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Nitrous oxide emissions from European agriculture – an analysis of variability and drivers of emissions from field experiments

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Abstract. Nitrous oxide emissions from a network of agricultural experiments in Europe were used to explore the relative importance of site and management controls of emissions. At each site, a selection of management interventions were compared within replicated experimental designs in plot-based experiments. Arable experiments were conducted at Beano in Italy, El Encin in Spain, Foulum in Denmark, Logården in Sweden, Maulde in Belgium, Paulinenaue in Germany, and Tulloch in the UK. Grassland experiments were conducted at Crichton, Nafferton and Peaknaze in the UK, Gödöllö in Hungary, Rzecin in Poland, Zarnekow in Germany and Theix in France. Nitrous oxide emissions were measured at each site over a period of at least two years using static chambers. Emissions varied widely between sites

and as a result of manipulation treatments. Average site emissions (throughout the study period) varied between 0.04 and 21.21 kg N_2O-N ha^{-1} yr^{-1}, with the largest fluxes and variability associated with the grassland sites. Total nitrogen addition was found to be the single most important determinant of emissions, accounting for 15 % of the variance (using linear regression) in the data from the arable sites ($p < 0.0001$), and 77 % in the grassland sites. The annual emissions from arable sites were significantly greater than those that would be predicted by IPCC default emission factors. Variability of N_2O emissions within sites that occurred as a result of manipulation treatments was greater than that resulting from site-to-site and year-to-year variation, highlighting the importance of management interventions in contributing to greenhouse gas mitigation.

1 Introduction

Terrestrial sources of nitrous oxide (N_2O) make an important contribution to Europe's net emissions of greenhouse gases. A recent continental study identified N_2O as the single most important greenhouse gas emitted from land-based sources with emissions from Europe equivalent to 97 Tg C yr^{-1} (Schulze et al., 2009). Agricultural soils used for grassland and arable production are a major source of N_2O, and strategies to reduce greenhouse gas emissions from the agricultural sector frequently highlight the importance of management interventions (Mosier et al., 1998; Rees et al., 2013). However, the contribution of management to mitigation can be difficult to assess against a background of fluxes that are highly variable in time and space, since emissions vary significantly in response to both climate and local environmental (particularly soil) conditions (Abdalla et al., 2010; Flechard et al., 2007; Skiba and Ball, 2002).

We now have a good understanding of the importance of individual variables in determining emissions, through their effect on the source processes of nitrification and denitrification (Dobbie and Smith, 2001; Smith et al., 1998; Wrage et al., 2001). Meta-analyses have shown that rates of fertiliser application, and soil properties, such as organic matter content, texture, drainage, pH, fertiliser timing and rate, all influence emissions (Bouwman et al., 2002). Within a farming system these factors interact with local climatic conditions to determine overall rates of emission. Climate has been shown to be particularly important in influencing emissions even under constant management. A study of European grasslands showed that the proportion of N released as N_2O from fertilisers (emission factor) could vary from 0.01 to 3.6 %, compared with the IPCC default value of 1 % (Flechard et al., 2007). Applications of constant amounts of fertiliser N to a grassland site in the UK over several years resulted in variation emission factors in different years of between 0.3 and 7 %, largely as a consequence of varying climatic condi-

Fig. 1. Locations of the European experimental sites. Circles represent arable sites and triangles grassland sites.

tions in different years (Smith and Dobbie, 2002). Variability in emission factors used for cereals was smaller, but still showed a five-fold variation.

Against such variability, it could be argued that management interventions make a relatively small contribution to the mitigation of emissions. Furthermore, such interventions are constrained by the societal needs to maintain food production, and the most attractive mitigation options are therefore those that increase utilisation of added N, and in so doing reducing losses.

In order to explore the relative importance of management, climate and site variability in influencing N_2O emissions, we have used a network of 14 experimental sites (eight arable and six grassland) established as a part of the NitroEurope project, for the measurement and reporting of N_2O emissions and related environmental drivers. At each site a range of management interventions were compared. Total annual emissions of N_2O from different treatment sites and years showed wide variability. Single variables were often poor predictors of emissions, and so multivariate statistical techniques were used to explore the relationships between annual emissions and underlying driving variables. The aim was to quantify the magnitude of changes in N_2O emission that could result from changes to agricultural management across a network of European sites.

2 Materials and methods

Manipulation experiments were established at sites across Europe in a coordinated research programme (NitroEurope)

Table 1. An overview of the soil and climatic conditions across the experimental network.

