Field N₂O, CO₂ and CH₄ fluxes in relation to tillage, compaction and soil quality in Scotland

Bruce C. Ball*, Albert Scott, John P. Parker

Environmental Division, SAC, West Mains Road, Edinburgh EH9 3JG, UK

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Abstract

Tillage practices and weather affect the release of greenhouse gases but there have been few integrated studies of the quantities released or the mechanisms involved. No-tillage may increase emissions of nitrous oxide (N₂O) and the fixation of carbon by decreasing carbon dioxide (CO₂) emissions. Tillage may also decrease the oxidation rate of atmospheric methane (CH₄) in aerobic soil. These effects are partly due to compaction and to the lack of both soil disturbance and residue incorporation. Our objective was to investigate how tillage practices, soil conditions and weather interact to influence greenhouse gas emissions. Here we present early measurements of N₂O and CO₂ emission and CH₄ oxidation in two field experiments in Scotland under a cool moist climate, one involving soil compaction plus residue incorporation and the other involving no-tillage and two depths of mouldboard ploughing of a former grass sward. The experiments were located 10–15 km south of Edinburgh on a cambisol and a gleyso. In order to monitor emissions regularly, at short intervals and over long periods, a novel automatic gas sampling system which allows subsequent automated determination of both N₂O and CO₂ fluxes was used. Both N₂O and CO₂ fluxes were episodic and strongly dependent on rainfall. Peak N₂O emissions were mainly associated with heavy rainfalls after fertilisation, particularly with no-tilled and compact soils. In the tillage experiment, N₂O fluxes and treatment differences were greater under spring barley (Hordeum vulgare L.) (up to 600 g N ha⁻¹ per day) than under winter barley. CO₂ emissions in the few weeks after sowing were not strongly influenced by tillage and diurnal variations were related to soil temperature. However, periods of low or zero CO₂ fluxes and very high N₂O fluxes under no-tillage were associated with reduced gas diffusivity and air-filled porosity, both caused by heavy rainfall. Early results show that CH₄ oxidation rates may best be preserved by no-tillage. The quality of the loam/clay-loams and the climate in these experiments makes ploughing, preferably to 300 mm depth, and the control of compaction necessary to minimise soil N₂O and CO₂ losses. The gas exchange response of different soil types to tillage, particularly methane oxidation rate which is affected by long-term soil structural damage, is a potentially useful aspect of soil quality when taken in conjunction with other qualities. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Tillage; Compaction; No-till; Trace gas exchange; Soil quality

1. Introduction

Gas exchange between soils and the atmosphere is an important contributory factor to global change due...
to increasing release of greenhouse gases (Bouwman, 1990). Three of the principal gases of interest are nitrous oxide (N$_2$O), carbon dioxide (CO$_2$) and methane (CH$_4$). Both N$_2$O and CO$_2$ are emitted from the soil whereas CH$_4$ is normally oxidised by aerobic soils making them sinks for atmospheric CH$_4$ (Goulding et al., 1995). The N$_2$O emissions are normally associated with N (as fertiliser or manure) application under wet conditions (Clayton et al., 1994) and CO$_2$ emissions with respiration which is often stimulated by tillage (Roberts and Chan, 1990). Reduced or no-tillage systems may decrease CO$_2$ emission, thereby increasing the storage of soil C (Kern and Johnson, 1993), but may increase N$_2$O emission (Aulakh et al., 1984). Soil compaction by tractor wheels can also increase N$_2$O emission above that associated with zero traffic levels (Douglas and Crawford, 1993). Soil conditions, particularly near the soil surface, have an important influence on N$_2$O emission (Arah et al., 1991). The production, consumption and transport of N$_2$O and CO$_2$ are strongly influenced by the changes in soil structural quality and in water content associated with tillage and compaction. One such soil quality influencing gas transport in soil is gas diffusivity. The influence of tillage and compaction on soil conditions (including gas diffusivity) and on consequent gaseous emissions may be the important aspects of soil quality.

The objective of this paper was to investigate how tillage practices, soil conditions and weather interact to influence greenhouse gas emissions. We show some early measurements of N$_2$O and CO$_2$ emission in two field experiments in south-east Scotland, one involving soil compaction and residue incorporation and the other involving no-tillage and two depths of mouldboard ploughing. Emissions were related to soil qualities and weather conditions.

