

Research and Development

Final Project Report

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Project title	The effect of cultivation and residue incorporation on N ₂ O emissions from arable soils		
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Executive summary (maximum 2 sides A4)

Nitrous oxide (N₂O), although emitted in much smaller quantities than either methane (CH₄) or carbon dioxide (CO₂), is important because its global warming potential is 200 times that of CO₂ and 8 times that of CH₄. It has been estimated that agriculture was responsible for nearly half of UK N₂O emissions in 1990, with the proportion rising due to reduced emissions from industrial processes.

Estimated emissions from crop residues in 1990 using the IPCC method were 9.6 Gg out of a total of 87 Gg N₂O-N per year.

The aim of this project was to measure emissions of the greenhouse gas nitrous oxide (N₂O) from arable crop residues from harvest in the autumn through to the following spring.

Experiments were carried out at two sites in eastern England, with contrasting soil textures: Hall Farm, Stetchworth, near Newmarket (sandy loam) and ADAS Boxworth (clay loam). Crops were barley, peas and sugar beet on the sandy loam soil, and wheat and oilseed rape on the clay loam. Cultivation was carried out by rotavator or heavy discs (to 10 cm) and plough (to 25 cm) and took place in August, October or January, as appropriate for the soil/crop combination.

Analysis of variance (ANOVA) of the results of the experiments involving barley and pea residues incorporated in August and October at Hall Farm showed no significant effect ($P > 0.05$) of any treatment in the first year, despite the fact that emissions from residues generally followed the order no residue < barley < peas, and those for cultivation treatments were rotovate < plough. However, in the second year, statistically significant ($P < 0.05$) effects of crop residue and cultivation treatment were determined. Average emissions (g N₂O-N ha⁻¹) were: no residue (180) < barley (310) < peas (405); and, rotovate (248) < plough (349) – i.e. in the same order as observed in the first year.

Statistically significant results were obtained in both years of the experiments involving sugarbeet residues incorporated in October and January. In the first year, there was a statistically significant interaction ($P < 0.05$) between date of

incorporation and crop residue; thus, emissions following incorporation of sugarbeet residues in October (1904 g N₂O-N ha⁻¹) were very much greater than those from the no residue treatment (666 g N₂O-N ha⁻¹), whereas following incorporation in January emissions were similar (917 and 938 g N₂O-N ha⁻¹, respectively). The same pattern of emissions was observed in the second year (albeit with lower values), but interpretation of the ANOVA results was complicated because a significant ($P < 0.05$) 3-way interaction between date of incorporation, crop residue and cultivation treatments was determined. This arose because ploughing appeared to exacerbate the 2-way interaction between crop residue and incorporation date to a greater extent than rotovating. Thus, whereas emissions for the no residue and sugarbeet treatments incorporated in October were 271 and 498 g N₂O-N ha⁻¹, respectively, following rotovating, they were 265 and 927 g N₂O-N ha⁻¹, respectively, following ploughing. In fact, the same trends were seen in the first year data, but the variability was such that this was determined as not statistically significant.

Analysis of variance (ANOVA) of the results from the ADAS Boxworth experiments showed no significant differences ($P > 0.05$) between treatments for the first year, although, on average total N₂O emissions from ploughed plots were less than those from disced plots. In the second experiment, a significant ($P < 0.05$) effect of incorporation method was determined; the effect of residue type was not significant ($P > 0.05$), although average emissions from oilseed rape were greater than those from winter wheat in both years.

The 5 crop residues investigated significantly ($P < 0.01$) influenced mean N₂O emissions. Sugarbeet residues had the narrowest C:N ratios (15-17) and the greatest N₂O emissions. Other residues had C:N ratios in the range 28 to 70; N₂O emissions decreased with increasing C:N. It was noticeable that despite a relatively constant C:N of the sugarbeet residues used in this project, there was a large variation in N₂O emission. This was the result of an interaction effect of date of incorporation on emissions from sugarbeet, where incorporation in October resulted in much higher N₂O fluxes than incorporation in February.

Average emission factors (i.e. the proportion of N incorporated subsequently lost as N₂O-N) for each crop residue were confounded by site, since different crops were grown and incorporated on different soil types. In addition, emission factors differed markedly between years for each crop/site combination. Taking the results for 1999-2000 as a baseline, since all crops residues were monitored in this year and the weather at the two sites was similar – the two sites being relatively close to each other – average emission factors increased in the order: sugarbeet > wheat < oilseed rape < barley < peas. However, this sequence was primarily determined by differences in crop residue N applied rather than N₂O emission, since average emissions for the crop residues were similar, whereas average N applications in crop residues were 140, 98, 100, 51 and 56 kg ha⁻¹ for sugarbeet, wheat, oilseed rape, barley and peas, respectively. The results indicated a large year-to-year variation, with the largest emission factors measured in 1998-9 and the smallest in 2000-1.

Nitrous oxide emission factors for all crop residues investigated in this study are lower than the default IPCC value (1.25 %). Except for sugarbeet, the range in total emissions was limited (< 1 kg N₂O-N ha⁻¹). Given the generally limited range in measured N₂O emissions, variation in calculated emission factors was mainly the result of variations in crop N residue content. More accurate estimates of UK emissions of N₂O can be obtained by improving the calculation of crop N residue content. Combining emissions determined in this study and data for the N content of UK crops results in an estimation of N₂O emissions from crop residues *ca.* 40 % of that determined by the default IPCC methodology.

Highest N₂O emissions were measured from plots where no crop had been grown. The absence of a plant sink for soil inorganic N appears to increase N₂O emissions. For sugarbeet, there was a statistically significant ($P < 0.05$) interaction with timing of incorporation on N₂O emission, with greater emissions occurring following incorporation in October. Thus, it may be possible to mitigate emissions from this crop by encouraging later harvest. There was no significant effect of cultivation method on the sandy loam soil, but emissions were significantly ($P < 0.05$) lower when crop residues were incorporated by ploughing compared to heavy discs. Thus, it may be possible to mitigate emissions on heavy-textured soils by incorporating residues by ploughing. Further work is required to determine whether the effect of cultivation arises because of its influence on nitrification or on the gaseous diffusion of the products of denitrification.

