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Seasonal nitrous oxide emissions from field soils under reduced tillage, compost application or organic farming

Bruce C. Ball[a,]*, Bryan S. Griffiths[a], Cairstiona F.E. Topp[a], Ron Wheatley[b], Robin L. Walker[c], Robert M. Rees[a], Christine A. Watson[c], Helen Gordon[a], Paul D. Hallett[d], Blair M. McKenzie[b] & Ian M. Nevison[e]

[a]*SRUC Crop and Soil Systems Research Group, West Mains Road, Edinburgh EH9 3JG, UK,* [b]*James Hutton Institute, Dundee DD2 5DA, UK,* [c]*SRUC Crop and Soil Systems Research Group, Craibstone Estate, Aberdeen AB21 9YA, UK,* [d]*present address: Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen, AB24 3UU, UK, and* [e]*Biomathematics and Statistics Scotland, James Clerk Maxwell Building, The King's Buildings, Edinburgh EH9 3JZ, UK.*

*Corresponding author: B.C. Ball.

Tel. +44 1315354379; fax +44 1315354144

E-mail: bruce.ball@sruc.ac.uk

ABSTRACT

Soil management practices shown to increase carbon sequestration include reduced tillage, amendments of carbon and mixed rotations. As a means to mitigate greenhouse gases, however, the success of these practices will be strongly influenced by nitrous oxide (N_2O) emissions that vary with soil wetness. Few seasonal data are available on N_2O under different soil managements so we measured seasonal N_2O emission in three field experiments between 2006 and 2009 in eastern Scotland. The experimental treatments at the three sites were (1) tillage: no-tillage, minimum tillage, ploughing to 20 cm with or without compaction and deep ploughing to 40 cm (2) organic residue amendment: application of municipal green-waste compost or cattle slurry and (3) rotations: stocked and stockless (without manure) organic arable farming rotations. Most seasons were wetter than average with 2009 the wettest, receiving 20 to 40% more rainfall than average. Nitrous oxide emissions were measured using static closed chambers. There was no statistical evidence, albeit with low statistical power, that reduced tillage affected N_2O emissions compared to normal depth ploughing. With organic residue amendments, only in the wet season in 2008 were emissions significantly increased by high rates of green waste compost (4.5 kg N_2O-N ha^{-1}) and cattle slurry (5.2 kg N_2O-N ha^{-1}) compared to the control (1.9 kg N_2O-N ha^{-1}). In the organic rotations, N_2O emissions were greatest after incorporation of the grass-clover treatments, especially during conversion of a stocked rotation to stockless. Emissions from the organic arable crops (1.9 kg N_2O-N ha^{-1} in 2006, 3.0 kg N_2O-N ha^{-1} in 2007) generally exceeded those from the organic grass/clover (0.8 kg N_2O-N ha^{-1} in 2006, 1.1 kg N_2O-N ha^{-1} in 2007) except in 2008 when the wet weather delayed manure applications and increased emissions from the grass/clover (2.8 kg N_2O-N ha^{-1}). Nevertheless, organic grassland was the land use providing the most effective overall mitigation. Although the magnitude of fluxes did not relate particularly well to rainfall differences between seasons, greater rainfall received during some growing seasons increased the differences between tillage, organic residue and crop rotation phase treatments, negating any possible mitigation by timing management operations in dry periods. This was partly attributed to applying tillage and manures late and/or in wet conditions. Of benefit would be different sampling strategies including closed chambers or eddy covariance with standardised methodology. Controlled soil management experiments with a wide geographic spread to specify land management for mitigation is also important.

Keywords: Soil management, no-tillage, compaction, greenhouse gas, biological N-fixation, green-waste compost, rainfall

Highlights:

- No statistical evidence of no-tillage and minimum tillage increasing N_2O emissions from well drained soil
- Municipal green-waste compost and cattle slurry more than doubled N_2O emissions in a wet season
- Ploughing out grass-clover was a major stimulus of N_2O emissions in an organic system
- High rainfall during the growing season enhanced soil management effects on N_2O

1. Introduction

Soil used for arable and grassland production is a major source of nitrous oxide (N_2O) emission, mainly in response to the application of inorganic and organic nitrogen as fertilisers, crop residues and manures. Changes in crop and soil management form important strategies to decrease N_2O emissions (Mosier et al., 1998). The main processes producing N_2O are microbial and vary with soil water status (Bateman and Baggs, 2005). For example, seasonal N_2O emissions in fertilised grassland are highly dependent on soil water and rainfall along with soil temperature (Flechard et al., 2007).

Interactions between soil water content and tillage (Ball et al., 2008; Rochette, 2008) and soil water content and compaction (Beare, 2009) are also very important in regulating the production and emission of N_2O. Mitigation strategies for emissions from soil that have been identified as potential win-win options include more efficient use of N inputs and greater recycling of residues (McLeod et al., 2010). Three such strategies are increased use of organic residues, decreased overall fertiliser N application rates and reduced tillage. The effectiveness of these mitigation strategies is currently in doubt in temperate Europe. For example, organic fertilisers can give very high N_2O fluxes in wet conditions (Jones et al., 2005). Even without the use of inorganic fertilisers, as in organic farming, fluxes can be similar to those from arable cropping under average fertiliser applications due to the release of available nitrogen from ploughed-in organic materials and decomposing legume residues (Ball et al., 2007). The use of no-tillage in well aerated soils can decrease N_2O emissions or have only a minor effect (Soane et al., 2012). However, no-tillage in fine textured soils can result in substantial fluxes of N_2O due to soil compaction preventing drainage and thus increasing soil wetness and concentration of carbon, nitrogen and microbial activity near the surface (Vinten et al., 2002).

Typical annual emissions of N_2O from arable crops in Scotland range from 0.6 to 6.6 kg N_2O-N ha^{-1} yr^{-1}. Within that range, emissions are predicted to increase with the duration of soil wetness (Lilly et al., 2009) and, although this relationship is supported by a large body of experimental evidence (Dobbie and Smith, 2001; Guo et al., 2010; Kliewer et al., 1995), verification with field data has been variable (Dobbie and Smith, 2003a). In this paper we present results for greenhouse gas emissions from field experiments on tillage, organic residue amendment and rotation and relate these to climate. For tillage, we compare no-tillage and minimum tillage with conventional plough tillage with or without regular compaction under spring barley. For organic materials we report on the influence of additions of green-waste compost and slurry combined with irrigation under spring barley. The tillage and organic materials trials received manufactured N fertilisers. For N source, we report on organic farming where a stockless rotation was introduced in a long-term, stocked, ley-arable experiment. The N source in this rotation was exclusively biologically-fixed N as legume residues from clover and beans in the stockless rotation and from clover residues, applications of farmyard manure and grazing in the stocked rotation.

