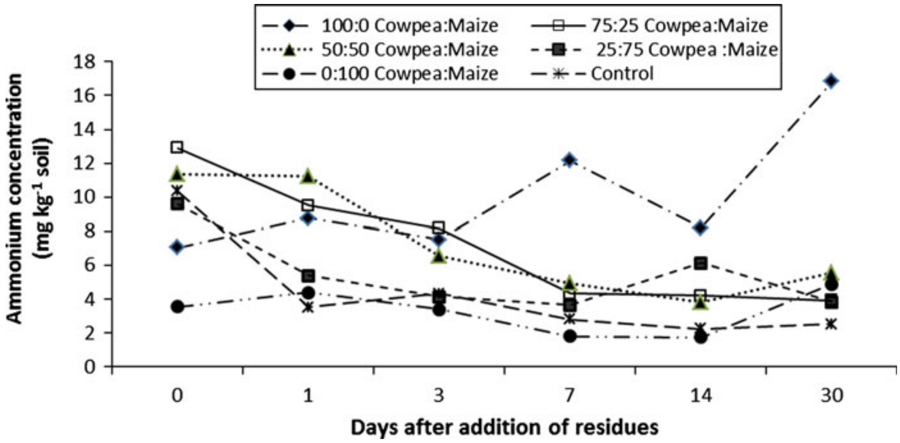


Fig. 4 Effect of addition of cowpea-maize residue mixtures on soil ammonium concentration

treatment) mg -N kg^{-1} soil (this maximum concentration was recorded on day 30). Apart from the 100:0 treatment, all the other treatments generally showed a decreasing pattern from day 0 to day 30 (Fig. 4). The 75:25 treatment had the highest initial NH_4^+ concentration. The 100:0 treatment differed significantly ($P < 0.05$) from the remaining treatments on days 7 and 30.

Nitrate concentration

The daily values ranged from 2.97 mg NO_3 kg^{-1} (for the 0:100 treatment) to 32.2 mg NO_3 kg^{-1} (for the 100:0 treatment). The concentrations of the 100:0 cowpea:maize treatment increased gradually from day 0 to day 30 while the 75:25 treatment reached a peak in day 3 (Fig. 5). The control had higher NO_3^- concentrations than the 0:100 treatment throughout the 30 days period except on day 7.

Mineral ^{15}N in soil

^{15}N Ammonium

The highest total $^{15}NH_4^+$ concentration (12.61 $^{15}NH_4^+$ kg^{-1} soil) was measured in the ^{15}N-labelled cowpea treatment, followed by the sole cowpea treatment (9.33 $^{15}NH_4^+$ kg^{-1} soil), with the sole maize treatment recording the least. The maximum daily values followed the same pattern. Figure 6 shows the temporal profile. With the exception of the ^{15}N-labelled maize treatment, all the other treatments reached their peak concentration in day 1. However, the maize labelled treatment showed a double peak, the lower in day 1 and the higher in day 7. All the treatments showed a significant decrease in $^{15}NH_4^+$ concentration in day 3; and only the ^{15}N-labelled cowpea treatment increased between day 14 and day 30.

^{15}N Nitrate

The highest total $^{15}NO_3$ (46.71 mg $^{15}NO_3$ kg^{-1}) was measured in the ^{15}N-labelled cowpea treatment and the lowest (2.13 mg $^{15}NO_3$ kg^{-1}) was measured in the sole maize treatment. The maximum daily concentrations exhibited a similar pattern in which the highest was recorded for the ^{15}N-labelled cowpea treatment (15.02 mg $^{15}NO_3$ kg^{-1}, measured on day 30) and the least was recorded for the sole maize treatment (0.98 mg $^{15}NO_3$ kg^{-1}). In Fig. 7, the cowpea labelled and the sole cowpea treatments had significantly higher NO_3 concentrations ($P > 0.05$) than the other treatments on day 1. However, on day 3, NO_3 concentration was significantly lower for all the treatments; and the same can be said for days 7 and 14 except that the ^{15}N-labelled cowpea treatment had significantly higher concentrations on these days and day 30. Apart from the cowpea labelled treatment, the rate of change in NO_3 concentrations for the other treatments was generally low. The sole maize treatment recorded the least NO_3 concentrations throughout the 30 days period.