Site name/ Country	Soil texture[a]	Soil organic C g kg^{-1} 0–20 cm	Bulk density g cm^{-3} 0–20 cm	Annual average temperature °C	Annual average rainfall mm	Coordinates	Reference
Arable							
Beano, Italy	L	17–20	1.2–1.4	13.2	1220	56.30′ N, 9°34′ W	Alberti et al. (2010)
El Encin, Spain	CL	8–12	1.3–1.4	14.9	484	40°32′ N, 3°37′ W	Meijide et al. (2009); Sanchez-Martin et al. (2010)
Foulum, Denmark	SL	22–23	1.3	9.3	660	56°30′ N, 9°35′ E	Chirinda et al. (2010)
Logården, Sweden	ZC	18–20	1.4	7.9	695	58°20′ N, 12°38′ E	Nylinder et al. (2011)
Maulde, Belgium	ZL	9–12	1.3–1.5	11.2	910	50°37′ N, 3°34′ E	Boeckx et al. (2011)
Paulinenaue, Germany	Organic	100–140	0.5	9.7	694	52°41′ N, 12°44′ E	Bell et al. (2012)
Tulloch, UK	SL	50–66	1.2	8.9	940	57°11′ N, 2°16′ W	Ball et al. (2002); Watson et al. (2011)
Harare, Zimbabwe	S/C	5–8	1.7	19.1	940	17°55′ S 30°55′ W	Mapanda et al. (2011)
Grassland							
Crichton[b], UK	SL	29	1.1	10.1	1183	55°02′ N, 3°35′ W	Gordon et al. (2011)
Gödöllö, Hungary	SL	17–41	1.1	9.9	582	47°60′ N, 19°37′ E	Horvath et al. (2010)
Nafferton, UK	NA	NA	1.1	9.5	664	54.51′ N, 7.36′ E	Reay (unpublished data)
Peaknaze, UK	NA	NA	0.18	9.2	875	53.47′ N, 13.91′ W	Levy et al. (2012)
Rzecin, Poland	Organic	420	0.06	8.5	536	52°45′ N, 16°18′ E	Chojnicki et al. (2007); Juszczak et al. (2012)
Zarnekow[c], Germany	Organic	277	0.38	12.0	730	53°52′ N 12°53′ E	
Theix, France	SL	NA	1.1	7.8	704	45°47′ N, 03°05′ E	Cantarel et al. (2011, 2012)

[a] S = sand, C = clay, SL = sandy loam, ZL = silty loam, CL = clay loam, L = loam, ZC = sandy clay, NA = not available

[b] The Crichton experiment involved the comparison of regionally typical management scenarios on adjacent fields in different years.

[c] The Rzecin/Zarnekow experiment involved the comparison of a dying/wetting and flooding experiments in Zarnekow (Germany), with a control site in Rzecin (Poland).

designed to cover a wide range of climatic conditions. At each site, a selection of management interventions were compared within replicated experimental designs in plot-based experiments. Each experiment was used to determine how changes in agricultural management or land use could affect N_2O emissions. Arable experiments were conducted at Beano in Italy, El Encin in Spain, Foulum in Denmark, Logården in Sweden, Maulde in Belgium, Paulinenaue in Germany, and Tulloch in the UK (Fig. 1). Some comparisons of European emissions data were also made with linked experiments undertaken in Harare, Zimbabwe. Grassland experiments were conducted at Crichton, Nafferton and Peaknaze in the UK, Gödöllö in Hungary, Rzecin in Poland,

Zarnekow in Germany and Theix in France. At the arable sites the treatments included alternative tillage treatments, organic and conventional system management, changes in nutrient management (including the amount and form of N added), land use change and drainage treatments. On the grassland sites, treatments included variations in N inputs, wetting, and changes in temperature and atmospheric CO_2 concentration (see Table 1 for a description of the experimental sites). At each site N_2O fluxes were measured using closed static chambers over a period of two years or more, with a minimum of 20 measurements per year (and often including more intensive measurements in periods where fluxes were anticipated, for example following

Table 2. A description of the experimental and analytical procedures used at each site.

Site name	Quantitative characteristics (replicate chambers per treatment; sampling frequency per year; samples per chamber; chamber closure time in minutes)	Methodology	Integration
Arable			
Beano	3; > 20; 3; 60;	Gas chromatography	Linear interpolation
El Encin	3; > 20; 3; 60	Gas chromatography	Linear interpolation
Foulum	4; > 24; 3; 90–180	Gas chromatography	Linear interpolation
Logården	4; > 20; 3; 60	Gas chromatography	Linear interpolation and modelling
Maulde	6; > 20; 6; 60	Photoacoustic analyser	Linear or non-linear regression (Hutchinson and Mosier, 1981)
Paulinenaue	6; > 20; 4; 60	Gas chromatography	Linear interpolation
Tulloch	3; > 25; 2–6; 60	Gas chromatography	Linear interpolation
Harare	3; > 20; 2–6; 60	Gas chromatography	Linear interpolation
Grassland			
Crichton	3; > 25; 2–6; 60	Gas chromatography	Linear interpolation
Gödöllö	3; > 20; 4; 30	Gas chromatography	Linear interpolation
Nafferton	6; > 20; 4; 60	Gas chromatography	Linear interpolation
Peaknaze	3; > 20; 4; 60	Gas chromatography	Linear interpolation
Rzecin/Zarnekow	3; > 25; 2–6; 60	Gas chromatography	Linear interpolation
Theix	3; > 20; 5; 60	Photoacoustic analyser	Linear interpolation

fertiliser applications). Many of the experiments compared in this study had been established prior to the start of the measurement period reported in this paper, and hence there were minor variations in experimental approaches (noted below). However, as far as possible, the methodology used for determining fluxes was standardised across sites (Table 2 and NitroEurope, unpublished). A total of 590 yr of data from individual plot combinations of treatment sites and years were compared in this analysis.