2. Materials and Methods

2.1 Sites and experimental treatments

Treatments were tested in three field experiments at two sites (Table 1). The sites where tillage and organic amendments were tested, Mid Pilmore and Low Pilmore respectively, were at the James Hutton Institute, Invergowrie, Dundee, UK (56˚27'N, 3˚W). The soil is a Dystric-Fluvic Cambisol according to the World Reference Base (WRB) classification with a sandy loam texture and free drainage. The Tillage Experiment at Mid Pilmore evaluated the impact of a range of cultivation, with the following main plot treatments (1) no tillage, (2) minimum tillage (3) normal plough (4) normal plough and compaction and (5) deep plough treatments (Table 1) sampled for N_2O emissions in this study. Each tillage treatment was replicated 3 times in a split-plot design, where each main plot was 33 x 33m (Table 1). Treatment plots were split with half planted with a range of winter barley (*Hordeum vulgare* L.) varieties and the other half a range of spring barley varieties. Sub-plots with different varieties were 1.55 x 6 m and our study was limited to the spring barley variety Optic. Inorganic compound fertiliser was applied such that 77 kg N ha-1 was drilled with the spring barley and an additional 33 kg N ha-1 was broadcast at mid-tillering. Further details of the site and treatments were given by Sun et al. (2011) and Newton et al. (2012).

The data reported here from the Amendment Experiment at Low Pilmore, adjacent to Mid Pilmore, are from part of a slightly larger experiment involving an additional slurry treatment and some extra control plots but from which no N_2O flux data were collected. The full trial was arranged in the field as a rectangular matrix of 6 rows by 9 columns of plots (15 m by 30 m). All six residue treatments (including the control receiving inorganic N & K fertiliser only) on which data were collected are listed in Table 1. All treatments were applied annually in every row and half of the rows were irrigated. There was an additional constraint on allocation of residue treatments to plots within columns. Each individual column contained only plots with either varying levels of slurry or varying levels of compost or control plots. No column contained plots of all treatments. The compost contained 52% dry matter with a total N concentration of 1.39% and the slurry was 4.9% solids with a total N concentration of 3.65% (Paterson et al., 2011). The total N in the slurry corresponded to 7 kg ha^{-1} t^{-1} applied of which *ca.* 40% was readily available. The organic materials were spread on the surface and incorporated using two passes of a disc and tine cultivator operating to 10-15 cm depth. Plots were sown with spring barley.

Irrigation of the three rows occurred overnight from crop emergence until anthesis with a moving linear irrigator at a rate sufficient to maintain the soil close to field capacity. This was to simulate the wet soil conditions that may be associated with climate change. Inorganic compound fertiliser was applied to all treatments, including the control, such that the rate of application of N was 87 kg N ha^{-1}.

The Rotation Experiment was at Tulloch, near Aberdeen, UK (57˚11'N, 2˚ 15'W) on a Leptic Podsol according to the WRB classification with a sandy loam texture. Drainage varies from free to impeded across the site. The experiment contained two rotations chosen to typify local six-year farming rotations, called Rotations 1 and 2. Every course in each rotation was present each year. Each course occupied a plot (27 m x 30 m) and there were two replicate blocks of each rotation. In the first year (2006), Rotation 1 was 3 years grass/white clover (*Trifolium repens* L.) and 3 years arable whereas Rotation 2 was 4 years grass/white clover and 2 years arable (Figure 1A). In the second and third years (2007-2008) the experimental design was changed so that Rotation 1 included barley and Rotation 2 was made stockless (Table 1 and Figure 1B and C). The addition of extra crops necessitated splitting plots in 2007 and in 2008 that were formerly third-year grass in Rotation 1 and that were formerly first- and second-year grass in Rotation 2 (Fig. 1B and 1C). Split plots were 27 m x 15 m. Sheep grazed the grass/clover at a rate of 1.7 livestock units ha^{-1} when herbage was available. The sequence of cropping in individual plots is shown in Fig. 1 from top (2006) to bottom (2008). The stockless rotation was introduced in response to the two demands from the farming and food trades for more organic food direct from the field and for more organic animal fodder. In Rotation 1 95, 59 and 71 kg total N ha^{-1} were applied as manure to the second year grass/clover, the third year grass clover and the swedes (*Brassica napobrassica* L.) respectively. In Rotation 2, in 2006, 136, 89 and 71 kg total N ha^{-1} were applied as farmyard manure to the second year grass/clover, the fourth year grass/clover and the oats

(*Avena sativa* L.) preceding grass/clover (oats undersown). The other crops received no manure. After Rotation 2 became stockless in 2007, none of the crops received manure. Further details of the site and the mixed rotation treatments were given by Taylor et al. (2006) and Watson et al. (2011).

2.2. Field gas and soil moisture measurements

Nitrous oxide fluxes were measured using manually closed static chamber techniques (Clayton et al., 1994). These covered 0.126 m^2 of soil and were closed for 1 h prior to sampling. Samples of ambient air were also taken when chambers were closed. Samples were collected at various intervals (Table 1) and stored in glass tubes encased in plastic (Scott et al., 1999). The concentration of N_2O was subsequently analysed in the laboratory by gas chromatography (Agilent Technologies 7890A, CA) using an electron capture detector. At the Tillage Experiment one chamber per Optic plot was used in 2008 and 2009. One chamber per plot was used at the Rotation and Amendment Experiments. Chambers remained in the same position throughout the measuring period. The N_2O flux was assessed by the change in gas concentration over the closure period (typically 40 min.), giving a daily value. Nitrous oxide emissions were calculated based on the increase in N_2O in the chamber, assuming a linear increase in concentration as commonly observed for this type of chamber (Chadwick et al., 2014). Fluxes for individual chambers were accumulated by linear interpolation between sampling occasions. Means and standard errors were then calculated. Soil water content at 0-5 cm depth was measured at each site using an ML2x Theta Probe (Delta-T Ltd., Cambridge, UK) at the Rotation Experiment and from gravimetric samples taken at 0-10 cm depth at the Amendment Experiment. No measurements were made at the Tillage Experiment so data were used from Delta-T probes located on plots under minimum tillage in a spring barley field adjacent to the Tillage Experiment. Water-filled pore space (WFPS) was calculated from soil water contents using total porosities derived from bulk density data. Monthly rainfalls at the sites during the periods of measurement and soil and air temperatures are presented in Tables 2 and 3.

2.3 Statistics

The analysis for the Amendment Experiment was conducted by fitting a mixed model using REML (restricted maximum likelihood) (GenStat 11th Edition. Release 11.1., VSN International Ltd., Oxford). The fixed effects model tested was the type of manure application crossed with irrigation. The random model was columns crossed with rows nested within blocks. For the Tillage Experiment, the tillage treatments were compared by analysis of variance as a randomised block. For the Rotation Experiment, mixed models were fitted in SAS (SAS 9.1th Edition, The SAS Company, Cary, North Carolina, USA). The random effects model was rotation nested within replicates and the fixed model was a factor representing a combination of crop and rotation number (RotTreat). Using SAS for the analysis allowed the contrast between the grass treatments and the arable treatments to be assessed. For all experiments the data were analysed separately for each year. This was partly because of the effect of climate on the emissions, and additionally, in the case of the Rotation Experiment, because the crops grown within the rotation changed in 2007. For all the experiments, in order to more closely meet the assumptions of the statistical analysis, the cumulative N_2O emissions data were transformed using natural logarithms. All references to statistical significance relate to $P < 0.05$.

