The influence of tillage on N_2O fluxes from an intensively managed grazed grassland in Scotland

Authors: N.J. Cowan [a, b], P.E. Levy [a], D. Famulari [a], M. Anderson [a], J. Drewer [a], M. Carozzi [c], D.S. Reay [b], U.M. Skiba [a]

[a] Centre for Ecology and Hydrology, Penicuik, Edinburgh, UK, EH26 0QB
[b] School of Geosciences, Kings Buildings, University of Edinburgh, Edinburgh, UK, EH9 3JG
[c] INRA, INRA-AgroParisTech, UMR 1402 EcoSys, 78850 Thiverval-Grignon, France.

Keywords: plough, greenhouse gas, nitrous oxide, gap filling

Correspondence to: Nicholas Cowan (nicwan11@ceh.ac.uk)

Abstract

Intensively managed grass production in high-rainfall temperate climate zones is a globally important source of N_2O. Many of these grasslands are occasionally tilled to rejuvenate the sward, and this can lead to increased N_2O emissions. This was investigated by comparing N_2O fluxes from two adjacent intensively managed grazed grasslands in Scotland, one of which was tilled. A combination of eddy covariance, high-resolution dynamic chamber and static chamber methods was used.

N_2O emissions from the tilled field increased significantly for several days immediately after ploughing and remained elevated for approximately two months after the tillage event contributing to an estimated increase in N_2O fluxes of 0.85 ± 0.11 kg N_2O-N ha^{-1}. However, any influence on N_2O emissions after this period appears to be minimal. The cumulative N_2O emissions associated with the tillage event and a fertiliser application of 70 kg-N ammonia nitrate from one field were not significantly different from the adjacent un-tilled field, in which two fertiliser applications of 70 kg-N ammonia nitrate occurred during the same period. Total cumulative fluxes calculated for the tilled and un-tilled fields over the entire 175 day measurement period were 2.14 ± 0.18 and 1.65 ± 1.02 kg N_2O-N ha^{-1}, respectively.

1 Introduction

Modern agriculture and intensive land management practices are believed to contribute over 39 % of total global anthropogenic emissions of the greenhouse gas (GHG) nitrous oxide (N_2O) (IPCC, 2014). N_2O is a naturally occurring GHG released into the atmosphere by the microbial processes of nitrification and denitrification which occur in soils and aquatic systems (Davidson et al., 2000; Seitzinger et al., 2000). Human activities which alter environmental conditions can have a significant impact on natural microbial processes, which in turn can increase N_2O emissions. Agricultural activities such as the use of nitrogen fertilisers, livestock production and land use changes are all important sources of anthropogenic N_2O from agricultural soils (Fowler et al., 2013).

There is still large uncertainty associated with the quantification of N_2O emissions released from agricultural soils on a national and global scale, due to the large spatial and temporal variability of N_2O fluxes (Cowan et al., 2015; Jahangir et al., 2011; Mathieu et al., 2006). Many past experiments have focussed on the release of N_2O from soils after the application of nitrogen fertilisers - which is the main cause of the rise of in N_2O emissions since pre-industrial times (e.g. Bouwman et al., 2002; Dobbie et al., 1999). Other factors affecting N_2O emissions from agricultural soils, such as tillage and compaction, are less well documented, thus preventing effective assessment of their role in controlling N_2O fluxes from the agricultural sector.

The addition of organic nitrogen in the form of decaying plant matter (crop residues) is a recognised potential source of N_2O following tillage, but the phenomenon is not well quantified (Baggs et al., 2003; Mutegi et al., 2010). Currently the IPCC emission inventories estimate that 1 % of all organic nitrogen applied to soils as crop residues will be emitted in the form of N_2O (IPCC, 2006). However, the degree to which tillage induces a change in N_2O emissions may be determined by several factors: the prior use of nitrogen fertilisers (Abdalla et al., 2010; Yamulki and Jarvis, 2002), soil compaction (Ball et al., 2008; Yamulki and Jarvis, 2002) and the method of tillage (Sheehy et al., 2013). Changes in the bulk density, water filled pore space (WFPS) and oxygen availability in soils which can lead to an increase or decrease in nitrification and denitrification rates depending on environmental conditions (Elmi et al., 2003; Palma et al., 1997).

The large number of variables which may alter microbiological processes in tilled soils can lead to a wide range of results between experiments carried out at different field sites, under different meteorological conditions. Some experiments have reported large increases in annual N_2O emissions varying from 0.89 to 3.37 kg N ha^{-1} dependent on application of fertiliser post-tillage (i.e. Chatskikh and Olesen, 2007; Merbold et al., 2014; Omonode et al., 2011; Pinto et al., 2004; Yamulki and Jarvis, 2002), whereas others have shown a zero (i.e. Boeckx et al., 2011; Choudhary et al., 2002) or potentially negative effect of tillage (-0.88 kg N ha^{-1}, Tan et al., 2009). There is little consensus among these studies on the relative effect of different drivers of N_2O production. However, it is commonly reported that factors influencing the aeration of the soil (such as WFPS and bulk density) are cited as influential in most tillage studies.

Improving our understanding of N_2O fluxes from tillage events is important, especially in countries such as the UK, where agriculture accounts for approximately 70 % of the total land coverage (DEFRA, 2012) and tillage is widely practiced. Improved grasslands alone account for 25 % of the total land coverage of the UK (Morton et al., 2011). Tillage events occurs on rotational grasslands, for sward rejuvenation on permanent grasslands, and in conversion to arable, and are a common enough occurrence that they could contribute significantly to the total national inventory of anthropogenic N_2O emissions. However, few experiments have been carried out on GHG emissions resulting from the tillage of grassland fields. The aim of this work was therefore (i) to use multiple N_2O flux measurement methodologies to add to the understanding of the N_2O fluxes from grasslands tilled for sward renewal, (ii) develop an improved statistical methodology which allows for uncertainties in cumulative flux emissions to be calculated for these events, and (iii) compare our estimates with those predicted using the current IPCC methodology.

2 Materials and method

2.1 Field site

Fluxes of N_2O were measured from an area of intensively managed, grazed grassland (Easter Bush, Scotland, 55° 51' 55.30"N, 3° 12' 22.17"W) before and after a tillage event on the 1st of May 2012, and were compared with fluxes measured from an adjacent grassland which remained un-tilled (as described in Jones et al., 2011) (Figure 1). The climate is temperate maritime, with an average annual rainfall of 921 mm and average annual air temperature of 9 ^{o}C (in the period 2001–2011). The two fields (each approximately 5.4 ha) have been managed for intensive livestock production for at least twenty years, and since 2002 were predominately grazed by sheep. The average stocking densities were 0.7 LSU ha^{-1} (livestock units) and average N fertiliser application rates have been approximately 200 kg N ha^{-1} y^{-1}. Mainly NH_4NO_3 or NPK compound fertilisers were applied in three split applications usually between March and July (Skiba et al., 2013).