The effect of soil type on N₂O emission requires further investigation. In particular, good hydrological models are required to adequately describe soil aeration in the topsoil following rainfall in soils of different textures.

Scientific report (maximum 20 sides A4)

1. INTRODUCTION

Nitrous oxide (N₂O), although emitted in much smaller quantities than either methane (CH₄) or carbon dioxide (CO₂), is important because its global warming potential is 200 times that of CO₂ and 8 times that of CH₄. It has been estimated that agriculture was responsible for nearly half of UK N₂O emissions in 1990, with the proportion rising due to reduced emissions from industrial processes.

Estimated emissions from crop residues in 1990 using the IPCC method [1] were 9.6 Gg out of a total of 87 Gg N₂O-N per year, somewhat less than the contributions from grazing (19.0 Gg) and fertiliser (15.8 Gg) and slightly ahead of that from the application of animal manures (7.9 Gg). The emission from crop residues is calculated by applying an emission factor (1.25 %) to the crop residue N returned to the soil using estimates of harvested area and crop yield and assumed values for the N content and the proportion of the crop removed from the field [7]. Whilst crop areas and yields are known with reasonably accuracy, the calculation of the quantity of N returned to the soil is rather coarse and better estimates can be made using UK data for crop N balances [11]. This calculation results in a much lower estimate for all crops except oilseed rape (and set-aside) and consequentially the calculated N₂O emission is reduced by 30-40 %. Furthermore, in establishing the default IPCC methodology for calculating emissions from crop residue N, it was recognised that the amount converted to N₂O was not known and the emission factor for fertiliser N was proposed [7].

Table 1. Comparison of selected crop N residues using IPCC method and UK data.

Crop	Area	Yield	Residue N (IPCC)	Residue N (ADAS)
	<i>000 ha</i>	<i>t DM ha⁻¹</i>	<i>Gg N</i>	<i>Gg N</i>
Wheat	2,013	5.92	197	80.5
Barley	1,516	4.43	111	60.6
Rye	8	4.15	1	0.3
Oats	107	4.22	7	3.7
Triticale	9	4.80	1	0.3
Oilseed rape	390	2.91	19	56.6
Linseed	34	1.87	1	0.7
Sugarbeet	194	9.37	30	25.2
Potatoes	177	7.30	21	17.7
Pulses	220	3.12	23	15.4

2. SCIENTIFIC OBJECTIVES

The objectives of this study, as set out in the MAFF (now DEFRA) CSG7 form, were as follows.

- To determine N₂O emissions following incorporation of: (a) cereal, sugarbeet and pea residues from light-textured soils; and (b) cereal and oilseed rape residues on heavy-textured soils.
- To contrast emissions following shallow incorporation and incorporation by ploughing.
- To contrast emissions from residues incorporated in August, October and February.
- To evaluate the effect of environmental and other (e.g. metalisable carbon) variables on N₂O emissions.
- To estimate N₂O emissions from crop residues in the UK using data obtained in this experiment and from other published statistics.

3. EXTENT TO WHICH THE OBJECTIVES WERE MET

All the objectives as set out in the CSG7 form were met. However, it must be recognised that given the well-documented temporal variation in N₂O emissions, conclusions based on only 2 site-years data for each site should be treated with due caution.

4. MATERIALS AND METHODS

The experiments on the light-textured soil (Moulton series – sandy loam over loamy sand and chalk rubble) were at Hall Farm, Stetchworth, near Newmarket and those on the heavy-textured soil (Hanslope series – clay over chalky boulder clay) were at ADAS Boxworth, near Cambridge; thus, the two sites were relatively close to each other.

4.1 Trial layout

In the first and second years of the project (1998-9 and 1999-2000), the effect on N₂O emissions of crop residue type, method of incorporation and date of incorporation was investigated on two separate experiments on a light-textured (sandy loam) soil. The treatment combinations were: (a) cereal (barley) and pea residues - incorporated in August or October by plough to 25 cm or by rotovator to 10 cm; (b) sugarbeet residues - incorporated in October or January by plough or rotovator; and (c) additional no residue (fallow) plots with cultivation in August, October or January by plough or rotovator. The trials were laid out in a split-split plot design (3 replicate blocks) with incorporation date on main plots, residue type on split plots and method of cultivation on split-split plots. However, because of the differing incorporation dates appropriate for each of the residues, statistical considerations required that trial was laid out as two interlocking experiments (barley and peas in one and sugarbeet in the other) with the no residue treatments for the October incorporation date represented in both. Each of the 60 split-split plots was 4 m wide by 12 m long.

In the second and third years of the project (1999-2000 and 2000-2001), the effect of crop residue type and method of incorporation was investigated on two separate experiments on a heavy-textured (clay) soil. Treatments were wheat and oilseed rape residues incorporated in August by plough or heavy discs, with additional fallow plots as before. The trials were laid out in a split plot design (3 replicate blocks) with residue type on main plots and method of cultivation on split plots. Each of the 18 split plots was 6 m wide by 12 m long.

4.2 Crop husbandry and management

At the Hall Farm sites, spring barley (*cv.* Optic in 1998-9, *cv.* Alexis in 1999-2000), pea (*cv.* Eiffel) and sugarbeet crops were grown and managed as commercial crops using farm equipment and appropriate regimes with respect to crop protection. Nitrogen applications were 150 and 120 kg ha⁻¹ to barley and sugarbeet, respectively, with 40 kg ha⁻¹ being applied in late March – early April and the balance in mid-May. Weeds were controlled on the fallow plots using herbicides or by manual hoeing, as appropriate.

At the ADAS Boxworth sites, winter wheat (*cv.* Apex) and winter oilseed rape (*cv.* Madrigal) were also grown and managed as commercial crops. Nitrogen applications were 180 kg ha⁻¹ to both crops, with 100 and 160 kg ha⁻¹ being applied in mid-March to wheat and oilseed rape, respectively, with the balance in early April. Weeds were controlled on the fallow plots as before.