Many of the different chambers used in this study were compared in order to understand the importance of chamber design in determining its ability to quantify a flux (Pihlatie et al., 2013). Gas samples were collected in evacuated glass vials (or flushed through vials using a pump (Logården)) and analysed by gas chromatography at all sites except the Belgian and French sites, where photoacoustic infrared spectroscopy was used (Boeckx et al., 2011; Cantarel et al., 2011), and fluxes calculated according to standard methodologies (Dobbie and Smith, 2003). Further details of the methodology used to estimate emissions are provided in the individual site references (Table 1) and in Table 2.

Measurements of soil carbon, N, pH, texture, and bulk density were made once at each site (Table 1). Records of biological N fixation where legumes were present (using an empirical approach; Hogh-Jensen et al., 2004), N deposition (EMEP, 2012), and N removal by crops were also reported

for each site. Annual N_2O emissions were estimated cumulatively by linear interpolation between individual events. The data were collated and N_2O data were log transformed ($\ln N_2O + 1$) prior to graphical presentation and analysis using multiple linear regression in GenStat (14th Edition) and Minitab (16th Edition). In the analysis, the random factor was specified to take into consideration site, year, block, replicate and treatments.

3 Results

Nitrous oxide fluxes varied widely between sites and as a result of manipulation treatments. Average site emissions (throughout the study period) varied between 0.04 and 21.21 kg N_2O-N ha^{-1} yr^{-1} (Fig. 2, Tables 3 and 4), with largest fluxes and variability associated with the grassland sites. Within the arable sites the fluxes varied between 0.6 and 5.3 kg N_2O-N ha^{-1} yr^{-1}, with the highest average fluxes observed from the Belgium tillage experiment at Maulde. The highest average grassland flux (21.2 kg N_2O-N ha^{-1} yr^{-1}) was observed from Crichton, an experiment located on an intensive dairy farm (receiving high inputs of inorganic and organic N) in the south-west of Scotland.

Within each site there was considerable variability in N_2O emissions resulting from year-to-year changes in climatic
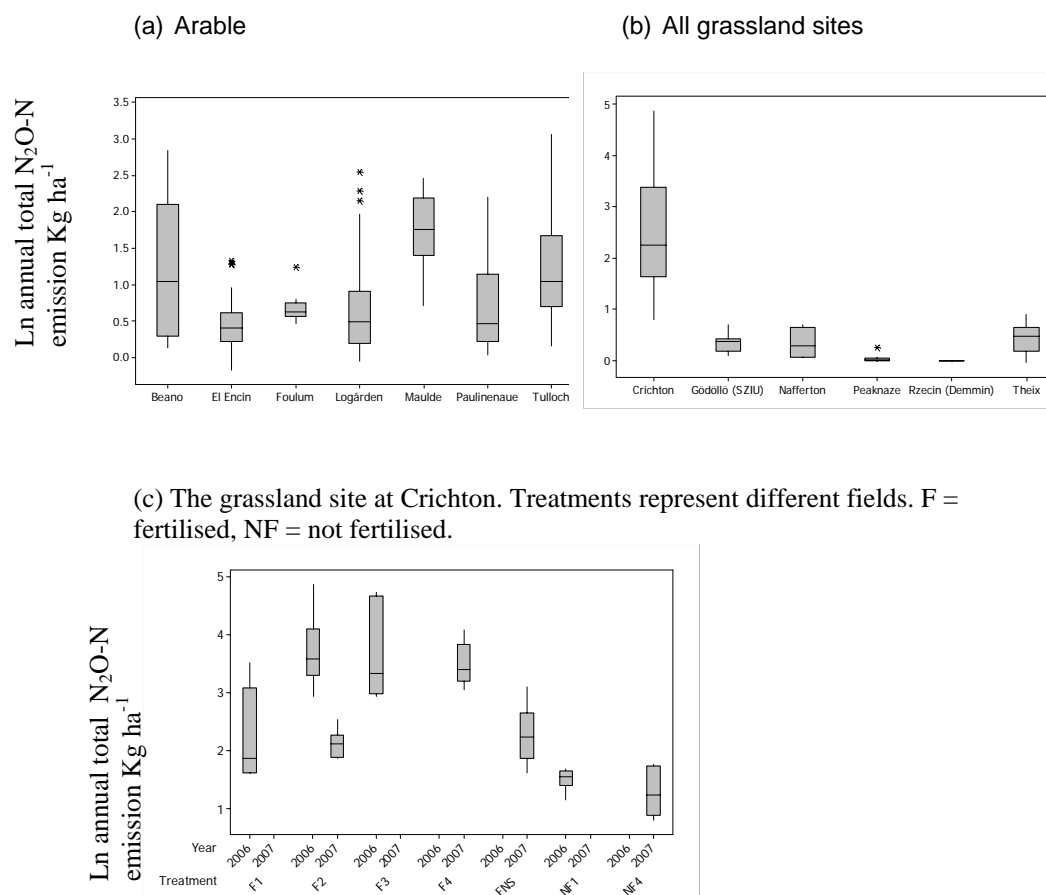
(a) Arable

(b) All grassland sites

(c) The grassland site at Crichton. Treatments represent different fields. F = fertilised, NF = not fertilised.

