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## Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage

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**Key words:** combined residue and fertiliser application, conventional tillage, nitrous oxide, soil nitrogen, zero tillage

### Abstract

Emissions of N<sub>2</sub>O were measured following combined applications of inorganic N fertiliser and crop residues to a silt loam soil in S.E. England, UK. Effects of cultivation technique and residue application on N<sub>2</sub>O emissions were examined over 2 years. N<sub>2</sub>O emissions were increased in the presence of residues and were further increased where NH<sub>4</sub>NO<sub>3</sub> fertiliser (200 kg N ha<sup>-1</sup>) was applied. Large fluxes of N<sub>2</sub>O were measured from the zero till treatments after residue and fertiliser application, with 2.5 kg N<sub>2</sub>O-N ha<sup>-1</sup> measured over the first 23 days after application of fertiliser in combination with rye (*Secale cereale*) residues under zero tillage. CO<sub>2</sub> emissions were larger in the zero till than in the conventional till treatments. A significant tillage/residue interaction was found. Highest emissions were measured from the conventionally tilled bean (*Vicia faba*) (1.0 kg N<sub>2</sub>O-N ha<sup>-1</sup> emitted over 65 days) and zero tilled rye (3.5 kg N<sub>2</sub>O-N ha<sup>-1</sup> over 65 days) treatments. This was attributed to rapid release of N following incorporation of bean residues in the conventionally tilled treatments, and availability of readily degradable C from the rye in the presence of anaerobic conditions under the mulch in the zero tilled treatments. Measurement of <sup>15</sup>N-N<sub>2</sub>O emission following application of <sup>15</sup>N-labelled fertiliser to microplots indicated that surface mulching of residues in zero till treatments resulted in a greater proportion of fertiliser N being lost as N<sub>2</sub>O than with incorporation of residues. Combined applications of <sup>15</sup>N fertiliser and bean residues resulted in higher or lower emissions, depending on cultivation technique, when compared with the sum of N<sub>2</sub>O from single applications. Such interactions have important implications for mitigation of N<sub>2</sub>O from agricultural soils.

### Introduction

Emissions of N<sub>2</sub>O are of concern because of the role of this gas in the greenhouse effect (Houghton et al., 1990) and the destruction of the ozone layer (Crutzen, 1976). Direct and indirect emissions from agricultural systems are now thought to contribute 6.2 Tg N<sub>2</sub>O-N yr<sup>-1</sup> to a total global source strength of 17.7 Tg N<sub>2</sub>O-N yr<sup>-1</sup> (Kroeze et al., 1999). Mosier et al. (1998) estimated that global emissions of N<sub>2</sub>O could be reduced by 0.39 Tg N<sub>2</sub>O-N yr<sup>-1</sup> through improved fertiliser management and by a further 0.15 Tg N<sub>2</sub>O-

N yr<sup>-1</sup> through improved cultivation and irrigation practices.

Emissions from soil have previously been shown to increase after application of inorganic fertiliser or incorporation of crop residues (e.g. Baggs et al., 2000; Duxbury and McConnaughey, 1986; Kaiser et al., 1998; Mosier, 1994). The magnitude of emissions varies depending on type, form and timing of inorganic fertiliser application (Clayton et al., 1997; Mosier, 1994), residue composition or quality, the quantity of biomass incorporated (Aulakh et al., 1991; Baggs et al., 2000; Reinertsen et al., 1984), and also with soil temperature, water content, aeration, soil type and cultivation (Stott et al., 1986). To date, these effects have

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mostly been examined following single applications of either inorganic fertiliser or plant residues. The effect of combined organic/inorganic applications on  $N_2O$  emissions and N availability, and possible interactions between the two sources, have yet to be adequately examined. For instance, Azam et al. (1985) reported that combined applications of ammonium sulphate with *Sesbania aculeata* residues reduced total losses of fertiliser N by up to 30% by increasing microbial immobilisation, yet increased the contribution of *Sesbania* N to losses as a result of increased mineralisation of *Sesbania* N. Further work is therefore required to determine the effects of such combined applications of organic and inorganic N sources on  $N_2O$  emissions. Cultivation techniques, such as zero till and ploughing, directly determine the proximity of residues to fertiliser N and the relative spatial concentrations of N, and hence interactions between residue/fertiliser application and cultivation are likely to determine  $N_2O$  production.

$N_2O$  emissions following combined applications of inorganic N fertiliser and crop residues and the effect of residue type and cultivation technique on these emissions were examined in a field experiment lasting two years in S.E. England. The hypothesis underlying this study was that applying crop or cover crop residues in combination with inorganic fertiliser would increase emissions when compared with single applications. This would be due to the supply of C from the residues stimulating denitrification in the presence of inorganic soil N. Cultivation technique and residue quality were hypothesised to effect these emissions by determining accessibility to decomposing micro-organisms, and C and N availability. In the second year isotopically labelled fertiliser was applied and the contribution of the fertiliser to  $N_2O$  emissions was determined by measurement of  $^{15}N-N_2O$ .