2. Methods and materials

2.1. Study sites

The compaction experiment was located on an imperfectly drained loam of Macmerry series (Cambisol) in 1995. The tillage experiment was located on an imperfectly drained clay loam of Winton series (Eutric Gleysol).

2.2. Tillage and compaction experiments

The design of the compaction experiment was a randomised complete block with fourfold replication. The plots were 24 m x 2.4 m. Further details were given by Ball and Ritchie (1999). Treatments were applied to soil which had been mouldboard ploughed the previous day, incorporating the chopped residues of the previous cereal crop. Treatments were (1) zero compaction, (2) light compaction (target depth of 100 mm) using a heavy roller (up to 1 Mg m$^{-1}$), (3) heavy compaction (target depth of 250 mm) using a laden tractor (up to 4.2 Mg) and (4) heavy compaction and the soil subsequently loosened down to 100 mm depth with a rotary cultivator. Ploughing and treatment application occurred twice in 1995, before sowing spring barley in April and before sowing winter barley in September. Nitrogen fertiliser was applied to the spring barley at sowing (12 April 1996) at 120 kg N ha$^{-1}$. For the winter barley, N was applied to the growing crop at 70 kg N ha$^{-1}$ on 7 March 1996 and at 110 kg N ha$^{-1}$ on 17 April 1996.

The experimental design of the tillage experiment was split-plot with prior sward composition (either grass or grass with clover) as the main blocks. The sub-treatments included timing of cultivation (either autumn or spring) and tillage. The split-plots were 12 m x 10 m. The tillage treatments were applied to a former 12 year-old grass sward and were either conventional mouldboard ploughing to 200 mm, deep mouldboard ploughing to 300 mm or no-tillage. No-tillage involved spraying the sward with paraquat and drilling with a single-disc drill which created seeding slits about 5 cm deep. Spring barley was sown on 5 April 1996. Nitrogen fertiliser was broadcast at 80 kg N ha$^{-1}$ at sowing. After harvest, barley was again sown as a winter versus spring treatment on 26 September 1996 and on 7 April 1997. The main fertiliser applications were made on 9 April 1997. The winter barley received 60 kg N ha$^{-1}$ on 12 March 1997 and on 9 April 1997. The spring barley received 80 kg N ha$^{-1}$ on 9 April 1997, which was 2 days after sowing.

2.3. Gas fluxes

Gas fluxes were measured using closed chamber systems. The atmosphere immediately above the soil
surface is enclosed by the chamber and is sampled 1 h after closure (CO₂ and N₂O) or at regular intervals over a 1 h period after closure (CH₄). For a constant net emission of N₂O or CO₂, we have found that the increase in concentration within closed chambers is linear over a period of up to 3 h. This change in concentration is a result of net emission from or uptake by the soil and enables gas flux to be determined. We have developed gas sampling techniques using both manually and automatically closed chambers.

The manual chambers (Clayton et al., 1994) were 0.2 m-tall polypropylene cylinders of diameter 0.4 m, pushed into the soil to a depth of 50 mm giving a head space of 16 dm³ on enclosure with an aluminium lid. Gas samples were taken in syringes (N₂O), Tedlar bags (CH₄) or aluminium sampling tubes (CO₂ and N₂O) and subsequently analysed in the laboratory by chromatography. In order to assess the effects of no-till drill slits on N₂O flux, small manual chambers (steel cylinders of diameter 73 mm) were pushed into the soil to a depth of 30 mm so as to either enclose a section of drill slit or the area between drill slits. These chambers were enclosed by close-fitting plastic caps, containing an injection port.