Fig. 2. Annual N_2O emissions compared between sites. Each bar represents the average emission from different treatments in different years. Each bar indicates the mean (central bar), upper and lower quartiles (outside bar) and 95 % range (lines). Outliers are represented by asterisks. See Table 3 for a description of the detailed treatment codes.

conditions and the manipulation treatments applied. An example of this variability is illustrated by considering fluxes from the Crichton grassland site. The annual average emission was $21.2\,kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$; however, this varied between 2.9 and $51.3\,kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$ in different treatments in 2007 (Fig. 2c, Table 3). There was also an annual variability (expressed as the difference between the mean emissions in each year) of $15.3\,kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$.

A comparison of treatment effects and annual climatic effects across different sites demonstrated that treatments applied to arable sites resulted in a range of emissions between treatments that was greater than that observed between sites (Table 3). At the Tulloch organic farming experiment for example, the range in treatment emissions (averaged over years) was $0.5\text{--}13.2\,kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$, while the range in the mean emission across all European arable sites was between 0.6 and $5.31\,kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$ (Table 3a).

The variability in annual flux data showed reasonable consistency across sites with the annual average flux being of similar magnitude to the standard deviation (Table 3). Annual variability within sites was also

important. The range of emissions between years (averaged over all treatments) at the El Encin site was $0.31\text{--}0.97\,kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$ (Table 4), which was less than the range between sites: $0.6\text{--}5.3\,kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$ (Table 3a). At grassland sites there was a range between treatments of $2.9\text{--}51.3\,kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$ at the Crichton site, which was comparable with the range of $0.00\text{--}21.21\,kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$ between sites (Table 3b).

An analysis of all annual data from across the different sites and years was used to identify the importance of a range of driving variables. Within the arable sites total N input (in the form of organic N and/or synthetic N fertiliser) had a significant effect on the emissions ($p < 0.001$; Fig. 3, Table 4a), with $\ln N_2O + 1 = 0.70\,(\pm 0.15) + 0.0018\,(\pm 0.00029) \times$ total N applied

The total water (rainfall + irrigation) applied to the crop also had a significant effect ($p = 0.0001$) on the total emissions from the site; however, in this case the constant was no longer significant.

$$\ln N_2O + 1 = 0.0020(\pm 0.00028) \times \text{ total N applied} + 0.0061$$
$$(\pm 0.00013) \times \text{ total water} \qquad (1)$$

Table 3 . Nitrous oxide emissions (annual total) in response to site and management conditions across the experimental network classified by site and treatment.

(a) Arable sites	Treatment	Annual emission N_2O kg^{-1} ha^{-1} yr^{-1} Standard deviation in brackets
Beano	Cropland no till (CNT)	6.17 (5.75)
	Cropland tilled (CT)	5.49 (4.34)
	Grassland tilled (GT)	1.03 (1.01)
Beano Average		**4.23 (4.65)**
El Encin	Control (C)	0.21 (0.22)
	Composted crop residue (CCR)	0.41 (0.15)
	Digested pig slurry (DPS)	0.71 (0.43)
	Mixed organic waste (MSW)	0.32 (0.23)
	Organic manure (OM)	0.89 (0.12)
	Urea (U)	1.17 (0.81)
	Untreated slurry (UPS)	0.36 (0.18)
El Encin Average		**0.63 (0.59)**
Foulum	Conventional without catch crops ($C - CC + M$)	1.24 (0.82)
	Organic with catch crops ($O + CC + M$)	0.98 (0.17)
	Organic without catch crops ($O - CC + M$)	0.83 (0.25)
Foulum Average		**1.02 (0.49)**
Logården	Integrated (Int)	1.29 (1.86)
	Organic (Org)	1.08 (1.49)
Logården Average		**1.15 (1.62)**
Maulde	Conventional tillage (CT)	4.96 (2.28)
	No tillage (NT)	5.68 (2.69)
	Reduced tillage (RT)	5.28 (3.39)
Maulde Average		**5.31 (2.76)**
Paulinenaue	Arable (AC)	2.83 (2.17)
	Arable converted to grassland (AG)	0.39 (0.36)
	Permanent grassland (PeM)	1.15 (1.99)
Paulinenaue Average		**1.46 (1.95)**
Tulloch	Barley (B)	9.27 (1.52)
	Barley undersown (B_{us})	13.21 (10.21)
	Ley oats (LO)	5.99 (3.98)
	Oats (O)	0.50 (0.46)
	Oats undersown (O_{us})	2.23 (0.71)
	Potato (Pot)	8.45 (8.23)
	Swede (S)	3.07 (4.80)
	Wheat undersown (W_{us})	4.87 (0.69)
	First year grass (Y1G)	0.72 (0.34)
	Second year grass (Y2G)	1.12 (0.80)
	Third year grass (Y3G)	1.90 (1.25)
	Fourth year grass (Y4G)	1.34 (0.43)
	Pulses (Pul)	3.10 (1.32)
	Grass red-clover (YGr)	3.75 (2.61)
Tulloch Average		**3.46 (4.10)**
Harare	Control (0N)	0.85 (1.01)
	30 kg ammonium nitrate-N (30 kg N)	0.48 (0.88)
	30 kg AN + manure (N + manure)	0.48 (0.61)
	60 kg ammonium nitrate-N (60 kg N)	0.67 (0.92)
	30 kg manure-N (30 kg manure N)	0.25 (0.27)
	60 kg ammonium nitrate-N (60 kg manure-N)	0.85 (0.97)
Harare Average		**0.60 (0.81)**
Grand Average		**1.80 (2.72)**

Table 3 . Continued.