### Materials and methods

A two-year field experiment was established in April 1999 on a silt loam soil (sand 17%, silt 68%, clay 15%, organic C 1.9%, pH 5.8, bulk density  $1.23 \text{ g cm}^{-3}$ ), of the Coombe series classified as a Cambisol (FAO classification), on the Imperial College at Wye Estate, UK. The site had previously been under cereal cultivation for 8 years.

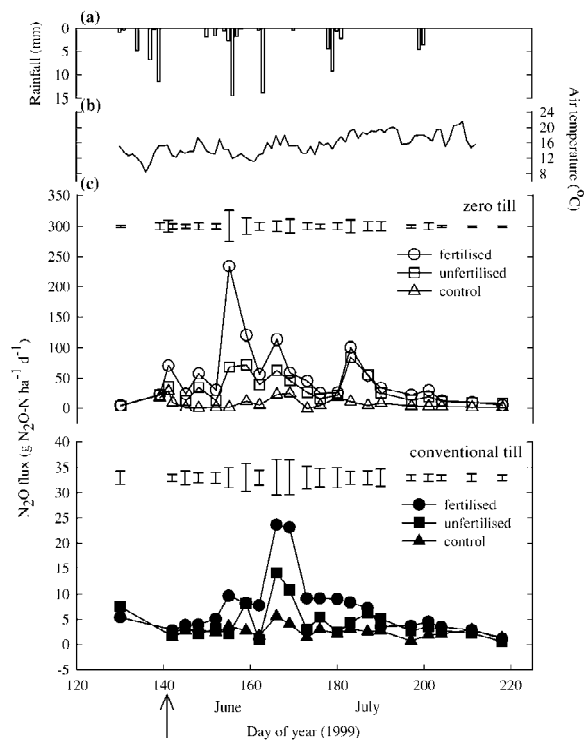


Figure 1. (a) Rainfall, (b) air temperature and (c)  $N_2O$  emissions following application of wheat residue and fertiliser to zero tilled and conventional tilled soil in 1999. Arrow indicates time of fertiliser application. Error bars represent  $\pm$  one s.e.d.

### 1999 season

The experiment was established in a split plot design consisting of four blocks divided into two main plots that were conventionally (CT) and zero tilled (ZT), and each of these was further divided into four subplots, to which  $NH_4NO_3$  was applied at two rates to two subplots each. This resulted in four treatments (Table 1), each replicated eight times. Plots were  $6 \times 15 \text{ m}$  in size. Four uncultivated control plots (two zero-tillage (ZTcontrol) and two conventional tillage (CTcontrol)) were established adjacent to each side of the main experimental blocks. These plots were established to enable 'background'  $N_2O$  emissions and soil N dynamics to be determined from unamended and uncropped soil.

All treatments, except controls, received  $6 \text{ t ha}^{-1}$  of wheat straw (*Triticum aestivum*) from the previous crop on 26 May 1999. This straw was incorporated to 25 cm depth in the CT treatments and surface mulched in the ZT treatments. Prior to application, the residue composition (or 'quality') was determined, as

Table 1. Experimental treatments established in 1999 and 2000

Year		Treatment	
1999	Zero till (ZT)	Wheat residue mulched	fertilised
			unfertilised
	Conventional till (CT)	Wheat residue incorporated	fertilised
			unfertilised
Zero till control	No residue	unfertilised	
Conventional till control	No residue	unfertilised	
2000	Zero till (ZT)	Rye residue mulched	fertilised
			unfertilised
		Bean residue mulched	fertilised
			unfertilised
	Conventional till (CT)	Rye residue incorporated	fertilised
			unfertilised
		Bean residue incorporated	fertilised
			unfertilised
Zero till control	No residue	unfertilised	
Conventional till control	No residue	unfertilised	