Water extractable carbon

WEC concentrations decreased immediately after residue additions and consistently up to day 30 (Fig. 8). However, unlike the other treatments, the rate of decrease in the control was insignificant throughout the 30 days period. Nevertheless, the control had higher WEC concentration than the 100:0 cowpea:maize treatment between days 1 and 30. The WEC concentration was significantly higher for the 0:100 cowpea:maize treatment from day 0 to day 7. The highest WEC concentration of 251 mg C kg^{-1} soil was measured on day 0 in the 0:100 cowpea:maize treatment while the least concentration of 52 mg C kg^{-1} soil was measured in the 100:0 cowpea:maize treatment on day 30.

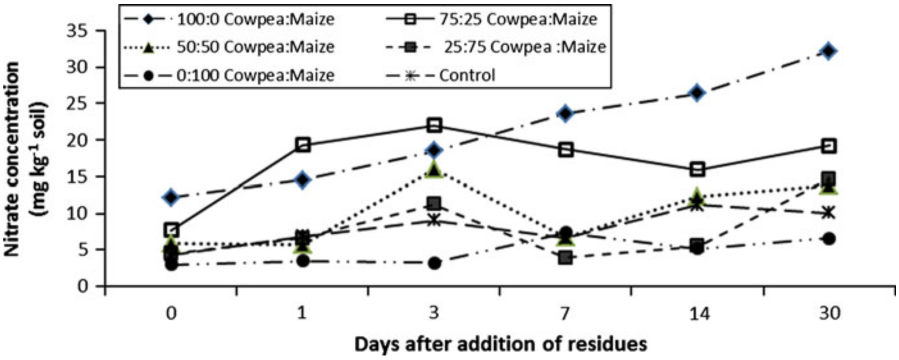


Fig. 5 Effect of addition of cowpea-maize residue mixtures on soil nitrate concentration

Fig. 6 Relative effect of cowpea-maize residue mixtures on labelled ammonium concentration in soil

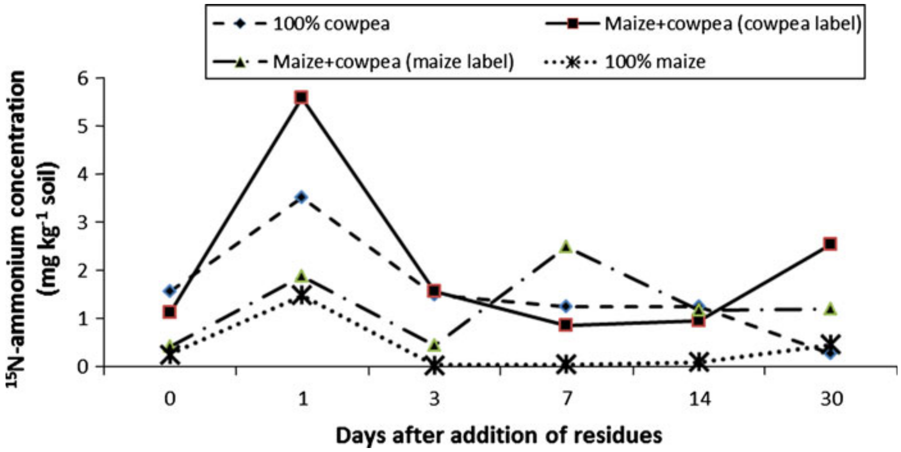


Fig. 7 Relative effect of cowpea-maize residue mixtures on labelled nitrate concentration in soil