4.3 Crop residue incorporation

At the Hall Farm sites, spring barley and pea crops were harvested from all the split plots in each year on the same date (29 August 1998 and 16 August 1999) using a plot combine harvester. Immediately prior to harvest, the yield of cereal straw and chaff and pea haulm were determined from 1 m² quadrats (2 per split plot). Nitrogen content was determined on sub-samples of this hand-harvested material by a modified Kjeldahl method [14]. For each plot after harvest, the straw or pea haulm was chopped and spread (together with the chaff for the barley plots) back onto the plot. Sugarbeet was harvested on two separate dates in each year (19 October 1998 and 7 January 1999 in the first year, and 18 October 1999 and 19 January 2000 in the second year). Sugarbeet tops were flailed off using a tractor-mounted topping flail; the roots were then lifted by hand, the crowns trimmed and the main roots removed from the plots. Immediately prior to harvest, 3 representative samples were taken per split plot to determine total fresh and dry weights and nitrogen content of 2 adjacent rows (0.48 m wide and 1.0 m long). The leaves and root crowns were cut at a similar height to that achieved by the tractor-mounted topping flail. As there was considerable variability in the growth of sugarbeet in the trial, additional sugarbeet residues were added to some plots, using material from a recently harvested crop in a nearby field. The amounts required were calculated from the results of the fresh weight of residue for each split plot as measured by two 1 m² quadrats.

At the ADAS Boxworth sites, winter wheat and winter oilseed rape crops were harvested from all the main plots in each year on the same date (3 August 1999 and 7 August 2000) using a plot combine harvester. Immediately prior to harvest, the yield of cereal straw and chaff and oilseed rape residue were determined from 1 m² quadrats (3 per split plot). Nitrogen content was determined on sub-samples of this hand-harvested material by a modified Kjeldahl method [14].

For each plot after harvest, the straw or oilseed rape residue was chopped and spread (together with the chaff for the wheat plots) back onto the plot.

Any weeds on the no residue plots at both sites were removed immediately prior to cultivation by hoe and rake.

4.4 Nitrous oxide flux

Nitrous oxide fluxes were determined using static chambers (15 cm diameter and 9.5 cm high) and analysis of headspace samples by gas chromatography (GC). Five (randomly located) chamber rings were hammered into each plot to a depth of 5 cm. Static chambers were placed onto the chamber rings for a timed period (usually 40, but never more than 50, minutes). To ensure mixing of the accumulated headspace gases, 50 mL was drawn from the chamber into a gas syringe and then forced back. A 20 mL sample was then withdrawn and injected into a pre-evacuated vial. In addition, 8 “ambient” (i.e. atmospheric) samples were taken at each site on each sampling date. Fluxes were calculated assuming a linear increase in N₂O concentration in the chamber headspace from the measured ambient concentration over the timed period; the flux for each plot was determined as the mean of the 5 chambers measurements. Measurements were made on *ca.* 30 occasions during a 7-month period; frequent measurements were made at and immediately after cultivation and after periods of heavy rain.

4.5 Soil analyses

At the start of each experiment, the site was sampled by randomly taking 25 cores of the 0-15 cm depth increment. The particle size distribution of the topsoil was determined from the bulked sample by standard methods [14]. In addition, each block for each experiment was sampled in the same way for determination of soil pH, extractable phosphorus, potassium and magnesium, total nitrogen and organic matter.

In addition, 12 cores per split plot at Hall Farm, or per main plot at ADAS Boxworth, were taken from 0-30 cm and 30-60 cm depth increments prior to each incorporation date. The cores were bulked and subsampled in the field after mixing. One subsample was submitted for soil inorganic nitrogen analysis at ADAS Laboratories, Wolverhampton, whilst the other subsample was used to determine moisture content at ADAS Boxworth, by standard methods [14]. At the end of each experiment, 6 cores per split-split plot at Hall Farm or per split plot at ADAS Boxworth were taken from 0-30 cm and 30-60 cm depth increments for soil inorganic nitrogen analysis, as before.

4.6 Mineralisation of soil nitrogen and water-soluble organic carbon

Mineralisation of soil nitrogen was determined monthly by the *in situ* core incubation technique [4]. Measurements were carried out from each split plot at ADAS Boxworth, and for each split-split plot following cultivation or split plot prior to cultivation at Hall Farm. Briefly, at 2 positions, a pair of cores were taken to a depth of 30 cm using a sharp gouge auger. The cores in a pair were taken within 10 cm of each other, and the soil core on the open face of the auger was cut flush to a standard sampling volume. One of each of the two pairs of cores were then placed in a polythene bag, frozen and submitted to ADAS Laboratories, Wolverhampton, for soil inorganic nitrogen and water-soluble organic carbon analyses. The other of each pair of cores were placed in a 1 L Kilner jar which was sealed and to which 10 mL of acetone-free acetylene was added. The Kilner jars were then placed in a trench, so that the lids were just below the soil surface, and covered with a wooden board. After 7 days, the soil samples were removed from the Kilner jars, frozen and submitted to ADAS Laboratories for soil inorganic nitrogen analysis.

4.7 Meteorological data and soil temperature

At Hall Farm, rainfall, relative humidity, air temperature and soil temperature at 5 cm depth were recorded at hourly intervals using a Delta-T weather station positioned adjacent to the site. The same data were recorded (except that soil temperature was at 10 cm) at the ADAS Boxworth meteorological station which was located less than 1 km from the experiment sites. In addition, for both Hall Farm and ADAS Boxworth, soil temperature at 5 cm was recorded every 2 hours by two TinyTalk dataloggers.

5. RESULTS

5.1 Hall Farm

5.1.1 Nitrous oxide flux

Results of N₂O flux measurements from the first year of the project are illustrated in Figure 1, which shows average emissions for the cultivation treatments from the crop residue plots.

Figure 1. Average emissions for incorporation treatments at Hall Farm, 1998-9.