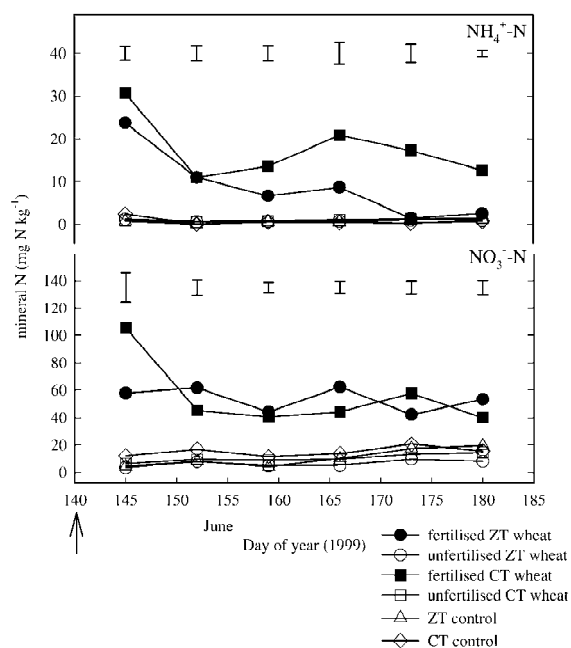


Figure 2. Available soil  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  following application of wheat residue and fertiliser to zero tilled and conventional tilled soil in 1999. Arrow indicates time of fertiliser application. Error bars represent  $\pm$  one s.e.d.

described below. All treatments, except controls, were sown to maize (*Zea mays*) on 27 May 1999 and subplots were broadcast fertilised with  $\text{NH}_4\text{NO}_3$  at rates

of 0 and  $200 \text{ kg N ha}^{-1}$  on 28 May 1999. The control plots had neither wheat straw nor fertiliser applied to them. Measurements of  $\text{N}_2\text{O}$  emissions, soil temperature, and determinations of available soil N were made prior to ('time-zero') and periodically following cultivation, as described below. Gas fluxes were measured daily in the first week after cultivation, and then less intensively for the following 10 weeks. The maize crop was harvested on 31 August 1999 and the above ground biomass was  $6.9$  and  $7.4 \text{ t dry matter ha}^{-1}$  in the unfertilised and fertilised zero till plots, respectively, and  $7.5$  and  $8.2 \text{ t dry matter ha}^{-1}$  in the unfertilised and fertilised conventional till plots, respectively. This above-ground biomass was removed from the field.

#### 2000 season

In October 1999, over wintering green manures of field bean (*Vicia faba*) or rye (*Secale cereale*) were sown on the same experiment. Treatments applied are shown in Table 1. The beans ( $5.3 \text{ t ha}^{-1}$  total above-ground biomass) or rye ( $3.9 \text{ t ha}^{-1}$  total above-ground biomass) were cut on 15 May 2000 and were incorporated in the CT treatments and surface mulched in the ZT treatments on 22 May, as in 1999. All plots, except controls, were sown to maize (*Zea mays*) on 23 May and broadcast fertilised with  $\text{NH}_4\text{NO}_3$  at rates of 0 and  $200 \text{ kg N ha}^{-1}$  on 28 May. Mi-

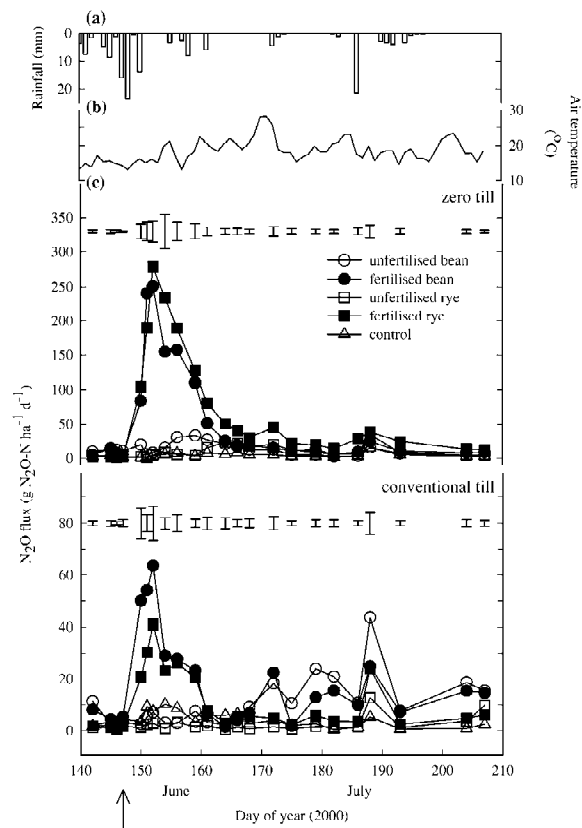


Figure 3. (a) Rainfall, (b) air temperature and (c)  $\text{N}_2\text{O}$  emissions following application of rye and bean residue and fertiliser to zero tilled and conventional tilled soil in 2000. Arrow indicates time of fertiliser application. Error bars represent  $\pm$  one s.e.d.

croplots,  $1 \times 0.75$  m, were established within each fertilised plot and fertilised with  $200 \text{ kg N ha}^{-1}$  as  $^{15}\text{NH}_4^{15}\text{NO}_3$  (1.4 atom%). Measurements of  $\text{N}_2\text{O}$  and  $\text{CO}_2$  emissions, soil temperature, and determinations of available soil N were made prior to ('time-zero') and periodically following cultivation, from both main plots and microplots, as described below. Gas fluxes were measured daily in the first week after cultivation, and then less intensively for the following 7 weeks.

