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

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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 and 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 greatly improved the temporal and spatial coverage of N_2O fluxes before and after the tillage event and is recommended to be followed in future studies.

Total cumulative fluxes calculated for the tilled and un-tilled fields over the 175 day measurement period were 2.45 ± 0.27 and 2.08 ± 0.23 kg N_2O-N ha^{-1}, respectively. 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 1.08 ± 0.14 kg N_2O-N ha^{-1}. Cumulative fluxes calculated over a 28 day period in August after the application of 70 kg-N ha^{-1} as ammonium nitrate to both fields were estimated at 0.42 ± 0.15 and 0.75 ± 0.14 kg N_2O N ha^{-1} for the tilled and un-tilled fields, respectively. The tillage event appears to have substantially increased N_2O fluxes from the tilled grassland field over a two month period; however, this increase may have been fractionally offset by a decrease in emissions after the August fertilisation event.

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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 measured the release of N_2O from soils after the application of nitrogen fertilisers - which are believed to be the most significant contributor to the rise of N_2O emissions since pre-industrial times (e.g. Bouwman et al., 2002; Dobbie et al., 1999). Other causes of N_2O emissions from agricultural soils, such as tillage and compaction, are less well documented, thus preventing effective assessment of their contribution to the overall annual N_2O flux from the agricultural sector.

The use of nitrogen fertilisers (Abdalla et al., 2010; Yamulki and Jarvis, 2002), the presence of crop residues (Baggs et al., 2003; Mutegi et al., 2010), soil compaction (Ball et al., 2008; Yamulki and Jarvis, 2002) and the regularity and method of tillage (Sheehy et al., 2013) have all been reported to affect tillage induced N_2O emissions. Changes in N_2O emissions after tillage events are believed to be partly due to altering 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 addition of nitrogen to tilled soils in the form of decaying plant matter (crop residues) is a recognised potential source of N_2O; however the emissions associated with specific crop residues are not well quantified. 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).

The large number of variables which may alter microbiological processes in tilled soils can lead to a wide variety of results between experiments carried out at different field sites under different meteorological conditions.

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As a result, tillage events in agricultural fields have been reported to have very different effects on N_2O production. Some experiments have reported large increases in N_2O emissions varying from 0.89 to 3.37 Kg N ha^{-1} (i.e. Chatskikh and Olesen, 2007; Merbold et al., 2014; Omonode et al., 2011; Pinto et al., 2004; Yamulki and Jarvis, 2002) dependant of fertiliser application post-tillage, 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 no consensus among these studies when quantifying the effect of different drivers of N_2O production; however, it is common that factors influencing the aerobicity 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). Although permanent grasslands are tilled less often than arable land, the conversion between arable and grazed pasture is a fairly common occurrence which requires a tillage event. Due to the large number of tillage events which occur annually across the country it is possible that even small perturbations in fluxes caused by these events could contribute significantly to the total national inventory of anthropogenic N_2O emissions. Unlike arable fields, many of which are tilled annually, intensively managed grasslands are only tilled occasionally (generally every 5 to 20 years depending on soil conditions and grazing intensity), either for conversion to arable use or to improve grass sward productivity. The regularity of sward renewal depends primarily on the condition of the grass available for grazing and desired stocking density and is entirely dependent on the opinion and experience of farm managers in different climates. Few experiments have been carried out on GHG emissions resulting from the tillage of grassland fields due to the infrequency of these events. The aim of this work was therefore (i) to use multiple N_2O flux measurement methodologies to add to the understanding of the magnitude of 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 the event, and (iii) compare our cumulative flux emissions with those predicted using the current IPCC methodology for crop residue emissions.

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 ºC (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).

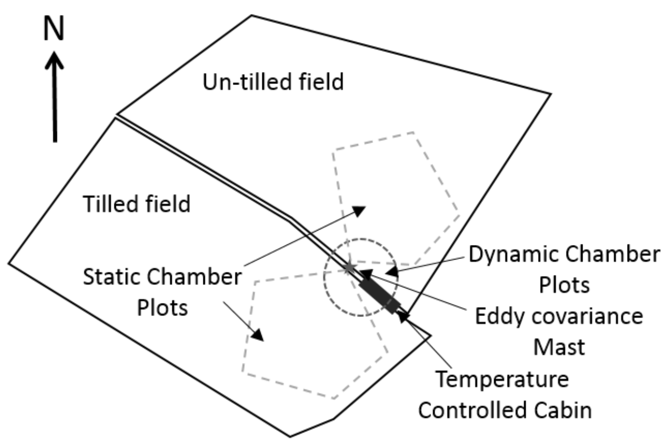

Figure 1 N_2O fluxes were measured from two adjacent grassland fields at the Easter Bush Farm (Penicuik, Scotland). The north field remained un-tilled, while the south field was ploughed on the 1st of May 2012. An eddy covariance mast was setup next to a permanent cabin positioned between the fields.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