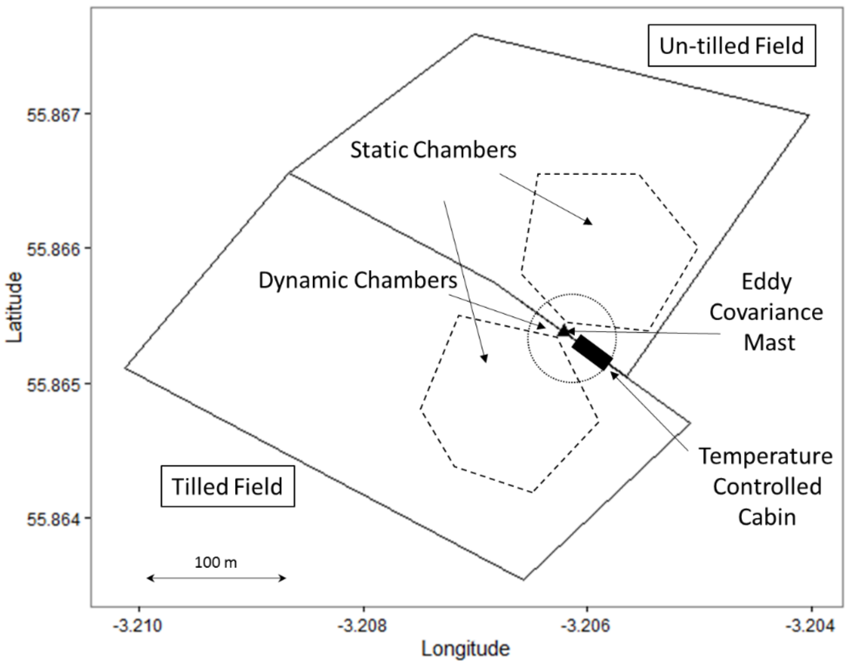

Figure 1 N_2O fluxes were measured from two adjacent grassland fields at the Easter Bush Farm (Penicuik, Scotland). The north field remained un-tilled, while the south field was ploughed on the 1st of May 2012. An eddy covariance mast was set up next to a permanent cabin positioned between the fields. Dynamic chamber measurements were made within a 30 m radius of the cabin. Static chambers were located within the fetch of the eddy covariance mast and moved periodically.

The soil in the fields is a clay loam with a sand/silt/clay texture of 52/20/28 and 57/19/24 for the top 30 cm in the un-tilled and tilled fields, respectively with a pH of approximately 5.1 (in H_2O). They are classed as an imperfectly drained Macmerry soil of the Rowanhill association (eutric cambisol, FAO classification). A drainage system had been installed about 50 years ago, but is no longer functioning well, resulting in frequent occurrence of surface water during rainy periods. The fields had not been tilled for at least twenty years, and the farmer had reported reduced fertility and productivity. One field (also called the South Field in Jones et al., 2011) was therefore tilled in May 2012 (Table 1).

As standard practice, glycophosphate (1.5 l ha^{-1}) was applied to kill the grass three days prior ploughing on the 27th of April. The field was ploughed to a depth of 30 cm on the 1st of May 2012. Two days after ploughing, the field was harrowed, and then rolled and sown with ryegrass (*Lolium perenne L.)* on the third day after ploughing. The un-tilled field (also called the North field in Jones et al., 2011 was managed as usual and grazed by sheep (approximately 30 sheep ha^{-1}). Fertilisation events continued as normal on the un-tilled field which received two ammonium nitrate (Nitram) fertiliser applications of 70 kg-N ha^{-1}, one on the 28th of May and the second on the 9th of August. The tilled field only received a 70 kg-N ha^{-1} Nitram application on the 9th of August, approximately four months after the tillage event.

Table 1 Field management events for both the tilled and un-tilled fields in 2012.

Date	Tilled Field (South)	Un-Tilled Field (North)
16th February 2012		Grazed by sheep (continuous)
27th April 2012	Glycophosphate application (1.5 l ha^{-1})	
1st May 2012	Ploughing at 30 cm depth	
3rd May 2012	Harrowing, seeding & rolling	
28th May 2012		70 kg-N ha^{-1} Nitram application
9th August 2012	70 kg-N ha^{-1} Nitram application	70 kg-N ha^{-1} Nitram application
19th September 2012	Grazed by sheep (continuous)	

Biomass samples were collected from the South Field prior to tillage in order to estimate the grass biomass that would be tilled into the soil. Twenty soil cores (12 cm deep and 5.8 cm diameter) were extracted from the field. At these points, all above-ground biomass was harvested and dried in an oven at 80℃ to constant weight. Once dry, the above-ground biomass was weighed. The soil cores were broken up by hand and dried at 100℃ until constant weight. After drying, the root material was separated from the soil by hand and weighed. Sub samples of the dried plant materials were prepared for elemental analysis of total carbon and nitrogen contents (vario EL cube, Elemaentar, Hanau, Germany).

Total (above- and below-ground) biomass on the tilled field before tillage averaged of 369 ± 310 g m^{-2}, with a root to shoot ratio of ~1.5. The nitrogen content was 2.5 %. Based on these measurements it is estimated that the tillage event added a total of 93.6 kg ha^{-1} of nitrogen to the field in the form of crop residues.

2.2 Flux Measurements

N_2O fluxes were measured from both tilled and un-tilled fields over a seven month period using three measurement methodologies; eddy covariance, static chamber and dynamic chamber techniques. The mixture of methods were used to try to obtain as many measurements as practically possible, both temporally and spatially, during the experiment. Eddy covariance was the primary measurement methodology used. However, due to unpredictable changes in wind direction at the site it was necessary to deploy manual chamber methodology to ensure that both fields were measured periodically during the experiment. The dynamic chamber measurements were used as a cost effective way to provide many (> 30) high-resolution N_2O fluxes on the days immediately after tillage without the need for time consuming GC lab analysis required by static chambers.

An eddy covariance system was installed on the 27th of March on the field boundary (Figure 1). An ultra-sonic anemometer (WindMaster Pro 3-axis, Gill, Lymington, UK) mounted at 2.4 m was used to measure fluctuations in 3-D wind components at a frequency of 10 Hz. Mixing ratios of N_2O, H_2O and CO_2 were measured at 10 Hz by a quantum cascade laser (QCL) gas analyser (CW-QC-TILDAS-76-CS, Aerodyne Research Inc., Billerica, MA, USA), housed in a temperature controlled cabin. The inlet line to the QCL was a 13.5 m length of Dekabon tubing (0.25 inch outer diameter), with a flow rate of approximately 13 l min^{-1}. Fluxes were calculated at 30 min intervals using the EddyPro software (Version 5.2.1) (Li-Cor, Lincoln, NE, U.S.A.), based on the covariance between the N_2O concentration (χ) and vertical wind speed (w):

$$F_{\chi} = \overline{\chi' w'} \quad \text{(Eq. 1)}$$

In the processing, we applied double coordinate rotation (vertical and crosswind), spike removal, block averaging, and time lag removal by covariance maximisation. Correction for the frequency response of the system, both high and low-frequency losses, were made using the method of Moncrieff et al., (1997). Corrections for density fluctuations were applied on a half-hourly basis using the method of (Burba et al., 2012). The quality control scheme of Foken et al., (2005), was used to remove poor quality flux measurements (their category 2). Initially, fluxes measured with a mean wind direction between 180 and 270 degrees from north were classed as from the tilled field; those measured at greater than 330 and less than 100 degrees were classed as from the un-tilled field. The remaining data were disregarded due to obstruction of the wind by the cabin and fence line.

Further footprint analysis was carried out in which we visually checked individual footprint plots of each 30 min flux (Figure 2). Any flux footprints in which the majority of the contribution came from a distance less than 10 m from the mast, or overlapped the two fields were removed from the dataset. Standard meteorological variables (rainfall, air temperature and soil temperature) were recorded by a tipping bucket, thermometers (2 m height & 10 cm depth) and TDR soil moisture probe at 10 cm depth. These measurements were made adjacent to the flux tower at the site.

