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# $N_2O$ AND $CH_4$ FLUXES IN SOIL INFLUENCED BY FERTILIZATION AND TRACTOR TRAFFIC

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**Summary**—The effects of fertilization and tractor traffic on $N_2O$ emission and $CH_4$ uptake in agricultural soil were studied in a field trial with different fertilization and soil compaction. The soil was a well-drained sandy loam and the crop rotation was rich in ley and legumes. The fertilization treatments were: NPK fertilizer (140 kg $NH_4NO_3$-N $ha^{-1}$); cattle slurry (CS) (189 kg total N $ha^{-1}$), CS (81 kg total N $ha^{-1}$), and an unfertilized treatment. The soil was experimentally compacted by two passes with a tractor, wheel by wheel, shortly before fertilization. Gas fluxes at the soil surface were measured by the soil cover method. Soil air at a depth of 7–12 cm was sampled through stationary soil air samplers. Concentrations of $N_2O$ in soil air were more than seven times higher in compacted, NPK-fertilized soil than in any other treatments. Maximum concentrations (1900 $\mu$l $N_2O$ $l^{-1}$) were observed shortly after periods with heavy rain. The accumulated $N_2O$ emissions from the NPK-fertilized treatment (4 June–8 July) corresponded to 5.3% of added $NH_4NO_3$-N in compacted soil, and 3.9% in uncompacted soil. Fertilization with cattle slurry equivalent to 81 kg total N $ha^{-1}$ gave an $N_2O$ emission corresponding to 3.1% of added $NH_4$-N in uncompacted soil, and 2.7% in compacted soil. Increasing levels of cattle slurry resulted in a reduction in $N_2O$ emission per kg $NH_4$-N added. The accumulated $CH_4$ uptake (4 June–8 July) in the soil was 9.7 mg $CH_4$ $m^{-2}$ in unfertilized and uncompacted soil. It was reduced by 52% by soil compaction, 50% on average by fertilization and 78% by soil compaction and fertilization combined. Fertilization with $NH_4NO_3$ or cattle slurry resulted in similar effects.

## INTRODUCTION

Soil is an important source of atmospheric $N_2O$, and a sink for $CH_4$ (Mosier *et al.*, 1991). The emission of $N_2O$ may be perceived as a leakage of intermediate products in nitrification and denitrification. These reactions are influenced by oxygen supply, water content, temperature, soil pH, organic matter, the presence of plants (Byrnes, 1990) and the concentrations of $NH_4$-N and $NO_3$-N in the soil (Jones and Morita, 1983). A well-drained soil acts as a sink for atmospheric $CH_4$ due to methane oxidation, by either ammonia oxidizers or methanotrophs (Bedard and Knowles, 1989). In arable land agricultural practices such as fertilization and tractor traffic as well as climate and soil type are likely to influence these gas fluxes. Numerous studies reviewed by Eichner (1990) show great variability in $N_2O$ fluxes from agricultural soils. Less work has been done on $CH_4$ flux. Mosier *et al.* (1991) report a $CH_4$ uptake of 2.6, 1.8 and 1.3 g C $ha^{-1}$ $d^{-1}$ in native grassland, fallow and wheat sites, respectively.

In some areas soil compaction is a serious problem. Very little work has been reported on the effect of soil compaction on $N_2O$ emission in a humid climate and no work on the effect on $CH_4$ uptake. In western Norway large areas are easily compacted, partly because of humid climate and partly because of fine textured soils and high content of organic material in the soils. The aim of this investigation was to study the influence of soil compaction through tractor traffic and fertilization with $NH_4NO_3$ or cattle slurry on $CH_4$ and $N_2O$ fluxes in an easily compacted soil in a humid climate.

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## MATERIALS AND METHODS

Gas fluxes and soil air composition were measured during the seventh year of a field experiment with different fertilization and soil compaction treatments (growth season 1991). The field experiment was located in Surnadal, Norway 25 m a.s.l., 63°00′00″ N, 8°88′44″ E. Precipitation in April, May and June was 457 mm, which is 179% of the normal precipitation. The average temperature for April, May and June was 7.7°C (normal 8.4°C). Soil temperature and precipitation during the period of measurement are given in Fig. 1.

The experiment had a split-plot factorial design with two replicates, soil compaction on main plots and fertilization on small plots (2.8 × 8 m, sample area 1.5 × 6.5 m). For each flux measurement, two soil cover chambers were placed at random within each field plot (minimum spacing 1 m). Soil air was sampled using two stationary soil air samplers (equilibrium chambers) in each plot. Thus, for each

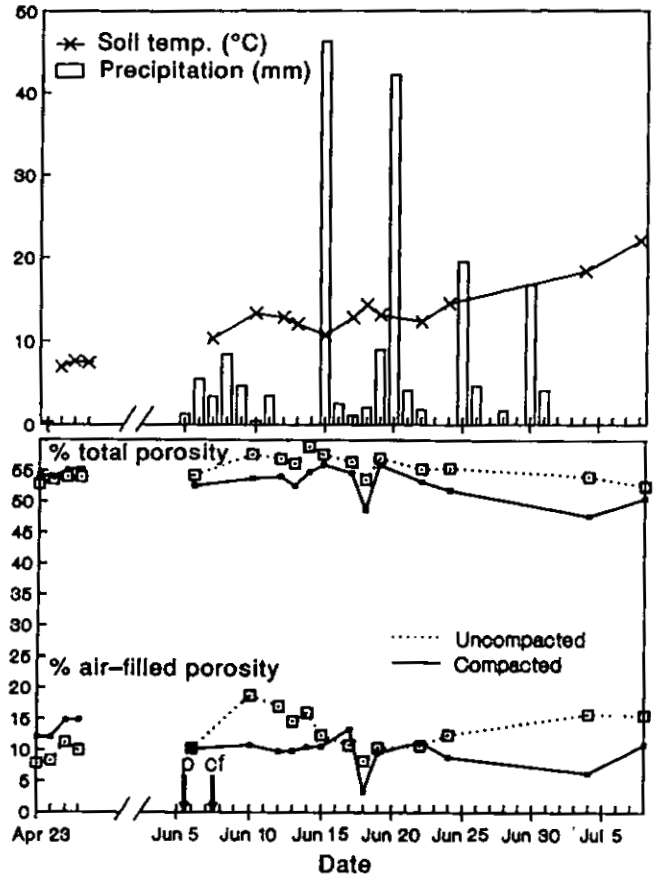


Fig. 1. Soil temperature (°C) at 15 cm depth, precipitation (mm), total porosity and air-filled porosity as a percentage of soil volume.

treatment, there were four parallel flux and soil air measurements taken on each day of measurement.