In order to calculate cumulative N₂O fluxes for the period of the experiment, two problems needed to be addressed. First, linear interpolation can be an adequate method to integrate fluxes over an extended period if each data point can be considered to sensibly represent the periods before and after, to the next data point. This usually implies reasonably evenly spaced data points and a smoothly varying function. It is apparent from Figure 1 that these conditions were not met, and in any case N₂O emission is recognised to be an extremely variable phenomenon, both spatially with emissions occurring from “hotspots” of activity and temporally with rapid responses to conditions which favour denitrification. The development of a methodology to interpolate between data points is dealt with later in this report, but as a first approximation, cumulative emissions were calculated on the basis of linear interpolation in the first instance. Second, on occasions small negative emissions were measured, although it is generally assumed that soils are not a sink for N₂O. These “apparent” small negative emissions undoubtedly resulted from measurements below the detection limit of the system employed in this study, and were not of themselves a problem. However, integration by linear interpolation for data which are not evenly spaced gives additional weight to data points which are far apart compared to those which are close together. It was important, therefore, to determine the detection limit for the system used in this study, so that all measurements below the detection limit could be discounted.

The detection limit for the project was calculated from the range in calculated flux which resulted from the variation in measurements of the “ambient” N₂O concentration made during the first year. This gave a detection limit of 2.3 g N₂O-N ha⁻¹ d⁻¹ and this value was used throughout the project. For each plot, emissions calculated to be less than the detection limit were assumed to be zero.

Cumulative N₂O emissions calculated by linear interpolation and taking into account the detection limit for flux determination are shown in Figures 2 and 3 for 1998-9 and 1999-2000, respectively. A similar pattern of results were observed in both years, although on average emissions in the second year were *ca.* 40 % of those in the first year.

Figure 2. Total N₂O emissions at Hall Farm, 30 August 1998 – 3 March 1999.

Figure 3. Total N₂O emissions at Hall Farm, 19 August 1999 – 9 March 2000.

Analysis of variance (ANOVA) of the results of the experiments involving barley and pea residues incorporated in August and October showed no significant effect ($P > 0.05$) of any treatment in the first year, despite the fact that emissions from residues generally followed the order no residue < barley < peas, and those for cultivation treatments were rotovate < plough. However, in the second year, statistically significant ($P < 0.05$) effects of crop residue and cultivation treatment were determined. Average emissions ($\text{g N}_2\text{O-N ha}^{-1}$) were: no residue (180) < barley (310) < peas (405); and, rotovate (248) < plough (349) – i.e. in the same order as observed in the first year.

Statistically significant results were obtained in both years of the experiments involving sugarbeet residues incorporated in October and January. In the first year, there was a statistically significant interaction ($P < 0.05$) between date of incorporation and crop residue; thus, emissions following incorporation of sugarbeet residues in October ($1904 \text{ g N}_2\text{O-N ha}^{-1}$) were very much greater than those from the no residue treatment ($666 \text{ g N}_2\text{O-N ha}^{-1}$), whereas following incorporation in January emissions were similar (917 and $938 \text{ g N}_2\text{O-N ha}^{-1}$, respectively). The same pattern of emissions was observed in the second year (albeit with lower values), but interpretation of the ANOVA results was complicated because a significant ($P < 0.05$) 3-way interaction between date of incorporation, crop residue and cultivation treatments was determined. This arose because ploughing appeared to exacerbate the 2-way interaction between crop residue and incorporation date to a greater extent than rotovating. Thus, whereas emissions for the no residue and sugarbeet treatments incorporated in October were 271 and $498 \text{ g N}_2\text{O-N ha}^{-1}$, respectively, following rotovating, they were 265 and $927 \text{ g N}_2\text{O-N ha}^{-1}$, respectively, following ploughing. In fact, the same trends can be seen in the first year data (Figure 2), but the variability in the data was such that this was determined as not statistically significant.

5.1.2 Soil analyses

Results of the initial soil samples confirmed that the sites for the two experiments were very similar (Table 2).

Table 2. Analyses of soils (0-15 cm) sampled at the beginning of each experiment at Hall Farm.

	Field 29 (1998-9)	Field 26 (1999-2000)
Soil pH	8.2	8.0
Total N (%)	0.24	0.19
Organic matter (%)	4.3	3.7
<i>Extractable nutrients (mg kg⁻¹)</i>		
P	16	21
K	114	199
Mg	24	30
<i>Particle size distribution</i>		
Sand (%)	57	57
Clay (%)	15	18

Samples for soil inorganic N analyses were taken from 0-30 and 30-60 depth increments immediately before each residue incorporation event and at the end of each experiment in each year. These results showed no significant effect of cultivation treatment, although there were differences between crop residues on some sampling occasions. The results from the first year experiment involving barley and pea crop residues for both depth increments are shown in Figure 4 by way of illustration. It is clear that differences between crop residues at the beginning had disappeared by the end of the experiment. For the first sampling occasion (28 August 1998), soil inorganic N followed the order barley < peas < no residue, but it is also worth noting that soil inorganic N concentrations were generally lower for the "October" plots compared to the "August" plots, despite the fact at this stage of the experiment these groups of plots were equivalent, neither having been cultivated. Thus, for the second sampling occasion (19 October 1998), the generally greater soil inorganic N in the plots which had been cultivated at the end of August, compared to those which had not been cultivated, could not be ascribed to the effect of the cultivation.

In contrast to the first year experiment, when soil inorganic N concentrations declined markedly between the end of August and mid-October and then increased in the period to the beginning of March, the results for the second year showed the opposite pattern (Figure 5). Although soil inorganic N concentrations followed the same order at the beginning of the second year experiment (sugarbeet ? barley < peas < no residue) as that at the beginning of the first year, the range was much less. Soil inorganic N concentrations then increased in the period to mid-October, particularly for the pea and barley crop residue treatments, and then declined; sugarbeet showed a slightly different pattern, increasing over the whole period of the experiment.

Figure 4. Soil inorganic concentration measured on 4 occasions from 2 depth increments – Hall Farm experiment for barley and pea crop residues, 1998-9.

