Springer

# Dear Author

Here are the proofs of your article.

- You can submit your corrections **online,** via **e-mail** or by **fax**.
- For **online** submission please insert your corrections in the online correction form. Always indicate the line number to which the correction refers.
- You can also insert your corrections in the proof PDF and **email** the annotated PDF.
- For **fax** submission, please ensure that your corrections are clearly legible. Use a fine black pen and write the correction in the margin, not too close to the edge of the page.
- Remember to note the **journal title**, **article number**, and **your name** when sending your response via e-mail or fax.
- **Check** the metadata sheet to make sure that the header information, especially author names and the corresponding affiliations are correctly shown.
- **Check** the questions that may have arisen during copy editing and insert your answers/corrections.
- **Check** that the text is complete and that all figures, tables and their legends are included. Also check the accuracy of special characters, equations, and electronic supplementary material if applicable. If necessary refer to the *Edited manuscript*.
- The publication of inaccurate data such as dosages and units can have serious consequences. Please take particular care that all such details are correct.
- Please **do not** make changes that involve only matters of style. We have generally introduced forms that follow the journal's style.
- Substantial changes in content, e.g., new results, corrected values, title and authorship are not allowed without the approval of the responsible editor. In such a case, please contact the Editorial Office and return his/her consent together with the proof.
- If we do not receive your corrections **within 48 hours**, we will send you a reminder.
- Your article will be published **Online First** approximately one week after receipt of your corrected proofs. This is the **official first publication** citable with the DOI. **Further changes are, therefore, not possible.**
- The **printed version** will follow in a forthcoming issue.

**Please note**

After online publication, subscribers (personal/institutional) to this journal will have access to the complete article via the DOI using the URL:

http://dx.doi.org/10.1007/s11104-013-1862-2

If you would like to know when your article has been published online, take advantage of our free alert service. For registration and further information, go to: http://www.springerlink.com.

Due to the electronic nature of the procedure, the manuscript and the original figures will only be returned to you on special request. When you return your corrections, please inform us, if you would like to have these documents returned.

AUTHOR'S PROOF

# Metadata of the article that will be visualized in OnlineFirst

**Please note: Images will appear in color online but will be printed in black and white.**

| | | | |
|---|---|---|---|
| 1 | Article Title | **Estimating the impact of changing fertilizer application rate, land use, and climate on nitrous oxide emissions in Irish grasslands** | |
| 2 | Article Sub- Title | | |
| 3 | Article Copyright - Year | **Springer Science+Business Media Dordrecht 2013 (This will be the copyright line in the final PDF)** | |
| 4 | Journal Name | Plant and Soil | |


| | | | |
|---|---|---|---|
| 5 | Corresponding Author | Family Name | **Kim** |
| 6 | | Particle | |
| 7 | | Given Name | **Dong-Gill** |
| 8 | | Suffix | |
| 9 | | Organization | University College Cork |
| 10 | | Division | HYDROMET, Centre for Hydrology, Micrometeorology and Climate Change, Department of Civil and Environmental Engineering |
| 11 | | Address | Cork, Ireland |
| 12 | | Organization | Hawassa University |
| 13 | | Division | Wondo Genet College of Forestry and Natural Resources |
| 14 | | Address | Shashemene, Ethiopia |
| 15 | | e-mail | donggillkim@gmail.com |
| 16 | Author | Family Name | **Rafique** |
| 17 | | Particle | |
| 18 | | Given Name | **Rashad** |
| 19 | | Suffix | |
| 20 | | Organization | University College Cork |
| 21 | | Division | HYDROMET, Centre for Hydrology, Micrometeorology and Climate Change, Department of Civil and Environmental Engineering |
| 22 | | Address | Cork, Ireland |
| 23 | | Organization | University of Oklahoma |
| 24 | | Division | Department of Microbiology and Plant Biology |
| 25 | | Address | Norman 73019, OK, USA |