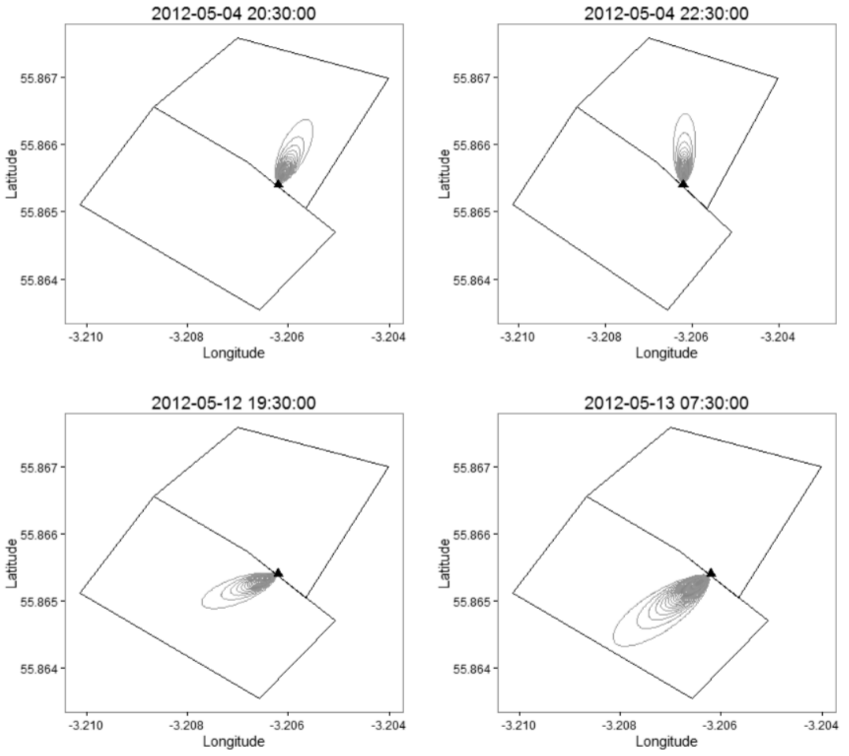

Figure 2 Four example flux footprints, with contours showing the relative contribution to the measured eddy covariance flux, based on the model of Kormann and Meixner (2001). Half-hourly flux data were only included if 97.5 % of the measured flux was attributed to either the untilled (top) or tilled (bottom) fields.

N_2O fluxes were also measured from both fields using static chamber and dynamic chamber techniques. The static chambers consisted of a cylindrical polyvinyl chloride (PVC) plastic pipe of 38 cm inner diameter (ID) and 22 cm height. These chambers were inserted 5 cm into the soil, giving a headspace of approximately 20.4 l. Chambers were closed for 40 mins, during which time three 100 ml gas samples were collected via a syringe and a three-way tap fitted to the lid, at t = 0, 20 and 40 mins. After each measurement, chamber height was measured at five points to estimate the chamber volume. Gas samples were stored in 20 ml glass vials which were flushed with 100 ml of air in the syringe using a double needle. Samples were analysed using a Hewlett Packard 5890 series II gas chromatograph (Agilent Technologies, Stockport, fitted with an electron capture detector) (Skiba et al., 2013).

Ten static chambers were positioned in each of the fields, within the estimated flux footprint of the eddy covariance system (10 to 200 m from the mast). Chambers in the fields were occasionally moved to prevent the effects of a micro-climate within the chambers that could bias measurements when compared to the surrounding field area, and also to allow access to farm vehicles during the different stages of the tillage operation. Manual chamber measurements were carried out between 9:00 and 15:00 on the measurement dates. Fluxes were calculated as:

$$F = \frac{dC}{dt} \cdot \frac{\rho V}{A} \quad \text{(Eq. 2)}$$

where *F* is the gas flux from the soil (nmol m^{-2} s^{-1}), *dC/dt* is the rate of change in concentration with time in nmol mol^{-1} s^{-1} estimated by linear regression, ρ is the density of air in mol m^{-3}, *V* is the volume of the chamber in m^3 and *A* is the ground area enclosed by the chamber in m^2. Static chamber measurements were made over a longer period than shown in this paper and are discussed in relation to a second tillage event by Drewer et al. (2016).

Fluxes were also measured using the QCL in a closed, dynamic chamber system (Cowan et al., 2014a). A chamber (39 cm inner diameter, 22 cm high) was placed onto a stainless steel collar inserted several cm into the soil (on average 5 cm) at least 15 mins prior to measurement. Two 30 m lengths of 3/8 inch ID Tygon® tubing connected the chamber to the inlet of the QCL and the outlet of a vacuum pump (SH-110, Varian Inc, CA, USA) to form a closed system. This allowed a 30 m possible radius from the instrument cabin in which the chamber could be placed (Figure 1). A flow rate of approximately 6 to 7 L min^{-1} was used, with a lag time of approximately 22 seconds between the chamber and analyser. Fluxes of N_2O were calculated with 1 Hz data over three minutes, using both linear and non-linear asymptotic regression methods (Levy et al., 2011; Pedersen et al., 2010). Using a mixture of goodness-of-fit statistics and visual inspection, the regression method that provided the best fit for the time series of mixing ratios of N_2O was chosen for each individual measurement. The detection limit of individual fluxes calculated by this method was approximately 0.04 nmol m^{-2} s^{-1} compared to 0.4 nmol m^{-2} s^{-1} when using the static chambers (Cowan et al., 2014a, 2014b).

In the first few days after the tillage event, the wind direction was north-easterly, meaning that the eddy covariance system could not record fluxes from the tilled field (to the south-west). The dynamic chamber measurements were primarily used to fill this gap in the eddy covariance time series with high precision chamber measurements.

2.3 Gap filling

Because the eddy covariance system was placed on the field boundary, observations could only be made on a single field at any given time. Furthermore, some data were missing because of instrument failure and some had to be rejected according to the quality control criteria used. In order to estimate cumulative fluxes from both fields, temporal interpolation of the missing data points was required. However, in the absence of a well-validated process-based model for N_2O fluxes on which to base predictions, it is not obvious how this is best achieved. The most common approach is to linearly interpolate in time between flux measurements. In this study, a general additive model (GAM) was used as an alternative approach, which accounted for temporal patterns at a range of time scales and nonlinear responses to environmental variables, implemented using the *mgcv* package in the R software (Wood, 2006).

Fluxes measured by eddy covariance and both chamber methods from the tilled and un-tilled fields were fitted to two separate GAMs using the same environmental terms for both fields. The environmental terms included were air temperature, soil temperature, precipitation, and time. Additional terms for temperature and precipitation aggregated over longer intervals (1, 6, 12, 24 and 48 hours preceding the flux measurement) were examined and included where they improved the fit. The GAM allows for non-linearity by fitting a smooth response with cubic splines. The degree of smoothing is optimised by the algorithm, but was also adjusted subjectively, such that the model was not over-fitting to noise in the data. Observations from eddy covariance and the two chamber methods were given equal weighting. Predictions from the GAM were used to fill gaps when observations were not available. Uncertainty in predictions was estimated by simulating 2000 replicate time series from the GAM, using the uncertainty in the fitted parameters, to estimate the posterior distribution. The quantiles of this posterior distribution provided the 95 % credibility interval at each predicted 30-min interval time step. To calculate cumulative fluxes, observed fluxes were used with their associated uncertainties (Finkelstein and Sims, 2001) when available; otherwise the GAM predictions were used.

3 Results

3.1 Meteorological data

A total of 1191 mm of rain was recorded in 2012, higher than the average annual rainfall of 921 mm (2001 to 2011) for the Easter Bush area (Figure 3a). The annual variation in temperature was fairly typical of the field site

(Figure 3b). The wind direction at the field site is predominantly south-westerly (85 %). However, during the measurement campaign, the wind direction was split fairly evenly between the tilled and un-tilled fields (Figure 4). This allowed a better basis for comparison of N_2O fluxes from the two fields, although data coverage for each field was low, 34 % and 24 % for tilled and un-tilled respectively.

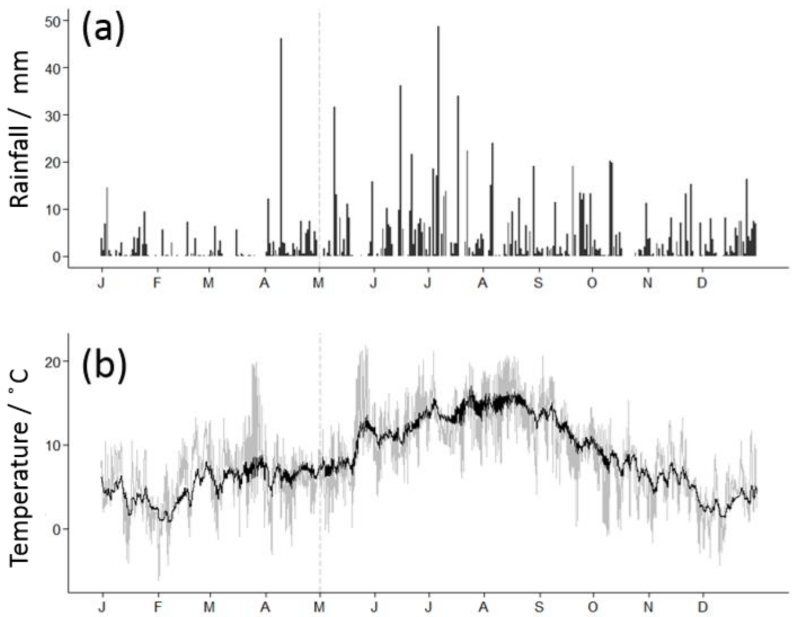

Figure 3 (a) Accumulated daily rainfall at the Easter Bush Field site during the year 2012. (b) Air temperature at height 3 m (grey) and soil temperature (black) recorded at the Easter Bush field site during the year 2012. Tillage occurred on the 1st of May 2012 (grey dashed vertical line).