The fertilization treatments were: NPK fertilizer (18% N, 3% P, 15% K) with 140 kg $NH_4NO_3$-N $ha^{-1}$, cattle slurry (CS) equivalent to 189 kg total N (116 kg $NH_4$-N) $ha^{-1}$, CS equivalent to 81 kg total N (50 kg $NH_4$-N) $ha^{-1}$, and an unfertilized treatment. CS was diluted with water up to 200% of the original volume and spread by can with a small spreading plate. NPK fertilizer was spread by hand. Fertilizers were raked into the top 5 cm of the soil immediately after application. This loosened the soil in the upper surface. Samples of cattle slurry were frozen for later analyses following the method described by Horwitz (1980).

The diluted slurry contained 64 g dry matter $l^{-1}$, 2.8 g Kjeldahl-N $l^{-1}$, 1.7 g $NH_4$-N $l^{-1}$, 25 mg $NO_3$-N $l^{-1}$, 1.5 g water soluble organic C $l^{-1}$ and had a pH of 7.6.

In 1991, soil compaction treatment comprised two passes of a 4 tonne tractor, wheel by wheel, shortly before fertilization, at a soil moisture tension equal to pF *ca* 2. The rear wheels were double-settings with a total tyre width of 140 cm (inflation pressure of 57 kPa). In front there were low pressure tyres with a total width of 100 cm.

Similar fertilizer and compaction treatments have been carried out every year from 1985 with the exception of 1990, when no extra compaction or fertilization was applied.

Tillage treatments (ploughing, two harrowings, rolling) and sowing were carried out across the experimental plots with tractors similar to those used for compaction. Thus, the uncompacted soil was to some extent affected by tractor traffic.

The experimental field has a slope of <2% and is placed on a naturally-drained sandy loam developed on fluvial deposits. The soil profile has a contrasting character in the subsoil layer (beneath 30–100 cm), with *ca* 50% by volume containing stones bigger than 4 cm, while the remainder is rich in gravel and coarse sand (Table 1).

The top soil contained 2.2% organic C, 0.17% organic N and had a pH ($H_2O$) of 6.1. Average bulk densities (7–11 cm depth) were 1.21 g $cm^{-3}$ in uncompacted soil and 1.30 g $m^{-3}$ in compacted soil.

The experiment was started in 1985. The crop rotation was adapted to ecological farming with milk production and had a high frequency of ley and legumes.

The 1991 crop was green fodder with rape (*Brassica napus*), barley (*Hordeum vulgare*), peas

Table 1. Soil texture. Percent by weight of the fraction < 2 mm, except for gravel which is given as a percentage of the total weight. Determined following Elonen (1971)*

| | Soil layer | | |
|---|---|---|---|
| | 0–20 cm | 20–25 cm | Subsoil |
| Gravel (0.2–4 cm) | 1–3 | 1–3 | 70–90 |
| Coarse sand (2.0–0.6 mm) | 1–2 | 1–2 | 34–68 |
| Medium sand (0.6–0.2 mm) | 5–7 | 7–15 | 22–37 |
| Fine sand (0.2–0.0 mm) | 38–44 | 33–42 | 5–27 |
| Coarse silt (0.06–0.02 mm) | 27–29 | 27 | 1–6 |
| Medium silt (0.02–0.006 mm) | 13–17 | 13 | 0–5 |
| Fine silt (0.006–0.002 mm) | 4–6 | 6–7 | 0–1 |
| Clay (< 0.002 mm) | 4–6 | 4 | 1–4 |

*Three samples behind the determination of soil texture 0–20 cm and 20–25 cm, eleven samples behind the determination of subsoil.

(*Pisum arvense*), vetch (*Vicia sativa*) and Westerwolth rye-grass (*Lolium multiflorum* Lam. var. *Westerwoldicum auct.*). Crops from 1985 to 1990 were: greenfodder, barley, 3 yr ley and oats. The oats straw was left on the soil surface during the winter and was removed shortly before ploughing in spring 1991.

The soil porosity and water content were determined in undisturbed soil samples taken by means of 100 $cm^3$ cylinders. At each sampling date, three samples were taken in both compacted and uncompacted areas (7–11 cm depth). Particle density used to calculate material and pore volume was determined following the method of De Boodt *et al.* (1967).

*Gas measurements*

Gas fluxes were measured shortly after snowmelt (23, 24 and 26 April), before and after ploughing (4 and 7 June) and after compaction and fertilization treatments (10, 12, 13, 14, 15, 17, 18, 19, 22, 24 June; 4 and 6 July).

Gas fluxes at the soil surface were measured by soil cover chambers (thin-walled tin cans, 22.5 cm i.d., 23 cm high) with a reflecting outer surface similar to that described by Bakken *et al.* (1987). This ensured minimal heating by direct sunlight. In order to prevent bulk flow of air into the soil while pushing the soil cover chambers into the ground (1 cm), three holes (12 mm dia) on the top were kept open. After placement of the chambers, these holes were closed with butyl rubber stoppers (type 20-B3P, Chromacol Ltd, London). Gas samples were taken through these stoppers with a two-way blood collection needle. The needle was pierced through the rubber stoppers and connected to 12 ml evacuated glass vials (N 20-10 Macherey–Nagel, Düren) as outlined by Magnusson (1989). Before sampling, the vials were closed with the same type of stoppers, covered with a layer of silicone and evacuated to $< 10^{-3}$ atm.

