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Biogeosciences Discussions

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 and Zimbabwe 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, Harare in Zimbabwe 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 in N_2O 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, 2011). 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 nitrogen (N) released as N_2O from fertilisers (emission factor) could vary from 0.01–3.6 % 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 0.3–7 %, largely as a consequence of varying climatic conditions 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 adding nitrogen, 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 co-ordinated research programme (NitroEurope) 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, Tulloch in the UK, and Harare in 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 further site and experimental manipulations and Table 2 for an overview of soil and climatic conditions). 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

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measurements per year (and often including more intensive measurements in periods where fluxes were anticipated, for example following fertiliser applications). As far as possible the methodology used for determining fluxes was standardised across sites (NitroEurope, unpublished). A total of 590 yr of data from individual plot combinations of treatments 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., 2009). Gas samples were collected in evacuated glass vials or flushed through vials using a pump (Logarten) 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). One off site measurements of soil carbon, nitrogen, pH, texture, and bulk density were made at each site (Table 2). Records of biological N fixation where legumes were present (using the an empirical approach, Hogh-Jensen et al., 2004), N deposition (EMEP, 2012), N removal by crops were also reported for each site. Annual N_2O emissions were estimated cumulatively by linear interpolation between individuals of 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).

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

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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 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-N ha^{-1} yr^{-1}, however, this varied between 2.9 and 33.9 kg N_2O-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-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 (Tables 3 and 4). At the Tulloch organic farming experiment for example, the range in treatment emissions (averaged over years) was 0.5–13.2 kg N_2O-N ha^{-1} yr^{-1}, while the range in the mean emission across all European arable sites was between 0.6–5.31 kg N_2O-N ha^{-1} yr^{-1} (Table 3). 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 0.31–0.97 kg N_2O-N ha^{-1} yr^{-1}, which was less than the range between sites 0.6–5.3 kg N_2O-N ha^{-1} yr^{-1} (Table 4a). In grassland sites treatments there was a range between treatments of 2.9–28.2 kg N_2O-N ha^{-1} yr^{-1} at the Crichton site which was comparable with the range of 0.04–21.21 kg N_2O-N ha^{-1} yr^{-1} between sites (Table 4b).

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 nitrogen input (in the form of organic N and/or synthetic N fertiliser) was the single most important determinant of emissions, accounting for 14.6 % of the variance in the data by linear regression ($p < 0.0001$; Fig. 3). Another notable feature of this regression analysis was the wide range of emissions (0–21 kg N_2O-N ha^{-1}) associated with

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sites receiving no added N (synthetic fertiliser or manure). Adding the additional terms (deposition, average daily temperature, total water applied including precipitation and irrigation, bulk density and SOC) to this regression against the natural log of the annual N_2O emission through a step-wise procedure increased the amount of variability accounted for to 37.1 %. However, when site and year are included in the stepwise regression, the added terms included average daily temperature and total water applied, 49.1 % of the variability was explained. Therefore, there are features of the sites and years (relating to soils and management) that impact on emissions. However, it was noted that, soil organic carbon and bulk density were not significant factors. In the case of the grassland sites, total nitrogen input explained 76.9 % of the variation (Fig. 4). The high N additions and N_2O emissions from the Crichton grasslands were important in contributing to the strength of this regression. Adding the total water applied and bulk density to the regression improved the variability explained to 81.4 %.

The emissions data presented here can also be used to identify those systems with the highest emissions (and therefore greatest mitigation potential). When the plots from all 438 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. 5a). When expressed on an intensity basis the ten highest emissions were also observed at three sites; Tulloch, Harare and Logården, with values ranging from 1.4–3.9 kg N_2O-N kg total N added^{-1} (Fig. 5b). Emissions from the grassland sites were generally lower than those from the arable sites with the exception of Crichton where emissions were approximately 2 orders of magnitude higher than other grassland sites (Fig. 6).

A three dimensional plot of N_2O emissions against annual total rainfall and irrigation and total annual N addition emphasises the combined affect 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. 7).

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 that 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 contributing to mitigation.

The change in emissions associated with increasing N inputs was not always consistent with the emissions 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). In 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 proportional changes in emissions were associated with changes in the inputs of N and irrigation at the Spanish site, which contributed to a 26 fold change in emissions, and changes across the different phases of an organic rotation (Tulloch) in the UK. The affects of reducing 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 also results in increased C storage, and so the affects on net greenhouse gas emissions may be less than that indicated by N_2O emissions. There is also emerging evidence to suggest that in the longer term, N_2O emissions from reduced till systems may be lower than that 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 residue decomposition by legumes. 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

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during the grassland phase giving relatively low emissions from the system overall (Ball et al., 2002). In this study the average 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, since 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, 7 from Zimbabwe, 2 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 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 in the arable and grassland sites. This was a reflection of the high N input (specifically in 2007 where total inputs in one treatment exceeded 600 kg N ha^{-1} yr^{-1} in some treatments) and mild and wet conditions that occur throughout the year and 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 Conclusions

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 site (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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References

Abdalla, M., Jones, M., and Williams, M.: Simulation of N_2O fluxes from Irish arable soils: effect of climate change and management, Biol. Fertil. Soils, 46, 247–260, 2010.