5.1.3 Mineralisation of soil nitrogen

The results of the net N mineralisation determinations are shown in Figure 6. Again, there was a difference in the pattern of results from the two experiments. In the first experiment, average net N mineralisation rates were very low immediately (actually negative, i.e. net N immobilisation of $0.1 \text{ kg N ha}^{-1} \text{ d}^{-1}$) after the first cultivation date (barley, peas and nil residue treatments). Mineralisation rates increased in the following month and peaked ($4.8 \text{ kg N ha}^{-1} \text{ d}^{-1}$) after the second cultivation date (barley, peas, sugarbeet and nil residues). Net immobilisation ($0.1 \text{ kg N ha}^{-1} \text{ d}^{-1}$) was measured again after the third incorporation date (sugarbeet and nil residues), before returning to net mineralisation ($2.7 \text{ kg N ha}^{-1} \text{ d}^{-1}$) in the final measurement at the beginning of March. In contrast, net N mineralisation rates in the second experiment were much more variable; the greatest measurement ($6.1 \text{ kg N ha}^{-1} \text{ d}^{-1}$) was determined immediately after the first incorporation date.

5.1.4 Water-soluble organic carbon

There were no significant effects of treatment on measured water-soluble organic carbon concentration in both years. Overall, water-soluble organic carbon concentration increased from the beginning of the experiment (August) to the end (March) in each year. However, there were large month-to-month variations (Figure 7), but these did not appear to be related to variations in net N mineralisation or soil inorganic N.

Figure 5. Average soil inorganic N concentrations (0-30 cm) measured at Hall Farm for crop residue treatments.

Figure 6. Average results of periodic net N mineralisation assays using in situ core incubation technique – Hall farm. Measurements in February 1998 were unreliable and are not shown. *Note that dates corresponding to residue incorporation and cultivation are indicated by arrows (3 in each year).*

Figure 7. Average water-soluble organic carbon concentrations (0-30 cm) measured at Hall Farm for crop residue treatments.

5.1.5 Rainfall and temperature

Average daily rainfall and air temperature for both experiments are shown in Figure 8. The automatic Delta-T weather station failed for a period (18 September 1999 – 23 October 1999) during the second experiment. Consequently, rainfall data for this period was taken from manually records of rainfall maintained by the manager of Hall Farm (Mr. Ron Gabain). In fact little rainfall was recorded at Hall Farm during (particularly the latter part of) this period. Rainfall recorded at Hall Farm agreed well with manual recording of rainfall at the site and rainfall records at ADAS Boxworth for the same period (see Figure 16, below).

The data indicate that temperatures were similar during the monitoring period (August – March) in both years and that rainfall was slightly less during 1999-2000 compared to 1998-9. Cumulative precipitation for the 1998-9 experiment was 517 mm whereas that for the 1999-2000 experiment was 479 mm, i.e. *ca.* 7 % less. However, the distribution of precipitation differed between years with a dry spell from the end of September to the end of October and low rainfall during January being particular features of the 1999-2000 experiment.

5.1.6 Effect of soil and environmental variables on N₂O emissions

Cumulative N₂O emissions, averaged across all plots, are contrasted for the two experiments in Figure 9. Average daily emissions ranged from 0.2 to 15 g N₂O-N ha⁻¹ in the first experiment and from 0 to 7 g N₂O-N ha⁻¹ in the second experiment. The range in emissions from individual treatments was (of course) greater, up to 54 and 15 g N₂O-N ha⁻¹ in the first and second experiments, respectively.

The temporal pattern in average fluxes indicated a relatively constant rate of N₂O emission during the period August to December which tended to decline in the period to March, albeit with occasional large emission events, not necessarily associated with cultivation or crop residue incorporation. Soil inorganic N, net N mineralisation and water-soluble organic N were determined less frequently than N₂O emission (i.e. 8 compared to 30 occasions) and often not on the same day (for logistical reasons), so no attempt was made to carry out numerical correlation analysis between these variables. However, from the temporal patterns (Figures 5, 6 and 7) there appeared to be no simple relationship between these variables and N₂O emission. Similarly, there was no readily apparent relationship between average daily N₂O emission and soil temperature at 10 cm (data not shown). However, correlation analysis between average daily N₂O emission and rainfall suggested that there was a relationship between cumulative rainfall and N₂O emission. In fact, the correlation

coefficient between average daily N₂O emission and rainfall was highly significant ($P < 0.001$) for cumulative rainfall over periods greater than 7 days; the maximum correlation coefficient ($r = 0.62$; $n = 45$) was obtained between average daily N₂O emission and cumulative rainfall for 13 days before the day of N₂O flux measurement.

Figure 8. Average precipitation (below) and air temperature (above) measured at Hall Farm.

Figure 9. Cumulative average emissions of N₂O measured at Hall Farm in two years.

Figure 10. Relationship between average daily N₂O emission and cumulative rainfall measured at Hall Farm in 2 years. (The R^2 values of the fitted line is 0.43).

Figure 11. Comparison of average cumulative N₂O emission estimated by linear interpolation and a regression relationship involving cumulative rainfall at Hall Farm in 2 years.

The relationship between cumulative rainfall and N₂O emission is shown in Figure 10, together with a fitted (quadratic) regression line. Although only 43 % of the total variation is explained by the regression line, ANOVA indicates that the

relationship was highly significant ($P < 0.001$). Using this relationship to calculate N₂O emissions on days when no measurements were made (Figure 11) confirmed the higher total fluxes estimated in 1998-9 (Figure 2) compared to 1999-2000, but indicated that linear interpolation overestimated emissions in the first experiment and underestimated emissions in the second year. Thus, cumulative average emissions for 1998-9 were 850 and 560 g N₂O-N ha⁻¹ by linear interpolation and using the cumulative rainfall relationship, respectively; and, for 1999-2000 were 322 and 500 g N₂O-N ha⁻¹.