#### Nitrous oxide and carbon dioxide fluxes

Gas samples for  $\text{N}_2\text{O}$  analysis were taken from closed flux chambers (0.2 m height by 0.3 m diameter), using gas-tight syringes, as described by Smith et al. (1995). Two chambers per subplot were inserted to a soil depth of 50 mm and remained *in situ* following cultivation of the experiment. Care was taken to minimise disruption to the soil, particularly to that inside of the chamber, during insertion. Chambers were closed one

hour before sampling. To minimise any effects of diurnal variation in  $\text{N}_2\text{O}$  emissions, as far as possible, samples were taken at the same time of day (10–12:00 GMT) on each occasion. Linearity of gas diffusion into the headspace over this closure period had previously been determined, so that each flux could be calculated from a single determination at the end of closure. Samples were analysed for  $\text{N}_2\text{O}$  in a Pye Unicam gas chromatograph fitted with an electron capture detector. Column and detector temperatures were 50 and 250 °C, respectively. Samples taken in year 2000 were also analysed for  $\text{CO}_2$  using an Infra Red Gas Analyser (ADC 225-MK3). Total emissions over specified periods of time were calculated by linear interpolation between daily fluxes.

$^{15}\text{N}$  enriched gas samples were stored in 125 mL gas tight glass bottles (Supelco, UK) and were analysed for  $^{15}\text{N-N}_2\text{O}$  using a Europa 20/20 isotope ratio mass spectrometer following condensing/cryofocusing of samples in an ANCA TGII (PDZ/Europa, Crewe, UK) gas module.

#### Soil and residue analysis

Five auger samples (0–0.25 m) from each treatment in each replicate were bulked. Subsamples (40 g) of the fresh soil were extracted with 1 M KCl in a 1:5 ratio of soil to extractant, and filtered through Whatman No. 1 filter paper. The concentrations of  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N in the extract were determined colorimetrically by continuous flow analysis on a Burkard SFA2 autoanalyser. Soil temperature at 5 and 10 cm depth were determined weekly using thermocouples inserted into the soil. Gravimetric water contents were determined for soil sampled from 0 to 0.25 m depth. Rainfall data and air temperature data were obtained from the meteorological station on the Imperial College at Wye Estate.

Residues were analysed for total C and N and lignin contents after grinding to <2 mm, according to the methods described by Handayanto et al. (1997). Total C and N were determined in a C/N analyser coupled to a Europa 20/20 isotope ratio mass spectrometer. Lignin was measured in an Ankom 220 fiber analyser. Results are shown in Table 2.

#### Statistical analysis

All data were analysed using the GENSTAT statistical package. Prior to analysis of variance between treatments, and t-tests between controls and treatments,

Table 2. Residue total N (%), total C (%), C:N and lignin (%) contents

	% N	% C	C:N	Lignin (%)
Winter wheat	0.6	41	68	9.0
Rye	1.1	45	41	4.4
Bean	3.4	42	12	5.1

data were tested for normality and log-transformed where appropriate (Parkin and Robinson, 1993).

## Results

### 1999 season

Total N<sub>2</sub>O emissions from the ZT treatments and ZT control were significantly higher ( $P < 0.01$ ) than emissions from corresponding CT treatments and CT control over 79 days after application of wheat residue (Table 3). Emissions from the main ZT treatments to which residue had been applied were significantly higher ( $P < 0.05$ ) than from the corresponding un-amended control. Application of fertiliser resulted in higher emissions ( $P < 0.05$ ) than where no fertiliser had been applied. The highest total emissions were measured from the ZT treatments with 4.0 and 2.5 kg N<sub>2</sub>O-N ha<sup>-1</sup> emitted from the fertilised ZT and unfertilised ZT wheat residue treatments, respectively, over 79 days. Up to 48% of this N<sub>2</sub>O was emitted during the first 3 weeks after residue application e.g. 1.6 kg N<sub>2</sub>O-N ha<sup>-1</sup> from the fertilised ZT treatment over 21 days.

Daily fluxes of N<sub>2</sub>O increased after application of residue in the ZT treatments, and further increased after fertilisation in both ZT and CT treatments (Figure 1). This increase in emissions was delayed in the fertilised CT treatment, compared with the fertilised ZT treatment e.g. maximum flux of 234 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> from the fertilised ZT treatment on day 155 (16 days after fertilisation), compared with 24 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> from the fertilised CT treatment on day 166. By 61 days after fertilisation emissions had returned close to 'background' levels as exemplified from the control plots. N<sub>2</sub>O emissions were significantly correlated with rainfall three days prior to emission and were more strongly correlated with emissions from unfertilised ( $r = 0.28 - 0.29$ ;  $P < 0.05$ ) than those from fertilised treatments ( $r = 0.11 - 0.21$ ;  $P < 0.05$ ).