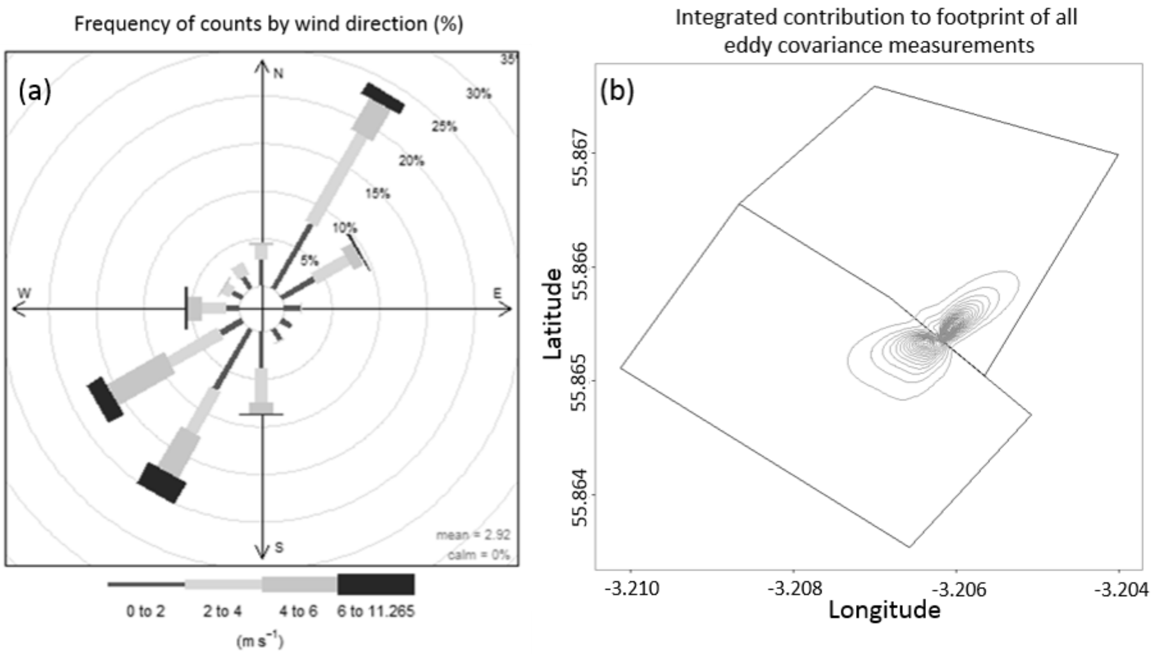

Figure 4 (a) Wind rose plot for the Easter Bush field site during eddy covariance measurements (March – October 2012). (b) Spatial distribution of the time-averaged flux footprint over the measurement period. The outer-most contour represents the area which, on average, contributed to 97.5 % of the measured half-hourly flux.

3.2 Comparison of N_2O fluxes measured from the un-tilled and tilled fields

Before the tillage event, N_2O fluxes were similar in the tilled and untilled fields. In both cases, around 90 % of measured fluxes were below 0.5 nmol m^{-2} s^{-1} (Figure 5). All three fertilisation events (the two fertiliser events in the untilled filed and single fertiliser event in the tilled field) were characterised by an emission peak of 5-10 nmol m^{-2} s^{-1} lasting a few days, which declined over the following days and weeks, often with considerable variability and some apparent secondary peaks (Figure 5). Fluxes had returned to background levels (<0.5 nmol m^{-2} s^{-1}) within 28 days of each of the fertilisation events. Fluxes measured by all methods agreed reasonably well in magnitude, and there is no strong evidence for a systematic bias, given the differences in the spatial and temporal sampling (for a more specific insight see e.g. Cowan et al., 2014a).

The tillage event also produced an increase in emissions, and although the peak was less clearly defined, the effect was more prolonged. Fluxes generally ranged from ~0 to 1.0 nmol m^{-2} s^{-1} in the days before tillage and ~0 to 8.8 nmol m^{-2} s^{-1} in the week immediately after tillage (Figure 5b). Three exceptionally high individual chamber measurements measured in the days immediately after the second fertilisation event in the un-tilled field which are included in the data analysis (19.5, 34.8 and 50 nmol m^{-2} s^{-1}) are not included in Figures 5 or 7 in order to keep the scale manageable. Fluxes from the tilled field from mid to late May were approximately 1 nmol m^{-2} s^{-1} higher than from the untilled field (before the latter was fertilised). There followed an apparent increase in N_2O fluxes lasting approximately four weeks from the tilled field from late May to late June, peaking mid-June (Figure 5b). Unfortunately, data coverage was rather low during this period due to changes in wind direction and a five day period in which the QCL was not operational. Because the tilled field had not been fertilised since the previous year, we infer that the increased fluxes were a result of the tillage event. Fluxes in the tilled field returned to pre-tillage magnitude during July. By July, a new sward of grass had grown in the tilled field, but sheep were not re-introduced into the field until September.