5.2 ADAS Boxworth

5.2.1 Nitrous oxide flux

Results of N₂O flux measurements from the two experiments carried out at ADAS Boxworth are shown in Figure 12. On average, total emissions in the second experiment were less than those in the first experiment, but there was much more variability in the first year results. This arose mainly because of very high emissions from two plots; plot 11 – nil residue, disc – 5,619 g N₂O-N ha⁻¹ and plot 12 – nil residue, plough – 1,319 g N₂O-N ha⁻¹. Excluding these, average emissions in the second year were 36 % of those in the first year.

Analysis of variance (ANOVA) of the results showed no significant differences ($P > 0.05$) between treatments for the first experiment. Given the large variability, this was not surprising, although it should be noted that the calculated probability of incorrectly rejecting the null hypothesis (of no difference between treatments) for incorporation method was only 10 %. Since there is an inverse relationship between the significance level (i.e. the probability of rejecting the null hypothesis when it is true – type I error) and the power (i.e. the probability of failing to reject the null hypothesis when it is false – type II error) of a statistical test, this result indicated that there was a high probability that the effect of incorporation method may not have been identified. On average, total N₂O emissions from ploughed plots were less than those from disced plots. In fact, in the second experiment, a significant ($P < 0.05$) effect of incorporation method was determined; the effect of residue type was not significant ($P > 0.05$), although average emissions from oilseed rape were greater than those from winter wheat in both years.

Figure 12. Total N₂O emissions at ADAS Boxworth, 6 August 1999 – 20 March 2000 and 8 August 2000 – 5 February 2001. *The LSD at the split plot level in each year is shown.*

5.2.3 Soil analyses

Results of the initial soil samples (Table 3) indicated that the sites for the two experiments were similar, although average soil pH was lower and soil organic matter was greater for Gow Ley compared to Pamplins North. (Extractable magnesium was also greater for Gow Ley, but this was not considered to have any agronomic significance). No statistical

analysis was carried out using the results for each block, but it was noticeable that soil pH and soil organic matter was lower in block 3 of the Gow Ley site compared to the other two blocks.

Table 3. Analyses of soils (0-15 cm) sampled at the beginning of each experiment at ADAS Boxworth.

	Gow Ley (1999-2000)	Pamplins North (2000-1)
Soil pH	7.3	7.9
Total N (%)	0.25	0.23
Organic matter (%)	3.3	2.5
<i>Extractable nutrients (mg kg⁻¹)</i>		
P	19	14
K	172	186
Mg	114	54
<i>Particle size distribution</i>		
Sand (%)	29	27
Clay (%)	45	47

The results of periodic soil inorganic N analyses (0-30 cm) are shown in Figure 13. In both experiments, there was a significant ($P < 0.05$) effect of residue type on the first sampling occasion (i.e. immediately before residue incorporation and cultivation), with concentrations following the order: nil > oilseed rape > wheat. There was no consistent pattern for subsequent sampling occasions, with a significant effect of residue treatment in October and March for the first experiment, and a significant effect of cultivation treatment in October and January for the second experiment.

Figure 13. Average soil inorganic N concentrations (0-30 cm) measured at ADAS Boxworth. *The LSD at the split plot level is shown.*

5.2.3 Mineralisation of soil nitrogen

The results of the net N mineralisation determinations are shown in Figure 14. There was a difference in the pattern of results from the two experiments. In the first experiment, average net N mineralisation rates were relatively constant (overall average 1.2 kg N ha⁻¹ d⁻¹). In contrast, net N mineralisation rates in the second experiment were much more variable, with net N mineralisation rates increasing to a maximum (4.2 kg N ha⁻¹ d⁻¹) *ca.* 1 month after cultivation before declining.

5.2.4 Water-soluble organic carbon

There were no significant effects of treatment on measured water-soluble organic carbon concentration in both years, although the temporal pattern differed markedly (Figure 15). In the first experiment, water-soluble organic carbon

concentration increased from the beginning of the experiment (August) to peak values in February, before declining in March. In the second experiment, water-soluble organic carbon concentrations were lower and relatively constant. These variations did not appear to be related to variations in net N mineralisation or soil inorganic N.

5.2.5 Rainfall and temperature

Average daily rainfall and air temperature for both experiments are shown in Figure 16. The data indicate that temperatures were similar during the monitoring period (August – March) in both years. Rainfall in the second experiment (467 mm) was greater than that in the first experiment (355 mm) but, crucially, there were significant differences in temporal distribution. Rainfall in August and September of 2001 was less than that in the same 2 months of 2000, particularly in the period preceeding, and immediately following, crop residue incorporation. A number of heavy rainfall events in late October and early November of 2001, and generally greater rainfall compared to 2000, resulted in the overall greater rainfall for 2001-2.

Figure 14. Average results of periodic net N mineralisation assays using in situ core incubation technique – ADAS Boxworth. Measurements in November 2000 were unreliable and are not shown.

5.2.6 Effect of soil and environmental variables on N₂O emissions

Cumulative N₂O emissions, averaged across all plots, are contrasted for the two experiments in Figure 17. Average daily emissions ranged from 0 to 70 g N₂O-N ha⁻¹ in the first experiment and from 0 to 17 g N₂O-N ha⁻¹ in the second experiment. The range in emissions was up to 178 and 21 g N₂O-N ha⁻¹ d⁻¹ for individual treatments in the first and second experiments, respectively.

The temporal pattern in average fluxes indicated initially high rates of emission immediately after residue incorporation and cultivation in the first experiment, followed by two periods when emissions were greater than the background trend; mid-September to mid-October, and December. In contrast, emissions from the second experiment were low and relatively constant throughout. Comparing the pattern of N₂O emissions with those for soil inorganic N, net N mineralisation and water-soluble organic N (Figures 13, 14 and 15) suggested that there was no simple relationship between these variables and N₂O emission. Similarly, there was no readily apparent relationship between average daily N₂O emission and soil temperature at 10 cm (data not shown). Correlation analysis suggested that there was a relationship between average daily N₂O emission and both rainfall ($r = 0.38$; $n = 55$, $P < 0.01$) and cumulative rainfall on the previous 5 days ($r = 0.33$; $n = 55$, $P < 0.05$). However, it was apparent from scattergrams of the data that significant

correlation had been obtained on the basis of data from the first experiment only; emissions from the second experiment were low over the full range of rainfall and cumulative 5-day rainfall values. Inspection of the raw data had already indicated that high emissions following cultivation in the first experiment followed a generally wet period, whereas low emissions following cultivation in the second experiment followed a generally dry period. Soil moisture determined on 4 occasions in each experiment (using soil inorganic N sub-samples) showed that moisture content was least prior to cultivation (early August). Moisture contents measured on the other 3 occasions were greater and similar on each occasion and between experiments.