Alberti, G., le Vedove, G., Zuliani, M., Peressotti, A., Castaldi, S., and Zerbi, G.: Changes in CO_2 emissions after crop conversion from continuous maize to alfalfa, Agric. Ecosys. Environ., 136, 139–147, 2010.

Baggs, E. M., Watson, C. A., and Rees, R. M.: The fate of nitrogen from incorporated cover crop and green manure residues, Nutr. Cycl. Agroecosys., 56, 153–163, 2000.

Ball, B. C., McTaggart, I. P., and Watson, C. A.: Influence of organic ley-arable management and afforestation in sandy loam to clay loam soils on fluxes of N_2O and CH_4 in Scotland, Agric. Ecosys. Environ., 90, 305–317, 2002.

Bell, M., Jones, E., Smith, J., Smith, P., Yeluripati, J., Augustin, J., Juszczak, R., Olejnik, J., and Sommer, M.: Simulation of soil nitrogen, nitrous oxide emissions and mitigation scenarios at 3 European cropland sites using the ECOSSE model, Nutr. Cycl. Agroecosys., 92, 161–181, 2012.

Boeckx, P., Van Nieuland, K., and van Cleemput, O.: Short-term effect of tillage intensity on N_2O and CO_2 emissions, Agron. Sustain. Develop., 31, 453–461, 2011.

Bouwman, A. F., Boumans, L. J. M., and Batjes, N. H.: Emissions of N_2O and NO from fertilized fields: summary of available measurement data, Global Biogeochem. Cy., 16, art-1058, 2002.

Cantarel, A. A., Bloor, J. M., Deltroy, N., and Soussana, J. F.: Effects of climate change drivers on nitrous oxide fluxes in an upland temperate grassland, Ecosystems, 14, 223–233, 2011.

Cantarel, A. A. M., Bloor, J. M. G., Pommier, T., Guillaumaud, N., Moirot, C., Soussana, J. F., and Poly, F.: Four-years of experimental climate change modifies the microbial drivers of N_2O fluxes in an upland grassland ecosystem, Glob. Change Biol., doi:10.1111/j.1365-2486.2012.02692.x, 2012.

Chirinda, N., Olesen, J. E., Porter, J. R., and Schjonning, P.: Soil properties, crop production and greenhouse gas emissions from organic and inorganic fertilizer-based arable cropping systems, Agric. Ecosys. Environ., 139, 584–594, 2010.

Chojnicki, B. H., Urbaniak, M., Jozefczyk, D., and Augustin, J.: Measurement of gas and heat fluxes a Rzecin wetland, in: Wetlands: Monitoring, Modeling and Management, edited by: T. Okruszko, Taylor and Francis Group, London, 2007.

Dobbie, K. E. and Smith, K. A.: The effects of temperature, water-filled pore space and land use on N_2O emissions from an imperfectly drained gleysol, Eur. J. Soil Sci., 52, 667–673, 2001.
Dobbie, K. E. and Smith, K. A.: Nitrous oxide emission factors for agricultural soils in Great Britain: the impact of soil water-filled pore space and other controlling variables, Glob. Change Biol., 9, 204–218, 2003.
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.-Atmos., 104, 26891–26899, 1999.
EMEP, European Monitoring and Evaluation Programme (EMEP), http://www.emep.int, 2012.
Flechard, C. R., Ambus, P., Skiba, U. M., Rees, R. M., Hensen, A., van Amstel, A., Pol-van Dasselaar, A. V., Soussana, J. F., Jones, M., Clifton-Brown, J., Raschi, A., Horvath, L., Neftel, A., Jocher, M., Ammann, C., Leifeld, J., Fuhrer, J., Calanca, P., Thalman, E., Pilegaard, K., Di Marco, C., Campbell, C., Nemitz, E., Hargreaves, K. J., Levy, P. E., Ball, B. C., Jones, S. K., van de Bulk, W. C. M., Groot, T., Blom, M., Domingues, R., Kasper, G., Allard, V., Ceschia, E., Cellier, P., Laville, P., Henault, C., Bizouard, F., Abdalla, M., Williams, M., Baronti, S., Berretti, F., and Grosz, B.: Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe, Agric. Ecosys. Environ., 121, 135–152, 2007.
Godfray, H. C. J., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., and Toulmin, C.: The Future of food and farming; Challenges and choices for global sustainability, London, UK, The Government office for Science, Foresight Report, 2011.
Gordon, H., Topp, C. F. E., Ball, B. C., and Rees, R. M.: Grassland management and climatic effects on nitrous oxide fluxes, Tenth Conference Proceedings, September 2011, Belfast, UK: British Grassland Society, 2011.
Hogh-Jensen, H., Loges, R., Jorgensen, F. V., Vinther, F. P., and Jensen, E. S.: An empirical model for quantification of symbiotic nitrogen fixation in grass-clover mixtures, Agric. Sys., 82, 181–194, 2004.
Horvath, L., Grosz, B., Machon, A., Tuba, Z., Nagy, Z., Czobel, S., Balogh, J., Peli, E., Foti, S. Z., Weidinger, T., Pinter, K., and Fuhrer, E.: Estimation of nitrous oxide emission from Hungarian semi-arid sandy and loess grasslands; effect of soil parameters, grazing, irrigation and use of fertilizer, Agric. Ecosys. Environ., 139, 255–263, 2010.