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The soils are clay loams with a sand/silt/clay texture of 28/20/52 and 24/19/57 for the top 30 cm in the un-tilled and tilled fields, respectively with a pH of 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. This together with the poor drainage led to the decision to till both fields.

In the first stage, only one field (also called the South Field in Jones et al., 2011) was tilled (Table 1). In preparation, glycophosphate (1.5 l ha^{-1}) was applied to kill the grass three days prior ploughing on the 27th of April. The addition of glycophosphate to the soil is considered standard practice when grassland fields are ploughed in the area and the effect that it may have had on microbiological processes or the decay of the grass materials ploughed into the soil are considered to be part of the tillage event as a whole in this study. The field was ploughed to a depth of 30 cm on the 1st of May 2012. Two days after ploughing the field was harrowed, then rolled and sown with ryegrass (*Lolium perenne L.)* three days 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)
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	70 kg-N ha^{-1} Nitram application	70 kg-N ha^{-1} Nitram application

Biomass samples were collected from the fields before tillage. Twenty soil cores (12 cm deep and 5.8 cm diameter) were extracted from the fields. All above ground biomass was removed from the soil and dried in

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an oven at 80℃ until constant weight. Once dry the above ground biomass was weighed. The remaining soil cores were broken up by hand and dried at 100℃ until constant weight. After drying, the root materials were separated from the soils by hand and weighed. Sub samples of the dried plant materials were prepared for combustion elemental analysis of total carbon and nitrogen contents (vario EL cube, Elemaentar, Hanau, Germany).

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. Eddy covariance was the primary measurement methodology used; however, due to unpredictable changes in wind direction at the site it was necessary to deploy chamber methodology to ensure that both fields were measured periodically during the experiment. The dynamic chamber measurements was 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 (See Figure 1). An ultra-sonic anemometer (WindMaster Pro 3-axis, Gill, Lymington, UK) mounted at 2.2 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):

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

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 Mauder & Foken, (2004) was used to remove poor quality flux measurements (their category 2). Data were also rejected on the basis of high instrumental noise, and friction velocity ($u*$) values less than 0.05

m s^{-1}. Fluxes measured with a mean wind direction between 150 and 300 degrees were classed as from the tilled field; those measured at greater than 320 and less than 130 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. Standard meteorological variables (rainfall, air temperature and soil temperature) were recorded by a nearby weather station.

N_2O was 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). Static chambers in the un-tilled field were kept in the same position for the duration of the experiment. Chambers in the tilled field were occasionally moved to allow access to farm vehicles during the different stages of the tillage operation. Chamber measurements were carried out between 9:00 and 15:00 on the measurement dates. Fluxes were calculated as:

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

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.

Fluxes were also measured using the QCL in a closed, dynamic chamber system (Cowan et al., 2014a). A chamber (39 cm ID, 22 cm high) was placed onto a stainless steel collar inserted several cm into the soil (on average 5 cm) 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.

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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).

We fitted the GAM with the same model terms to the separate data sets from the tilled and un-tilled fields. The 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

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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, given 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 time step. To calculate cumulative fluxes, observed fluxes were used with their associated uncertainties 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 2a). Historically, the wind direction at the field site is predominantly south-westerly (85 %). However, during the measurement campaign, the wind direction was split more evenly between the tilled and un-tilled fields (Figure 3). This allowed a better basis for comparison of N_2O fluxes from the two fields, although data coverage for each field was low, 27 % and 25 % for tilled and un-tilled respectively.