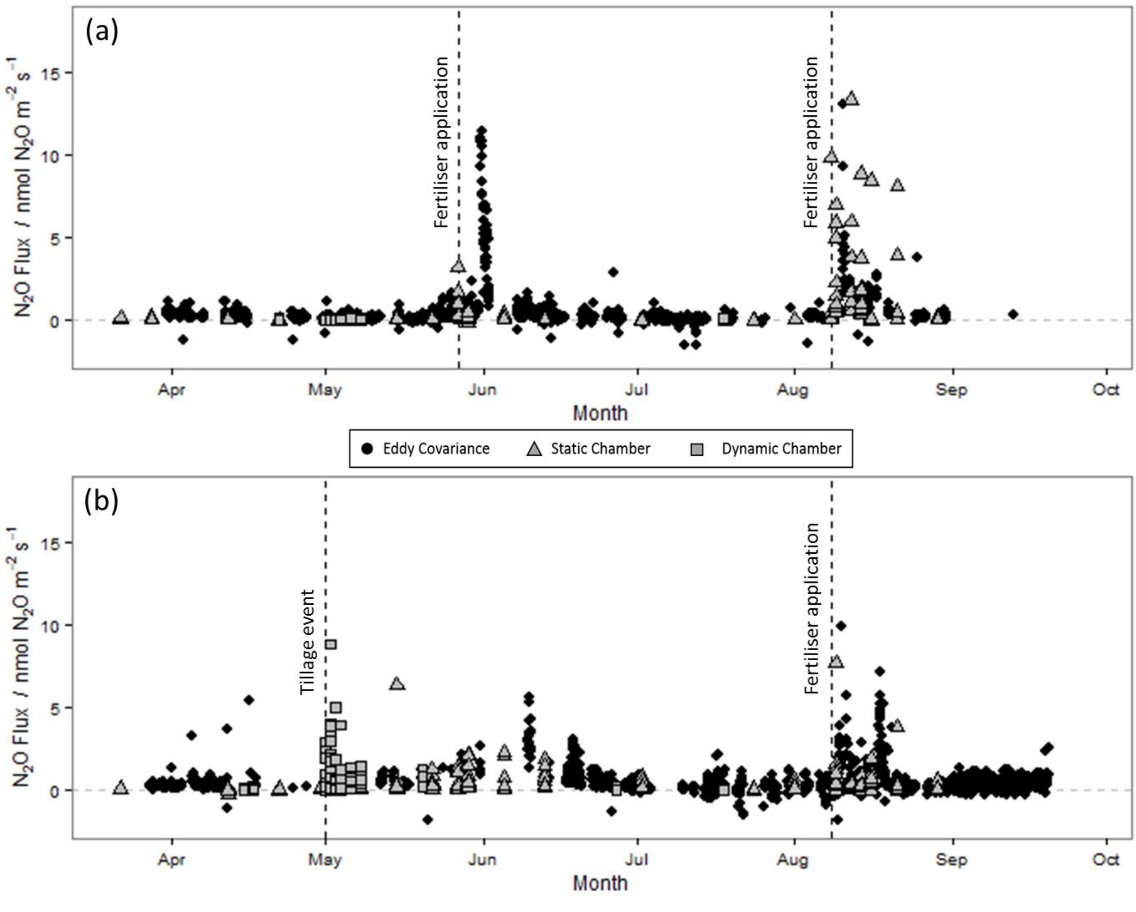

Figure 5 Fluxes of N_2O from the (a) un-tilled and (b) tilled fields measured at the Easter Bush field site in 2012. Fertiliser was applied to the un-tilled field on the 28th of May and to both fields on 9th August (vertical dashed lines). Tillage began on 1st May. The Y-axis is limited to 15 nmol m^{-2} s^{-1} for better comparison between the fields. Only three static chamber measurements in the un-tilled field recorded fluxes above 15 nmol m^{-2} s^{-1} in the first few days after the August fertilisation.

The relatively high N_2O fluxes measured from the tilled field in the weeks after tillage (May to July) occur in a similar timeframe to the fertilisation event in the un-tilled field (Figure 5). Beyond the analytical footprint analysis, we wanted to check that the high N_2O fluxes, which we attribute to the tillage, actually do come from the tilled field, and are not influenced by N_2O from fertilisation events on surrounding fields. The CO_2 fluxes (measured by QCL instrument) provide a suitable tracer. We know that no significant photosynthesis took place on the tilled field between 1st of May and 17th of June, as there was no green foliage visible until after this period. Therefore, if the CO_2 fluxes showed no day-time uptake on the tilled field, we can be reasonably certain that the measured N_2O fluxes were also coming from the tilled field. Figure 6 shows that this was the case: in fluxes attributed to the tilled field, there was no day-time uptake of CO_2; in fluxes attributed to the un-tilled field, the normal diurnal cycle in CO_2 flux is seen. By inference, we can attribute the high N_2O emissions after tillage to the tilled field.

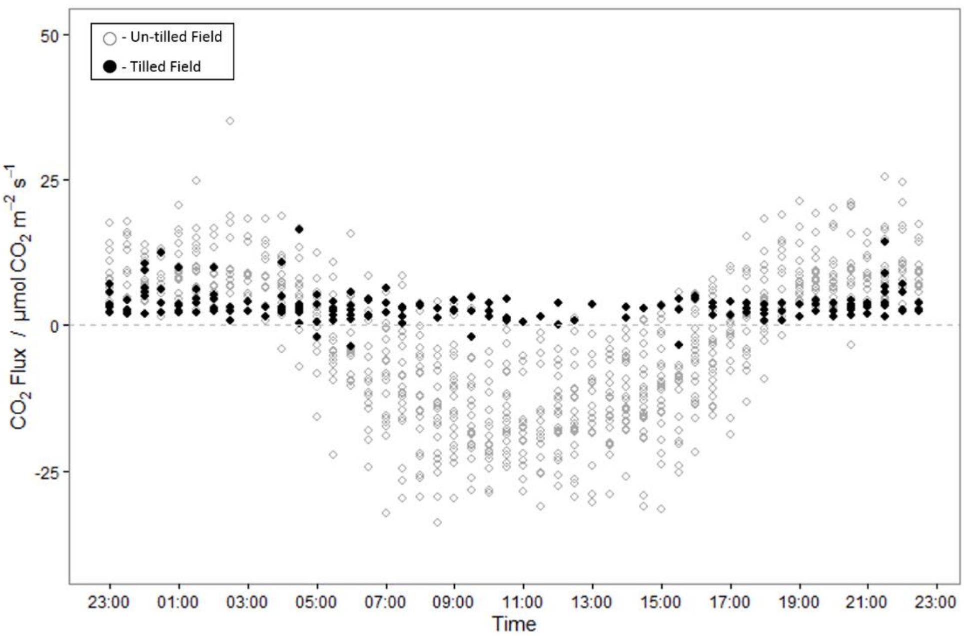

Figure 6 CO_2 flux measurements made from the un-tilled (grey) and tilled (black) fields between the 1st of May and the 17th of June. Uptake is denoted as a negative quantity. The results show a clear difference between the fields, with no day-time uptake on the tilled field. This implies that the high N_2O fluxes measured after the tillage event can also be attributed to the tilled field.

The GAM method was used to gap-fill flux data to calculate cumulative fluxes for both fields separately using the fluxes measured from each. (Figure 7). The total number of individual eddy covariance, dynamic chamber and static chamber flux measurements used to fit the GAMs were 1563:273:234 and 1153:56:221 for the tilled and un-tilled fields, respectively. Cumulative N_2O fluxes calculated for the tilled and un-tilled fields from 1st of April to the 16th of September were 2.14 ± 0.18 and 1.65 ± 1.02 kg N_2O-N ha^{-1}, respectively (Figure 8). Uncertainty in the GAM prediction is particularly large when no measurements are available in which to fit the model. There are sustained periods in which very few eddy covariance measurements were recorded from the un-tilled field due to the wind direction being predominantly south westerly (Figure 7a). The uncertainty in predicted flux becomes very large when compared to periods when measurements data is available and these uncertainties propagate significantly in cumulative flux estimates (Figure 8).