3. Results

Measurement of flux covered 2-3 years though the durations of continuous measurements were shorter because periods of crop establishment and harvest required chambers to be inserted or removed (Table 1). However, all flux measurements covered crop establishment to fertiliser application in spring and the early autumn when most of the yearly loss of N_2O occurs. Thus cumulative fluxes for individual years refer principally to the growing seasons.

In the Tillage Experiment, differences in N_2O flux between treatments were neither significant (P=0.204) in 2008 nor in 2009 (P=0.441) (Table 4). Cumulative fluxes were relatively small for spring barley (Lilly et al., 2009), and were greater in 2009 in all treatments than in 2008 (Tables 4 and 9), though the monitoring period was relatively short in 2008. Measured fluxes are about 0.6 – 1.0 % of N applied in inorganic fertiliser.

In the Amendment Experiment, in 2007 there was little evidence of an effect of irrigation (P=0.288) or an interaction of irrigation with residue type (P=0.086) on N_2O emissions (Fig. 2a). However, there was weak evidence that both slurry and compost (P=0.053) altered N_2O emissions with increases of 1.7-2.5 times compared to the N+K treatment. However the application rate of 35 t ha^{-1} of compost resulted in a non-significant minor decrease of 0.06 kg N_2O-N ha^{-1} in emissions compared to the N+K application. In 2008, when N_2O emissions were substantially greater, cumulative N_2O fluxes differed significantly (P=0.026) between the treatments. Both types of residue significantly increased cumulative N_2O fluxes by 1.5-2.7 times (P=0.026) (Table 6) except at the 20 t ha^{-1} slurry and the 100 t ha^{-1} compost application rates. With the exception of the lowest compost rate, fluxes from the greater rates of residue application significantly exceeded those from the smaller rates (1.9 times greater for slurry and 1.5 times greater for compost). There was no evidence of differences in emission caused by irrigation (P=0.332) or of an interaction between irrigation and residue type (P=0.180).

In the Rotation Experiment, the effect of combinations of rotation and arable crop type (RotTreat) on N_2O emissions was not significant in 2006 (P=0.081), 2007 (P=0.17) or 2008 (P=0.12). However, the arable treatments had significantly higher emissions than the grass treatments in 2006 (P=0.010) and 2007 (P=0.021) (Table 7 and Table 8). Nevertheless, in 2008, the arable and grass treatments were not significantly different from each other (P=0.83) (Table 8). This reflects the inconsistent response of the treatments. For example, the flux from undersown barley was more than double the average for the arable treatments in 2007, but low in 2008 (Table 8). The fluxes from the grass/clover treatments were less than from the arable treatments in 2007 (Fig. 3). However the reverse was true in 2008 when the fluxes from most grass/clover treatments were, with one exception, at least two times greater than in 2007. The sequence of fluxes resulting from the change in treatment and rotational cropping phase is illustrated in Fig. 1. Overall fluxes were lowest in 2006.

Annual rainfall (Table 2) clearly exceeded the long term average between 2007 and 2009 at all sites. Total rainfall received during the flux measurement periods, adjusted to include entire seasons only, is given in Table 9. There was no clear relationship between cumulative flux and rainfall. In 2009, the annual rainfall at The Rotation Experiment was 140% of the long term average. WFPS data are shown in Figs. 4 and 5 and Table 5. The soil WFPS roughly followed the trends in rainfall. Differences in soil temperature between seasons were less marked than in rainfall.

4. Discussion

In the Tillage Experiment, the higher cumulative flux in 2009 than in 2008, (Tables 5 and 9) was partly a consequence of the longer monitoring period but may also have resulted from the very wet conditions from May through to December (Table 2). Although the weather was wet, the fluxes of 1 to 2 kg N_2O-N ha^{-1} in 2008 were comparable only to the lowest fluxes at the adjacent Amendment Experiment site in the non-irrigated N & K control (Fig. 2). This lower flux at the Tillage Experiment may have resulted from the lower WFPS (Table 5) than at the Amendment Experiment (Fig. 5). The fluxes from no-tillage were similar to those measured on a comparable well-drained soil type near Edinburgh (Ball et al.,

1999) but considerably less than those from a wetter site on finer textured soils near Edinburgh (Vinten et al., 2002). Our results support the conclusion of Rochette (2008) that the impact of no-tillage on N_2O emissions is small in well-aerated soil. There was no statistical evidence that the compaction treatment in the Tillage Experiment influenced fluxes compared to normal ploughing, albeit with low statistical power. Kuan et al. (2007) found that soil from a site adjacent to this field and of the same type was relatively resistant to compaction and these results appear to confirm this. Moreover, secondary cultivation of the compacted seedbed at planting may have alleviated the impact in the top few centimetres of soil where greatest microbial activity occurs.

In the Amendment Experiment the greater N_2O flux in 2008 than in 2007 (Table 6 and Fig. 2) may have resulted from wetter soil caused by the high rainfall in April 2008 on soil that was already wet (Fig. 5), just after the fertiliser and treatment applications. The high rates of application of residues enhanced the N_2O fluxes significantly only in 2008, the wetter season.

Green waste compost might be expected to immobilise the N applied as fertiliser. However, Paterson et al. (2011), working on the same experiment, reported that the application of compost increased soil mineral N to the same concentrations as those in the slurry treatment. The high fluxes of N_2O in the wet, late spring of 2008 supports the suggestion of Vaughan et al. (2011) that relatively fresh green-waste compost stimulates microbial respiration, resulting in the development of anaerobic microsites in the soil and ultimately enhanced N_2O production via denitrification. Griffiths et al. (2010) showed that the application of green-waste compost and the cattle slurry caused similar increases in soil quality and decomposition, with equal increases in potential losses from the system. A more specific study by Paterson et al. (2011) concluded that the compost had a greater biological effect on N-cycling than the slurry due to the greater influence on microbial activity and nematode abundance. Rochette et al. (2008) also identified that additional C substrates and enhancement of respiration also encourage denitrification. The wet conditions were also likely to have stimulated the mineralisation of N in the organic materials and the proportion subsequently denitrified. Although the N_2O emission from the 200 t ha^{-1} compost treatment was high, accumulation of carbon occurred (17 (±1.1) g $100g^{-1}$ of readily available organic matter in the 0-5 cm layer compared to 6 (±0.38) g $100g^{-1}$ in the control and 40t ha^{-1} slurry treatment, unpublished data) supporting the use of compost as a means of carbon sequestration (Powlson et al., 2012). The lack of significant influence of irrigation on N_2O

emissions is a likely consequence of irrigation having no effect on water content in 2007 and only a small increase in 2008, such that its influence was less than that of the weather.