Soil temperatures were up to 5 °C higher in the top 10 cm and more temporally variable in ZT than in CT treatments (data not shown) and gravimetric soil water contents were up to 15% higher in ZT than in CT treatments, and were more variable in the CT treatments (data not shown). There was no significant relationship between N<sub>2</sub>O emission and soil water content or soil temperature at either 5 or 10 cm depths.

There was no significant correlation between N<sub>2</sub>O emissions and available N throughout the experimental period. However, both available NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> were higher ( $P < 0.05$ ) in fertilised than in unfertilised treatments (Figure 2). Available NH<sub>4</sub><sup>+</sup> in the fertilised CT treatment was significantly higher than that in the fertilised ZT treatment from day 166 (27 days after fertilisation) until the end of the sampling period (day 180). Nitrification appeared to be more rapid in the CT fertilised treatment than in the ZT fertilised treatment. Concentrations of mineral N in unfertilised ZT and CT treatments were not significantly different from concentrations in the respective controls.

### 2000 season

Similar to 1999, total N<sub>2</sub>O emissions over the 65 day sampling period were significantly higher ( $P < 0.01$ ) from fertilised than from unfertilised treatments (Table 3). The highest total emissions were measured from the fertilised rye ZT treatment, with 3.5 kg N<sub>2</sub>O-N ha<sup>-1</sup> emitted over 65 days following fertiliser application. There was a significant interaction between tillage and residue application ( $P < 0.001$ ) i.e. emissions from the fertilised ZT rye treatment were significantly higher ( $P < 0.05$ ) than from the fertilised ZT bean treatment while emissions from the fertilised and unfertilised CT rye treatments were significantly lower ( $P < 0.05$ ) than from the corresponding fertilised and unfertilised CT bean treatments (Table 4). Between 71 and 81% of the total N<sub>2</sub>O emitted over 65 days was lost during the first 3 weeks following fertiliser application to the ZT treatments, and 51–59% was lost from the fertilised CT treatments during this time. Daily N<sub>2</sub>O fluxes were increased immediately following fertiliser application on 28 May (day 147), with fluxes of 250 and 279 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup> measured from the fertilised ZT bean and rye treatments, respectively, 5 days after fertilisation (Figure 3).

An estimated 937 kg CO<sub>2</sub>-C ha<sup>-1</sup> (or 240 kg CO<sub>2</sub>-C t biomass<sup>-1</sup> ha<sup>-1</sup> when taking into account the

Table 3. Total N<sub>2</sub>O emissions (g N<sub>2</sub>O-N ha<sup>-1</sup>) over the first 21 days and 79 days after fertiliser application in 1999 and over the first 23 and 65 days after fertiliser application in 2000. Values in parentheses represent ± one standard error of the mean. Different superscript letters within a column in each year represent significant difference at *P* < 0.05 determined by analysis of variance (treatments) and *t*-test (controls versus treatments)

Year	Treatment	Total emission (g N <sub>2</sub> O-N ha <sup>-1</sup> )	
		21 days	79 days
1999	fertilised ZT wheat residue	1632 (± 489) <sup>a</sup>	4025 (± 680) <sup>a</sup>
	unfertilised ZT wheat residue	708 (± 223) <sup>b</sup>	2460 (± 450) <sup>b</sup>
	fertilised CT wheat residue	109 (± 33) <sup>c</sup>	560 (± 157) <sup>c</sup>
	unfertilised CT wheat residue	64 (± 35) <sup>c</sup>	328 (± 113) <sup>c</sup>
	ZT control	134 (± 68) <sup>c</sup>	569 (± 86) <sup>c</sup>
	CT control	53 (± 16) <sup>c</sup>	199 (± 81) <sup>d</sup>
	s.e.d	144	261
2000		23 days	65 days
	fertilised ZT rye residue	2465 (± 284) <sup>a</sup>	3542 (± 493) <sup>a</sup>
	fertilised ZT bean residue	2058 (± 318) <sup>a</sup>	2581 (± 399) <sup>b</sup>
	unfertilised ZT rye residue	156 (± 9) <sup>b</sup>	675 (± 128) <sup>c</sup>
	unfertilised ZT bean residue	113 (± 17) <sup>c</sup>	790 (± 118) <sup>c</sup>
	fertilised CT rye residue	348 (± 42) <sup>d</sup>	590 (± 60) <sup>c</sup>
	fertilised CT bean residue	527 (± 97) <sup>e</sup>	1034 (± 107) <sup>b</sup>
	unfertilised CT rye residue	39 (± 9) <sup>f</sup>	158 (± 18) <sup>d</sup>
	unfertilised CT bean residue	469 (± 62) <sup>e</sup>	790 (± 142) <sup>c</sup>
	ZT control	104 (± 4) <sup>c</sup>	312 (± 9) <sup>d</sup>
	CT control	131 (± 52) <sup>c</sup>	226 (± 78) <sup>d</sup>
s.e.d	89	155	