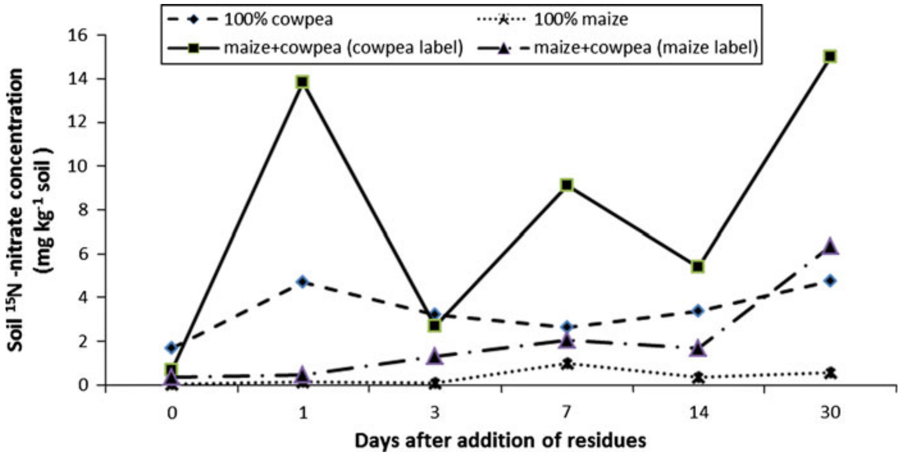
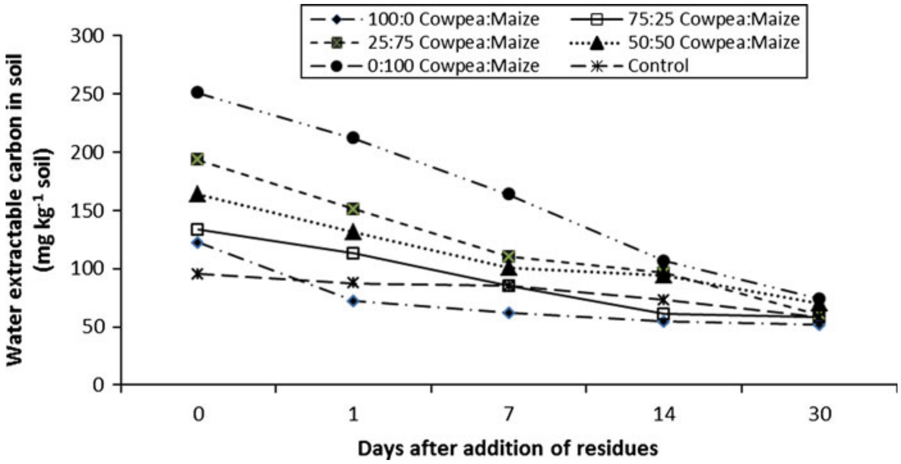


Fig. 8 Effect of cowpea-maize residue mixes on water extractable carbon content of soil



Discussion

Effects of residue quality on N_2O emission and mineral N release

Addition of the low C:N ratio cowpea residue resulted in a greater N_2O emission compared to the control, but N_2O emission from the sole maize amended treatment was not significantly different from the control (Fig. 1). N_2O emission generally decreased with increasing rate of maize residue in the mixture. It is likely that addition of cowpea residues created anaerobic microsites, stimulating microbial activity (Tiedje et al. 1984), which coupled with the provision of residue-N and -C, would have promoted N_2O generating processes such as denitrification or nitrate ammonification. Given that the soils were maintained at 60% WFPS, the enhanced N_2O emission observed can be attributed to residue N availability as residue N mineralization may have been favoured under the prevailing aerobic condition in the soil (Gentile et al. 2008; Kaewpradit et al. 2008; Khalil et al. 2002; Millar et al. 2004). This is in accordance with the findings of Abdalla, et al. (2010) that decreasing N availability from applied fertilizer and other sources significantly decrease N_2O emissions.

N_2O emission from soils amended with crop residue has often been reported to be influenced by initial N content, C:N ratio, lignin content, polyphenol content, and lignin:N ratio, polyphenol:N ratio or (lignin + polyphenol):N ratio (Constantinides and Fownes 1994; Garcia-Ruiz and Baggs 2007; Millar and Baggs 2004; Palm and Rowland 1997). In this experiment, however, the lignin and extractable polyphenol contents of the cowpea and maize residues were lower than the 15% lignin and 3–4% polyphenol threshold levels proposed in the Organic Resources Database (Palm et al. 2001) and by other authors (Constantinides and Fownes 1994; Palm et al. 2002; Palm and Rowland 1997) to retard residue N mineralization. Therefore, in this experiment, only the initial N contents and the C:N ratios of the residues were expected to affect N_2O emission and mineral N concentrations.