The automatic chambers (0.7 m × 0.7 m (1996) or 1 m × 0.5 m (1997)) have an actuator-driven, lid-closing system. The actuator is controlled by an external, battery-operated, timing and sampling unit, which allows remote collection of gas samples to be carried out at programmed time intervals. Samples (1 ml) are collected by pumping into one of 24 isolated copper loops, attached to two rotary valves. The entire valve/loop assembly is removed and replaced by another assembly in order to preserve continuity of sampling. The filled loop assembly is transported to the laboratory for gas chromatographic analysis of either N₂O or CO₂. In 1997, an improved sampling system was introduced. In this system the gas samples were stored in aluminium tubes (30 ml) instead of copper loops. The increased volume permitted multiple, simultaneous analysis of CO₂ and N₂O. Further details are given in Scott et al. (1999). In both manual and automated chamber systems, ambient air is collected and used as the reference for calculating gas fluxes. For both tillage and compaction experiments, the automated chambers were programmed to close for a duration of 1 h starting at 13:00 hours and remain open for 3 h, thereby giving eight flux assessments per day. The manual chambers were assessed once or twice per week. Due to the large number of samples generated by the auto-systems, only one replicate per treatment was possible. Spatial variability was determined using the manual chambers (six per treatment).

In the compaction experiment, automatic chambers were used to measure N₂O emissions shortly after fertiliser application in 1996. To make measurements on the remaining 12 plots, manual chambers were used to measure N₂O emission after fertiliser application to spring and winter barley and during autumn growth of the winter barley. In the tillage experiment, in 1996, automatic chambers were used to measure CO₂ flux from just after sowing until May, and N₂O flux from May to June. Both gases were also measured about once per week using manual chambers. Finally, as an initial exploratory study, methane oxidation rate was measured once in December 1996 using manual chambers in one plot of both spring and winter barley treatments, and in duplicate in woodland and grassland immediately adjacent to the experimental plots.

In order to estimate the production and consumption of N₂O in the near-surface zone, we measured its concentration in the soil using 4 mm ID, 6 mm OD stainless steel tubes of length 450 mm with four pairs of holes (2 mm diameter) allowing gas access and spaced at 10 mm intervals from the closed end of the tube. The tube was bent at right angles to the holes 260 mm from the closed end to allow sampling access to the other end which was sealed using a rubber/Teflon septum. The completed tubes were inserted horizontally into the soil at right angles to the direction of the plough or drill at depths of 10, 20, 50, and 100 mm in one plot of each treatment. Care was taken to locate the centres of the holes at the depth of interest. The sealed ends of the tubes protruded above the soil surface. 1 ml of the soil atmosphere was sampled and analysed within 4 h by gas chromatography. Measurements were made at intervals of 3–8 days between 18 April and 28 May 1997.

Nitrous oxide was measured using a Pye Unicam 4500 gas chromatograph fitted with a 63Ni electron capture detector at 360°C, using Pureshield Argon (BOC, Manchester) as carrier gas (35 ml min⁻¹). Separation was carried out on a 1 m column (55°C) packed with HayeSep Q, 60–80 mesh (Haye Separations, Bandera, TX). Carbon dioxide was measured using a Hewlett Packard 5890 (Avondale, PA) gas
chromatograph fitted with a thermal conductivity detector at 60°C. Separation in this instance was performed on a 1.5 m column (80°C) packed with Porapak Q, 50–80 mesh (Millipore, Millford, MA) using Grade A Helium (BOC) as carrier gas (40 ml min⁻¹). Analysis of both gases was complete within 4 min of injection.

Gas diffusivity was measured in situ in the tillage experiment in Spring 1996 by injecting Freon into a chamber enclosing the soil surface and measuring its subsequent rate of escape into the soil (Ball et al., 1997). Measurements were made at one location in each of four subplots of each treatment. Bulk density was measured in the compaction experiment from 0–250 mm depth in cores at increments of 50 mm, two samples per depth.

3. Results and discussion

3.1. Nitrous oxide fluxes

Nitrous oxide is emitted by soils as a result of denitrification in anaerobic soil and nitrification in aerobic soil with the anaerobic production considered more important. Thus emissions generally increase with increasing soil moisture. In the compaction experiment, although the soil at treatment and fertiliser application under the spring barley was quite wet (22–30% w/w), no treatment effects on N₂O emission were found, probably because of insufficient soil compaction to the target depths. This, combined with the subsequent dry weather was considered the reason for the low N₂O fluxes detected using the manual chambers throughout the spring barley season (Table 1).