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IPCC: IPCC Guidelines for National Greenhouse Gas Inventories; prepared by the National Greenhouse Gas Inventories Programme, IPCC, Kanagawa, Japan, 2006.
Juszczak, R., Acosta, M., and Olejnik, J.: Comparison of daytime and nighttime ecosystem respiration measured by the closed chamber technique on wetland site, Rzecin case study, Pol. J. Environ. Stud., 21, 643–58, 2012.
Levy, P. E., Burden, A., Cooper, M. D. A., Dinsmore, K. J., Drewer, J., Evans, C., Fowler, D., Gaiawyn, J., Gray, A., Jones, S. K., Jones, T., McNamara, N. P., Mills, R., Ostle, N., Sheppard, L. J., Skiba, U., Sowerby, A., Ward, S. E., and Zielinski, P.: Methane emissions from soils: synthesis and analysis of a large UK data set, Glob. Change Biol., doi:10.1111/j.1365-2486.2011.02616.x, 2012.
Mapanda, F., Mupini, J., Wuta, M., Nyamangara, J., and Rees, R. M.: A cross-ecosystem assessment of the effects of land cover and land use on soil emission of selected greenhouse gases and related soil properties in Zimbabwe, Eur. J. Soil Sci., 61, 721–733, 2010.
Meijide, A., Garcia-Torres, L., Arce, A., and Vallejo, A.: Nitrogen oxide emissions affected by organic fertilization in a non-irrigated Mediterranean barley field, Agric. Ecosys. Environ., 132, 106–115, 2009.
Mosier, A. R., Duxbury, J. M., Freney, J. R., Heinemeyer, O., and Minami, K.: Assessing and mitigating N_2O emissions from agricultural soils, Clim. Change, 40, 7–38, 1998.
Neftel, A., Flechard, C., Ammann, C., Conen, F., Emmenegger, L., and Zeyer, K.: Experimental assessment of N_2O background fluxes in grassland systems, Tellus B, 59, 470–482, 2007.
Nylinder, J., Stenberg, M., Jansson, P. E., Klemedtsson, A. K., Weslien, P., and Klemedtsson, L.: Modelling uncertainty for nitrate leaching and nitrous oxide emissions based on a Swedish field experiment with organic crop rotation, Agric. Ecosys. Environ., 141, 167–183, 2011.
Pihlatie, M., Christiansen, J., Aaltonen, H., Korhonen, J., Rasilo, T., Benanti, G., Giebels, M., Helmy, M., Hirvensalo, J., Jones, S., Juszczak, R., Klefoth, R., Lobo, R., do Vale, Rosa, A. P., Schreiber, P., Serca, D., Vicca, S., Wolf, B., and Pumpanen, J.: Comparison of static chambers to measure N_2O and CH_4 fluxes from soils, Geophys. Res. Abstr., 11, 8742–8743, 2009.
Rees, R. M.: Global nitrous oxide emissions: sources and opportunities for mitigation, in: Understanding Greenhouse Gas Emissions from Agricultural Management, American Chemical Society, 257–273, doi:10.1021/bk-2011-1072, 2011.
Rochette, P. and Janzen, H.: Towards a revised coefficient for estimating N_2O emissions from legumes, Nutr. Cycl. Agroecosys., 73, 171–179, 2005.

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Sanchez-Martin, L., Meijide, A., Garcia-Torres, L., and Vallejo, A.: Combination of drip irrigation and organic fertilizer for mitigating emissions of nitrogen oxides in semiarid climate, Agric. Ecosys. Environ., 137, 99–107, 2010.

Schulze, E. D., Luyssaert, S., Ciais, P., Freibauer, A., and Janssens, E. A.: Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance, Nature Geosci., 2, 842–850, 2009.

Six, J., Ogle, S. M., Breidt, F. J., Conant, R. T., Mosier, A. R., and Paustian, K.: The potential to mitigate global warming with no-tillage management is only realized when practised in the long term, Glob. Change Biol., 10, 155–160, 2004.

Skiba, U. and Ball, B.: The effect of soil texture and soil drainage on emissions of nitric oxide and nitrous oxide, Soil Use Manage., 18, 56–60, 2002.

Smith, K. A. and Conen, F.: Impacts of land management on fluxes of trace greenhouse gases, Soil Use Manage., 20, 255–263, 2004.

Smith, K. A. and Dobbie, K. E.: Another look at N_2O emission factors for agricultural soils, and implications for inventory calculations, non-CO_2 greenhouse gases: scientific understanding, Control Opt. Pol. Asp., 245–250, 2002.

Smith, K. A., McTaggart, I. P., and Tsuruta, H.: Emissions of N_2O and NO associated with nitrogen fertilization in intensive agriculture, and the potential for mitigation, Soil Use Manage., 13, 296–304, 1997.

Smith, K. A., Thomson, P. E., Clayton, H., McTaggart, I. P., and Conen, F.: Effects of temperature, water content and nitrogen fertilisation on emissions of nitrous oxide by soils, Atmos. Environ., 32, 3301–3309, 1998.

Stockdale, E. A., Lampkin, N. H., Hovi, M., Keatinge, R., Lennartsson, E. K. M., Macdonald, D. W., Padel, S., Tattersall, F. H., Wolfe, M. S., and Watson, C. A.: Agronomic and environmental implications of organic farming systems, Adv. Agron., 70, 261–327, 2001.