Equilibrium chambers for soil air sampling at depths of 7–12 cm were installed shortly after rolling the field. The equilibrium chambers were constructed of pointed cylinders of stainless steel, with 19.5 cm length, 9 mm o.d. and 4 mm i.d., and eleven 1 mm holes. The holes were countersunk in order to avoid clogging by the soil. Gas samples (6 ml) were taken through viton rubber septa at the top of the equilibrium chambers in the same way as for flux measurements (N 20-5/4 Macherey–Nagel, Düren).

Within 14 days after sampling, the gas samples were analysed on a gas chromatograph (Fractovap 4200, Carlo Erba, Italy) equipped with three detectors. The storage of gas samples in the same vials and rubber stoppers was tested by Sitaula *et al.* (1992). After 30 days storage they found a recovery of 97% $N_2O$, 100% $CH_4$ and 94% $CO_2$.

Moderate concentrations ($< 40\ \mu l\ l^{-1}$) of $N_2O$ were measured on an ECD (electron capture detector, type ECD40), and higher concentrations on a TCD (thermal conductivity detector). $CH_4$ was measured by FID (flame ionizing detector), and $CO_2$ by TCD. The column was a 25 m × 0.53 mm Poraplot Q (Chrompac, Middelburg, The Netherlands), connected directly to a 6-port injection valve (type C6W, VALCO Instrument Co. Inc., Houston, U.S.A.) with a 0.2 ml sampling loop. The carrier gas (He) flow was 7 ml $min^{-1}$. The temperatures of the oven, TCD and ECD were 35, 70 and 350°C, respectively. The outline of the gas chromatograph system is described by Sitaula *et al.* (1992).

$N_2O$ and $CH_4$ concentrations in the soil cover chambers at the start of each closure period were estimated by the arithmatical mean of air samples taken 20 cm above the ground simultaneously with samples of flux and soil air. These measurements of atmospheric background displayed some variability (SD = 0.09 $\mu l\ l^{-1}$ for $CH_4$ and 0.1 $\mu l\ l^{-1}$ for $N_2O$, $n = 19$). This variability was a combination of real variation in gas concentrations and analytical errors. The latter was important for ambient concentrations of $N_2O$ due to base line instability. Standards with higher $N_2O$-concentrations gave reasonable stable signals (coefficient of variation = 5% for ECD determination of a 6.43 $\mu l\ l^{-1}$ standard and only 2–3% for TCD determinations of standards > 40 $\mu l\ l^{-1}$).

Gas samples were taken 3 h after placement of the soil cover chambers, except for two measurements which were extended to 5 h. In these cases (15 and 17 June) samples were taken after both 3 and 5 h. Flux was estimated by the increased concentration during the first 3 h. A comparison of 0–3 and 3–5 h flux measurements in 15 and 17 June gave an average estimated flux of 12.6 mg $N_2O$-N $m^{-2}\ d^{-1}$ in the 0–3 h estimate and 13.2 mg $N_2O$-N $m^{-2}\ d^{-1}$ in the 3–5 h estimate. Thus, there was no evidence of a retardation of the fluxes towards the end of the 5 h incubation.

The area under the flux curves (straight lines between data points, Figs 2 and 3) were used to estimate the accumulated $N_2O$ emission and $CH_4$ uptake during the period of measurements (4 June–8 July).

*Statistical analyses and calculations*

The main effects and interactions of soil compaction, fertilization and date were tested with

analyses of variance (ANOVA) and the Newman–Keul's test. The interaction replicate–compaction was used as an error term to test the effect of compaction. Studentized residuals were used to test the normality of the distributions with residual plots and procedure Univariate (SAS Institute, 1988). The concentration of $CH_4$ in the soil air was normally distributed and the $CH_4$ flux and the $CO_2$ concentrations were so close to normal distribution that they were treated statistically as if that was the case. Fluxes and soil atmospheric concentrations of $N_2O$ were log-normally distributed and the data were log-transformed with natural logarithms before the statistical analyses were run. In the case of $N_2O$ fluxes, some of the data were negative and a constant number (10) was added to all numbers before log-transformation and analyses of variance.

The means and standard errors of the mean (SEM) of log-normally distributed $N_2O$ data were calculated using Finney's method, described by Parkin *et al.* (1988). They compared the method of moments, maximum likelihood and Finney's method to estimate mean, variance and coefficient of variation of log-normally distributed data. It was found that Finney's method had least bias when the coefficient of variation of the underlying log-normal frequency distribution exceeded 100%, which is the case for our $N_2O$ data.

$CH_4$ uptake rates were calculated in accordance with first-order kinetics. This is in agreement with the observations by Sitaula and Bakken (unpubl.), who found that $CH_4$ concentrations in a soil cover chamber closely followed an exponential function during the first 8 h of incubation.

Since estimates of accumulated $N_2O$ emission and $CH_4$ uptake are linear functions of the flux data, the standard error could be calculated accordingly, based on the estimate variance for each sampling day (after Cochran and Cox, 1957, p. 71).

In order to compare the fertilization effects on $N_2O$ emission rates with those reported by Eichner (1990), the average value for daily fertilizer-derived $N_2O$ emissions in g $N_2O$-N $kg^{-1}$ mineral N added has been calculated (Table 2). This is calculated as the average daily $N_2O$ emission in fertilized treatments minus average daily $N_2O$ emission in the unfertilized treatment, divided by the amount of mineral N in the fertilizer.

In order to investigate treatment effects on $N_2O$ diffusion, the ratio between measured flux and the measured concentration gradient ($C_S$–$C_A$, $C_S$ = $N_2O$-concentration at soil depths of 7–12 cm, $C_A$ = $N_2O$-concentration 20 cm above soil surface) was calculated for each treatment. The ratio was log-normally distributed and treatment means and SEM were calculated according to Finney's method (Parkin *et al.*, 1988). Log-transformed data were used in analyses of variance and the Newman–Keul's test. To avoid negative flux values, the calculations were based on observations from 15 June to 8 July.