Figure 15. Average water-soluble organic carbon concentrations (0-30 cm) measured at ADAS Boxworth for crop residue treatments.

Figure 16. Average precipitation (below) and air temperature (above) measured at ADAS Boxworth.

Figure 17. Cumulative average emissions of N₂O measured at ADAS Boxworth in two years.

Figure 18. Relationship between average daily N₂O emission in the 28 days following early August cultivation and cumulative rainfall measured at ADAS Boxworth in 2 years. (*The R² value of the fitted line is 0.73*).

Further correlation analysis, using only data from the first 4 weeks of each experiment again suggested that there was a relationship between average daily N₂O emission and both rainfall ($r = 0.62$; $n = 19$, $P < 0.001$) and cumulative rainfall on the previous 5 days ($r = 0.85$; $n = 19$, $P < 0.001$).

Figure 19. Comparison of average cumulative N₂O emission by linear interpolation and a regression relationship involving cumulative rainfall following cultivation at ADAS Boxworth in 2 years.

The relationship between cumulative rainfall and N₂O emission for 4 weeks after cultivation (Figure 18) was used in place of linear interpolation to calculate N₂O emissions during this period when no measurements were made (Figure 19). Cumulative average emissions for 1999-2000 were 829 and 726 g N₂O-N ha⁻¹ by linear interpolation alone and including the cumulative rainfall relationship, respectively; and, for 2000-1 were 161 and 301 g N₂O-N ha⁻¹.

5.3 Effect of crop residue type on N₂O emission

The 5 crop residues investigated significantly ($P < 0.01$) influenced mean N₂O emissions (Figure 20). Sugarbeet residues had the narrowest C:N ratios (15-17) and the greatest N₂O emissions. Other residues had C:N ratios in the range 28 to 70; N₂O emissions decreased with increasing C:N. It was noticeable that despite a relatively constant C:N of the sugarbeet residues used in this project, there was a large variation in N₂O emission. This was the result interaction effect of date of incorporation on emissions from sugarbeet (see 5.1.1, above) where incorporation in October resulted in much higher N₂O fluxes than incorporation in February.

5.4 Nitrous oxide emission factors

Average emission factors (i.e. the proportion of N incorporated and subsequently lost as N₂O-N) were calculated for each crop residue (Table 4). The results for crop residues are obviously confounded by the site, since different crops were grown and incorporated on different soil types. In addition, emission factors differed markedly between years for each crop/site combination. Taking the results for 1999-2000 as a baseline, since all crops residues were monitored in this year and the weather at the two sites was similar – the two sites were relatively close to each other – average emission factors increased in the order: sugarbeet > wheat < oilseed rape < barley < peas. However, this sequence was primarily determined by differences in crop residue N applied rather than N₂O emission, since average emissions for the crop residues were similar whereas average N applications in crop residues were 140, 98, 100, 51 and 56 kg ha⁻¹ for sugarbeet, wheat, oilseed rape, barley and peas, respectively. Average emission factors for crop residues at ADAS Boxworth were lower than those for crop residues at Hall Farm. This seems to be supported if the results for barley at Hall Farm are

compared with those for wheat at ADAS Boxworth, both incorporated in August. However, the greater part of this difference can again be explained in terms of the difference in crop residue N. The results indicate a large year-to-year variation, with the largest emission factors measured for 1998-9 and the smallest for 2000-1.

Figure 20. Relationship between C:N of crop residue and mean cumulative N₂O emission.

Table 4. Average emission factors for crop residues.

Site	Crop	Month incorporated	1998-9	1999- 2000	2000-1	Average
Hall Farm	Barley	August	1.32	0.74		1.03
		October	1.41	0.48		0.94
	Peas	August	1.48	0.81		1.15
		October	1.66	0.65		1.16
	Sugarbeet	October	1.16	0.47		0.81
		January	1.20	0.17		0.69
Hall Farm average			1.37	0.55		0.96
ADAS Boxworth	Wheat	August		0.32	0.13	0.22
	Oilseed rape	August		0.57	0.48	0.52
ADAS Boxworth average				0.45	0.30	0.37

6. DISCUSSION

Direct emissions of nitrous oxide (N₂O) from agricultural soils are calculated on the basis on nitrogen (N) inputs [7], including those from crop residues [10; 12; 15]. The range in emissions obtained in this study is consistent with other recent work. For example, Baggs *et al.* [2] reported maximum emission rates of 41-67 g N₂O-N ha⁻¹ d⁻¹ from lettuce residues on a freely drained loamy sand in Scotland 8-11 days after incorporation and emission rates of < 15 g N₂O-N ha⁻¹ d⁻¹ from wheat and oilseed rape residues on a sandy loam soil. Kaiser *et al.* [6] reported emission rates ranging from 0 to 155 g N₂O-N ha⁻¹ d⁻¹ during a 33-month period on a loamy silt soil in Germany where winter wheat, winter barley, winter oilseed rape and sugarbeet were cultivated using conventional soil management and a range of N fertiliser treatments; in this study, 50 % of the annual N₂O emission occurred during the winter (October to February) period.

In this study, emission rates ranged up to 53 g N₂O-N ha⁻¹ d⁻¹ from sugarbeet incorporated in October 1998 on the sandy loam site and 178 g N₂O-N ha⁻¹ d⁻¹ from nil residue plots which had been cultivated using heavy discs in August 1999.