| | | | |
|---|---|---|---|
| 26 | | e-mail | |
| 27 | | Family Name | **Leahy** |
| 28 | | Particle | |
| 29 | | Given Name | **Paul** |
| 30 | | Suffix | |
| 31 | | Organization | University College Cork |
| 32 | Author | Division | HYDROMET, Centre for Hydrology, Micrometeorology and Climate Change, Department of Civil and Environmental Engineering |
| 33 | | Address | Cork, Ireland |
| 34 | | Organization | University College Cork |
| 35 | | Division | Environmental Research Institute |
| 36 | | Address | Cork, Ireland |
| 37 | | e-mail | |
| 38 | | Family Name | **Cochrane** |
| 39 | | Particle | |
| 40 | | Given Name | **Mark** |
| 41 | | Suffix | |
| 42 | Author | Organization | Cork Institute of Technology |
| 43 | | Division | Department of Civil, Structural and Environmental Engineering |
| 44 | | Address | Cork, Ireland |
| 45 | | e-mail | |
| 46 | | Family Name | **Kiely** |
| 47 | | Particle | |
| 48 | | Given Name | **Gerard** |
| 49 | | Suffix | |
| 50 | | Organization | University College Cork |
| 51 | Author | Division | HYDROMET, Centre for Hydrology, Micrometeorology and Climate Change, Department of Civil and Environmental Engineering |
| 52 | | Address | Cork, Ireland |
| 53 | | e-mail | |



| | | | |
|---|---|---|---|
| 54 | | Received | 22 November 2012 |
| 55 | Schedule | Revised | |
| 56 | | Accepted | 24 July 2013 |

57 Abstract

**Aim:** This study examines the impact of changing nitrogen (N) fertilizer application rates, land use and climate on N fertilizer-derived direct nitrous oxide ($N_2O$) emissions in Irish grasslands.
**Methods:** A set of N fertilizer application rates, land use and climate change scenarios were developed for the baseline year 2000 and then for the years 2020 and 2050. Direct $N_2O$ emissions under the different scenarios were estimated using three different types of emission factors and a newly developed Irish grassland $N_2O$ emissions empirical model.
**Results:** There were large differences in the predicted $N_2O$ emissions between the methodologies, however, all methods predicted that the overall $N_2O$ emissions from Irish grasslands would decrease by 2050 (by 40–60 %) relative to the year 2000. Reduced N fertilizer application rate and land-use changes resulted in decreases of 19–34 % and 11–60 % in $N_2O$ emission respectively, while climate change led to an increase of 5–80 % in $N_2O$ emission by 2050.
**Conclusions:** It was observed in the study that a reduction in N fertilizer and a reduction in the land used for agriculture could mitigate emissions of $N_2O$, however, future changes in climate may be responsible for increases in emissions causing the positive feedback of climate on emissions of $N_2O$.

58 Keywords separated by ' - '

Nitrous oxide - Nitrogen fertilizer - Land-use change - Climate change - Scenario analysis

59 Foot note information

Responsible Editor: Per Ambus.

JrnlID 11104_ArtID 1862_Proof# 1 - 02/08/2013

Plant Soil
DOI 10.1007/s11104-013-1862-2

REGULAR ARTICLE

# Estimating the impact of changing fertilizer application rate, land use, and climate on nitrous oxide emissions in Irish grasslands

**Dong-Gill Kim · Rashad Rafique · Paul Leahy · Mark Cochrane · Gerard Kiely**

Received: 22 November 2012 / Accepted: 24 July 2013


**Abstract**
*Aim* This study examines the impact of changing nitrogen (N) fertilizer application rates, land use and climate on N fertilizer-derived direct nitrous oxide ($N_2O$) emissions in Irish grasslands.
*Methods* A set of N fertilizer application rates, land use and climate change scenarios were developed for the baseline year 2000 and then for the years 2020 and 2050. Direct $N_2O$ emissions under the different scenarios were estimated using three different types of emission factors and a newly developed Irish grassland $N_2O$ emissions empirical model.
*Results* There were large differences in the predicted $N_2O$ emissions between the methodologies, however, all methods predicted that the overall $N_2O$ emissions from Irish grasslands would decrease by 2050 (by 40–60 %) relative to the year 2000. Reduced N fertilizer application rate and land-use changes resulted in decreases of 19–34 % and 11–60 % in $N_2O$ emission respectively, while climate change led to an increase of 5–80 % in $N_2O$ emission by 2050.
*Conclusions* It was observed in the study that a reduction in N fertilizer and a reduction in the land used for agriculture could mitigate emissions of $N_2O$, however, future changes in climate may be responsible for increases in emissions causing the positive feedback of climate on emissions of $N_2O$.

**Keywords** Nitrous oxide · Nitrogen fertilizer · Land-use change · Climate change · Scenario analysis

Responsible Editor: Per Ambus.