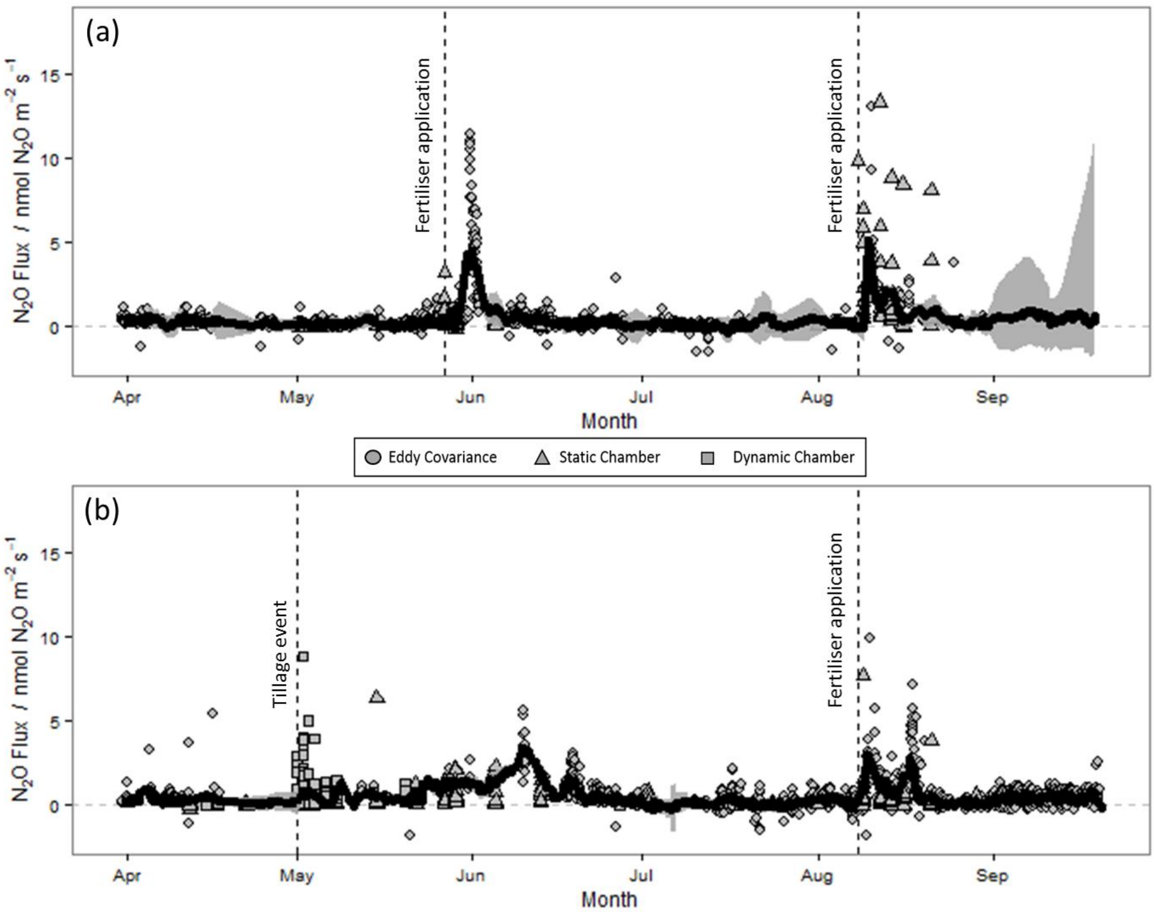

Figure 7 The GAM method (black line) provides an estimated N_2O flux which can be used to gap-fill measurements from both the (a) un-tilled and (b) tilled fields at 30 min intervals. The 95 % confidence interval in the estimated flux reported by the GAM is included (grey). Tillage and fertiliser dates are indicated (vertical lines).

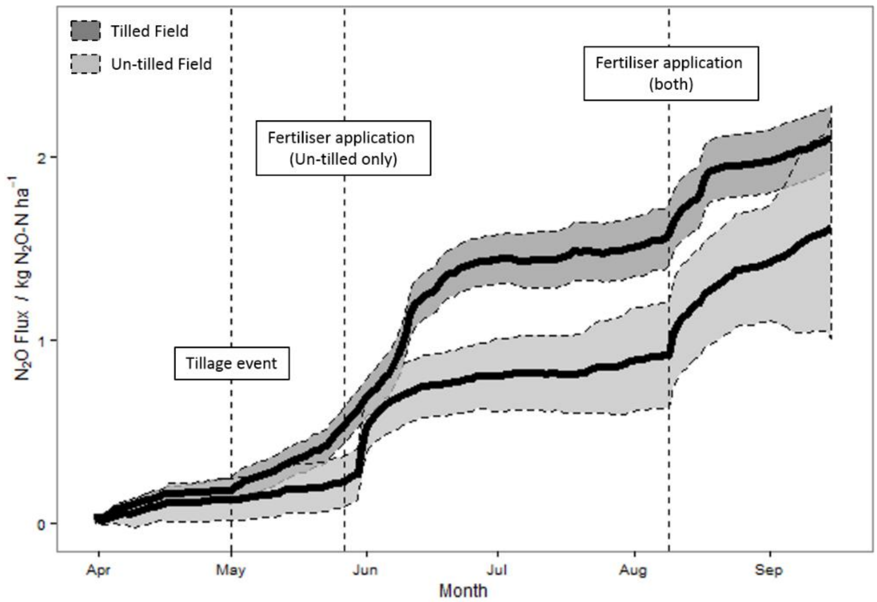

Figure 8 Cumulative flux is calculated for the tilled (dark grey) and un-tilled fields (light grey) using the gap-filled flux data. The cumulative 95 % confidence intervals are shown (grey areas). Fertiliser was applied to the untilled field on the 28th of May and to both fields on the 9th of August and tillage occurred on the 1st of May (black dashed vertical lines).

4 Discussion

4.1 The influence of tillage on N_2O fluxes

The comparison of pre-tillage and post-tillage fluxes from the tilled field suggests that the tillage event was directly responsible for an immediate increase in N_2O fluxes (Figures 5 & 8). N_2O fluxes significantly larger than those measured pre-tillage were observed from the tilled field over two separate periods during which no changes in N_2O fluxes were observed in the adjacent un-tilled field. The initial increase in N_2O flux from the tilled field is a short lived peak which occurs directly after the disturbance of the soil caused by ploughing and harrowing. The second is a sustained increase which is observed throughout May and June. In the two month period in which fluxes from the tilled field were elevated, a total of 1.26 ± 0.12 kg N_2O-N ha^{-1} was estimated to have been released. Assuming fluxes in the tilled field had remained at approximately pre-tillage magnitude had the tillage event not taken place (~0.27 nmol m^{-2} s^{-1}, based on an average of fluxes measurements before the tillage event), it can be concluded that the tillage event contributed to an additional 0.85 ± 0.11 kg N_2O-N ha^{-1} emitted from the field over a two month period.

Increases in N_2O flux lasting up to two months after grassland tillage events have been observed before in other studies using both static chamber and eddy covariance measurements (Chatskikh and Olesen, 2007; Merbold et al., 2014). Reported fluxes can be relatively high over a sustained period of time (several days or weeks) and similar in magnitude to those recorded after fertilisation events. The mechanisms driving these large sustained fluxes are believed to be partly due to the mineralisation of organic materials in the soils (decaying grass materials from the previous sward in tilled grasslands) (Baggs et al., 2003; Hellebrand, 1998; Pimentel et al., 2015). The large quantities of decaying organic matter ploughed into the soils would have provided a gradual release of carbon and nitrogen into the soils, which provide substrate for the microbial processes of nitrification and denitrification (Pimentel et al., 2015; Seastedt et al., 1992). According to IPCC estimates, 1 % of N added to soils in the form of crop residues can be expected to be released as N_2O (IPCC, 2006). Based on our pre-tillage biomass measurements made prior to tillage (93.6 kg N ha^{-1}),we would expect to see N_2O fluxes of approximately 0.94 kg N_2O-N ha^{-1} from the field. This estimated value is within the range of uncertainty of our calculated cumulative fluxes in this study (0.85 ± 0.11 kg N_2O-N ha^{-1}). High emissions from crop residues tilled into arable crops have been recorded in similar wet soils with high clay content (Ball, 1999) which may indicate a similar process is occurring under these conditions at other field sites in the area.

Large N_2O fluxes (> 0.5 nmol m^{-2} s^{-1}) are observed from both fields after fertilisation events. Elevated fluxes recorded from the fields after fertilisation typically last three to four weeks with an occasional large spike lasting 24 to 48 hours before returning to pre-fertilisation levels. This month long period in which the majority of large fluxes occur after fertilisation is also generally observed by other similar studies from the local area (Skiba et al., 2013; Smith et al., 2012). Assuming the majority of N_2O emitted after a fertilisation event occurs within a 28 day period after the fertiliser application, the 28 day cumulative flux emissions associated with the fertilisation events on the 28th of May and 9th of August on the un-tilled field were 0.55 ± 0.05 and 0.76 ± 0.24 kg N_2O-N ha^{-1}, respectively. This equates to 0.79 and 1.09 % of the total nitrogen applied, respectively. The 28 day cumulative flux emissions associated with the fertilisation event on the tilled field was 0.77 ± 0.34 kg N_2O-N ha^{-1}, or 1.10 % of the total nitrogen applied. Assuming the 28 day periods account well for the emission factors of the fertiliser events, these results are well within the range of uncertainty of the generic 1 (0.3 to 3.0) % value reported by the IPCC for N fertiliser events (IPCC, 2014).