Net N mineralization occurred in the 100:0 cowpea treatment, but the 0:100 cowpea:maize treatment showed net N immobilization throughout the 30 days, leading to lower N_2O production (Velthof et al. 2002) irrespective of a large supply of organic C. The net N mineralization and net N immobilization observed in in the 100:0 and 0:100 cowpea:maize treatments, respectively confirmed the initial hypothesis that the addition of N-rich cowpea residues will promote rapid net mineralization while the addition of high C:N ratio maize residue will result in initial N immobilization (Azam et al. 1993; Bird et al. 2001; Vityakon et al. 2000). Previous authors (e.g. Frankenberger and Abdelmagid 1985; Myers et al. 1994) explained that immediate net mineralization generally occurs after incorporation of residues with C:N ratios below approximately 20–25. Here, the initial N concentration (3.4%) in the cowpea residue was higher than the threshold of 1.8–2.5% N suggested by Palm et al. (2001), but the initial N content of the maize residue (0.9%) was less than this threshold.

N_2O emissions were lower in the mixed cowpea and maize treatments than in the sole cowpea treatment, and were much lower in the treatments where maize residues in the mixture comprised 50% or more. This indicates an interactive effect of mixing maize residue with cowpea residues to decrease N_2O emission, which suggests that mixing maize residues with cowpea residues offers the potential as a management strategy for the lowering of N_2O emissions from cowpea-maize intercropping systems where residues are applied to soil after harvest.

Total mineral N concentrations (NH_4^+ and NO_3^-) over 30 days period in the 100:0 cowpea:maize treatment were significantly higher ($P < 0.05$) than in the other treatments and this decreased with increasing content of maize residue, suggesting that the addition of high C:N maize residue probably modified the total residue N input and C:N ratio of the cowpea:maize mixtures depending on the quantity of maize residue mixed with cowpea residue. However, in the labelled experiment, higher interactive effect was shown as the total NH_4^+ and NO_3^- concentration over the 30 days period were highest in the ^{15}N-labelled cowpea treatment. This, in combination with the observed N_2O emissions, seems to suggest that increasing the quantities of cowpea and maize residues incorporated on a 50:50 ratio is likely to minimize N_2O emission and increase mineral N release. This can presumably be due to a large supply of available C in the presence of a high N supply, a situation that might account for the observed gradual increase in mineral N.

Implications for using cowpea-maize residue mixtures for soil N management

Net N mineralization and N_2O emission decreased with increasing proportion of maize residue in the mixes, especially where maize residue constituted 50% or more of the mix, indicating that mixing cowpea and maize residue offered the potential to lower N_2O emission in cowpea-maize intercrop systems. Low NO_3^- concentration and net N immobilization in the 25:75 cowpea:maize treatment also suggest that NO_3 leaching and N loss as N_2O through denitrification can be minimized in this treatment, leading to potentially increased nitrogen availability and use efficiency (NUE). This observation indicates that there is a scope for manipulating N release from N-rich cowpea residue by the addition of a high amount of a high C:N maize residue. This will ensure a better synchrony between residue N release and crop uptake, resulting in an increase in the overall NUE and a decrease in N_2O emission from cowpea amended soils. However, this requires further investigation at field scale where NUE can be verified in the presence of a crop.

The peak N_2O flux on day 1 from the 100:0 cowpea:maize treatment was higher ($P < 0.05$) than that from the 75:25 cowpea:maize treatment. Although NO_3^- concentration was higher in the 100:0 treatments than in the 75:25 treatments on day 0, WEC on day 0 was higher in the latter, indicating that increased NO_3^- availability rather than available C concentration was likely to have been responsible for the difference between N_2O fluxes on day 1 from the 100:0 and the 72:25 cowpea:maize treatments. This agrees with Firestone and Davidson (1989) who stated that NO_3 concentration and low oxygen concentration, other than soluble C availability, were believed to be the most important condition for denitrification at the bacterial cell level. This observation further indicates that in addition to denitrification, other processes such as nitrate ammonification could have also contributed to the peak N_2O fluxes on day 1, but since source partitioning was not done in this experiment the contributions of different processes to N_2O fluxes could not be determined. After day 1, NO_3 concentration in the 100:0, 75:25 and 50:50 cowpea:maize treatments increased, whilst their NH_4^+ concentrations decreased, indicative of net N mineralisation.