D.-G. Kim
Wondo Genet College of Forestry and Natural Resources, Hawassa University, Shashemene, Ethiopia

D.-G. Kim (✉) · R. Rafique · P. Leahy · G. Kiely
HYDROMET, Centre for Hydrology, Micrometeorology and Climate Change, Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland
e-mail: donggillkim@gmail.com

R. Rafique
Department of Microbiology and Plant Biology, University of Oklahoma, Norman, 73019 OK, USA

P. Leahy
Environmental Research Institute, University College Cork, Cork, Ireland

M. Cochrane
Department of Civil, Structural and Environmental Engineering, Cork Institute of Technology, Cork, Ireland

## Introduction

Increases in $N_2O$ concentrations add to the greenhouse effect (e.g. Wang et al. 1976) and ozone depletion (Crutzen 1970). In a 100-year time horizon the global warming potential of $N_2O$ is 298 times that of carbon dioxide ($CO_2$) and 12 times that of methane ($CH_4$) (Forster et al. 2007). Among anthropogenic $N_2O$ emissions (6.7 Tg $N_2O$–N $y^{-1}$), agricultural soils are estimated to provide 2.8 Tg $N_2O$–N $year^{-1}$ (Denman et al.

JrnlID 11104_ArtID 1862_Proof# 1 - 02/08/2013


2007). The use of N fertilizers and animal manures are the main anthropogenic sources, estimated at about 24 % of annual $N_2O$ emissions (Bouwman 1996; IPCC 2007). It has been suggested that N fertilizer use, land use and its management, and climate are the major controlling factors of $N_2O$ emissions from agricultural lands (e.g. de Klein et al. 2010).

According to the statistics of the International Fertilizer Industry Association (IFADATA 2013), N fertilizer consumption in Europe increased linearly from 1961 up to 1999 (12.2 Mt N in 1999), and then decreased by 1.3 Mt N between 2000 and 2005. Similarly, in Ireland, N fertilizer consumption decreased from 0.44 Mt N in 1998 to 0.32 Mt N in 2006 (Department of Agriculture, Fisheries and Food 2008). The EU Nitrates Directive became part of Irish law in February 2006 (Department of Environment, Heritage and Local Government 2006; Humphreys 2008). The legal instrument, called the European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2006, SI 378 of 2006, deals with the protection of waters from pollution caused by nitrates and phosphates from agricultural sources (Department of Environment, Heritage and Local Government 2006). Irish farming must now comply with SI 378 of 2006 and should follow Teagasc (The Irish National Agricultural Research Organisation) nutrient advice, which indicates the need for nutrient supply to match to crop requirements both in quantity applied and time of application (Coulter and Lalor 2008; Humphreys 2008). Considering the recent downward trend of N fertilizer consumption, rising prices of N fertilizer and the implementation of the Nitrates Directive, it is expected that N fertilizer consumption will decrease in the future in Ireland (Hsieh et al. 2005). Such changes to N fertilizer usage will likely have important consequences for direct and indirect $N_2O$ emissions (Sun and Huang 2012).

According to the statistics of the Food and Agriculture Organisation (FAO) of the United Nations (FAOSTAT 2013), the agricultural land area in Europe decreased by 12 million ha (2.4 %) between 1995 and 2005, with the total agricultural land area being 480 million ha in 2005. Similarly, agricultural land in Ireland decreased from 4.44 million ha in 2000 to 4.27 million ha in 2007 (Department of Agriculture, Fisheries and Food 2008). According to spatially explicit and alternative scenarios of future environmental change and agricultural land use in Europe based on the IPCC Special Report on Emissions Scenarios, Rounsevell et al. (2005) state that across Europe agricultural land use is expected to decline by as much as 50 % from current areas; of which a rate of 40–60 % reduction in croplands and 5–63 % reduction in grasslands is expected by 2080. These land-use changes are likely to have important consequences for $N_2O$ emissions (e.g. Flynn et al. 2005; Roelandt et al. 2007; Nol et al. 2011; Bodirsky et al. 2012).

The Community Climate Change Consortium for Ireland (C4I) project predicts future increases in temperature and changes in precipitation patterns (Dunne et al. 2008). Temperatures for summer and autumn are predicted to increase 1.2–1.4 °C by 2050 and up to 3.4 °C towards the end of the century (Dunne et al. 2008). A wetter climate is predicted for autumn and winter (5–10 % increase by the middle of the century, and 15–25 % towards the end of the century) and summers drier (5–10 % decrease between 2021 and 2060; 10–18 % decrease towards the end of the century) (Dunne et al. 2008). These climate changes are likely to increase direct $N_2O$ emissions (e.g. Roelandt et al. 2007; Eckard and Cullen 2011).