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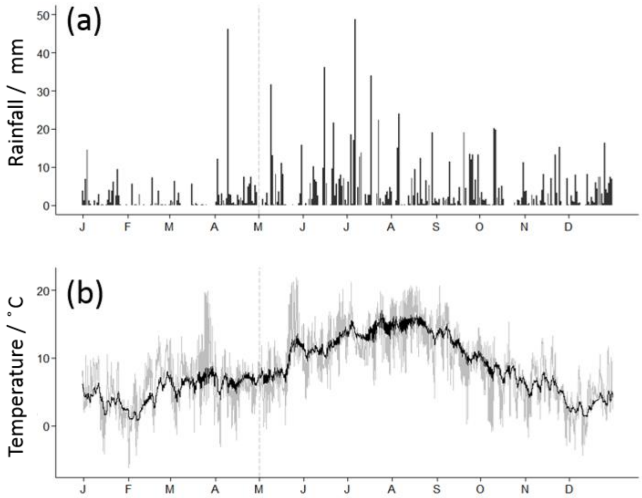

Figure 2 (a) Accumulated daily rainfall at the Easter Bush Field site during the year 2012. (b) Air temperature at height 3 m (grey) and soil temperature (black) recorded at the Easter Bush field site during the year 2012. Tillage occurred on the 1st of May 2012 (grey dashed vertical line).

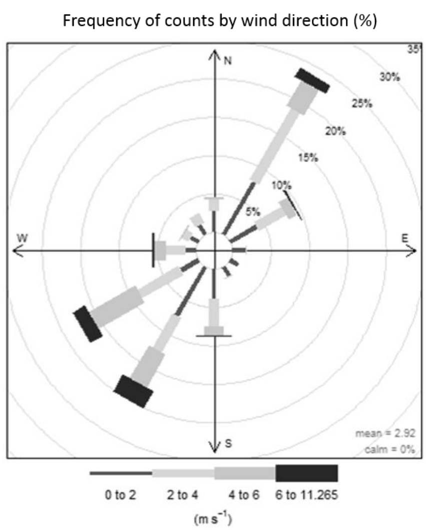

Figure 3 Wind rose plot for the Easter Bush field site during eddy covariance measurements (March – October 2012).

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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 fluxes were below 0.5 nmol m^{-2} s^{-1} (Figure 4). 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 4b). 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 in the first week in June (Figure 5c). Unfortunately, data coverage was rather low during this period due to changes in wind direction and a one week period in which the QCL was unavailable. 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 late August.

The GAM method was used to gap fill flux data to calculate cumulative fluxes (Figure 6). Cumulative N_2O fluxes calculated for the tilled and un-tilled fields for the 175 days from 27th of March to the 18th of October were 2.45 ± 0.27 and 2.08 ± 0.23 kg N_2O-N ha^{-1}, respectively (Figure 7).

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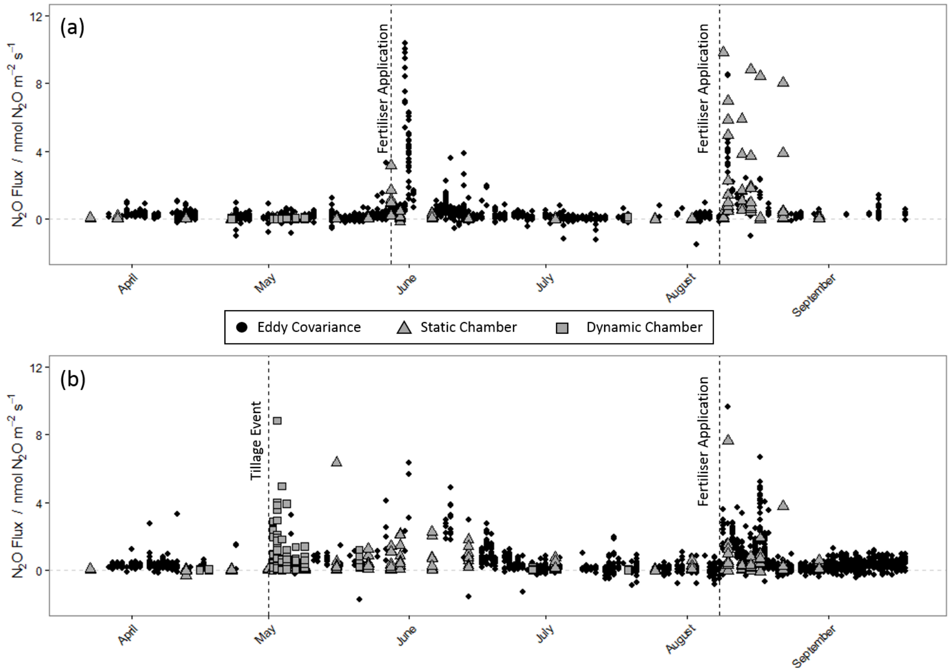

Figure 4 Fluxes of N_2O from the (a) un-tilled and (b) tilled fields measured at the Easter Bush field site in 2012. Fertiliser was applied to the un-tilled field on the 28th of May and to both fields on 9th August. Tillage began on 1st May. The Y-axis is limited to 12 nmol m^{-2} s^{-1} for better comparison between the fields. Only four static chamber measurements in the north field recorded fluxes above 12 nmol m^{-2} s^{-1} in the first few days after the August fertilisation.