## RESULTS

### *$N_2O$ emission and soil air concentration*

Fertilization resulted in increased $N_2O$ emission and concentration in soil air ($P < 0.01$). There was no significant difference between cattle slurry and NPK fertilization in uncompacted soils (Fig. 2, Table 2). In compacted soils the average soil air concentrations of $N_2O$ were seven times higher in NPK-fertilized plots than in plots fertilized with 189 kg N $ha^{-1}$ in cattle slurry. Very high $N_2O$ concentrations in soil air were found in compacted, NPK-fertilized soil after heavy rain (Fig. 2). Moreover, high $N_2O$ fluxes were observed from NPK-fertilized treatments, but in compacted soil the $N_2O$ flux was lower than might have been expected considering the extremely high $N_2O$ concentrations in the soil air (Fig. 2, Table 2). The amounts of cattle slurry added had little effect on $N_2O$ flux and soil atmospheric concentration (Fig. 2, Table 2).

Emissions of $< 2.5$ mg $N_2O$-N $m^{-2}$ $d^{-1}$ were found in the measurements taken in April. These data are not presented in the tables or figures.

The accumulated $N_2O$ emission from the NPK-fertilized treatment for the period from June 4 to July 8 (Table 2) corresponded to 5.3% of added $NH_4NO_3$-N in compacted soil, and 3.9% in uncompacted soil. Fertilization with cattle slurry equivalent to 81 kg total N $ha^{-1}$ gave an $N_2O$ emission that corresponded to 3.1% of added $NH_4$-N in uncompacted soil, and 2.7% in compacted soil. Increasing levels of cattle slurry resulted in a reduction in $N_2O$ emission per kg $NH_4$-N added. Fertilization with cattle slurry equivalent to 189 kg total N $ha^{-1}$ gave an $N_2O$ emission of 1.9% of added $NH_4$-N in uncompacted soil, and 1.4% in compacted soil. The $N_2O$ emissions from unfertilized treatments are subtracted from the total emissions in these estimates.

An increase in $N_2O$ flux was first observed about 7 days after fertilization and was found to be most marked for compacted soils fertilized with NPK fertilizer (Fig. 2). Plots treated with cattle slurry gave lower $N_2O$ fluxes and later increases than $NH_4NO_3$-fertilized plots. This was particularly obvious for compacted soils fertilized with a high level of cattle slurry, in which maximum $N_2O$ emissions were observed at the end of the examination period.

The $N_2O$ concentrations in soil air varied throughout the growing season (Fig. 2) with a temporal pattern depending on the fertilizer type ($P < 0.01$). The $N_2O$ concentration in soil air started to increase 7 days after fertilization, in both NPK and cattle slurry fertilization. In unfertilized soil there was no marked increase in $N_2O$ concentration in soil air throughout the investigation period. As for the $N_2O$ flux, the seasonal variation in the soil air concentration was significantly affected by soil compaction ($P < 0.01$), fertilization ($P < 0.01$) and the interaction between soil compaction and fertilization

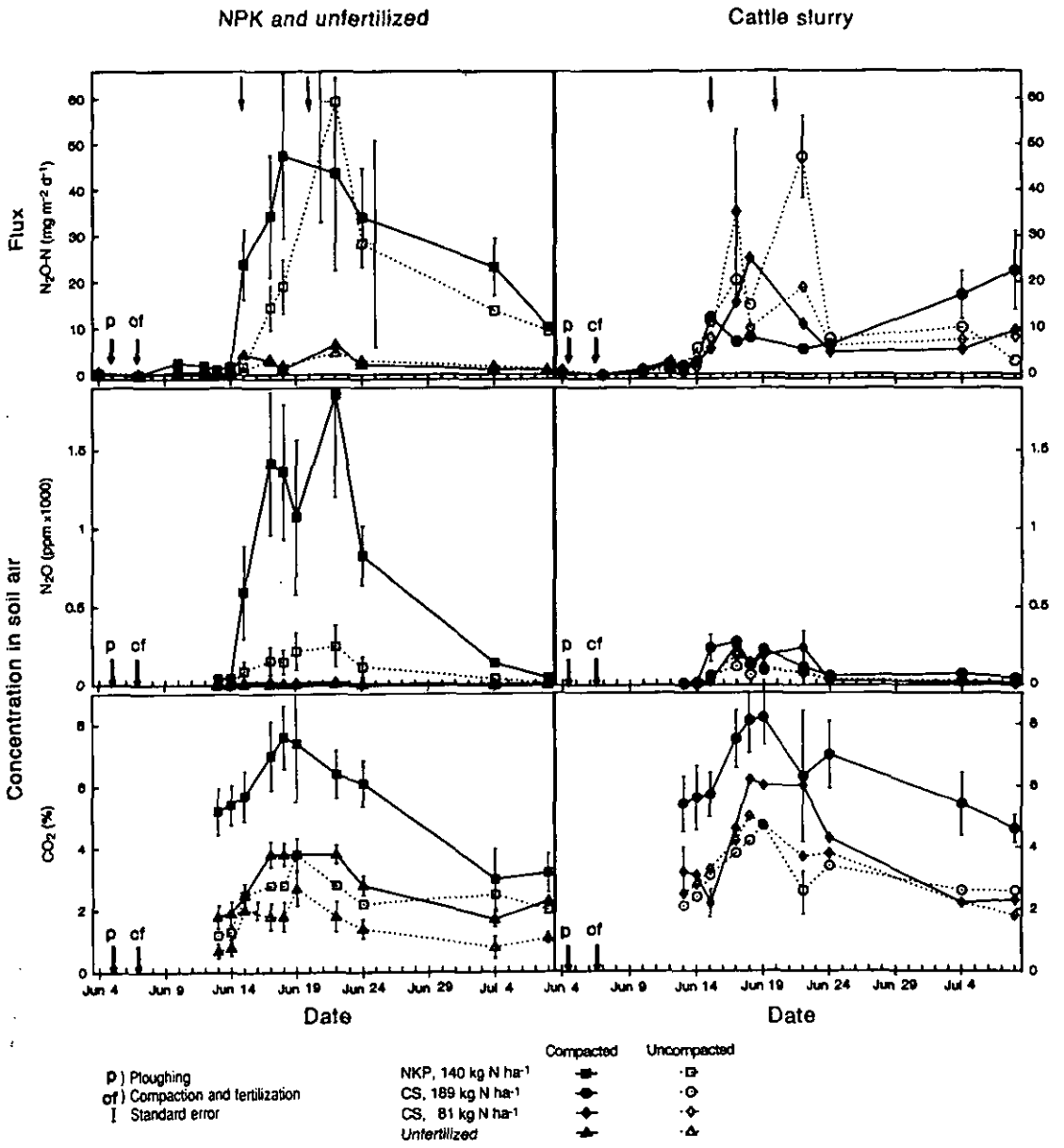


Fig. 2. $N_2O$ and $CO_2$ concentrations in soil air (7–12 cm deep) and $N_2O$ fluxes with different soil compaction, cattle slurry (CS) and NPK fertilization. Vertical lines are means ± SEM ($n = 4$). Arrows at the top indicate heavy rainfall (> 40 mm d$^{-1}$).