(b) Grassland sites	Treatment	Average of total N_2O-N kg^{-1} ha^{-1} yr^{-1} Standard deviation in brackets
Crichton	Site 1 fertilised & grazed (F1)	11.68 (11.63)
	Site 2 fertilised & grazed (F2)	28.21 (34.89)
	Site 3 fertilised & grazed (F3)	51.27 (44.28)
	Site 4 fertilised & grazed (F4)	33.90 (13.86)
	Site 5 fertilised & grazed (FNS)	9.89 (6.10)
	Site 6 slurry & grazed (NF1)	3.62 (0.80)
	Site 7 slurry & grazed (NF4)	2.88 (1.59)
Crichton Average		**21.21 (28.13)**
Gödöllö	Control (C)	0.38 (0.19)
	Elevated CO_2 (CO_2)	0.23 (0.17)
	Fertilizer (F)	0.62 (0.30)
	Wetted (W)	0.40 (0.12)
Gödöllö Average		**0.41 (0.23)**
Nafferton	Control (C)	0.55 (0.66)
	Wetted (W)	0.36 (0.40)
Nafferton Average		**0.45 (0.46)**
Peaknaze	Control (C)	0.04 (0.03)
	Drought (D)	0.09 (0.16)
	Warming (T)	0.00 (0.03)
Peaknaze Average		**0.04 (0.09)**
Rzecin/ Zarnekow	Control (C)	0.526 (0.001)
	Dry/wet grassland (DW)	0.004 (0.001)
	Re-flooded grassland (RF)	0.004 (0.001)
Rzecin/ Zarnekow Average		**0.04 (0.013)**
Theix	Control (C)	0.52 (0.43)
	Increased temperature (T)	0.69 (0.46)
	Increased temperature & drought (TD)	0.64 (0.47)
	Inc. temperature, CO_2 & drought (TDCO$_2$)	0.63 (0.44)
Theix Average		0.62 (0.44)
Grand Average		**7.00 (18.45)**

In the case of the grassland sites, total N applied was also significant ($p < 0.0001$; Fig. 3, Table 4).

$$\ln N_2O + 1 = 0.32(\pm 0.15) + 0.0062(\pm 0.00070) \times \text{total N applied} \quad (2)$$

Similarly to the arable sites, the total annual rainfall ($p < 0.0001$) was also an important determinant of emissions from grassland sites.

$$\ln N_2O + 1 = -0.42(\pm 0.21) + 0.00059(\pm 0.00063) \times \text{total N applied}$$
$$+ 0.00096(\pm 0.00023) \times \text{total water} \quad (3)$$

The high N additions and N_2O emissions from the Crichton grasslands were important in contributing to the strength of this regression. Another notable feature of this regression analysis was the wide range of emissions (0–21 kg N_2O-N ha^{-1}) associated with sites receiving no added N (synthetic fertiliser or manure). It was noted that

soil organic carbon (SOC) and bulk density were not significant factors for either arable or grassland sites.

The emissions data presented here can also be used to identify those systems with the highest emissions (and therefore greatest mitigation potential). When the data from all 438 combinations of site and treatment years from the arable experiments were compared, the ten highest emissions were observed at just three sites when expressed on an emission per unit area basis: these were Tulloch, Beano, and Maulde (Fig. 4). When expressed on an intensity basis, the ten highest emissions were also observed at three sites: Tulloch, Harare and Logården, with values ranging from 0.06 to 0.8 kg N_2O-N kg total N added^{-1} (Fig. 4). Emissions from the grassland sites were generally lower than those from the arable sites with the exception of Crichton where emissions were approximately two orders of magnitude higher than other grassland sites (Fig. 4).

Table 4. Nitrous oxide emissions in response to site and management conditions across the experimental network classified by site and year (average of total N_2O-N kg^{-1} ha^{-1} yr^{-1} ± standard deviation).