In the Rotation Experiment, seasonal weather differences also strongly influenced N_2O fluxes. In 2006, the substantial cumulative flux from the oats (Table 7) was likely to have been associated with a flush of mineralised N from the freshly cultivated grass-clover (Davies et al., 2001). This will have happened late in the year due to the delayed occurrence of any prolonged rainfall from the period following spring sowing until October (Table 2). A sharp increase in soil WFPS would not have resulted until this time (Fig. 4). Whole season fluxes were lower than the averages of 2 kg N ha^{-1} for grass-clover and 3 kg N ha^{-1} for arable at this site reported by Ball et al. (2002). In 2007, the high seasonal fluxes from most of the stockless treatments were likely due to the very wet weather during the growing season and the mineralisation of N from numerous treatments ploughed-out to allow establishment of the new arable crops (Fig. 1). This seemed to occur irrespective of the duration of the grass-clover, possibly because organic-N is easier to mineralise the more recently it has been formed (Hansen et al., 2005). The rate of nitrogen fixation in grass-clover leys is variable, but would likely have been between 12 and 110 kg ha^{-1} y^{-1} (Sanders, 2002).

In 2008 the lower fluxes from the arable treatments (average 3.4 kg N ha^{-1}) may have resulted from fewer grass/clover crops being ploughed-out prior to establishment. The average differences in emissions between the grass and arable crops were small (Fig. 3 and Table 8). High fluxes from the grass/clover in 2008 (average 4.0 kg N ha^{-1}) were likely due to nitrogen released from farm yard manure which was applied late in 2007 and in July 2008 that preceded a very wet August (116 mm) when the soil was relatively warm (Table 2).

The overall fluxes in 2007 and 2008 exceeded those from earlier measurements due to the conversion of one of the rotations to stockless, as observed by Syvasalo et al. (2006), and due to the higher rainfall increasing soil WFPS (Fig. 4). WFPS was mostly in the range 50-70%, so that both nitrification and denitrification are likely to be important sources of N_2O (Bateman and Baggs, 2005) as also observed by Ball et al. (2007) under organic barley production on the same soil type. Thus ploughing and manuring increased fluxes and these were further increased when wet soil delayed these operations so that they were made when soil conditions were warmer and wetter than normal. There is some potential to modify operational timings of both cultivation and farm yard manure applications in an attempt to reduce N_2O emissions. Early cultivation and establishment of arable crops in the spring have the potential to provide more efficient crop uptake and thereby reduce the vulnerability to N losses to the environment. Likewise, after good early season growth, manure application in a dry period immediately after silage offtake should also help mitigate N losses and improve N use efficiency. However, the unpredictability of the weather, particularly rainfall and associated adverse soil conditions, can force management to operate outside these ideal scenarios, often with knock-on effects later in the season.

Some of the seasonal emissions in wet years exceeded those in the typical range for fertilised soils of 1-3 kg N_2O-N ha^{-1} y^{-1} (Bouwman et al., 2002) and, under organic cereals, were greater than the ranges predicted by Lilly et al. (2009). Annual fluxes from the organic grass/clover phases were generally low but were nevertheless close to the average fertilised fluxes reported by Flechard et al. (2007). The fluxes under the very wet conditions of 2009 were less than those recorded by Dobbie and Smith (2003b), who, at a grassland site close to Edinburgh, found that annual fluxes increased with rainfall irrespective of fertiliser type.

The strong interaction of site and year on N_2O emissions was associated with the differing influence of the weather on soil water content and temperature at and after tillage and N application. Daily rainfalls and soil temperatures for these periods are probably more relevant to cumulative seasonal N_2O fluxes than seasonal totals or averages. WFPS data for these times is also important, particularly in relation to earlier data, indicating the need for monitoring through the season to improve the poor predictability of N_2O fluxes. Alternative water factors such as matric potential of soil water (Castellano et al., 2010) or gas relative diffusivity (Petersen et al., 2008) may prove to be better for prediction of fluxes. The addition and incorporation of organic materials and decomposing clover residues, whether by ploughing or reduced tillage, had a marked effect on biological N cycling and on N_2O fluxes. Any increases in N_2O emissions would add to the overall greenhouse gas budget.

The appreciable variability in fluxes of N_2O measured across sites and seasons highlights the need to ensure that appropriate standardised methodologies are used in order to make comparisons between measurements. The use of static chambers to measure N_2O emissions is not without problems given the limited spatial and temporal coverage of measurements. Alternative long path-length approaches to measurement are available, using eddy covariance approaches, and these have been shown to correlate well with static chamber measurements (Jones et al. 2011). However, when multiple replicated treatment comparisons are being made on relatively small plots, the only practical option is to use static chambers. Recommendations for the standardisation of chamber methodologies have recently been published by the Global Research Alliance (de Kleine & Harvey, 2013). Further refinements of this methodology have been suggested by (Chadwick et al., 2014) to allow large scale treatment comparisons to be made using a standardised methodology.

5. Conclusions

Although there were marked differences in seasonal cumulative N_2O fluxes between individual residue, tillage and cropping phase treatments, these were only statistically significant in single seasons at the highest residue levels or where crop and rotation interacted. Fluxes were highly variable, highlighting the need for greater replication and for frequent sampling during the main period of emissions. It is also important to recognise the effect that the soil/climate interactions have on emissions, and thus the treatment effects may differ between years. There was no statistically significant effects of no-tillage or minimum tillage treatments on N_2O fluxes, even in unusually wet seasons; however there are suggestions from the observed data that ploughing tends to result in lower emissions indicative of better aeration conditions than under no-till (Soane et al., 2012).

Soil management appeared to have a greater influence on seasonal fluxes than inter-annual variations in rainfall. Aiming to time management operations in dry periods may be a mitigation option. However, high rainfall during the growing season appeared to accentuate the differences between residue, tillage and cropping phase treatments and could nullify any mitigation effect. The most effective overall mitigation strategy was organic grassland. The small influence of moderate rates of slurry and compost application on N_2O fluxes indicates that, if inorganic fertiliser N concentrations could be decreased in the presence of moderate rates of application of organic amendments, these may prove effective for mitigation. Exploration of the interaction between inorganic and organic fertiliser types in medium term experiments on a wider range of soil types and management strategies may be useful.

The inherent variability of field scale measurements such as these indicate the need for more data from controlled experiments, giving a greater geographic spread to specify land management for mitigation and to specify currently unknown local parameters in models of greenhouse gas emission. In designing such experiments we recommend the use of closed chambers with standardised methodology and the development of a greater understanding of the interaction between physical and biological processes to improve prediction of N_2O emissions at the field level (Ball, 2013). This can be achieved by inclusion of indicators of aeration status, such as WFPS and gas diffusivity, and detailed analysis of microbial communities (Philipot et al., 2009).