These treatments also gave the greatest cumulative emissions of 1.9 and 1.5 kg ha⁻¹, respectively, although for the other residue treatments (barley, wheat, oilseed rape and peas) cumulative emissions were less, ranging from 0.1 to 0.8 kg ha⁻¹.

The results suggested that crop residue C:N was the best indicator of cumulative emissions (Figure 20) with greater emissions from residues with narrower ratios. Large emissions from lettuce residues have been attributed to the narrow C:N ratio (7.5) of this material [2], since materials with narrow C:N ratios are known to promote mineralisation and may therefore induce or enlarge anaerobic microsites where denitrification can take place [13]. It should be noted, however, that the relationship between N₂O emission and C:N ratio determined in this study differs markedly from that reported by Kaiser *et al.* [6], where emissions were generally greater. However, in that study, high flux rates were associated with physical release of subsurface-produced N₂O during deep soil freezing as well as daily thawing and freezing cycles. It is likely that the milder maritime of eastern England reduced the effect of these processes in comparison to the more extreme winter conditions found in central Germany (Braunschweig, Lower Saxony).

The results also suggested, taking into account the different crop residues at each site, that N₂O emissions were similar for both soils. This was unexpected, although this has also been reported by other workers [8], because greater N₂O production was anticipated from the heavier-textured soil. Two factors may have given rise to this observation. First, Arah *et al.* [3] noted that N₂O produced at depth was reduced to dinitrogen (N₂) on its way up the soil profile, especially in heavier-textured soils where diffusion was slow. Second, the higher water-holding capacity and poorer drainage characteristics of the clay soil may have resulted in conditions more favourable for N₂ (rather than N₂O) production. It is generally recognised [9] that N₂O emission from soil is a function of water-filled pore space (WFPS) and is a maximum in the region *ca.* 60-80 %. Approximate WFPS of sandy soils at field capacity is 40 %, while that of clay soils is 80 %. Thus, depending on rainfall intensity and distribution, it is entirely possible that anaerobic conditions associated with maximum N₂O emissions may persist for longer periods in lighter-texture soils compared to heavier-textured soils. This scenario is consistent with the observed pattern of emissions in this study. For example, the lower emissions in 2000-1 compared to 1999-2000 may, in part, have arisen because of the more "patchy" distribution of rainfall in 1999-2000 which allowed soils to dry out with a resulting increase in N₂O emission. The largest emissions from ADAS Boxworth in fact occurred from two plots which had noticeably poorer drainage than the rest of the site, but crucially at the start of the monitoring period when moisture contents were least. This suggests that higher moisture contents during the rest of the monitoring period resulted in WFPS greater than that for maximum N₂O emission potential.

The importance of WFPS has been noted above and, together with soil temperature and soil nitrate concentration, is recognised as a key factor controlling N₂O emission [5]. A number of variables were examined for their ability to predict average N₂O emissions, but only those based on rainfall appeared to be useful, suggesting that factors other than soil moisture (in reality, soil aeration) were not limiting. The fact that only data immediately following cultivation (0-28 days) contributed to a useful relationship for the heavier-textured soil probably relates to the fact that it was only during this period that this soil was *dry* enough to generate appreciable N₂O emissions. Similarly, the difference between the soils in terms of the period of cumulative rainfall (13 days on the sandy loam, 5 days on the clay) probably reflects the hydrology of the soils, with greater and more rapid drainage occurring on the lighter-textured soil. Thus, persistent rainfall was required to generate sufficiently anaerobic conditions for significant N₂O emissions at Hall Farm.

Emission factors (Table 4) were calculated on the basis cumulative N₂O emissions determined by linear interpolation. Comparisons between these results and those obtained using regression relationships showed quite large discrepancies (Figures 11 and 19). However, average results for the 2 years at each site were much closer and, in the absence of a more robust model for data interpolation, represent the best data available. It should be noted that the emission factors presented in Table 4 are based on *measured* quantities of N incorporated as crop residues. Emission factors based on assumed crop residue N values [7] give different values. Factors for oilseed rape would be overestimated, since the IPCC methodology underestimates residue N, whilst those for the other crops would be underestimated, since crop residue N is overestimated.

7. MAIN IMPLICATIONS

- I. **Nitrous oxide emission factors for all crop residues investigated in this study are lower than the default IPCC value (1.25 %).**
- II. Measurements were carried out from August to March in two years for each crop, and for this limited data there was a statistically significant ($P < 0.01$) relationship between C:N of the crop residue and total N₂O emission.

- However, except for sugarbeet (C:N 15-17), the range in total emissions was limited (< 1 kg N₂O-N ha⁻¹). Further data are required to determine the robustness of this relationship with respect to a wide range of crops and weather conditions.
- III. Given the generally limited range in measured N₂O emissions, variation in calculated emission factors was mainly the result of variations in crop N residue content. **More accurate estimates of UK emissions of N₂O can be obtained by improving the calculation of crop N residue content.**
- IV. **Combining emissions determined in this study and data for the N content of UK crops results in an estimated of N₂O emissions from crop residues ca. 40 % of that determined by the default IPCC methodology.**
- V. Highest N₂O emissions were measured from plots where no crop had been grown. **The absence of a plant sink for soil inorganic N appears to increase N₂O emissions .**
- VI. For sugarbeet, there was a statistically significant (P < 0.05) interaction with timing of incorporation on N₂O emission with greater emissions occurring following incorporation in October. **Thus, it may be possible to mitigate emissions from this crop by encouraging later harvest.**
- VII. There was no significant effect of cultivation method on the sandy loam soil, but emissions were significantly (P < 0.05) lower when crop residues were incorporated by ploughing compared to heavy discs. **Thus, it may be possible to mitigate emissions on heavy-textured soils by incorporating residues by ploughing .** Further work is required to determine whether the effect of cultivation arises because of its influence on nitrification or on the gaseous diffusion of the products of denitrification.
- VIII. The effect of soil type on N₂O emission requires further investigation. **In particular, good hydrological models are required to adequately describe soil aeration in the topsoil following rainfall in soils of different textures.**

8. TECHNOLOGY TRANSFER

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