Under winter barley, the heavy compaction treatment was made more effective by a 25% increase in the weight of the tractor through the use of ballast. This was demonstrated by the significantly greater bulk density of the soil under the heavy compaction compared to the zero treatment (Table 2). This greater compaction, combined with wetter weather after fertiliser applications in the spring, resulted in greater emissions of N₂O after sowing and, particularly, after fertiliser application (Table 1). The lowest emitting treatment was light compaction and the treatments giving the highest peaks were those involving heavy compaction. The difference in emission between the zero compaction and the heavy compaction treatments is shown more clearly by the fluxes from the automated closed chambers after spring fertilisation (Fig. 1). The heavy compaction treatment gave a greater emission response to rainfall than the zero compaction treatment. Treatment differences were more marked and more consistent than those shown by the manual chambers. Fig. 1 illustrates the importance of the frequent, regular sampling possible with the automatic chambers in detecting peaks of emissions which might be otherwise undetected in a manual system. In a similar compaction experiment in Norway, Hansen et al. (1993) also found that emissions from soil compacted by a tractor (similar to our heavy compaction treatment) were greater than in soil

Table 1
Total rainfall and average nitrous oxide emission in the manual chambers over three periods in the compaction experiment

<table>
<thead>
<tr>
<th>Crop</th>
<th>Period</th>
<th>Total rainfall (mm)</th>
<th>N₂O emission (µg N m⁻² h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Zero compaction</td>
</tr>
<tr>
<td>Spring barley (1995)</td>
<td>5 April–14 July</td>
<td>119</td>
<td>11.7</td>
</tr>
<tr>
<td>Winter barley (1995–96)</td>
<td>29 September–7 March (pre-fertilisation)</td>
<td>338</td>
<td>22.1</td>
</tr>
<tr>
<td>Winter barley (1996)</td>
<td>8 March – 22 May (post-fertilisation)</td>
<td>117</td>
<td>26.7</td>
</tr>
</tbody>
</table>

Table 2
Bulk density (Mg m⁻³) at two soil depths 1 month after the second treatment application in the compaction experiment

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Zero Compaction</th>
<th>Light compaction</th>
<th>Heavy compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–100</td>
<td>1.21a</td>
<td>1.26a</td>
<td>1.40b</td>
</tr>
<tr>
<td>100–250</td>
<td>1.26a</td>
<td>1.32b</td>
<td>1.39b</td>
</tr>
</tbody>
</table>

*Means with different letters within the same row differ significantly (p < 0.05).
subject to normal traffic. However our emissions were considerably lower than those reported by Douglas and Crawford (1993) in an experiment on the response of ungrazed ryegrass (*Lolium perenne* L.) to compaction on a clay loam. Further details of N$_2$O emissions in this experiment were given by Ball et al. (1999).

In the tillage experiment, the sequence of individual N$_2$O fluxes in the automatic chambers in the first season (Fig. 2), although measured 7 weeks after sowing and fertilisation, showed a marked response to rainfall events and were very high, particularly under no-tillage. Such high levels so long after fertilisation are unlikely to be associated with direct fertiliser loss and conform with the suggestion of Smith et al. (1994) that nitrogen fertilisation should be regarded as a stimulus to the nitrogen dynamics of the system, thereby giving N$_2$O production over a long period. The dead grass sward is likely to have provided a source of readily mineralisable nitrogen. However, in the second season, emissions were again very high from the no-tilled spring barley reaching even higher peaks after heavy rainfall than in the first season (Fig. 3). These emissions were much greater than those under the winter barley in adjacent plots where there was little difference between tillage treatments and emissions were less than 45 g N ha$^{-1}$ per day. The lower emission from the winter barley is related to the presence of an actively growing crop in spring at the time of fertiliser spreading which takes up the applied nitrogen more quickly and maintains the soil drier than under spring barley. The N$_2$O emissions were least from the ploughed to 300 mm treatment in both seasons. Infrequent assessments of N$_2$O emissions using the manual chambers (data not shown) indicated differences of similar magnitude between treatments.