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Table 1

Treatments and periods and frequency of measurements

Site	Treatments	Flux measurement period	Frequency of flux measurements
The Amendment Experiment, Dundee	Normal fertiliser application (control), 20 t/ha slurry, 40 t/ha slurry, 35 t/ha compost, 100 t/ha compost, 200 t/ha compost. All with and without irrigation.	January 2007-April 2009	Weekly in spring, fortnightly in summer and monthly in winter
The Tillage Experiment, Dundee	No-tillage, minimum tillage to 7 cm by discs, normal plough to 20 cm plus discing, normal plough to 20 cm and compaction of entire area by one pass of a loaded tractor plus discing and deep plough to 40 cm plus discing	April-September 2008 (normal plough compacted not measured)	Weekly in the spring, monthly in the summer
		March 2009-April 2010	Weekly in the spring, fortnightly in the summer, monthly in autumn and winter
The Rotation Experiment, Aberdeen	Rotation 1; 1st, 2nd and 3rd year grazed grass+clover, oats, swedes and undersown[a] oats	March 2006-February 2007	Weekly in spring and summer, fortnightly in autumn and winter
	Changed to include lea barley; 1st, 2nd and 3rd year grazed grass+clover, barley+ oats[b], swedes and undersown oats	April 2007-January 2009	Weekly in spring and summer in the first period, all other seasons and periods fortnightly
	Rotation 2; 1st, 2nd,3rd and 4th year grazed grass+clover, oats and undersown oats	March 2006-January 2007	As above
	Changed to stockless; 1st year grass, potatoes+undersown wheat[b], undersown beans, undersown barley and undersown oats	April 2007-April 2008 and May 2008 to January 2009	As above

[a] Undersowing was with grass plus white clover on all occasions

[b] Plots were split to allow two crops

Table 2

Monthly rainfall (mm) at the sites

	2006	2007	2008	2009	Long-term average (1971-2000)
Tulloch					
January	24	46	146	64	80
February	65	119	18	65	51
March	148	37	71	47	57
April	27	26	84	32	54
May	52	104	25	102	62
June	28	90	92	74	56
July	22	138	48	139	62
August	48	102	116	64	79
September	56	67	51	102	71
October	156	20	65	204	79
November	74	124	56	152	74
December	32	65	127	88	71
Total	**731**	**940**	**899**	**1133**	**797**
Mid and Low Pilmore					
January	23	71	154	54	68
February	24	91	26	48	47
March	118	38	42	25	50
April	6	11	69	27	45
May	68	58	19	73	48
June	41	105	56	44	52
July	34	117	104	102	53
August	55	76	142	106	52
September	88	20	46	95	64
October	110	26	50	74	67
November	72	90	25	147	52
December	69	39	48	51	66
Total	**710**	**742**	**781**	**846**	**664**

Table 3

Monthly soil temperature (˚C) at 10 cm depth at Mid and Low Pilmore and at Tulloch.

	Mid and Low Pilmore			Tulloch			
	2007	2008	2009	2006	2007	2008	2009
January	3.4	2.8	1.6	3.0	2.5	1.9	2.0
February	3.5	3.4	2.6	2.3	3.2	2.9	2.9
March	4.8	3.4	4.5	2.7	4.6	3.0	4.5
April	9.7	6.8	9.1	6.1	8.7	6.3	7.8
May	11.5	12.5	11.2	10.2	10.7	11.3	10.9
June	13.8	15.0	15.3	14.9	13.2	13.8	14.1
July	15.3	16.0	16.6	18.2	14.5	16.2	16.2
August	14.4	15.1	15.1	14.9	13.9	14.3	14.7
September	12.1	12.2	12.4	13.1	11.0	12.3	12.0
October	9.0	6.9	9.2	10.3	8.7	7.2	9.0
November	5.5	4.1	5.3	5.2	5.4	4.9	5.7
December	2.8	2.2	1.8	2.6	2.2	2.8	2.4

Table 4

The natural log transformed and back transformed N_2O emissions for Tillage Experiment in 2008 and 2009

Tillage	2008		2009	
	Ln cumulative N_2O flux	Back transformed cumulative flux (kg N_2O-N ha^{-1})	Ln cumulative N_2O flux	Back transformed cumulative flux (kg N_2O-N ha^{-1})
Deep Ploughing	-0.76	0.47	-0.47	0.63
Ploughing	-1.42	0.24	-0.21	0.81
Ploughing and compaction			0.18	1.19
Minimum tillage	-1.00	0.37	0.14	1.15
No tillage	-1.34	0.26	0.11	1.11
SED	0.30		0.40	

Table 5

Monthly cumulative N_2O fluxes and average monthly water-filled pore space, averaged over all treatments with standard errors, and monthly rainfall at The Tillage Experiment.

Year	Month	Cumulative flux (averaged over treatments) (g N_2O-N ha^{-1})	Mean monthly WFPS (%)	Monthly rainfall (mm)
2008	May	67 ± 17	29.7 ± 0.4	18.7
	June	50 ± 9	33.4 ± 0.5	56.5
	July	183 ± 21	35.1 ± 0.4	104.5
	August	121 ± 16	48.9 ± 0.4	141.5
2009	April	108 ± 12	n.d.	26.7
	May	165 ± 33	n.d.	72.7
	June	74 ± 11	23.5 ± 0.9	44.3
	July	96 ± 9	38.6 ± 0.6	102.2
	August	78 ± 8	46.8 ± 0.5	105.8

n.d. = not determined.

Table 6

The natural log transformed and back transformed N_2O emissions for manure treatments averaged over irrigation level at The Amendment Experiment in 2007 and 2008 with the subscript letters indicating significant differences ($P < 0.05$).

Manure	Rate ($t\ ha^{-1}$)	2007		2008	
		Ln cumulative N_2O flux	Back transformed cumulative flux (kg N_2O-N ha^{-1})	Ln cumulative N_2O flux	Back transformed cumulative flux (kg N_2O-N ha^{-1})
N+K control		-0.96	0.38	0.64^{a}	1.89
Slurry	20	-0.32	0.73	1.01^{ab}	2.75
Slurry	40	-0.21	0.81	1.65^{d}	5.20
Compost	35	-1.13	0.32	1.09^{bc}	2.97
Compost	100	-0.42	0.66	1.06^{ab}	2.89
Compost	200	-0.06	0.95	1.51^{cd}	4.54
SED		0.298		0.218	

Values in the column with the same subscript letter are not significantly different

Table 7

Nitrous oxide fluxes after analysis of combinations of rotation and treatment and contrasts between pooled grass and arable treatments at The Rotation Experiment in 2006. The contrasts are a measure of central tendency covering either the arable or the grass/clover treatments. See text for a description of the significance of the treatments.