	Year						
	2004	2005	2006	2007	2008	2009	2010
Arable sites							
Beano				0.27 ±0.10	6.62 ±5.06	5.80 ±4.23	
El Encin			0.31 ±0.23 ±0.64	0.71 ±0.47	0.79 ±1.00	0.97 ±0.55	0.50
Foulum				1.15 ±0.67	0.89 ±0.19		
Logården	1.72 ±1.26	1.76 ±1.60	1.03 ±2.08	0.19 ±0.13			
Maulde				6.83 ±2.07	3.78 ±2.54		
Paulinenaue				2.73 ±2.80	1.04 ±1.13	0.59 ±0.56	
Tulloch			2.27 ±2.77	4.56 ±4.83			
Harare				0.58 ±0.84	0.89 ±0.9	0.33 ±0.6	
Grassland sites							
Crichton			28.86 ±35.96	13.55 ±14.22			
Gödöllö				0.35 ±0.19	0.43 ±0.25		
Nafferton			0.83 ±0.26	0.07 ±0.00			
Peaknaze				0.04 ±0.09			
Rzecin				0.00 ±0.16	0.00 ±0.00		
Theix				0.62 ±0.23	1.06 ±0.29	0.18 ±0.26	

Legend: —— Regression –·– 95% CI – · · UpperConf - - - 95% PI - - - 95% PI
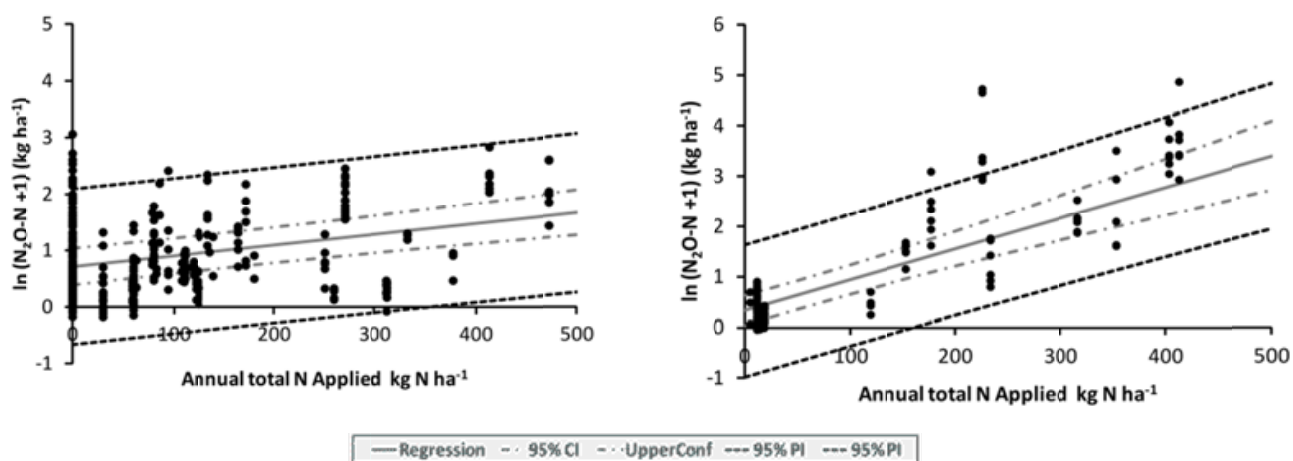
Fig. 3. The relationship between N_2O emissions and added N input (in the form of organic manures and synthetic N fertiliser) for **(a)** arable sites and **(b)** grassland sites. Ln(N_2O) (kg N_2O-N ha^{-1}). The data set includes multiple data points from each site.
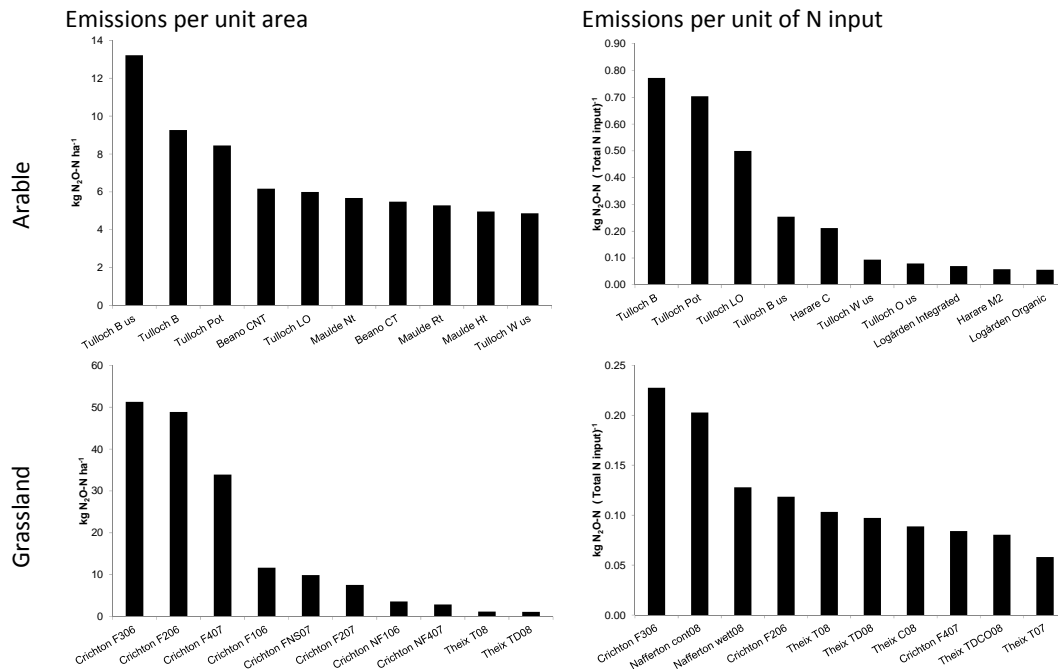
Fig. 4. Ranking of annual emissions data from individual arable plots. The top 10 sites are ranked on emissions per unit area (kg N_2O-N ha^{-1}) and per unit of N_2O per unit of N total input (synthetic fertiliser, manure and biological N fixation (kg N_2O-N kg N input^{-1}). See Table 3 for a description of the treatment codes.
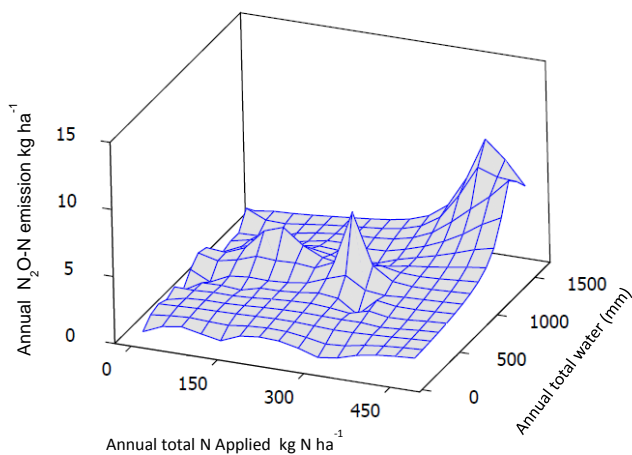