The greater emissions of N$_2$O under no-tillage corresponded to lower in situ gas diffusivities and higher water contents (Table 3) near the soil surface than in the ploughed treatments. In the compaction experiment, the increased emission of N$_2$O as a result of compaction (Table 1) was also accompanied by decreased diffusivity near the soil surface, though
Fig. 2. Temporal variability of N₂O fluxes and 3-hourly rainfall in the tillage experiment under spring barley 7–10 weeks after sowing and fertilisation of 80 kg N ha⁻¹ in spring 1996, assessed using the automatic chambers. The crop was sown and fertilised on 5 April.

Fig. 3. Weekly average N₂O fluxes and rainfall in the tillage experiment under spring barley 1–11 weeks after sowing and fertilisation of 80 kg N ha⁻¹ in spring 1997, assessed using the automatic chambers sampling eight times per day. The crop was sown and fertilised on 7 April.
there was little difference in water content between treatments. Hence the no-tilled and compacted soils were likely to have been less aerobic than the tilled soils but with restricted opportunities for gas escape.

The low diffusivity near the no-tilled soil surface (Table 3) did not hamper the rapid emission of N\textsubscript{2}O under spring barley, possibly because the sites of production were close to the soil surface, as shown by the high concentrations at shallow depth (Fig. 4). This also explains the importance of surface disturbance by the drill in increasing N\textsubscript{2}O emission from no-tilled soil as revealed by emissions from soil enclosing a drill slit (Table 4) being double those from soil between slits. Under wheat cropping in Saskatchewan, Canada, Aulakh et al. (1984) found that gaseous losses of nitrogen were twofold higher under no-tilled than under conventional tilled systems with emissions of up to 700 g N\textsubscript{2}O–N ha\textsuperscript{–1} per day under no tillage in the 2–3 month period after sowing. They attributed the higher gaseous losses under no-tillage to higher bulk density and larger soil aggregates, reducing gas diffusivity, and greater water conservation near the soil surface overall making the soil less aerobic than under conventional tillage. Further, Arah et al. (1991) found very low emissions (<1.5 g N\textsubscript{2}O–N ha\textsuperscript{–1} per day) at a site at South Road, Bush Estate, near to the tillage experiment on similar soil under long-term no-tillage, despite the presence of significant concentrations of N\textsubscript{2}O in the soil profile. This effect was attributed to restriction of gas diffusivity in soil near the surface, permitting consumption of N\textsubscript{2}O produced below the layer near the surface. Although the emission of N\textsubscript{2}O is very episodic, it may
provide an indicator of soil quality if measured as the response to fertiliser application.

3.2. Carbon dioxide fluxes

Carbon dioxide is produced in soil as a result of decomposition of organic material by micro-organisms and root respiration. Effects of tillage on CO₂ fluxes measured using the automated chambers were less consistent than for N₂O emission (Figs. 5 and 6). For this reason, the results for 1997 (Fig. 6), corresponding to the longer period of measurement, are shown as weekly means. Differences between tillage treatments were small in the first weeks after tillage in both seasons. Reicosky and Lindstrom (1993) also reported small differences in CO₂ fluxes between tillage treatments. In the short period after tillage, high fluxes caused by increasing depth of tillage, were related to the rougher surface and larger voids produced by increasing tillage depth. The sequence of individual CO₂ emissions in 1996 (Fig. 5) shows marked diurnal cycling which differs between treatments and which reflects soil temperature at 50 mm depth. In 1996 (Fig. 5), peak emissions from the deep (300 mm) ploughed soil were greater than from the soils of the other treatments. However, in 1997 (Fig. 6), emissions were generally greatest in the 200 mm ploughed treatment.

Carbon dioxide emission decreased sharply under no-tillage in 1997 after heavy rainfall. Under no-tillage, macroporosity was considerably less than in the ploughed treatments (M.F. O’Sullivan, unpublished data, 1998). Thus the sharp decrease in emission may have resulted from restriction of the soil macroporosity by the heavy rainfall, reducing soil air-filled pore space and respiration and increasing anaerobism. This conclusion is supported by the concurrent increase in N₂O emission in these post-rainfall periods (Fig. 3). The sustained high production of CO₂ in the tilled treatments in the wet period may have resulted from greater aerobic respiration as a result of the lower water-filled pore space than under no-tillage as observed by Linn and Doran (1984).