Watson, C. A., Baddeley, J. A., Edwards, A. C., Rees, R. M., Walker, R. L., and Topp, C. F. E.: Influence of ley duration on the yield and quality of the subsequent cereal crop (spring oats) in an organically managed long-term crop rotation experiment, Org. Agric., 1, 147–159, 2011.

Wrage, N., Velthof, G. L., van Beusichem, M. L., and Oenema, O.: Role of nitrifier denitrification in the production of nitrous oxide, Soil Biol. Biochem., 33, 1723–1732, 2001.

Table 1. A description of the experimental site network and manipulation experiments.

Site name	Manipulation	Treatments		Reference
Beano Italy	Crop rotation	1 CNT	Cropland tilled	Alberti et al. (2010)
		2 CT	Cropland no till	
		3 GT	Grassland tilled	
El Encin Spain	Irrigation nitrogen	1 A	Ammonium sulphate	Meijide et al. (2009); Sanchez-Martin et al. (2010)
		2 CCR	Composted crop residue	
		3 DPS	Digested pig slurry	
		4 MSW	Solid pig slurry	
		5 OM	DMPP inhibitor	
		6 U	Digested pig slurry	
		7 UPS	Mixed organic waste	
Foulum Denmark	Organic arable rotation	1 C-CC+M	Conventional	Chirinda et al. (2010)
		2 O+CC+M	Organic + catch crop	
		3 O-CC+M	Organic – catch crop	
Logården Sweden	Organic and integrated rotations	1 Int	Integrated	Nylinder et al. (2011)
		2 Org	Organic	
Maulde Belgium	Tillage	1 NT	No tillage	Boeckx et al. (2011)
		2 RT	Reduced tillage	
		3 CT	Conventional tillage	
Paulinaue Germany	Land use change	1 AC	Arable	Bell et al. (2012)
		2 AG	Arable to grass	
		3PeM	Permanent grass	
Tulloch UK	Organic grass/arable rotation	1 B	Barley	Ball et al. (2002) Watson et al. (2011)
		2 B us	Barley undersown	
		3 LO	Ley oats	
		4 O	Oats	
		5 O us	Oats undersown	
		6 Pot	Potato	
		7 S	Swede	
		8 W us	Wheat undersown	
		9 Y1G	First year grass	
		10 Y2G	Scond year grass	
		11 Y3G	Third year grass	
		12 Y4G	Fourth year grass	
		13 Pul	Pulses	
		14 YGr	Grass red clover	

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Table 1. (Continued.)

Site name	Manipulation	Treatments		Reference
Harare Zimbabwe	Fertiliser addition	C	Control (0N)	Mapanda et al. (2010)
		F1	30 Kg N	
		F1M1	N + manure N	
		F2	60 kg N	
		M1	30 kg manure-N	
		M2	60 kg manure N	
Crichton UK	Nitrogen input and grazing	F1	Site 1 fertilised & grazed	Gordon et al. (2011)
		F2	Site 2 fertilised & grazed	
		F3	Site 3 fertilised & grazed	
		F4	Site 4 fertilised & grazed	
		FNS	Site 5 fertilsed & grazed	
		NF1	Site 6 slurry & grazed	
		NF4	Site 7 slurry & grazed	
Gödöllö Hungary	CO_2, fertiliser, wetness	C CO_2 F W	Control Elevated CO_2 Fertilizer Wetted	Horvath et al. (2010)
Nafferton UK	Flooding	C	Control	Reay Unpublished
		W	Wetted	
Peakneaze UK	Warming, drought	C	Control	Levy et al. (2012)
		D	Drought	
		T	Warming	
Rzecin Poland/ Zarnekow Germany**	Flooding	C	Control	Chojnicki et al. (2007); Juszczak et al. (2012)
		DW	Dry/wet grassland	
		RF	Reflooded grassland	
Theix France	CO_2, warming, drying	C	Control	Cantarel et al. (2011, 2012)
		T	Increased temperature	
		DD	Drought	
		DCO_2	Drought and elevated CO_2	

* The Crichton experiment involved the comparison of regionally typical management scenarios on adjacent fields in different years.
** The Rzecin/Zarnekow experiment involved the comparison of a dying/wetting and flooding experiments in Zarnekow (Germany), with a control site in Rzecin (Poland).

Table 2. An overview of the soil and climatic conditions across the experimental network.

Site name	Country	Soil texture*	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	Coordinate
Arable							
Beano	Italy	L	17–20	1.2–1.4	13.2	1220	56°30′ N 9°34′ W
El Encin	Spain	CL	8–12	1.3–1.4	14.9	484	40°32′ N 3°37′ W
Foulum	Denmark	SL	22–23	1.3	9.3	660	56°30′ N 9°35′ E
Logården	Sweden	ZC	18–20	1.4	7.9	695	58°20′ N 12°38′ E
Maulde	Belgium	ZL	9–12	1.3–1.5	11.2	910	50°37′ N, 3°34′ E
Paulinaue	Germany	SL	80	0.5	9.7	694	52°68′ N 12°72′ E
Tulloch	UK	SL	50–66	1.2	8.9	940	57°11′ N 2°16′ W
Harare	Zimbabwe	S/C	5–8	1.7	19.1	940	17°55′S 30°55′ W
Grassland							
Crichton	UK	SL	29	1.1	10.1	1183	55°02′ N 3°35′ W
Gödöllö	Hungary	SL	17–41	1.1	9.9	582	47°60′ N 19°37′ E
Nafferton	UK	NA	NA	1.1	9.5	664	54°51′ N 7°36′ E
Peakneaze	UK	NA	NA	0.18	9.2	875	53°47′ N 13°91′ W
Rzecin/	Poland	Organic	NA	0.06	8.5	536	52°76′ N 16°31′ E
Zarnekow	Germany	Organic	277	0.38	12.0	730	53°88′ N 12°88′ E
Theix	France	SL	NA	1.1	7.8	704	45°47′ N 3°05′ E

* Textures: SL sandy loam, ZL silty loam, CL clay loam, L loam, NA, not available.