Fig. 5. The relationship between N_2O emissions and annual total rainfall plus irrigation and total N input across the arable site network.

A three-dimensional plot of N_2O emissions against annual total rainfall and irrigation and total annual N addition emphasises the combined effect of N addition and total water addition in determining emissions. Under dry conditions with 500 mm of rainfall or less, emissions remained below 3 kg N_2O-N ha^{-1} at rates of N application of up to 450 kg ha^{-1}. However, as the rainfall and irrigation increased to 1500 mm, emissions rose to around 10 kg N_2O-N ha^{-1} (Fig. 5).

4 Discussion

We know from previous studies that emissions of N_2O from landscapes are controlled by site-specific factors such as soil conditions and climate as well as the way in which these systems are managed (e.g. fertiliser use and agronomy) (Dobbie et al., 1999; Smith and Conen, 2004). This study has allowed us to compare the relative magnitude of these effects across a large number of sites, and has demonstrated that the changes associated with management interventions are equal to or greater than those associated with differences between site and year. There was a large variability in fluxes observed as a consequence of manipulation treatments introduced within each site and between measurement years. Characterising the magnitude of potential mitigation is an essential prerequisite for the implementation of policies designed at reducing greenhouse gas emissions from the agricultural sector. It has been suggested that interventions which include better nutrient use efficiency, improved soil management and improved agronomy could achieve a reduction in emissions of 10–30 % (Mosier et al., 1998; Smith et al., 1997). The results presented here are consistent with these estimates, and have highlighted the importance of reducing the N supply in order to contribute to mitigation.

The change in emissions associated with increasing N inputs observed in our experiments was not always consistent with those that would be estimated by default IPCC emissions factors, where 1 % of added N would be predicted to be

lost as N_2O (IPCC, 2006). At the arable sites emissions were 37 % greater than this value, and despite the large variability, this was significantly greater ($p < 0.0001$) than 1 % of N inputs. The grassland sites did not show a significant difference from the default emission factor, but relatively few of these sites included N addition. The largest variation in emissions across treatments within an individual site was associated with changes in the inputs of N and cropping at the Scottish organic rotation at Tulloch (Table 3). This site reported a 26-fold difference in emissions (0.5–13.2 kg N_2O-N ha^{-1} yr^{-1}), across the different treatments (which included different years of the rotation). The effects of reduced tillage treatments resulted in a much smaller proportional change (increased N_2O emissions) in Italy and Belgium (Alberti et al., 2010; Boeckx et al., 2011). However, it should be considered that reducing tillage intensity may also result in increased C storage, and so the effects on net greenhouse gas emissions may be less than those indicated by N_2O emissions alone. There is also emerging evidence to suggest that, in the longer term, N_2O emissions from reduced till systems may be lower than those from conventional tillage (Six et al., 2004).

There was a significant effect of N addition across all sites on N_2O emissions, as illustrated by the regression analysis, which is consistent with previous meta-analyses of N_2O emissions (Bouwman et al., 2002). However, it was not possible to explain more than 23 % of the variability in emissions by N input from synthetic fertilisers and manures alone. The large range of emissions associated with sites receiving no N as fertiliser or manure is of particular importance. Many of these sites would receive N by biological fixation from leguminous crops sometimes over a period of several years prior to flux measurements. Biological N fixation is assumed by IPCC not to be directly associated with increased emissions of N_2O (IPCC, 2006). Such systems may, however, generate increased emissions as a consequence of decomposition of N-rich legume residues. The magnitude of such emissions remains highly uncertain and is likely to be highly site-specific (Baggs et al., 2000; Rochette and Janzen, 2005).