Carbon dioxide measurements have been used to reveal suppression of gross biological activity associated with harvest damage during forest operations, in spite of operations to mitigate any such damage to soil structure (Dulohery et al., 1996). Gas exchange properties may thus provide useful indicators of soil quality related to structural damage in agricultural soils.

3.3. Methane oxidation rates

Methane oxidation rate can be reduced by tillage due to the disturbance of the methane-oxidising microbes, but is also influenced by gaseous diffusivity as this affects the rate of supply of atmospheric CH₄. A decrease in the ability of the soil to oxidise atmospheric CH₄ can also indicate long-term damage to CH₄ oxidisers and soil porosity associated with the disruption of soil structure by tillage (Ball et al., 1997). Initial measurements in December 1996 in the tillage experiment (Table 5) show that after 8 months of arable cropping, the CH₄ oxidation rate was reduced, by ploughing to 200 mm, to about one-quarter of that under no-tillage, which remained similar to that under the undisturbed grassland. This was in spite of gas diffusivity at the soil surface being lower under no-tillage (Table 3) than under ploughing to

Table 5
Methane oxidation rate in the tillage experiment, December 1996

<table>
<thead>
<tr>
<th>Tillage treatment</th>
<th>Land use</th>
<th>Methane oxidation rate (mg CH₄ m⁻² per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ploughed to 200 mm</td>
<td>Arable for 3 months</td>
<td>0.8</td>
</tr>
<tr>
<td>Ploughed to 300 mm</td>
<td>Arable for 3 months</td>
<td>0.6</td>
</tr>
<tr>
<td>No-tilled</td>
<td>Arable for 3 months</td>
<td>0.6</td>
</tr>
<tr>
<td>Ploughed to 200 mm</td>
<td>Arable for 8 months</td>
<td>0.2</td>
</tr>
<tr>
<td>Ploughed to 300 mm</td>
<td>Arable for 8 months</td>
<td>0.5</td>
</tr>
<tr>
<td>No-tilled</td>
<td>Arable for 8 months</td>
<td>0.8</td>
</tr>
</tbody>
</table>

*The grassland was changed to arable using the indicated tillage treatments on April 1996 or September 1996.
Fig. 5. Temporal variability of CO₂ fluxes and soil temperature at 50 mm depth in the tillage experiment under spring barley in the 2 weeks after sowing in spring 1996, assessed using the automatic chambers. The crop was sown and fertilised on 5 April 1996.
200 mm, thereby restricting the entry of atmospheric CH₄. These results confirm earlier observations by Dobbie et al. (1996) and others that CH₄ oxidation is a useful indicator of land use and tillage change. Methane oxidation rate is less episodic than N₂O and CO₂ emission and may provide a useful indicator of soil quality. Other studies in Scotland (MLURI, 1997) have used microbial gaseous products (including methane) as quality indicators of soils undergoing land use change. However, trace gas exchange is determined by a complex interaction of several soil factors so that the measurement of any one of several trace gas exchange properties is unlikely to be a satisfactory indicator of soil quality without accompanying measurements of soil structure and chemical properties.

4. Conclusions

1. Temporal variability of gas fluxes was marked in tillage and compaction treatments and was readily assessed using an automated gas sampling system at frequent measurement intervals. Episodic N₂O fluxes were mainly associated with the period after fertilisation and were strongly dependent on rainfall, particularly in no-tilled and in compact soils. In the tillage experiment, N₂O fluxes and treatment differences were greater under spring barley than under winter barley.

2. Carbon dioxide emissions in the few weeks after sowing were not strongly influenced by tillage and were related to soil temperature. Periods of low CO₂ flux and high N₂O flux under no tillage were associated with reduced gas diffusivity and air-filled porosity caused by heavy rainfall. At this location, the quality of these loam/clay-loam soils makes both ploughing and control of compaction necessary in order to minimise soil N₂O and CO₂ losses.

3. Although CH₄ consumption appears to be reduced by tillage, the reduction is unlikely to be sufficient to offset the lower N₂O emissions from the tilled soil. The gas exchange response of different soil types to tillage, particularly CH₄ oxidation rate, which is affected by long-term soil structural damage, is an aspect of soil quality worthy of further investigation in conjunction with other qualities.
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References