Rotation	Crop	Log cumulative flux	Back transformed cumulative flux (kg N/ha)
1	Oats	1.43	4.18
1	Oats undersown	0.42	1.52
1	Swedes	-0.85	0.43
1	Year 1 Grass/clover	-0.66	0.52
1	Year 2 Grass/clover	-0.19	0.83
1	Year 3 Grass/clover	0.18	1.20
2	Oats	1.53	4.62
2	Oats undersown	0.54	1.72
2	Year 1 Grass/clover	-0.28	0.75
2	Year 2 Grass/clover	-0.25	0.78
2	Year 3 Grass/clover	-0.01	0.99
2	Year 4 Grass/clover	0.00	1.00
Contrast	Grass/clover	-0.17	0.84
	Arable	0.62	1.85
	SED	0.255	

Table 8

Nitrous oxide fluxes after analysis of combinations of rotation and treatment and contrasts between pooled grass and arable treatments at The Rotation Experiment in 2007 and 2008. The contrasts are a measure of central tendency covering either the arable or the grass/clover treatments. See text for a description of the significance of the treatments.

Rotation	Crop	2007		2008	
		Log cumulative flux	Back transformed cumulative flux (kg N/ha)	Log cumulative flux	Back transformed cumulative flux (kg N/ha)
1	Barley	1.91	6.73	0.71	2.03
1	Oats	1.06	2.90	-0.20	0.82
1	Oats undersown	-0.16	0.85	2.23	9.30
1	Swedes	0.835	2.30	0.58	1.78
1	Year 1 Grass/clover	-0.96	0.38	0.02	1.02
1	Year 2 Grass/clover	-0.47	0.63	1.95	7.01
1	Year 3 Grass/clover	0.74	2.09	0.34	1.40
2	Barley undersown	2.11	8.22	0.25	1.28
2	Oats undersown	0.62	1.85	1.46	4.32
2	Potatoes	1.44	4.22	1.77	5.88
2	Beans undersown	0.81	2.24	0.72	2.05
2	Wheat undersown	1.14	3.12	1.22	3.39
2	Year 1 Grass/clover	1.10	2.99	1.86	6.43
Contrast	Grass/clover	0.10	1.11	1.04	2.84
	Arable	1.08	2.95	0.97	2.64
	SED	0.383		0.363	

Table 9

Rainfall and cumulative N_2O fluxes during seasonal flux measurement periods.

Site	Period of N_2O flux measurement	Cumulative N_2O flux, averaged over treatments (kg N ha^{-1})	Rainfall (mm)
The Amendment Experiment	January – December 2007	0.64	742
	January – December 2008	1.15	781
The Tillage Experiment	April to September 2008	0.35	379
	March 2009-April 2010	1.34	891
The Rotation Experiment	March 2006-January 2007	1.75	615
	April 2007-April 2008	3.82	1014
	May 2008 – January 2009	4.19	612

Figure Captions

Figure 1 Cropping sequence and cumulative N_2O emissions at the Rotation Experiment in 2006 (A), 2007 (B) and 2008 (C). The treatment sequence for successive years runs from top to bottom. Split plots are shown below bifurcating arrows. For example, second year grass (Y2G) in 2006 was followed in 2007 by undersown wheat and potatoes established after splitting the plots and in 2008 by undersown beans (Pul us) occupying whole plots. Error bars represent standard errors. Y1G, Y2G, Y3G, Y4G = 1st, 2nd, 3rd or 4th year of grass/clover, O = oats, O = Oats, B = Barley, W = Wheat, Pul = Pulse (Beans), Pot = Potatoes, S = Swedes and us = the crop was undersown with grass/clover or clover only.

Figure 2 Cumulative N_2O emissions for 2007 and 2008 at the Amendment Experiment for (a) the control and residue treatments averaged over irrigation rates and (b) yearly totals for individual treatment combinations. For clarity, the error bars represent either plus or minus the standard error of the mean.

Figure 3 Cumulative N_2O emissions averaged over arable and over grass/clover treatments at the Rotation Experiment in 2007 and 2008. For clarity, the error bars represent either plus or minus the standard error of the mean.

Figure 4 Water-filled pore space at 0-5 cm depth at the Rotation Experiment. Error bars represent standard errors.

Figure 5 Water-filled pore space at 0-10 cm depth at the Amendment Experiment. Error bars represent standard errors.