Another factor potentially contributing to emissions from unfertilised sites and not accounted for in this study would be the mineralisation of soil organic matter. Following land use change or within rotational systems, there may be a release of mineral N from the organic N pool due to tillage, providing a substrate for nitrification- and denitrification-driven N_2O release. In organic farming systems this build-up of organic N within the grassland phase of a rotation is used to provide nutrients (particularly N) for subsequent arable crops (Stockdale et al., 2001; Watson et al., 2011). This can lead to some high emissions in individual years from organic farming systems, particularly where the system exists in mild and wet climates such as that at Scottish organic site at Tulloch (despite no apparent input of N in that year). However, high emissions from individual years within an organic phase of an organic rotation are often offset by lower emissions during the grassland phase, giving relatively low emissions

Table 5a. The parameter estimates, standard errors and the probabilities for the coefficients included in the multiple regressions for the arable sites.

Parameter	Estimate	s.e.	$t(431)$	t pr.
Constant	−1.875	0.449	−4.18	< 0.001
Total N applied	0.00214	0.000292	7.32	< 0.001
Deposition	0.0223	0.00318	7.02	< 0.001
Average daily temperature	−0.059	0.00779	−7.57	< 0.001
Total water	0.00032	0.000104	3.03	0.003
Bulk density	1.65	0.276	5.95	< 0.001
SOC	0.151	0.0317	4.77	< .001

Table 5b. The parameter estimates, standard errors and the probabilities for the coefficients included in the multiple regressions for the grassland sites.

Parameter	Estimate	s.e.	$t(148)$	t pr.
Constant	−1.004	0.223	−4.50	< 0.001
Total N applied	0.00572	0.000446	12.84	< 0.001
Total rainfall	0.00106	0.000205	5.17	< 0.001
Bulk density	0.618	0.150	4.12	< 0.001

from the system overall (Ball et al., 2002). In this study the average of emissions over the three cropped organic sites was 1.58 kg N_2O-N ha^{-1}, compared with an overall mean of 2.37 kg N_2O-N ha^{-1} from the arable sites.

There is a trade-off between reducing N_2O emissions by reduced N input and food production, since restricting N input can often lead to proportional decreases in crop yields and an effective displacement of emissions. This is because reductions in emissions that are achieved by lowering production can lead to an import of food, which itself would be associated with emissions (Godfray et al., 2011).

For this reason the emissions intensity provides a useful index of the effectiveness of mitigation. Some of the highest emission intensities were associated with individual phases of organic rotations at Tulloch (4.0 g N_2O-N kg N uptake^{-1}) and Logården (2.1 g N_2O-N kg N uptake^{-1}). This highlights the need to increase the utilisation efficiency of N between different crop types within some production systems in order to lower emission intensities.

The implementation of mitigation measures to reduce N_2O emissions from agriculture is likely to depend on regionally specific changes in management practice that take account of local soil and climatic conditions. We have shown that those locations associated with high N inputs and high annual rainfall and irrigation (above 1000 mm) are most prone to large emissions. El Encin is an example of such a site, and studies there have identified inorganic fertiliser N as being a particularly important contributor to emissions. Studies at the Spanish site were able to demonstrate that replacement

of fertiliser by organic N substrates or the combination of organic and synthetic fertiliser was able to reduce emissions of N_2O significantly (Meijide et al., 2009; Sanchez-Martin et al., 2010).

A number of sites reported a net annual uptake of N_2O within individual plots of a treatment. This included 12 plots at El Encin, seven from Zimbabwe, two at Logården and one at Maulde. Dry or well-drained soil conditions together with low N availability appear to favour net uptake. The mechanism responsible is uncertain, but it is likely to involve the use of N_2O as a terminal electron acceptor in circumstances where soil aggregation allows uptake of N_2O from the air into oxygen-depleted sites where N_2O can be used instead of O_2 (Neftel et al., 2007).

The grassland sites included in this study were very diverse but included only one highly intensive production system on a dairy farm in Scotland (Crichton). Here, emissions were higher than any measured from elsewhere at the arable and grassland sites. This was a reflection of the high N input (specifically in 2007 when total inputs in one treatment exceeded $600 \, \mathrm{kg \, N \, ha^{-1} \, yr^{-1}}$ in some treatments) and mild and wet conditions that occur throughout the year, which are conducive to high N_2O emissions (Flechard et al., 2007). The remaining grassland sites received much lower N inputs and were generally associated with low N_2O emissions, highlighting the importance of N input in driving N_2O emissions.

5 Conclusion

This study has allowed a wide-ranging comparison of the relative importance of agricultural management and site-specific determinant of N_2O emissions. The magnitude of emissions varies widely, and N input to systems was shown to be the principal driver across sites and treatments. Grasslands with high N input showed the largest annual emissions, but arable sites receiving high N and water inputs were also prone to large emissions, thus illustrating the importance of restricting N supply in controlling N_2O emissions. There was a significantly greater emission of N_2O from N added to arable sites than would be predicted from IPCC default emission factors. This study has also demonstrated that while sites (and climate) are important determinants of the magnitude of N_2O emissions, agricultural management practices are of equal or greater importance.

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