Table 4. Difference in emission between treatments in 2000 indicating interactions between tillage and residue application

	Difference in emission over 65 days (g N <sub>2</sub> O-N ha <sup>-1</sup> )	
	ZT	CT
fertilised rye minus fertilised bean	961	-444
unfertilised rye minus unfertilised bean	-115	-632

quantity of biomass applied) was emitted from the fertilised ZT rye treatment over 47 days (Table 5). Emissions were significantly lower from the unfertilised CT rye treatment than from all other CT and ZT treatments and control (*P* < 0.05) over the first 47 days after fertilisation. Application of N fertiliser increased (*P* < 0.05) CO<sub>2</sub> emissions from the CT rye treatments but not from the bean or any of the ZT

treatments. Up to 56% of the total CO<sub>2</sub> emitted over 47 days was lost during the first 3 weeks.

Similar to 1999, there was no significant relationship between N<sub>2</sub>O emissions and available soil N (Figure 4). There was no significant relationship between N<sub>2</sub>O and CO<sub>2</sub> emissions with soil temperature (data not shown), either at 5 or 10 cm depth. Soil temperatures were up to 4 °C higher at 5 than at 10 cm depth, but cultivation technique had no significant effect on temperature at either depth in 2000.

The contribution of fertiliser N to N<sub>2</sub>O fluxes as measured by the <sup>15</sup>N method decreased throughout the experimental period (Figure 5). Two days after fertiliser application, the percentage of N<sub>2</sub>O emissions derived from fertiliser N ranged from 91 to 93% in ZT and 66 to 75% in CT treatments. There was no significant effect of tillage or residue type on this day. On days 172 and 186 (25 and 39 days after fertilisation, respectively) emissions from the ZT fertilised rye

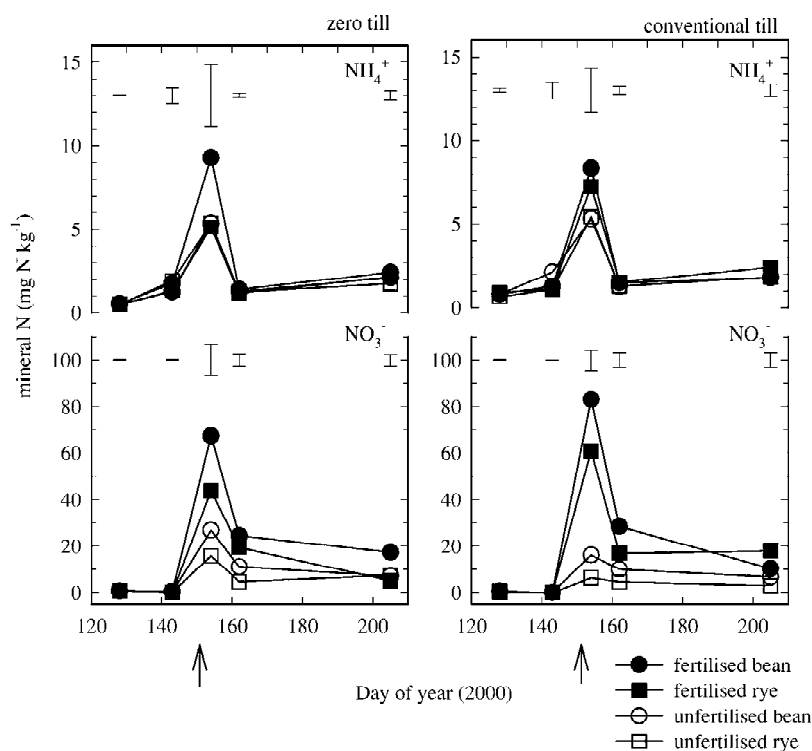


Figure 4. Available soil  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  following application of rye and bean residue and fertiliser to zero tilled and conventional tilled soil in 2000. Arrows indicate time of fertiliser application. Error bars represent  $\pm$  one s.e.d.