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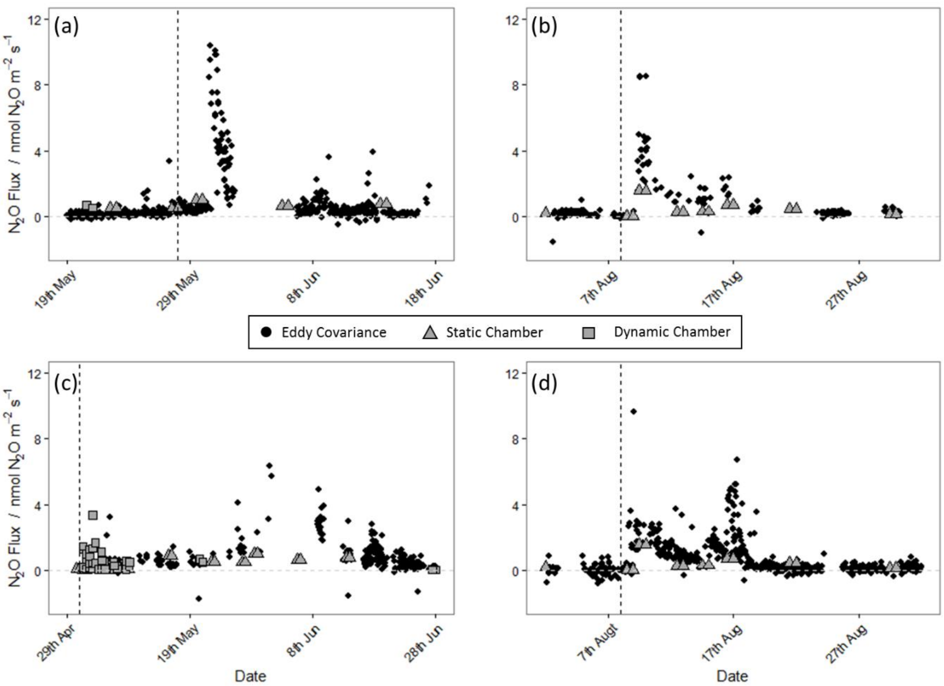

Figure 5 Elevated fluxes of N_2O were measured from the un-tilled field after (a) a 70 kg-N ha^{-1} application of Nitram on the 28th of May and (b) a second 70 kg-N ha^{-1} application of Nitram on the 9th of August. Elevated fluxes of N_2O were measured from the tilled field (c) immediately after the tillage event on the 1st of May which remained above pre-tillage magnitude until the end of June. Elevated fluxes of N_2O were also observed from the tilled field (d) after a 70 kg-N ha^{-1} application of Nitram on the 9th of August.