($P < 0.01$). This is illustrated by the large peak in $N_2O$ concentration in soil air in the compacted, NPK-fertilized treatment (Fig. 2). These effects were tested with ANOVA as interactions between time, fertilization and soil compaction.

There was a good correlation between $N_2O$ concentration in the soil air and $N_2O$ flux ($r = 0.67$, $P < 0.01$). The closest correlation was found in NPK-fertilized, uncompacted soil, where 50% of the variation in $N_2O$ flux could be explained by the variation in $N_2O$ concentration in soil air (Table 3). In compacted soil fertilized with 189 kg N in cattle slurry, the flux and soil air concentrations were not significantly correlated. The $N_2O$ emission was either weakly correlated or not correlated with concentrations of $CO_2$ in soil air, but $N_2O$ concentrations in soil air were more strongly correlated with $CO_2$ concentrations (Table 3). The air-filled porosity was negatively correlated with both $N_2O$ parameters in the uncompacted soil, in contrast to compacted soil where no significant correlation was found.

Periods with heavy rain, resulting in lowered air-filled porosity, increased $CO_2$ and $N_2O$ concentrations and $N_2O$ fluxes. Peak values for $N_2O$ fluxes were observed about 2 days after heavy rainfall (Figs 1 and 2).

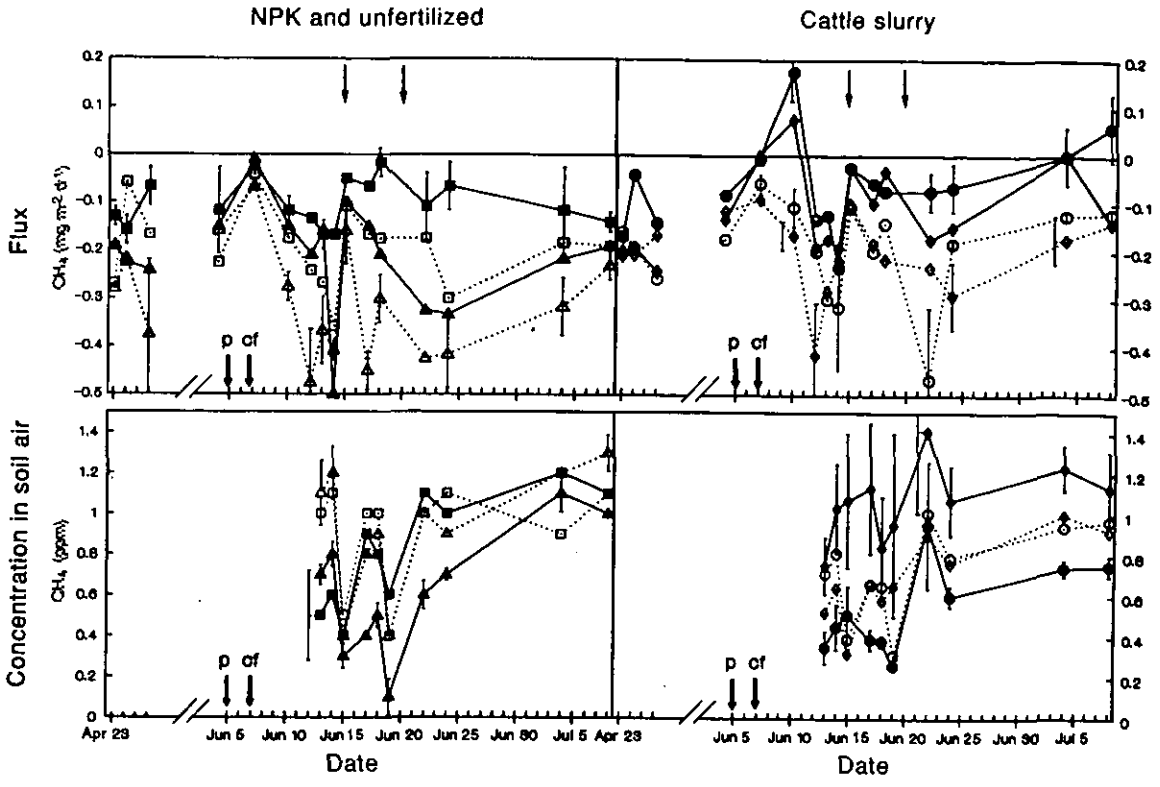


Fig. 3. $CH_4$ fluxes and concentrations in soil air (7–12 cm deep) with different soil compaction, cattle slurry (CS) and NPK fertilization. Same symbols as in Fig. 2.

Theoretically, an incubation period lasting as long as 3 h could cause retarded $N_2O$ emissions as a result of a reduction in the concentration gradient from soil to chamber air. In >90% of the cases the $N_2O$ concentration at 7–12 cm in soil air was more than eight times higher than that measured in the soil cover chambers after a 3 h closure (Table 4). Under such circumstances the $N_2O$ concentration gradient was not reduced by more than 12–13% during the 3 h. Hence, the flux is unlikely to be more seriously affected.