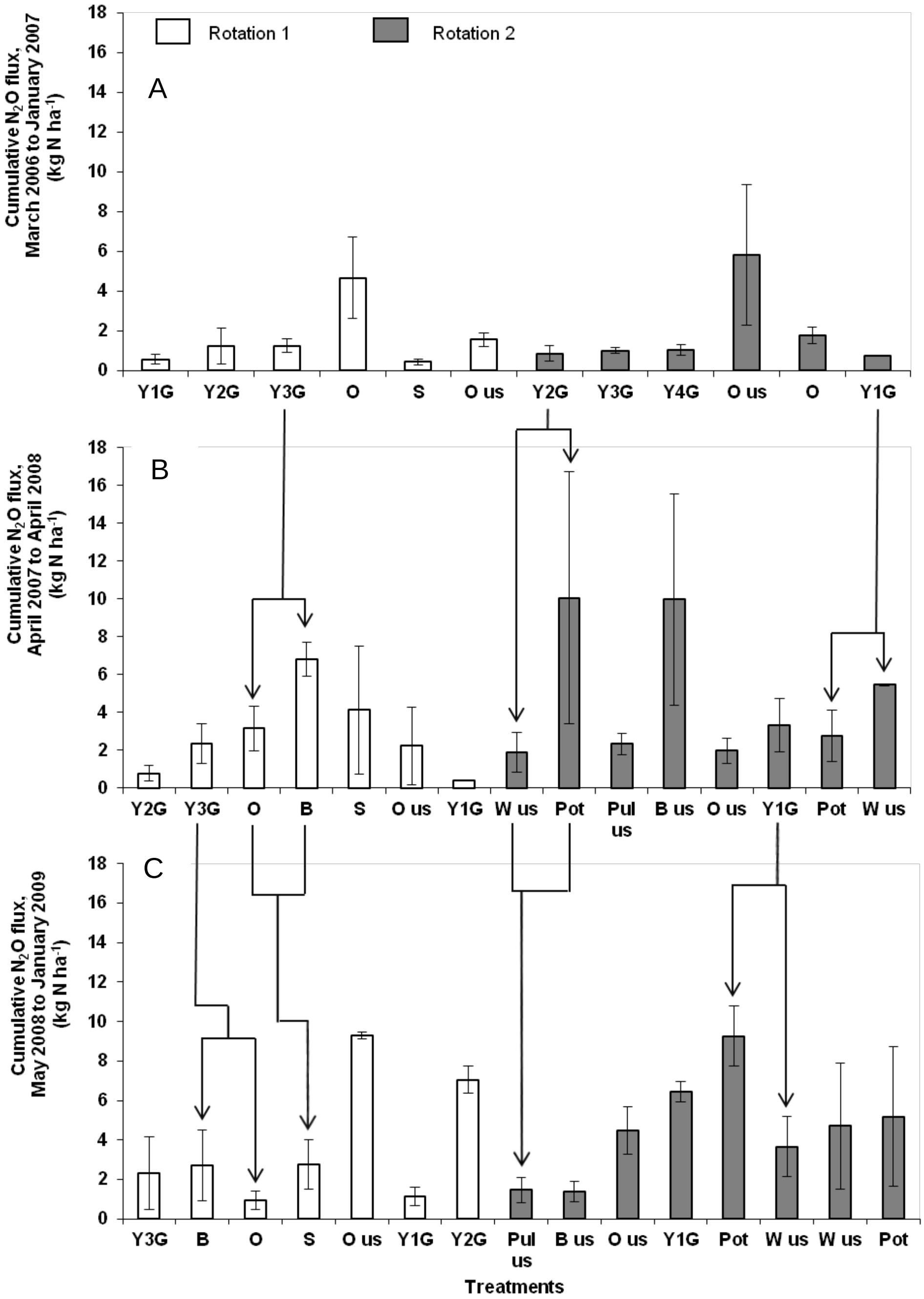

Figure 1 Cropping sequence and cumulative N_2O emissions at the Rotation Experiment in 2006 (A), 2007 (B) and 2008 (C). The treatment sequence for successive years runs from top to bottom. Split plots are shown below bifurcating arrows. For example, second year grass (Y2G) in 2006 was followed in 2007 by undersown wheat and potatoes established after splitting the plots and in 2008 by undersown beans (Pul us) occupying whole plots. Error bars represent standard errors. Y1G, Y2G, Y3G, Y4G = 1st, 2nd, 3rd or 4th year of grass/clover, O = oats, O = Oats, B = Barley, W = Wheat, Pul = Pulse (Beans), Pot = Potatoes, S = Swedes and us = the crop was undersown with grass/clover or clover only.

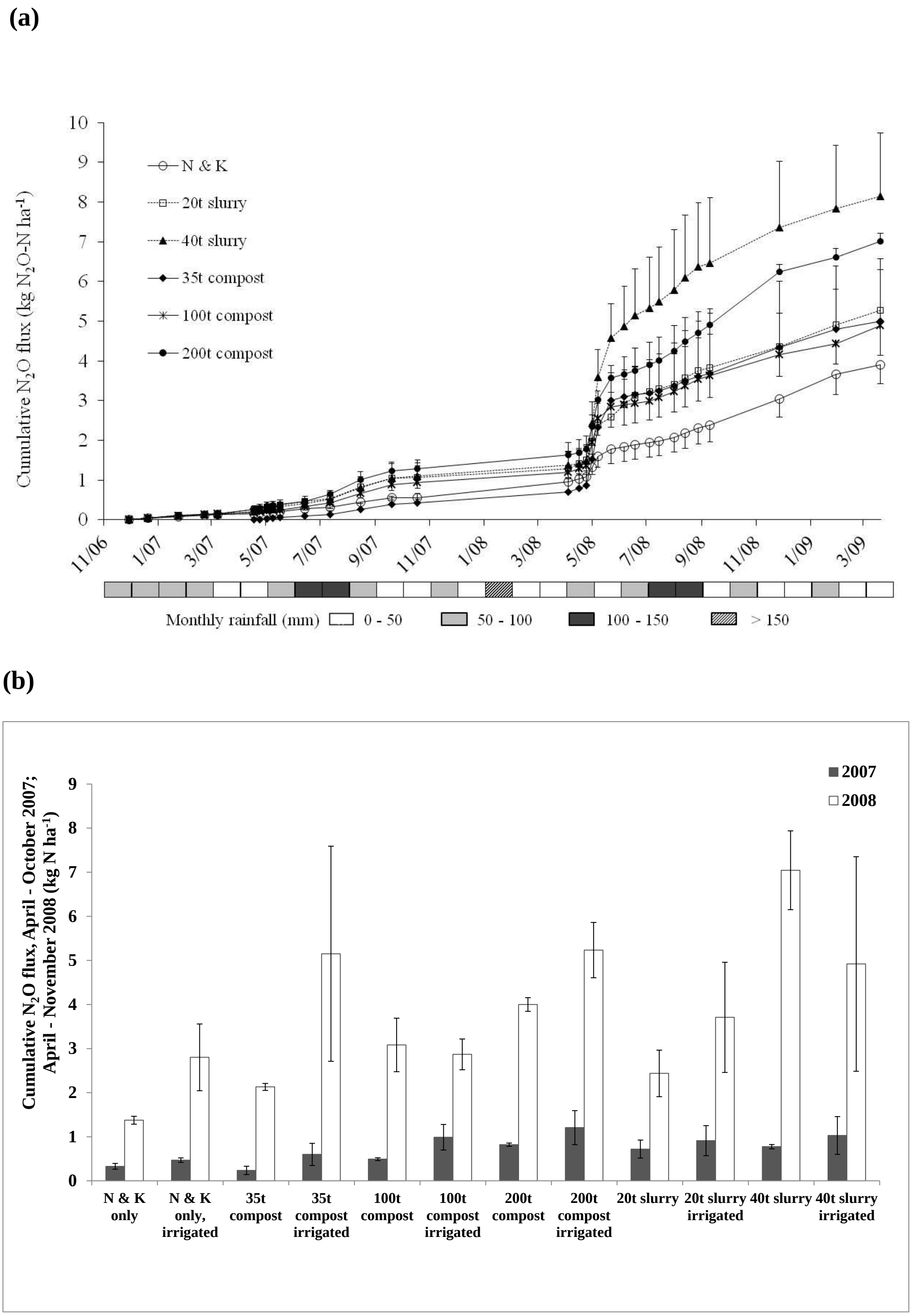

Figure 2 Cumulative N$_2$O emissions for 2007 and 2008 at the Amendment Experiment for (a) the control and residue treatments averaged over irrigation rates and (b) yearly totals for individual treatment combinations. For clarity, the error bars represent either plus or minus the standard error of the mean.