4.2 Gap filling of N_2O fluxes

Gap-filling N_2O flux measurements is challenging due to the lack of reliable process-based models on which to base predictions. N_2O fluxes are believed to be driven primarily by the availability of nitrogen compounds in the soils (ammonium and nitrate) (Davidson et al., 2000) as well as physical properties of the soil such as WFPS, aerobic extent, soil type, temperature and compaction (Ball et al., 2008; Butterbach-Bahl et al., 2013; Choudhary et al., 2002; Davidson et al., 2000; Turner et al., 2008). The collection of these data on a temporal/spatial scale which would allow these models to be applied is not often logistically possible or affordable. The GAM method used in this study incorporates readily-available meteorological data with the temporal pattern in the data, to provide an empirical but practical means of temporal interpolation, which makes use of more information than simple linear interpolation. Although the GAM method has proved useful, we would also emphasise the dangers of extrapolating to conditions beyond those to which the model was fitted. For example, as we have not measured fluxes during the cold months in winter, the GAM is unable to reliably predict fluxes in temperatures lower than those measured during the study. The method deals appropriately with the large uncertainties where measurement data are unavailable, contributing considerably to the total uncertainty in cumulative flux estimates.

In this study, spatial variability was not explicitly accounted for in the cumulative flux uncertainty and this remains a potentially large error if extrapolating to areas larger than the measurement footprint. Eddy covariance is able to integrate over a large area of the field (several 100 m^2) (Eugster and Merbold, 2015) but these measurements are still subject to an element of spatial variability which is difficult to fully account for given the spatially heterogeneous nature of N_2O fluxes. Any study which plans to report cumulative flux estimates should consider how to minimise the uncertainties which arise when interpolating and/or extrapolating measurements to larger temporal and spatial scales (e.g. from occasional chamber measurements to annual field-scale emissions). Further studies may require more complex statistical analysis, using methods such as Bayesian statistics, to properly quantify the uncertainty in estimates of cumulative fluxes over large areas.

5 Conclusion

N_2O emissions from the grassland field after the tillage event were relatively large and sustained, similar in magnitude to a nitrogen fertilisation event. The tillage event in this study is estimated to be responsible for a period of high and sustained N_2O emissions lasting over a two month period after tillage (0.85 ± 0.11 kg N_2O-N ha[-1]), with a cumulative flux value akin to an 85 Kg-N fertiliser application according to IPCC emission factor estimates. Relatively little difference in N_2O fluxes were observed between the tilled and un-tilled fields after a subsequent identical application of nitrogen fertiliser in August 2012. Our results agree with several other similar studies that tillage and the resultant addition of crop residues into soils can result in significant emissions of N_2O, similar in magnitude to 1 % of the nitrogen available in those residues (0.9 % in this study). This study highlights that the tillage of grassland fields can potentially result in a short term but significant increase in emissions of N_2O, with the potential to affect regional or national greenhouse gas budgets.

6 Acknowledgements

We thank farm manager Wim Bosma, for the Easter Bush field site, who provided us with the opportunity to carry out this experiment. We thank DEFRA and the UK Devolved Administrations for financial support through the UK GHG Platform project AC0116 (The InveN2Ory project). We also thank the INGOS EU funded Integrating Activity for support of the field infrastructure.

7 References

Abdalla, M., Jones, M., Ambus, P. and Williams, M.: Emissions of nitrous oxide from Irish arable soils: effects of tillage and reduced N input, Nutr. Cycl. Agroecosystems, 86(1), 53–65, doi:10.1007/s10705-009-9273-8, 2010.

Baggs, E. M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H. and Cadisch, G.: Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage, Plant Soil, 254(2), 361–370, doi:10.1023/A:1025593121839, 2003.

Ball, B.: Soil and residue management effects on arable cropping conditions and nitrous oxide fluxes under controlled traffic in Scotland 1. Soil and crop responses, Soil Tillage Res., 52(3–4), 177–189, doi:10.1016/S0167-1987(99)00080-X, 1999.

Ball, B., Crichton, I. and Horgan, G.: Dynamics of upward and downward N_2O and CO_2 fluxes in ploughed or no-tilled soils in relation to water-filled pore space, compaction and crop presence, Soil Tillage Res., 101(1–2), 20–30, doi:10.1016/j.still.2008.05.012, 2008.

Boeckx, P., Van Nieuland, K. and Van Cleemput, O.: Short-term effect of tillage intensity on N_2O and CO_2 emissions, Agron. Sustain. Dev., 31(3), 453–461, doi:10.1007/s13593-011-0001-9, 2011.

Bouwman, A. F., Boumans, L. J. M. and Batjes, N. H.: Modeling global annual N_2O and NO emissions from fertilized fields: N_2O and NO emissions from fertilizers, Glob. Biogeochem. Cycles, 16(4), 28-1-28–9, doi:10.1029/2001GB001812, 2002.

Burba, G., Schmidt, A., Scott, R. L., Nakai, T., Kathilankal, J., Fratini, G., Hanson, C., Law, B., McDermitt, D. K., Eckles, R., Furtaw, M. and Velgersdyk, M.: Calculating CO_2 and H_2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio, Glob. Change Biol., 18(1), 385–399, doi:10.1111/j.1365-2486.2011.02536.x, 2012.

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R. and Zechmeister-Boltenstern, S.: Nitrous oxide emissions from soils: how well do we understand the processes and their controls?, Philos. Trans. R. Soc. B Biol. Sci., 368(1621), 20130122–20130122, doi:10.1098/rstb.2013.0122, 2013.

Chatskikh, D. and Olesen, J. E.: Soil tillage enhanced CO_2 and N_2O emissions from loamy sand soil under spring barley, Soil Tillage Res., 97(1), 5–18, doi:10.1016/j.still.2007.08.004, 2007.

Choudhary, M. ., Akramkhanov, A. and Saggar, S.: Nitrous oxide emissions from a New Zealand cropped soil: tillage effects, spatial and seasonal variability, Agric. Ecosyst. Environ., 93(1–3), 33–43, doi:10.1016/S0167-8809(02)00005-1, 2002.

Cowan, N. J., Famulari, D., Levy, P. E., Anderson, M., Bell, M. J., Rees, R. M., Reay, D. S. and Skiba, U. M.: An improved method for measuring soil N_2O fluxes using a quantum cascade laser with a dynamic chamber, Eur. J. Soil Sci., 65(5), 643–652, doi:10.1111/ejss.12168, 2014a.

Cowan, N. J., Famulari, D., Levy, P. E., Anderson, M., Reay, D. S. and Skiba, U. M.: Investigating uptake of N_2O in agricultural soils using a high-precision dynamic chamber method, Atmospheric Meas. Tech., 7(12), 4455–4462, doi:10.5194/amt-7-4455-2014, 2014b.

Cowan, N. J., Norman, P., Famulari, D., Levy, P. E., Reay, D. S. and Skiba, U. M.: Spatial variability and hotspots of soil N_2O fluxes from intensively grazed grassland, Biogeosciences, 12(5), 1585–1596, doi:10.5194/bg-12-1585-2015, 2015.

Davidson, E. A., Keller, M., Erickson, H. E., Verchot, L. V. and Veldkamp, E.: Testing a Conceptual Model of Soil Emissions of Nitrous and Nitric Oxides: Using two functions based on soil nitrogen availability and soil water content, the hole-in-the-pipe model characterizes a large fraction of the observed variation of nitric oxide and nitrous oxide emissions from soils, BioScience, 50(8), 667–680, doi:10.1641/0006-3568(2000)050[0667:TACMOS]2.0.CO;2, 2000.

Dobbie, K. E., McTaggart, I. P. and Smith, K. A.: Nitrous oxide emissions from intensive agricultural systems: Variations between crops and seasons, key driving variables, and mean emission factors, J. Geophys. Res., 104(D21), 26891, doi:10.1029/1999JD900378, 1999.

Elmi, A., Madramootoo, C., Hamel, C. and Liu, A.: Denitrification and nitrous oxide to nitrous oxide plus dinitrogen ratios in the soil profile under three tillage systems, Biol. Fertil. Soils, 38(6), 340–348, doi:10.1007/s00374-003-0663-9, 2003.

Eugster, W. and Merbold, L.: Eddy covariance for quantifying trace gas fluxes from soils, SOIL, 1(1), 187–205, doi:10.5194/soil-1-187-2015, 2015.

Finkelstein, P. L. and Sims, P. F.: Sampling error in eddy correlation flux measurements, J. Geophys. Res. Atmospheres, 106(D4), 3503–3509, doi:10.1029/2000JD900731, 2001.