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

(a) Arable sites	Treatment	Annual emission N_2O-N kg ha^{-1} yr^{-1}	Standard deviation N_2O-N kg ha^{-1} yr^{-1}
Beano	Cropland no till	6.17	5.75
	Cropland tilled	5.49	4.34
	Grassland tilled	1.03	1.01
Beano Total		4.23	4.65
El Encin	Control	0.21	0.22
	CCR	0.41	0.15
	Digested pig slurry	0.71	0.43
	MSW	0.32	0.23
	Organic manure	0.89	0.12
	Urea	1.17	0.81
	Untreated slurry	0.36	0.18
El Encin Total		0.63	0.59
Foulum	Conventional + catch crops	1.24	0.82
	Organic + catch crops	0.98	0.17
	Organic + catch crops	0.83	0.25
Foulum Total		1.02	0.49
Logården	Integrated	1.29	1.86
	Organic	1.08	1.49
Logården Total		1.15	1.62
Maulde	Conventional tillage	4.96	2.28
	No tillage	5.68	2.69
	Reduced tillage	5.28	3.39
Maulde Total		5.31	2.76
Pau	Arable	2.83	2.17
	Arable converted to grassland	0.39	0.36
	Permanent grassland	1.15	1.99
Pau Total		1.46	1.95
Tulloch	Barley	9.27	1.52
	Barley undersown	13.21	10.21
	Ley oats	5.99	3.98
	Oats	0.50	0.46
	Oats undersown	2.23	0.71
	Potato	8.45	8.23
	Swede	3.07	4.80
	Wheat undersown	4.87	0.69
	First year grass	0.72	0.34
	Second year grass	1.12	0.80
	Third year grass	1.90	1.25
	Fourth year grass	1.34	0.43
	Pulses	3.10	1.32
	Grass red-clover	3.75	2.61
Tulloch Total		3.46	4.10
Harare	Control	0.85	1.01
	30 kg ammonium nitrate-N	0.48	0.88
	30 kg AN + manure	0.48	0.61
	60 kg ammonium nitrate-N	0.67	0.92
	30 kg manure-N	0.25	0.27
	60 kg ammonium nitrate-N	0.85	0.97
Harare Total		0.60	0.81
Grand Total		1.80	2.72

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Table 3. (Continued.)

(b) Grassland sites	Treatment	Average of total N_2O-N kg ha^{-1} yr^{-1}	Standard deviation of total N_2O-N kg ha^{-1} yr^{-1}
Crichton	Site 1 fertilised & grazed	11.68	11.63
	Site 2 fertilised & grazed	28.21	34.89
	Site 3 fertilised & grazed	51.27	44.28
	Site 4 fertilised & grazed	33.90	13.86
	Site 5 fertilised & grazed	9.89	6.10
	Site 6 slurry & grazed	3.62	0.80
	Site 7 slurry & grazed	2.88	1.59
Crichton Total		**21.21**	**28.13**
Gödöllö	Control	0.38	0.19
	Elevated CO_2	0.23	0.17
	Fertilizer	0.62	0.30
	Wetted	0.40	0.12
Gödöllö total		**0.41**	**0.23**
Nafferton	Control	0.55	0.66
	Wetted	0.36	0.40
Nafferton total		**0.45**	**0.46**
Peaknaze	Control	0.04	0.03
	Drought	0.09	0.16
	Warming	0.00	0.03
Peaknaze total		**0.04**	**0.09**
Rzecin/ Zarnekow	Control	0.526	
	Dry/wet grassland	0.004	0.001
	Re-flooded grassland	0.004	0.001
Rzecin/Zarnekow total		**0.04**	**0.13**
Theix	Control	0.52	0.43
	Increased temperature	0.69	0.46
	Increased temperature & drought	0.64	0.47
	Inc. temperature, CO_2 & drought	0.63	0.44
Theix total		0.62	0.44
Grand Total		**7.00**	**18.45**

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Table 4. Nitrous oxide emissions in response to site and management conditions across the experimental network classified by site and year.