Table 5. Estimated total  $\text{CO}_2$  emissions ( $\text{kg CO}_2\text{-C ha}^{-1}$ ) after the first 23 and 47 days after fertiliser application in 2000. Values in parentheses represent  $\pm$  one standard error of the mean. Different superscript letters within a column represent significant difference at  $P < 0.05$  determined by analysis of variance (treatments) and  $t$ -test (controls versus treatments)

Treatment	Total emission ( $\text{kg CO}_2\text{-C ha}^{-1}$ )	
	23 days	47 days
fertilised ZT rye residue	371 ( $\pm 25$ ) <sup>a</sup>	937 ( $\pm 144$ ) <sup>a</sup>
fertilised ZT bean residue	468 ( $\pm 39$ ) <sup>b</sup>	848 ( $\pm 50$ ) <sup>a</sup>
unfertilised ZT rye residue	356 ( $\pm 37$ ) <sup>a</sup>	813 ( $\pm 39$ ) <sup>a</sup>
unfertilised ZT bean residue	480 ( $\pm 65$ ) <sup>b</sup>	901 ( $\pm 49$ ) <sup>a</sup>
fertilised CT rye residue	306 ( $\pm 106$ ) <sup>a</sup>	648 ( $\pm 207$ ) <sup>b</sup>
fertilised CT bean residue	314 ( $\pm 41$ ) <sup>a</sup>	560 ( $\pm 95$ ) <sup>b</sup>
unfertilised CT rye residue	132 ( $\pm 12$ ) <sup>c</sup>	277 ( $\pm 40$ ) <sup>c</sup>
unfertilised CT bean residue	321 ( $\pm 42$ ) <sup>a</sup>	901 ( $\pm 49$ ) <sup>a</sup>
ZT control	204 ( $\pm 46$ ) <sup>d</sup>	490 ( $\pm 15$ ) <sup>b</sup>
CT control	194 ( $\pm 41$ ) <sup>d</sup>	367 ( $\pm 58$ ) <sup>b</sup>
s.e.d.	45	73

treatment consisted of a significantly higher proportion of N derived from  $^{15}\text{N}$ -labelled fertiliser than all other treatments ( $P < 0.05$ ).

## Discussion

### Effect of cultivation technique

The method of cultivation affected the magnitude and pattern of  $\text{N}_2\text{O}$  emissions, presumably by varying the supply of organic C and N to micro-organisms, and by changing the soil water/aeration status around the residues (Aulakh et al., 1991). In both years ZT of cereal residues resulted in higher total  $\text{N}_2\text{O}$  emissions than CT. Such increases in emissions following reduced or zero tillage are well documented (e.g. Aulakh et al., 1984; Bouwman, 1996; Baggs et al., 2000; Linn and Doran, 1984).

Emissions of  $\text{CO}_2$ , indicative of heterotrophic microbial activity and particularly mineralisation, were higher in ZT than in CT treatments. This confirms results of other studies in which higher rates of microbial activity were found in the surface layers of ZT than



in ploughed soils (Broder et al., 1984; Doran, 1980a, b; Linn and Doran, 1984). This is despite the fact that cultivation of soil is known to increase organic matter mineralisation (Smith and Sharpley, 1990; Varco et al., 1989).  $\text{CO}_2$  emissions were positively correlated with  $\text{N}_2\text{O}$  emissions from all treatments except fertilised ZT rye and fertilised CT bean treatments. Maximum  $\text{N}_2\text{O}$  fluxes from both unfertilised rye and bean ZT treatments occurred before the peak emissions from corresponding CT treatments, confirming that mineralisation was more rapid in the ZT treatments. Surface mulching of residues also created conditions conducive to denitrification under the residues by increasing the soil water content, supplying available C, indicated by high measured microbial activity, and most likely creating anaerobic microsites.

The percentage of  $\text{N}_2\text{O}$ -N derived from the  $^{15}\text{N}$ -labelled fertiliser was higher from ZT than from CT treatments, indicating that surface mulching of residues resulted in a greater proportion of fertiliser N being lost as  $\text{N}_2\text{O}$  than with incorporation of residues. This confirms the higher  $\text{N}_2\text{O}$  emissions measured from the ZT than from the CT treatments.

#### Effect of residues

Greater  $\text{N}_2\text{O}$  emissions were measured in the presence of residues than from the bare soil controls, except in the unfertilised CT rye treatment. In the 2000 season residue type and quantity of biomass applied had a significant effect on these emissions, with higher emissions measured following incorporation of low C:N ratio (12) bean residues than following incorporation of high C:N ratio (36) rye residues in the unfertilised CT and ZT treatments. Such an effect of residue application on  $\text{N}_2\text{O}$  emissions is in close accordance with previously reported results (Baggs et al., 2000; Kaiser et al., 1998), and was attributed to more rapid release of N from the N-rich bean resulting in availability of N for nitrification and denitrification. This was compounded by the fact that the quantity of bean residue biomass applied ( $5.3 \text{ t ha}^{-1}$ ) was greater than that of rye residue ( $3.9 \text{ t ha}^{-1}$ ), so that bean treatments received four times as much organic N as the rye treatments. More rapid decomposition in the unfertilised bean than in the unfertilised rye treatments was evidenced by significantly higher  $\text{CO}_2$  emissions from the unfertilised bean treatment in the case of CT; this was even the case on a per biomass basis.