Foken, T., Göockede, M., Mauder, M., Mahrt, L., Amiro, B. and Munger, W.: Post-Field Data Quality Control, in Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis, edited by X. Lee, W. Massman, and B. Law, pp. 181–208, Springer Netherlands, Dordrecht. [online] Available from: http://dx.doi.org/10.1007/1-4020-2265-4_9, 2005.

Fowler, D., Coyle, M., Skiba, U., Sutton, M. A., Cape, J. N., Reis, S., Sheppard, L. J., Jenkins, A., Grizzetti, B., Galloway, J. N., Vitousek, P., Leach, A., Bouwman, A. F., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M. and Voss, M.: The global nitrogen cycle in the twenty-first century, Philos. Trans. R. Soc. B Biol. Sci., 368(1621), 20130164–20130164, doi:10.1098/rstb.2013.0164, 2013.

Hellebrand, H. J.: Emission of Nitrous Oxide and other Trace Gases during Composting of Grass and Green Waste, J. Agric. Eng. Res., 69(4), 365–375, doi:10.1006/jaer.1997.0257, 1998.

Intergovernmental Panel on Climate Change, Ed.: Climate Change 2013 - The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge. [online] Available from: http://ebooks.cambridge.org/ref/id/CBO9781107415324 (Accessed 24 November 2015), 2014.

(Intergovernmental Panel on Climate Change, I.: IPCC guidelines for national greenhouse gas inventories. Chapter 11: N2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application., [online] Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf, 2006.

Jahangir, M., Roobroeck, D., Van Cleemput, O. and Boeckx, P.: Spatial variability and biophysicochemical controls on N_2O emissions from differently tilled arable soils, Biol. Fertil. Soils, 47(7), 753–766, doi:10.1007/s00374-011-0580-2, 2011.

Jones, S. K., Famulari, D., Di Marco, C. F., Nemitz, E., Skiba, U. M., Rees, R. M. and Sutton, M. A.: Nitrous oxide emissions from managed grassland: a comparison of eddy covariance and static chamber measurements, Atmospheric Meas. Tech. Discuss., 4(1), 1079–1112, doi:10.5194/amtd-4-1079-2011, 2011.

Kormann, R. and Meixner, F. X.: An Analytical Footprint Model For Non-Neutral Stratification, Bound.-Layer Meteorol., 99(2), 207–224, doi:10.1023/A:1018991015119, 2001.

Levy, P. E., Gray, A., Leeson, S. R., Gaiawyn, J., Kelly, M. P. C., Cooper, M. D. A., Dinsmore, K. J., Jones, S. K. and Sheppard, L. J.: Quantification of uncertainty in trace gas fluxes measured by the static chamber method, Eur. J. Soil Sci., 62(6), 811–821, doi:10.1111/j.1365-2389.2011.01403.x, 2011.

Mathieu, O., Leveque, J., Henault, C., Milloux, M., Bizouard, F. and Andreux, F.: Emissions and spatial variability of N_2O, N_2 and nitrous oxide mole fraction at the field scale, revealed with 15N isotopic techniques, Soil Biol. Biochem., 38(5), 941–951, doi:10.1016/j.soilbio.2005.08.010, 2006.

Merbold, L., Eugster, W., Stieger, J., Zahniser, M., Nelson, D. and Buchmann, N.: Greenhouse gas budget (CO_2 , CH_4 and N_2O) of intensively managed grassland following restoration, Glob. Change Biol., 20(6), 1913–1928, doi:10.1111/gcb.12518, 2014.

Moncrieff, J. B., Massheder, J. M., de Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Soegaard, H. and Verhoef, A.: A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide, J. Hydrol., 188–189, 589–611, doi:10.1016/S0022-1694(96)03194-0, 1997.

Omonode, R. A., Smith, D. R., Gál, A. and Vyn, T. J.: Soil Nitrous Oxide Emissions in Corn following Three Decades of Tillage and Rotation Treatments, Soil Sci. Soc. Am. J., 75(1), 152, doi:10.2136/sssaj2009.0147, 2011.

Palma, R. M., Rímolo, M., Saubidet, M. I. and Conti, M. E.: Influence of tillage system on denitrification in maize-cropped soils, Biol. Fertil. Soils, 25(2), 142–146, doi:10.1007/s003740050294, 1997.

Pedersen, A. R., Petersen, S. O. and Schelde, K.: A comprehensive approach to soil-atmosphere trace-gas flux estimation with static chambers, Eur. J. Soil Sci., 61(6), 888–902, doi:10.1111/j.1365-2389.2010.01291.x, 2010.

Pimentel, L. G., Weiler, D. A., Pedroso, G. M. and Bayer, C.: Soil N_2O emissions following cover-crop residues application under two soil moisture conditions, J. Plant Nutr. Soil Sci., 178(4), 631–640, doi:10.1002/jpln.201400392, 2015.

Pinto, M., Merino, P., del Prado, A., Estavillo, J. M., Yamulki, S., Gebauer, G., Piertzak, S., Lauf, J. and Oenema, O.: Increased emissions of nitric oxide and nitrous oxide following tillage of a perennial pasture, Nutr. Cycl. Agroecosystems, 70(1), 13–22, doi:10.1023/B:FRES.0000049357.79307.23, 2004.

Seastedt, T. R., Parton, W. J. and Ojima, D. S.: Mass loss and nitrogen dynamics of decaying litter of grasslands: the apparent low nitrogen immobilization potential of root detritus, Can. J. Bot., 70(2), 384–391, doi:10.1139/b92-052, 1992.

Seitzinger, S. P., Kroeze, C. and Styles, R. V.: Global distribution of N_2O emissions from aquatic systems: natural emissions and anthropogenic effects, Chemosphere - Glob. Change Sci., 2(3–4), 267–279, doi:10.1016/S1465-9972(00)00015-5, 2000.

Sheehy, J., Six, J., Alakukku, L. and Regina, K.: Fluxes of nitrous oxide in tilled and no-tilled boreal arable soils, Agric. Ecosyst. Environ., 164, 190–199, doi:10.1016/j.agee.2012.10.007, 2013.

Skiba, U., Jones, S. K., Drewer, J., Helfter, C., Anderson, M., Dinsmore, K., McKenzie, R., Nemitz, E. and Sutton, M. A.: Comparison of soil greenhouse gas fluxes from extensive and intensive grazing in a temperate maritime climate, Biogeosciences, 10(2), 1231–1241, doi:10.5194/bg-10-1231-2013, 2013.

Smith, K., Dobbie, K., Thorman, R., Watson, C., Chadwick, D., Yamulki, S. and Ball, B.: The effect of N fertilizer forms on nitrous oxide emissions from UK arable land and grassland, Nutr. Cycl. Agroecosystems, 93(2), 127–149, doi:10.1007/s10705-012-9505-1, 2012.

Tan, I., Vanes, H., Duxbury, J., Melkonian, J., Schindelbeck, R., Geohring, L., Hively, W. and Moebius, B.: Single-event nitrous oxide losses under maize production as affected by soil type, tillage, rotation, and fertilization, Soil Tillage Res., 102(1), 19–26, doi:10.1016/j.still.2008.06.005, 2009.

Turner, D. A., Chen, D., Galbally, I. E., Leuning, R., Edis, R. B., Li, Y., Kelly, K. and Phillips, F.: Spatial variability of nitrous oxide emissions from an Australian irrigated dairy pasture, Plant Soil, 309(1–2), 77–88, doi:10.1007/s11104-008-9639-8, 2008.

Wood, S. N.: Generalized additive models: an introduction with R, Chapman & Hall/CRC, Boca Raton, FL., 2006.

Yamulki, S. and Jarvis, S.: Short-term effects of tillage and compaction on nitrous oxide, nitric oxide, nitrogen dioxide, methane and carbon dioxide fluxes from grassland, Biol. Fertil. Soils, 36(3), 224–231, doi:10.1007/s00374-002-0530-0, 2002.