(a) Arable			
Arable sites	Year	Average annual N_2O-N kg ha^{-1} yr^{-1}	Standard deviation N_2O-N kg ha^{-1} yr^{-1}
Beano	2007	0.27	0.10
	2008	6.62	5.06
	2009	5.80	4.23
Beano Total		**4.23**	**4.65**
El Encin	2006	0.31	0.23
	2007	0.71	0.64
	2008	0.79	0.47
	2009	0.97	1.00
	2010	0.50	0.55
El Encin total		**0.63**	**0.59**
Foulum	2007	1.15	0.67
	2008	0.89	0.19
Foulum total		**1.02**	**0.49**
Logården	2004	1.72	1.26
	2005	1.76	1.60
	2006	1.03	2.08
	2007	0.19	0.13
Logården total		**1.15**	**1.62**
Maulde	2007	6.83	2.07
	2008	3.78	2.54
Maulde total		**5.31**	**3.00**
Paulinaue	2007	2.73	2.80
	2008	1.04	1.13
	2009	0.59	0.56
Paulinaue total		**1.46**	**1.95**
Tulloch	2006	2.27	2.77
	2007	4.56	4.83
Tulloch total		**3.46**	**4.10**
Harare	2007	0.58	0.84
	2008	0.89	0.90
	2009	0.33	0.60
Harare, total		**0.60**	**0.81**
Grand Total		**1.80**	**2.72**

Table 4. (Continued.)

(b) Grassland

Grassland sites/year	Average of total N_2O-N $kg\,ha^{-1}\,yr^{-1}$	Standard deviation of total N_2O-N $kg\,ha^{-1}\,yr^{-1}$
Crichton	**21.21**	**28.13**
2006	28.86	35.96
2007	13.55	14.22
Gödollo Total	**0.41**	**0.23**
2007	0.35	0.19
2008	0.43	0.25
Nafferton Total	**0.45**	**0.46**
2008	0.83	0.26
2009	0.07	0.00
Peaknaze Total	**0.04**	**0.09**
2007	0.04	0.09
Rzecin Total	**0.04**	**0.13**
2007	0.05	0.16
2008	0.00	0.00
Theix Total	**0.62**	**0.44**
2007	0.62	0.23
2008	1.06	0.29
2009	0.18	0.26
Grand Total	**7.00**	**18.45**

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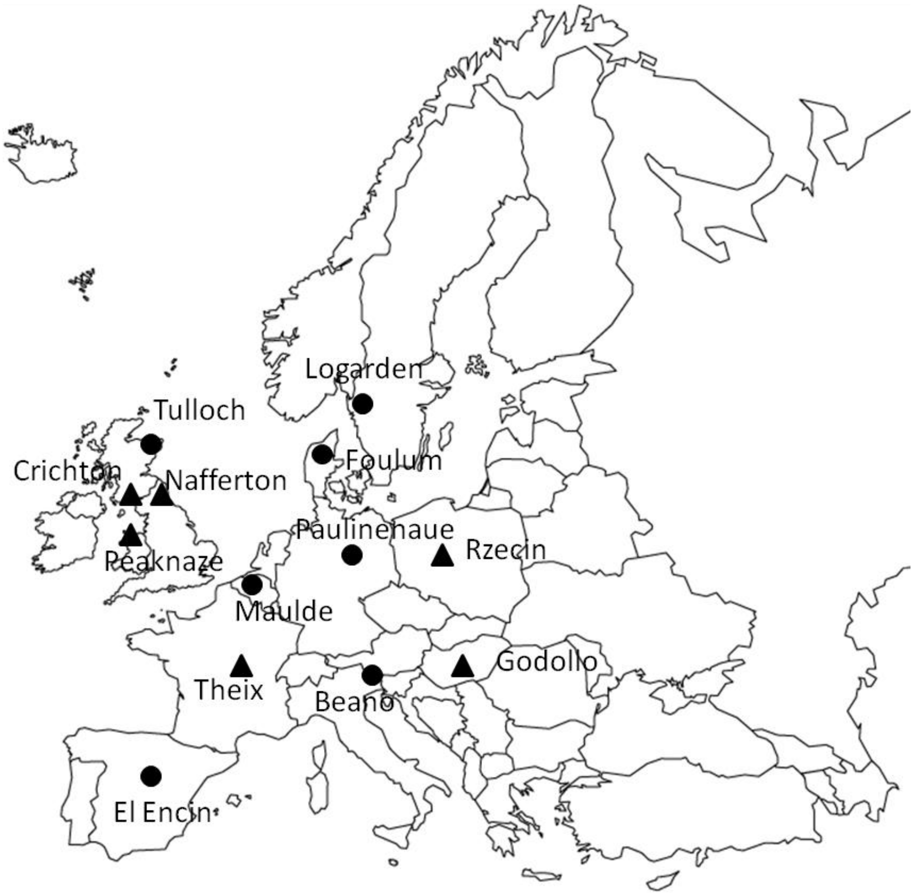

Fig. 1. Locations of the European experimental sites. Circles represent arable sites and triangles grassland sites.

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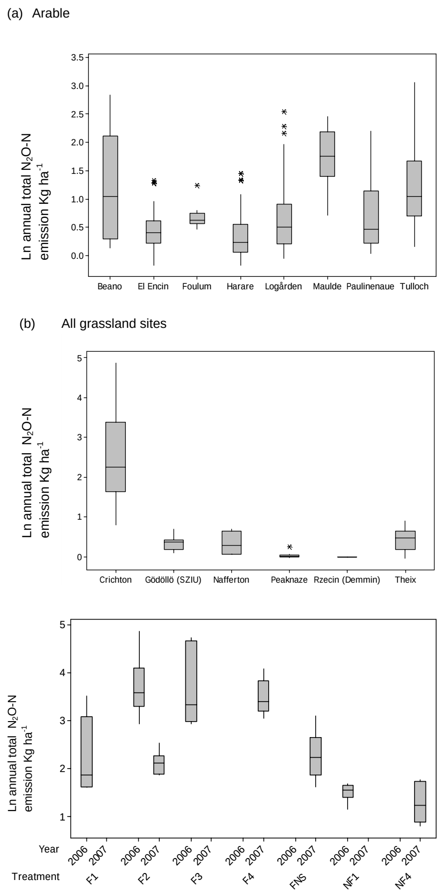

Fig. 2. Annual N_2O emissions compared between sites. Each bar represents the average emission from different treatments in different years. Each bar indicates the mean (central bar), upper and lower quartiles (outside bar) and 95 % range (lines). Outliers are represented by asterisks. See Table 1 for a description of the detailed treatment codes.