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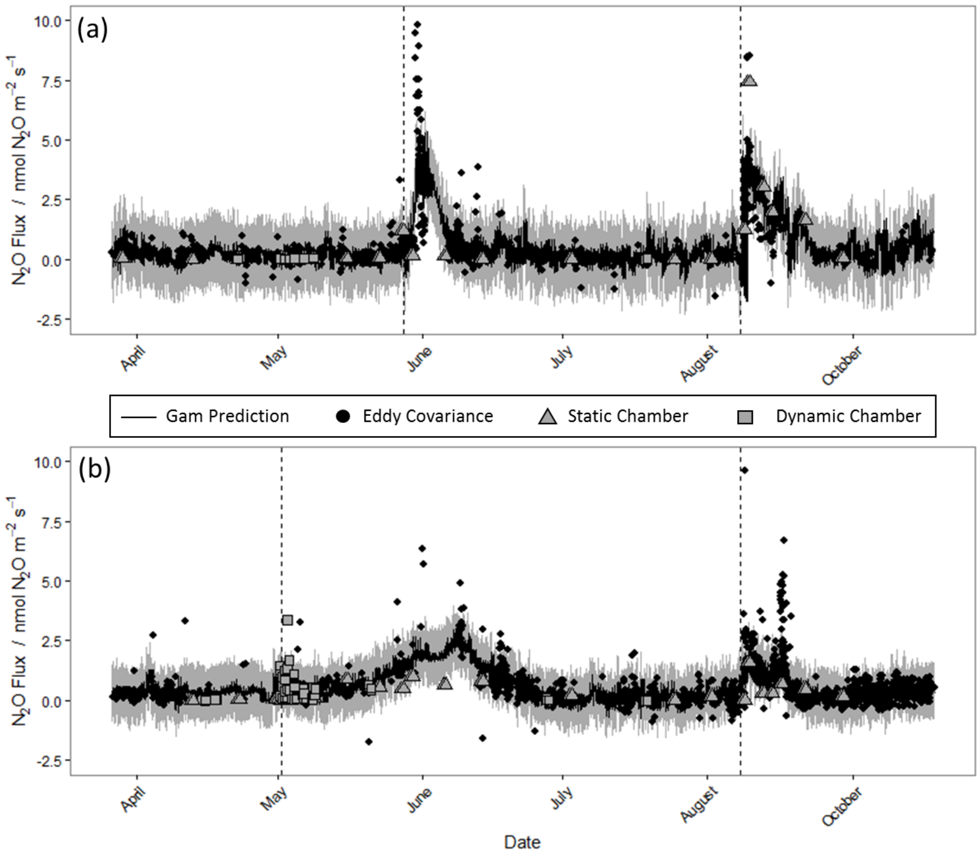

Figure 6 The GAM method provides an estimated N_2O flux which can be used to gap fill measurements from both the (a) un-tilled and (b) tilled fields at 30 min intervals. The 95 % confidence interval in the estimated flux reported by the GAM is included (grey). Tillage and fertiliser dates are indicated (vertical lines)

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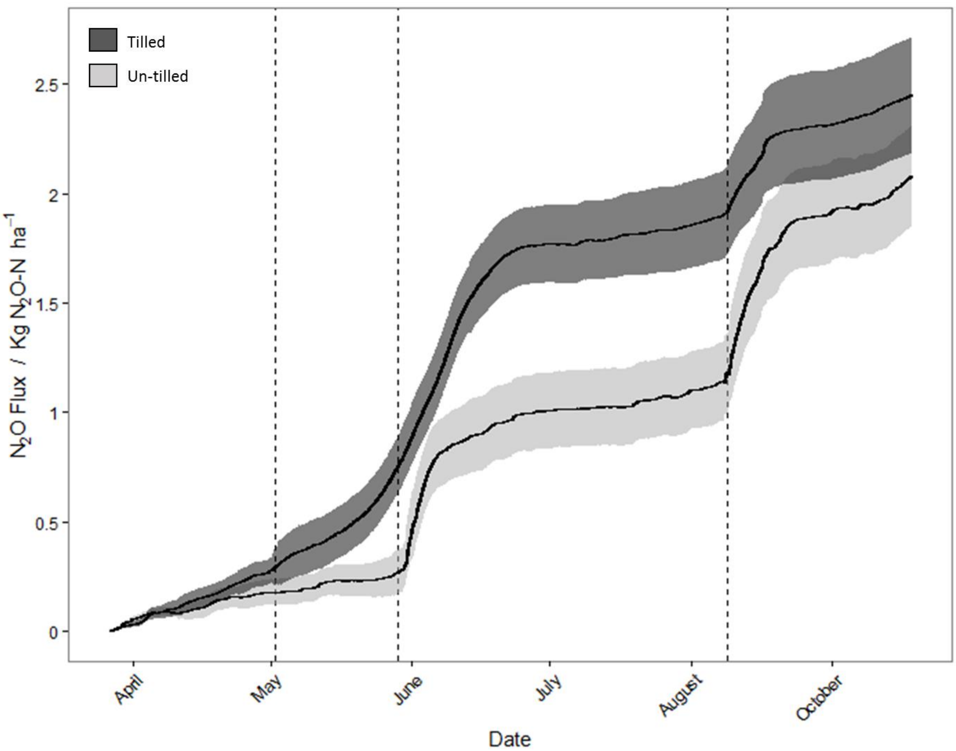

Figure 7 Cumulative flux is calculated for the tilled (dark) and un-tilled fields (light) using the gap filled flux data. The propagated 95 % confidence intervals estimated using the sum of least squares method (grey areas). Fertiliser was applied to the untilled field on the 28th of May and to both fields on the 9th of August and tillage occurred on the 1st of May (black dashed vertical lines).