*$CH_4$ uptake and concentration in soil air*

The accumulated $CH_4$ uptake by soil, for the period 4 June–8 July, ranged from 1 to 10 mg $CH_4$ $m^{-2}$ (Table 2). Both fertilization ($P < 0.01$) and soil compaction ($P = 0.06$) reduced $CH_4$ uptake. Estimates of total $CH_4$ uptake based on straight lines between measured fluxes (Fig. 3) are presented in Table 2. The $CH_4$ uptake was reduced by 52% by soil compaction, 50% by fertilization and 78% by the combination of soil compaction and fertilization.

Table 2. $CH_4$ and $N_2O$-flux in the period 4 June–8 July, based on measured flux during the first 3 h of incubation; average values for each treatment ± SE and ratio between $N_2O$ emission and concentration gradient from soil to atmosphere

| Treatment | Accumulated flux | | Fertilizer derived flux g $N_2O$-N $d^{-1}$ $kg^{-1}$ min-N† | Ratio*‡ |
|---|---|---|---|---|
| | CH4 (mg $m^{-2}$)* | $N_2O$ (mg N $m^{-2}$) | | |
| Uncompacted | | | | |
| NPK, 140 kg N $ha^{-1}$§ | 6.2 ± 0.6$^a$ | 532 ± 162$^a$ | 1.1 | 38 ± 13$^a$ |
| CS, 189 kg N $ha^{-1}$ | 5.6 ± 0.4$^a$ | 358 ± 36$^a$ | 0.8 | 48 ± 9$^a$ |
| CS, 81 kg N $ha^{-1}$ | 6.4 ± 0.6$^a$ | 252 ± 37$^a$ | 1.2 | 38 ± 10$^a$ |
| Unfertilized | 9.7 ± 0.6$^b$ | 62 ± 12$^b$ | | 57 ± 15$^a$ |
| Compacted | | | | |
| NPK, 140 kg N $ha^{-1}$ | 3.0 ± 0.4$^a$ | 736 ± 112$^a$ | 1.6 | 12 ± 4$^b$ |
| CS, 189 kg N $ha^{-1}$ | 1.1 ± 0.6$^a$ | 268 ± 44$^b$ | 0.6 | 19 ± 7$^{ab}$ |
| CS, 81 kg N $ha^{-1}$ | 2.4 ± 0.7$^a$ | 217 ± 41$^b$ | 1.0 | 49 ± 23$^a$ |
| Unfertilized | 6.8 ± 0.5$^b$ | 57 ± 10$^c$ | | 21 ± 5$^a$ |

*Within each column, figures which are not significantly different, share the same letter (Newman–Keul's test, $\alpha = 0.05$).

†Average daily fertilizer derived $N_2O$ emission in g $N_2O$-N $kg^{-1}$ mineral N added.

‡Ratio = 100 emission (mg $N_2O$-N $m^{-2}$ $d^{-1}$)/concentration gradient ($\mu l\ l^{-1}$ $N_2O$), average values for each treatment ± SEM.

§NPK = NPK fertilizer; CS = cattle slurry.

Table 3. Correlation between $N_2O$ emission, $N_2O$ and $CO_2$ concentration in soil air and air-filled porosity (Pearson correlation coefficients)†

| | $N_2O$-emission‡ | | | Soil-$N_2O$ | |
|---|---|---|---|---|---|
| Treatments | Soil-$N_2O$ | Soil-$CO_2$ | Air-filled porosity | Soil-$CO_2$ | Air-filled porosity |
| Uncompacted | | | | | |
| NPK, 140 kg N $ha^{-1}$§ | 0.71*** | 0.46** | −0.48** | 0.78*** | −0.65*** |
| CS, 189 kg N $ha^{-1}$ | 0.59*** | 0.15ns | −0.45** | 0.59*** | −0.77*** |
| CS, 81 kg N $ha^{-1}$ | 0.54*** | 0.33ns | −0.49** | 0.72*** | −0.77*** |
| Unfertilized | 0.44** | 0.24ns | −0.32ns | 0.76*** | −0.57*** |
| Compacted | | | | | |
| NPK, 140 kg N $ha^{-1}$ | 0.64*** | 0.48** | −0.22ns | 0.41* | 0 |
| CS, 189 kg N $ha^{-1}$ | 0.23ns | −0.55** | −0.14ns | 0.21ns | 0 |
| CS, 81 kg N $ha^{-1}$ | 0.58*** | 0 | −0.14ns | 0.54*** | 0 |
| Unfertilized | 0.60*** | 0.56*** | 0.22ns | 0.63*** | 0 |

*Significant at 5% level; **significant at 1% level; ***significant at 0.1% level.
†Numbers of observations behind each correlation coefficient are 33–36.
‡$N_2O$-emission = ln $N_2O$ emission; soil-$N_2O$ = ln $N_2O$ concentration 7–12 cm in soil air; Soil-$CO_2$ ± $CO_2$ concentration 7–12 cm in soil air; air-filled porosity = % air of soil volume 7–11 cm in soil.
§NPK = NPK fertilizer; CS = cattle slurry.
nsNon-significant.

Table 4. Measured concentrations of $N_2O$ in chambers after 3 h, expressed as a percentage of the concentrations measured in soil air. Frequency distribution of all measurements in the period 4 June–July

| Chamber concentration in % of soil air concentration | Relative frequency |
|---|---|
| 0.01 | 0.33 |
| 0.5–2.5 | 0.41 |
| 2.4–12.5 | 0.18 |
| 12.5–62.5 | 0.06 |
| 62.5–125 | 0.02 |

There was no significant difference between fertilization with $NH_4NO_3$ or that with cattle slurry. Neither did the amount of cattle slurry added affect the $CH_4$ uptake significantly. There was no interaction between fertilizers and soil compaction with respect to $CH_4$ uptake.

Both $CH_4$ uptake and $CH_4$ concentration in soil air varied throughout the growing season ($P < 0.01$), but there was no significant correlation between these two parameters.

In three of the fertilizer treatments (NPK, CS 189 and unfertilized), $CH_4$ concentrations and fluxes were lower in compacted than in uncompacted soil. In the CS 81 treatment, compacted soil had lower fluxes and much higher concentrations than those in uncompacted soil (Fig. 3).