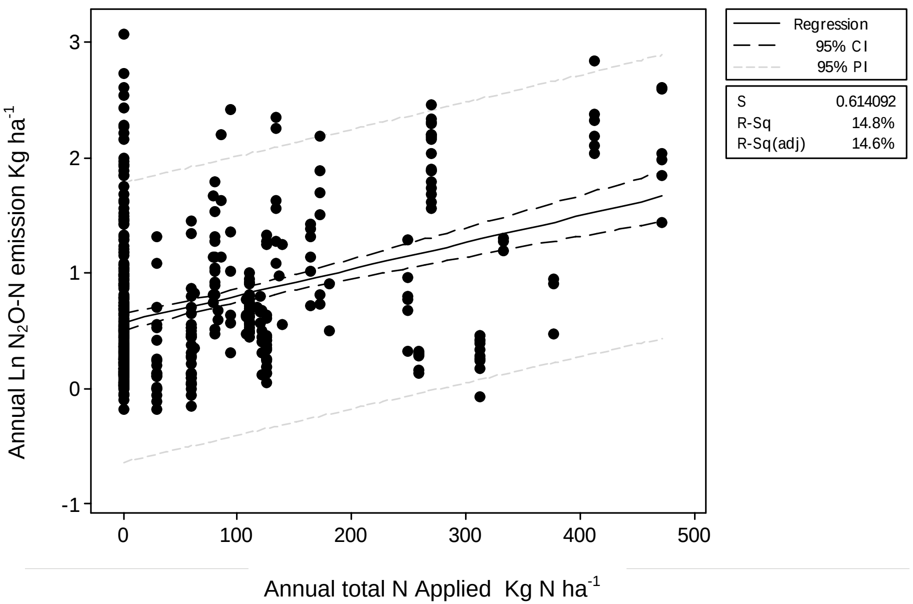

Fig. 3. The relationship between N_2O emissions and added N input (in the form of organic manures and synthetic N fertiliser) for arable sites. $\ln(N_2O)$ ($\text{kg } N_2O\text{-N ha}^{-1}$) = 0.5750 + 0.002602 total N applied.

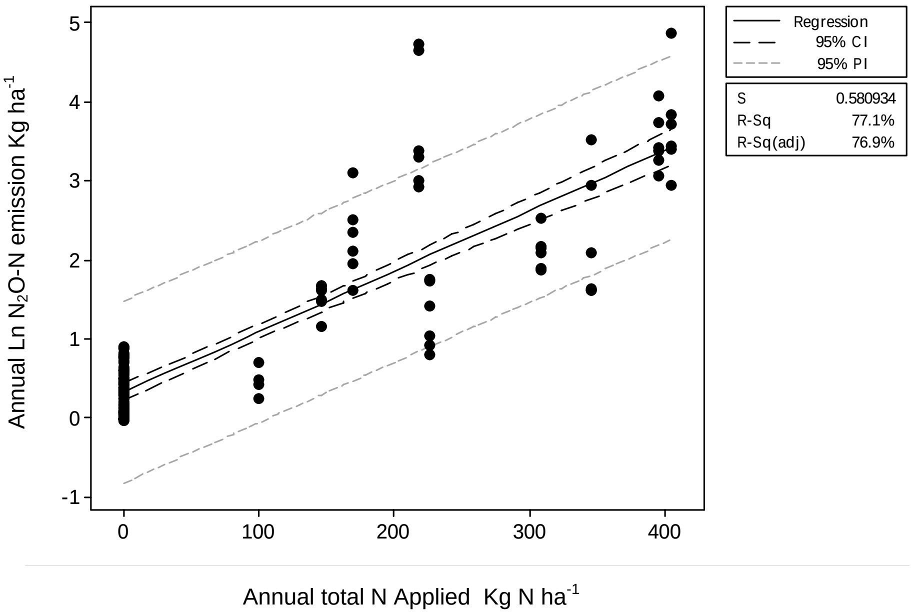

Fig. 4. The relationship between N_2O emissions and added N input (in the form of organic manures and synthetic N fertiliser) for grassland sites. $\ln(N_2O)$ (kg N_2O-N ha^{-1}) = 0.3342 + 0.007631 total N applied.