In this study WEC decreased rapidly in all treatments, levelling off in all treatments by day 7. Low C availability is reported to hinder heterotrophic bacteria activity, and promote growth and functioning of autotrophic nitrifiers, which obtain their energy from NH_3 oxidation (Verhagen and Lambroek 1991). This experiment was conducted under non-leaching conditions, therefore under the WFPS maintained here (60% WFPS), NO_3 accumulation and NH_4 decline in the 100:0, 75:25 and 50:50 cowpea:maize treatments between days 1 and 30 were indicative of low denitrification, but high nitrification rates. Therefore, here N_2O emissions after day 1 were likely to have been driven mainly by nitrification rather than denitrification. Autotrophic nitrifiers have been shown to produce both N_2O and NO under oxic conditions as direct metabolic products of chemolithotrophic ammonia oxidising bacteria or from other soil processes dependent on these organisms as a source of nitrite (Tortoso and Hutchinson 1990).

Between days 0 and 7, WEC was higher in the 0:100, 25:75 cowpea:maize treatments than in the 100:0, 75:25 and 50:50 cowpea:maize treatments, suggesting that the extent of heterotrophic microbial activity during this period could have also varied between the treatments. The results showed that organic C was not limited in any of the treatments, but as a result of N immobilisation, N limitation in the 0:100 and 25:75 cowpea:maize treatments compared to the other treatments would have lowered NH_3 substrate availability for autotrophic nitrifier N_2O production through ammonia oxidation (Verhagen and Lambroek 1991). NH_4^+ immobilisation in the 0:100 and 25:75 cowpea:maize treatments could be explained by insufficient residue-N supply in the presence of a large supply of labile C. In the ^{15}N-labeled cowpea treatment, a positive correlation was found between $^{15}N_2O$ fluxes and $^{115}NH_4^+$ concentrations ($r = 0.99$, $P < 0.05$) over the first 7 days, confirming that ammonia oxidation contributed to N_2O emission from these treatment.

Overall, the findings indicate the potential of enhancing N mineralization (and consequently availability) and reduction in N_2O emission from cowpea residues used as a source of N in arable systems. However, while these findings are plausible, they were obtained under optimal, laboratory conditions and may therefore not reflect field conditions. As the study was conducted at constant soil moisture content and temperature, field studies could vary due to changing soil temperature and moisture content which influence microbial activity. It is therefore recommended that future studies (whether in the field or laboratory) consider assessing the effect of different soil moisture contents and temperature on nitrous oxide emissions and N mineralization in soils amended with different cowpea:maize mixtures. This will improve understanding and management of cowpea residues in agroecosystems.

Conclusions

This study was done to quantify the N_2O emissions and mineral N dynamics from different rates of cowpea:maize residue mixtures in a tropical luvsiol. The results suggest that N_2O emission and mineral dynamics are significantly affected by interactions between cowpea and maize residues. N_2O emission is lowered when the proportion of maize residues in the mixes is higher (50% or more). The experiment also indicated that nitrification contributed to N_2O production, especially after day 1. Consequently, in mixed cowpea and maize amended soils, residue quality (initial N content and C:N ratio) and proportional ratios of residues mixtures are important factors governing N availability for N_2O emission. The results further confirmed that the interactive effect of mixing maize and cowpea residues decreased soil mineral N availability and subsequent N_2O emission relative to sole addition of cowpea residues, suggesting an increased immobilisation of cowpea N with increasing proportion of high C:N maize residue in the mixes incorporated. It could therefore, be concluded that mixing high quality cowpea residue with high C:N maize residue, particularly with 50% or more of maize residue in the mixture, could be adopted as a soil fertility management strategy to minimize N loss as N_2O.

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