Favourable conditions for $N_2O$ production are unfavourable for $CH_4$ oxidation and a negative correlation between these two processes was expected. No clear correlation between $CH_4$ uptake or $CH_4$ concentration in soil air and $N_2O$ emission or concentration in soil air was found, however (Table 5). The $CH_4$ concentration in soil air was negatively correlated with $CO_2$ concentration in soil air (Table 5), but there was no correlation between $CO_2$ concentration in soil air and $CH_4$ uptake in the soil.

## DISCUSSION

### *$N_2O$ emission and soil air concentration*

Our estimated $N_2O$ emissions (corresponding to 1–5% of added mineral N, Fig. 2, Table 2) are large compared with results reported in the review by Eichner (1990) where $N_2O$ emissions corresponding to 0.01–1.7%, or 4.4–174.5 mg daily $N_2O$-N $kg^{-1}$ added $NH_4NO_3$-N are reported. The large $N_2O$ emissions found in our study can probably be explained by the extremely high precipitation together

Table 5. Correlation between uptake and soil air concentration of $CH_4$, $N_2O$ emission and $N_2O$ and $CO_2$ concentration in soil air (Pearson correlation coefficients)†

| | $CH_4$-uptake‡ | | Soil-$CH_4$ | | |
|---|---|---|---|---|---|
| Treatments | $N_2O$-flux | Soil-$N_2O$ | $N_2O$-flux | Soil-$N_2O$ | Soil-$CO_2$ |
| Uncompacted | | | | | |
| NPK, 140 kg N $ha^{-1}$§ | 0 | 0.37* | 0.06ns | 0.41* | −0.73*** |
| CS, 189 kg N $ha^{-1}$ | −0.37* | 0 | 0.29ns | −0.20ns | −0.47** |
| CS, 81 kg N $ha^{-1}$ | 0 | 0.11ns | 0 | −0.25ns | −0.53*** |
| Unfertilized | 0 | 0 | 0 | −0.51** | −0.76*** |
| Compacted | | | | | |
| NPK, 140 kg N $ha^{-1}$ | 0.35* | 0.44** | 0.17ns | 0.31ns | −0.49** |
| CS, 189 kg N $ha^{-1}$ | 0.13ns | 0.39* | 0.44** | 0 | −0.47** |
| CS, 81 kg N $ha^{-1}$ | 0.26ns | 0.12ns | −0.26ns | 0 | 0.29ns |
| Unfertilized | −0.17ns | 0.22ns | −0.21ns | −0.38* | −0.53*** |

*Significant at 5% level; **significant at 1% level; ***significant at 0.1% level.
†Numbers of observations behind each correlation coefficient are 33–36.
‡$CH_4$-flux = $CH_4$ uptake; Soil-$CH_4$ = $CH_4$ concentration 7–12 cm in soil air.
§NPK = NPK fertilizer; CS = cattle slurry.
nsNon-significant.

with soil conditions that preclude efficient draining of the topsoil. As a result of abrupt textural change between the top layer and the gravelly subsoil, there is poor capillary contact to deeper soil layers and the soil moisture tension has to reach a relatively low level (pF 1.5–2) before draining to the gravel layer can begin. Thus the water will not drain out during long periods of rain and the water content in the soil will remain high. From 15 to 22 June there was 107 mm rain and the soil was already wet in advance of this rain [water-filled pore space (WFPS) in compacted soil was 81 and 73% in uncompacted soil]. Throughout this rainy period the water-filled pore space increased further and air-filled porosity in the soil decreased (Fig. 1). Even in uncompacted soil, air-filled porosity decreased to $<10\%$.

Because of the high water content in the soil and the weak structure in this sandy loam, the soil structure is easily deteriorated by soil compaction. Thus the tractor traffic on the compacted soils has probably caused greater damage on the soil structure and more anaerobic conditions than similar compaction would do in most areas with similar agricultural practises. We observed that soil compaction resulted in reduced air-filled porosity (Fig. 1) and increased $CO_2$ concentration in soil air (Fig. 2). In addition, Hansen (unpubl. data) demonstrated a decreased number of earthworms as a result of the compaction. The low air-filled porosity and high $CO_2$ concentrations in compacted soil indicate retarded diffusion through the upper soil layer. The $CO_2$ concentrations were particularly high in the treatments fertilized with 140 kg $NH_4NO_3$-N or 189 kg N in cattle slurry (Fig. 2). The same treatments had a very low $N_2O$ emission: $N_2O$ gradient ratio (Table 2).

As reviewed by Davidson (1991), denitrification becomes increasingly important as a source of $N_2O$ when WFPS exceeds 60%. In our experiment the mean WFPS (10 June–8 July) was 82% in compacted soils. Fertilization with $NO_3$-N in compacted soil would therefore easily cause $N_2O$ release by denitrification. The high peaks in $N_2O$ concentration in soil air that were found when soil compaction and $NH_4NO_3$ fertilization were combined (Fig. 2) are probably due to high denitrification rates. $N_2O$ emission caused by nitrification has probably played a minor role in our investigation because of the high moisture content in the soil. According to Davidson (1991), 30–70% WFPS is an optimal range for nitrification; in our study WFPS varied between 68 and 93%.

Considering the high WFPS values in our soil, a significant fraction of the N lost through denitrification will probably end up as $N_2$ (Davidson, 1991). Thus, measured $N_2O$-emissions (Table 2) probably constitute only a portion of nitrogen loss caused by denitrification. In a previous study in the same experimental field Hansen and Bakken (unpubl. data) estimated that nitrogen loss by denitrification during the first 2 weeks after fertilization with 126 kg $NH_4NO_3$-N $ha^{-1}$ was increased by about 50 kg N $ha^{-1}$ as a result of compaction. Nitrogen losses caused by denitrification are also reported elsewhere and the potential losses are large. von Rheinbaben (1990) refers to denitrification estimates by the $^{15}N$ balance and acetylene inhibition methods ranging from 0 to 77% of total fertilizer N. With the help of the acetylene method, Colbourn *et al.* (1984) found a denitrification potential of 320–390 g N $ha^{-1}$ $d^{-1}$ $kg^{-1}$ applied $NO_3$-N in field and laboratory experiments.