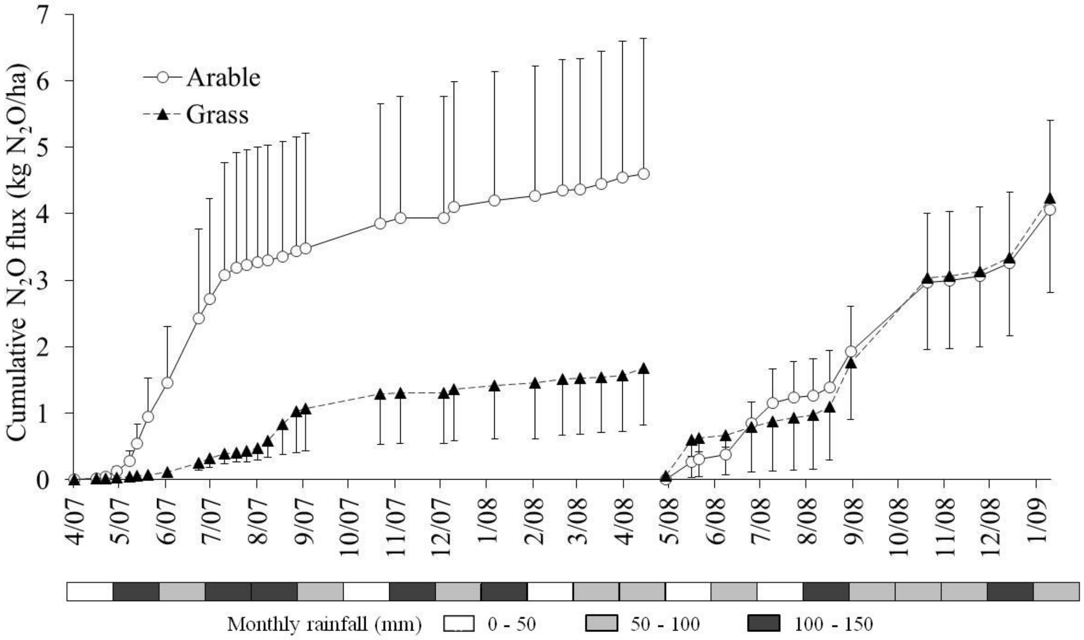

Figure 3 Cumulative N_2O emissions averaged over arable and over grass/clover treatments at the Rotation Experiment in 2007 and 2008. For clarity, the error bars represent either plus or minus the standard error of the mean.

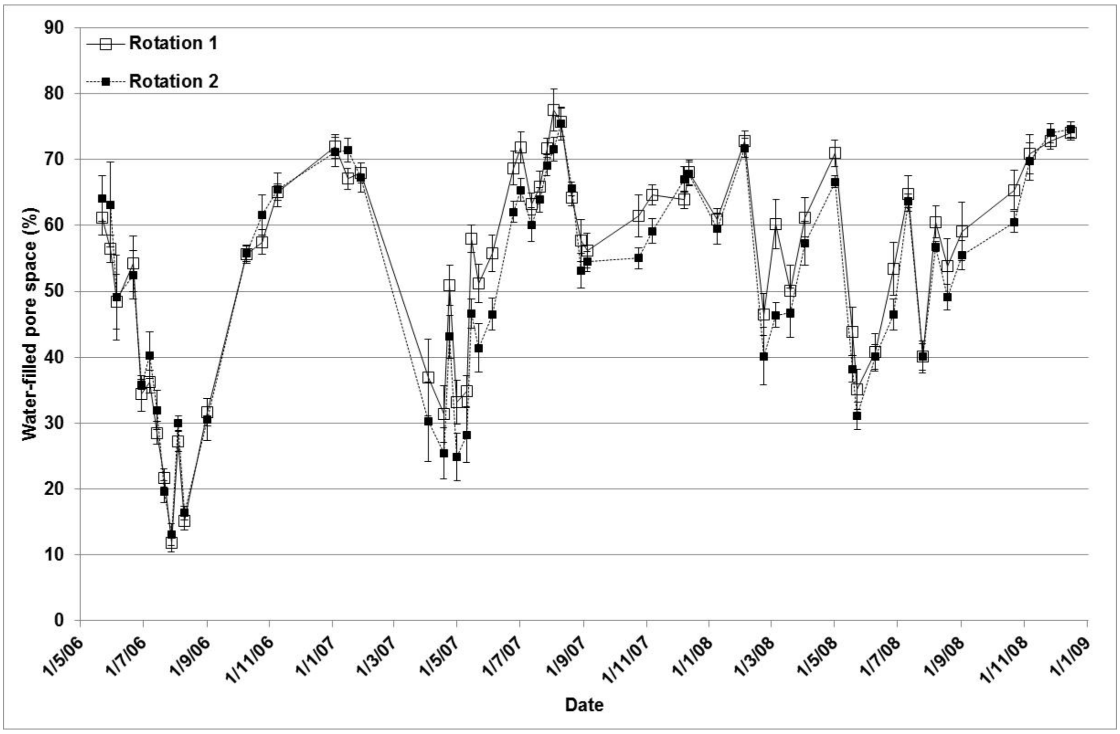

Figure 4 Water-filled pore space at 0-5 cm depth at the Rotation Experiment. Error bars represent standard errors.

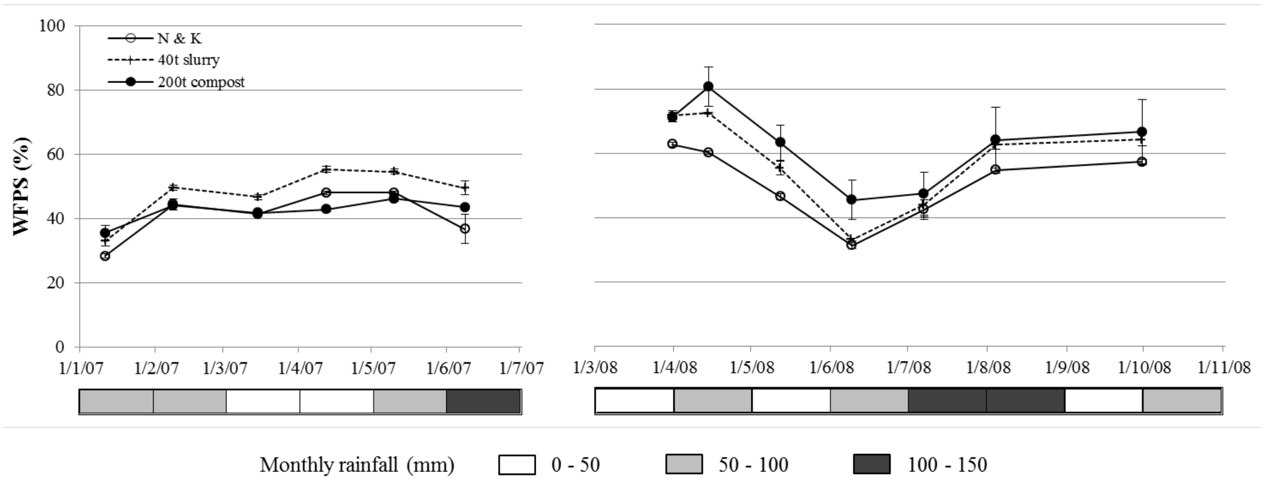

Figure 5 Water-filled pore space at 0-10 cm depth at the Amendment Experiment. Error bars represent standard errors.