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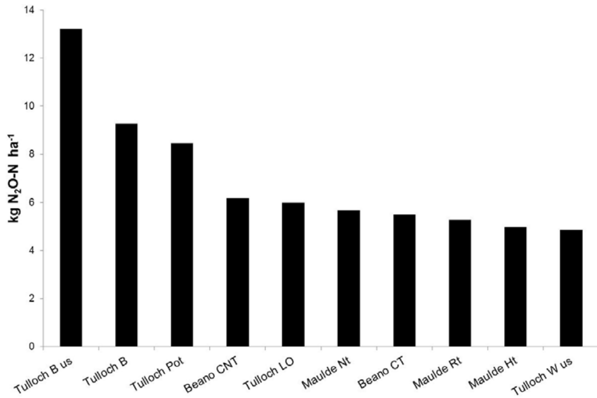
(a) On an area basis



(b) By intensity

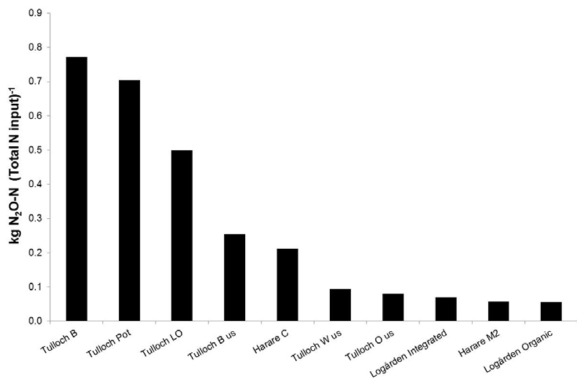


Fig. 5. Ranking of annual emissions data from individual arable plots. The top 10 sites are ranked on emissions per unit area **(a)** and per unit of N_2O per unit of N total input (synthetic fertiliser, manure and biological N fixation) **(b)**. See Table 1 for a description of the treatment codes.

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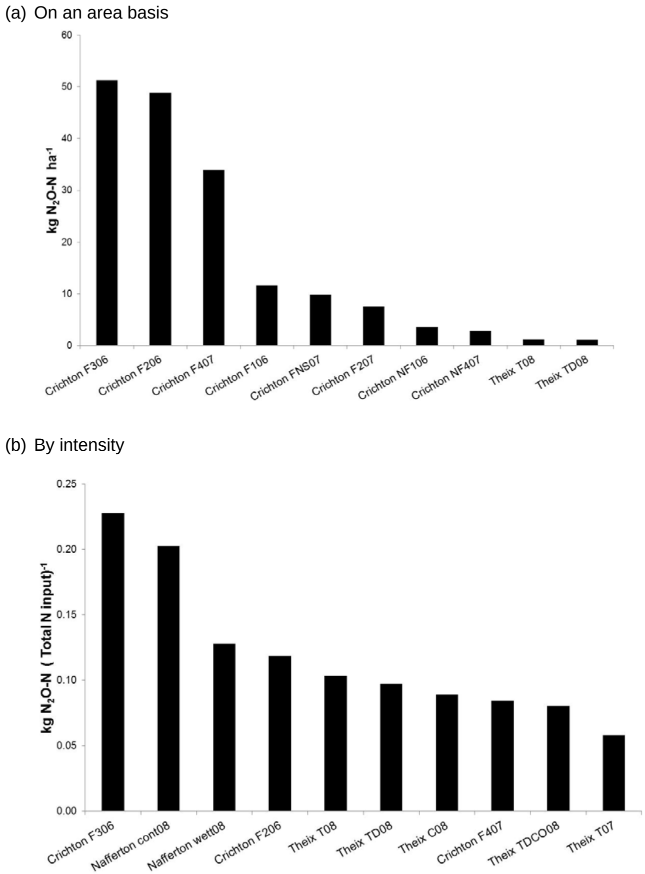

Fig. 6. Ranking of annual emissions data from individual grassland plots. The top 10 sites are ranked on emissions per unit of N_2O per unit of N total input (synthetic fertiliser, manure, deposition and biological N fixation). See Table 1 for a description of the treatment codes.

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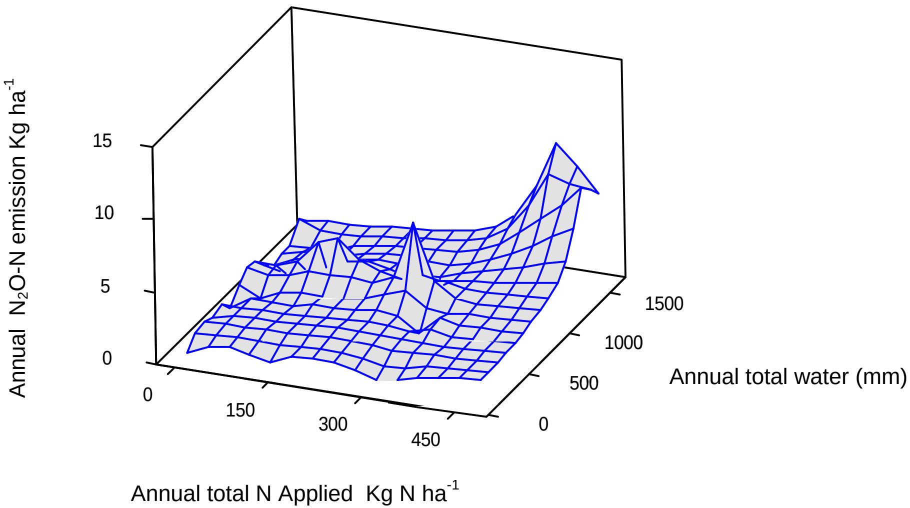

Fig. 7. The relationship between N_2O emissions and annual total rainfall plus irrigation and total N input across the arable site network.

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