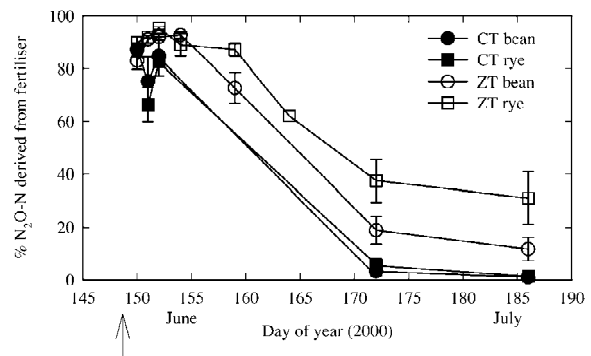


Figure 5. Percentage of  $\text{N}_2\text{O}$ -N derived from fertiliser in 2000. Arrow indicates time of fertiliser application.

#### Interaction between residue type and cultivation technique

There was a strong interaction between cultivation technique and residue type in the 2000 season (Table 4).  $\text{N}_2\text{O}$  emissions from the fertilised and unfertilised CT bean treatments were higher than emissions from corresponding CT rye treatments, whereas emissions from the fertilised ZT rye treatment were higher than from the fertilised ZT bean treatment. When taking account of the quantity of biomass applied emissions over both time periods from the unfertilised ZT rye were higher than from the corresponding bean treatment. Incorporation of the low C:N bean residue in the CT treatments resulted in rapid decomposition, as evidenced by the increased  $\text{CO}_2$  emissions, and N release, resulting in higher  $\text{N}_2\text{O}$  emissions than following incorporation of rye residues. It is possible that the high  $\text{N}_2\text{O}$  emissions from the ZT rye treatments resulted from the release of unprotected degradable C compounds from the rye for denitrification in anaerobic microsites under the mulch (Doran, 1980a, b).

#### Combined application of residues and fertiliser N

In both years,  $\text{N}_2\text{O}$  emissions were increased in the presence of residues, except in the CT rye treatment, and were further increased where fertiliser N was applied. However, the degree of the response of  $\text{N}_2\text{O}$  emission from addition of fertiliser to the residues depended on their type. Combined applications of fertiliser and residue either had no interactive effect on  $\text{N}_2\text{O}$  emissions, or a slight positive or negative effect depending on the residue type and cultivation technique. Application of  $^{15}\text{N}$ -labelled fertiliser to mi-

croplots in 2000 enabled the contribution of fertiliser N to N<sub>2</sub>O emissions to be determined over 23 days. The total emission measured over 23 days from the ZT bean treatment was slightly higher than the sum of that emitted from the unfertilised ZT bean and the <sup>15</sup>N-N<sub>2</sub>O from this treatment (1.8 kg N<sub>2</sub>O-N ha<sup>-1</sup>) and thus application of fertiliser had a positive additive effect on N<sub>2</sub>O emissions. In contrast, total emissions over 23 days measured from the fertilised CT bean treatment were lower than the sum of the two components (0.8 kg N<sub>2</sub>O-N ha<sup>-1</sup>). Emissions measured from the fertilised CT and ZT rye treatments were not significantly different from the sum following single applications and thus fertiliser addition had no additive effect on emissions from these treatments. Our results show that unexpected interactions may occur between residue type and fertiliser when applied together.

## Conclusions

Emissions of N<sub>2</sub>O were two to seven times higher from fertilised ZT treatments than from fertilised CT treatments. This was possibly a result of creation of anaerobic conditions under the mulch with localised concentrations of mineralised C and inorganic fertiliser NO<sub>3</sub><sup>-</sup> conducive to denitrification. Analysis of <sup>15</sup>N-N<sub>2</sub>O confirmed that higher emissions from ZT treatments were, in part, explained by the stimulation of greater losses of applied fertiliser N. There was a significant interaction between residue type and cultivation technique with higher emissions measured from ZT rye treatments than from ZT bean treatments, but higher emissions from CT bean treatments than from corresponding CT rye treatments. <sup>15</sup>N-N<sub>2</sub>O emissions indicated that combined additions of bean residues and fertiliser had an additive effect on N<sub>2</sub>O emissions, which were positive under ZT and negative under CT. Further investigations will verify the mechanisms involved in these interactions, so that residue application under different cultivation systems and combined applications of plant residues and inorganic fertilisers in such systems can reliably be used to mitigate N<sub>2</sub>O emissions from agricultural soils.

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