3.3 Biomass measurements

Biomass measurements made from the tilled field before tillage estimated that there was an average of 369 ± 310 g m^{-2} of grass materials (dried weight) growing across the field with a root to shoot ratio of ~1.5. The elemental analysis of the dry grass materials measured an average total carbon content of 45.7 % and nitrogen content of 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.

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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 (Figure 4b & 5c). 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 occurs directly after the disturbance of the soil caused by ploughing and harrowing. In the two month period in which fluxes from the tilled field were elevated, a total of 1.47 ± 0.16 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 (~0.27 nmol m^{-2} s^{-1}) had the tillage event not taken place, it can be concluded that the tillage event contributed to an additional 1.08 ± 0.14 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 (93.6 kg N ha^{-1}) if these estimates were true 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 (1.08 ± 0.14 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

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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 0.72 ± 0.14 and 0.75 ± 0.14 kg N_2O-N ha^{-1}, respectively. The 28 day cumulative flux emissions associated with the fertilisation event on the tilled field was 0.42 ± 0.15 kg N_2O-N ha^{-1}. As each fertilisation event consisted of the same application rate of 70 kg N ha^{-1} of Nitram pellets, these cumulative fluxes account for a 1.03, 1.07 and 0.60 % of the total applied nitrogen in each case. Assuming the 28 day periods account well for the emission factors of the fertiliser events, these results agree well with the generic 1 % value reported by the IPCC for N fertiliser events (IPCC, 2014).

The reason for the large difference in fluxes associated with the fertiliser events between the two fields in this study is unknown. As the weather was the same for both fields it is assumed that temperature and rainfall was not a factor. After sward renewal on the tilled field, the grass grew back very thick and appeared much healthier than the more established grass in the un-tilled field. One theory is that the healthier, more productive grass in the tilled field consumed more of the available fertiliser than in the un-tilled field, leaving less N available for N_2O producing microbial processes. Another possible explanation is that physical changes to the soil since tillage (such as bulk density, WFPS and soil organic carbon content) altered the microbial processes in a way that reduced N_2O emissions from the fertiliser event (Ball et al., 2008; Choudhary et al., 2002; Davidson et al., 2000; Turner et al., 2008). From the limited soil data available, it is not possible to say for certain why fluxes from the tilled field in August were lower than those recorded in the adjacent field. As the driving forces of N_2O emissions from agricultural soils are not understood well in general, it complicates our ability to comprehend what is happening at the microbial level.

4.2 Gap filling of N_2O fluxes

Gap-filling N_2O flux measurements is difficult 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; 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. A two week gap in measurements in early June when the QCL instrument was out of commission has left a large gap in data, which makes a considerable contribution to the total uncertainty in the cumulative flux following the tillage event.

In this study spatial variability was not explicitly accounted for in the cumulative flux uncertainty and this remains a potentially large error. Eddy covariance is able to integrate over a large area of the field (several 100 m^2) but these measurements are still subject to an element of spatial variability which is unaccounted for. 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 of uncertainties using methods such as Bayesian statistics to improve uncertainty estimates in methodology.

5 Conclusion

Total cumulative fluxes calculated for the tilled and un-tilled fields over a 175 day period were 2.45 ± 0.27 and 2.08 ± 0.23 kg N_2O-N ha^{-1}, respectively. N_2O emissions after tillage were relatively large and sustained, similar in magnitude to a nitrogen fertilisation event. The tillage event is estimated to be responsible for emissions of 1.08 ± 0.14 kg N_2O-N ha^{-1} over a two month period after tillage. Further differences in N_2O fluxes were observed between the tilled and un-tilled fields after a subsequent nitrogen fertilisation in August 2012. Cumulative fluxes of N_2O estimated for a four week period after fertilisation for the tilled and un-tilled fields were 0.42 ± 0.15 and 0.75 ± 0.14 kg N_2O-N ha^{-1}, respectively. It is uncertain whether the tillage event or other factors were the reason for lower emissions from the tilled field after the fertilisation event. The results reported in this study agrees with several other studies that nitrogen added to soils in the form of crop residues may contribute to high emissions of N_2O similar to those expected from fertiliser events. This observation highlights a potentially large un-quantified and poorly understood source of anthropogenic N_2O emissions at a global scale. The study also highlights the need for more detailed investigation of the microbiological processes in soils to describe processes driving emissions from tilled soils and crop residues which also remain poorly understood.

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