In compacted soil fertilized with cattle slurry the denitrification rate is likely to increase throughout the growth period. This is indicated by increasing $N_2O$ emissions towards the end of the examination period in these treatments (Fig. 2). Organic material and $NO_3$-N from nitrification of $NH_4$-N in the cattle slurry are available, and at the same time the air content in the compacted soil is very low. In uncompacted soil, the risk of denitrification towards the autumn is much less. The plants grow better, more $NO_3$ is taken up by the crop and more oxygen is available.

*Source of error in the $N_2O$ emission estimates*

The use of an average value for atmospheric $N_2O$ concentration as a starting concentration for each cylinder (time zero) creates some uncertainty in flux estimates. The variability of atmospheric background was quite large; the SD being 0.1 $\mu l$ $l^{-1}$. An error of 0.1 $\mu l$ $l^{-1}$ in estimated $N_2O$ accumulation during a 3 h incubation period is equivalent to a flux error of 0.2 mg $N_2O$-N $m^{-2}$ $d^{-1}$. This is equivalent to 7 mg $N_2O$-N $m^{-2}$ for the whole 35-day period of our measurements, which probably represents the maximum error due to the uncertainty in the initial concentrations. This uncertainty is equivalent to 12–13% of the total estimated emission in unfertilized treatments and $<4\%$ in the fertilized ones.

As most measurements in the present investigation were carried out around noon, diurnal variation and temperature increase could theoretically cause erroneously high $N_2O$ emissions (Denmead *et al.*, 1979; Ryden *et al.*, 1978). The total $N_2O$ flux values are probably not seriously affected. This is because of the reflecting surface of the soil cover chambers (Bakken *et al.*, 1987), and because most of the measured $N_2O$ release took place in periods with cloudy weather (Blackmer *et al.*, 1982).

*$CH_4$ uptake and concentration in soil air*

Our estimates of $CH_4$ uptake in agricultural soil are in the same order of magnitude as the estimates of Mosier *et al.* (1991). The decrease in $CH_4$ uptake caused by fertilization is probably an effect of nitrogen (Fig. 2, Table 2). This is in agreement with the findings of Mosier *et al.* (1991), Steudler *et al.* (1989) and has been attributed to concentration of $NH_3$: $NH_4^+$ in the soil (Bedard and Knowles, 1989). $NH_3$

and $CH_4$ apparently compete for the same active site on the monooxygenases, the enzymes catalyzing the first oxidation step of $CH_4$ and $NH_4^+$ in methanotrophs and nitrifiers (Bedard and Knowles, 1989). Jones and Morita (1983) found that a concentration level of $NH_4$-N or $NO_3$-N of 10 $\mu$l $l^{-1}$ increased the $CH_4$ oxidation by ammonia oxidizers (*Nitrosomonas europea*, *Nitrosococcus oceanus*). Increasing concentrations of $NH_4$-N above this level (50 and 100 $\mu$l $l^{-1}$) decreased $CH_4$ oxidation, but $CH_4$ oxidation was not influenced by a similar increase in $NO_3$-N concentration.

In our study the mineral N concentrations in the soil were not determined during the growing season 1991, but earlier observations of $NH_4$-N concentrations in the same field experiment showed a range of $NH_4$-N concentration in the soil from 2 to 15 $\mu$g $g^{-1}$ dry wt (three measurements yearly in 5 previous years, unpubl.). Fertilization seemed to increase the amount of $NH_4$-N in the soil only slightly (average increase = 0.5 $\mu$g $g^{-1}$ dry wt, max registered increase = 6.4 $\mu$g $g^{-1}$ dry wt). We neither know the reactions of nitrifiers in this range, nor how methanotrophs would respond to increasing $NH_4$-N concentrations, but the slight differences in concentrations of $NH_4$-N suggest that the inhibiting effect of fertilization on $CH_4$ uptake cannot only be due to the $NH_4$-N concentration in the soil. On the other hand a bulk measurement of $NH_4$-N in the soil might be very different from the $NH_3$ actually available in the active site of the monooxygenases in nitrifiers and methanotrophs. Measured nitrification would be a much better measurement of ammonia available for nitrifiers and methanotrophs. Mosier *et al.* (1991) suggested that it is the N turnover rate (mineralization and nitrification) rather than the mineral N content that influences the $CH_4$ oxidation.

The reduction in $CH_4$ uptake caused by soil compaction (Fig. 2, Table 2) is probably attributable to retarded diffusion. This explanation is supported by the fact that soil compaction reduced the soil air concentration as well as the flux. The only exception to this pattern was CS 81 kg N $ha^{-1}$.

The lack of correlation between $CH_4$ uptake and $N_2O$ emission (Table 5) is in contrast to the results of Mosier *et al.* (1991), who found that $N_2O$ emissions from the soils were inversely related to $CH_4$ uptake. We had a very high moisture content and consequently low air-filled porosity during the whole period of measurement. Our results would probably have been different if we had measured flux over a large range of soil moisture contents.

To summarize, soil compaction and fertilization had an effect on both $N_2O$ and $CH_4$ flux. The accumulated $N_2O$ emission from the NPK-fertilized treatment corresponded to 5.3% of added $NH_4NO_3$-N in compacted soil, and 3.9% in uncompacted soil. Fertilization with cattle slurry equivalent to 81 kg total N $ha^{-1}$ gave an $N_2O$ emission corresponding to 3.1% of added $NH_4$-N in uncompacted soil, and 2.7% in compacted soil. Fertilization with cattle slurry equivalent to 189 kg total N $ha^{-1}$, gave a $N_2O$ emission of 1.9% of added $NH_4$-N in uncompacted soil, and 1.4% in compacted soil. Increasing levels of cattle slurry resulted in a reduction in $N_2O$ emission per kg $NH_4$-N added. The $CH_4$ uptake in the soil, ranging from 1 to 10 mg $CH_4$ $m^{-2}$, was reduced by 52% by soil compaction, 50% on average by fertilization and 78% by a combination of soil compaction and fertilization. Fertilization with $NH_4NO_3$ or cattle slurry had a similar effect on $CH_4$ uptake.

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