Several methodologies have been developed to estimate $N_2O$ emissions from agricultural areas. The current IPCC Tier 1 methodology (IPCC 1996 and 2006) uses emissions factors (EFs), which specify that a fixed proportion of the N applied is considered to be emitted from the soil to the atmosphere as $N_2O$. Although the EFs methodology has the advantage of being easy to use with readily available fertiliser data, it does not take into account the spatial and temporal variability of $N_2O$ emissions from soils (e.g. Rafique et al. 2011a), or the effects of crop type or climate, which are known to regulate $N_2O$ production. Empirical $N_2O$ emission models based on statistical analysis of the main driving variables for $N_2O$ emission (e.g. temperature, rainfall and N fertilizer; Roelandt et al. 2005) and simple regression models based on the relationship between direct $N_2O$ emission, environmental factors, and management-related factors (e.g. Flynn et al. 2005; Flechard et al. 2007) have been developed and used to estimate site- or regional-scale emissions. Process-based models, which consider all the proximal factors acting on nitrification and denitrification processes, have been developed to simulate terrestrial ecosystem carbon (C) and N biogeochemistry (e.g. DAYCENT, Parton et al. 2001; DNDC, Rafique et al. 2011b). When sufficient data to run process-based models are not available, climate variable EF methodologies and empirical $N_2O$ emission models can be used to assess the impact of potential future N fertilizer use, land use, and climate change on direct $N_2O$ emissions (e.g. Flynn et al. 2005; Flechard et al. 2007; Roelandt et al. 2007).

Nitrogen fertilizer use, land use, and climate are major controlling factors of $N_2O$ emissions from agricultural lands (Forster et al. 2007) and these factors are undergoing change in Ireland. It is therefore important to estimate the changes in $N_2O$ emissions in future scenarios and provide accurate information to consider the changes in the strategies and efforts to mitigate $N_2O$ emission and so climate change. Ireland provides an ideal case study to assess these methodologies, as its estimated $N_2O$ emissions from agriculture are a significant contributor to the national GHG inventory estimate (Environmental Protection Agency 2011). The objective of this study is to estimate the impact of changing N fertilizer application rate, land use, and climate on direct $N_2O$ emissions in Irish grasslands using EFs (IPCC default and two, climate-variable, EFs) and an empirical $N_2O$ emission model.

## Methods and materials

### Study area

The study area comprised all 8 regions (as defined for the Water Framework Directive purposes) and 26 counties in the Republic of Ireland. Agricultural lands account for 70.1 % (arable lands 7.9 %, grasslands 54.3 %, and heterogeneous agricultural areas 7.9 %) out of an entire area 6.94 million ha (Eaton et al. 2008). The soils of the central north eastern and midland regions consist mainly of gleys and grey-brown podzolic soils (Fay et al. 2007). Acid brown earths are dominant in the soil cover of the south-eastern region (Fay et al. 2007). There is a significant occurrence of gleys, grey-brown podzolic, and rendzinas in the soils of the south-western region (Fay et al. 2007). Due to the moderating influence of the Atlantic, Ireland has a temperate oceanic climate (The Irish Meteorological Service 2013): the average annual temperature is about 9 °C and the eastern part of the country has between 750 and 1,000 mm annual rainfall, while the west has generally in excess of 1,250 mm. The wettest months are December and January, with April the driest and August the warmest (The Irish Meteorological Service 2013).

### Scenarios of future changes

#### *Land-use change*

Information on the agricultural land area in each of the 26 counties in the baseline year 2000 was derived from the year 2000 Census of Agriculture by Irish Central Statistical Office (http://www.cso.ie/releasespublications/documents/agriculture/2004/tables1to15.pdf). The census was carried out in June 2000 and covered all farms with at least 1 ha of land. Predictions for future Irish agricultural land-use change were provided by the Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM) project (Rounsevell et al. 2005). The ATEAM project produced Europe-wide agricultural land-use change scenarios for cropland and grassland at a resolution of 10 min. latitude and longitude for the baseline year 2000 and for years 2020, 2050, and 2080. The scenarios were based on an interpretation of the four storylines (A1, A2, B1, and B2) of the SRES using a supply and demand model of agricultural area quantities at the European scale and the disaggregation of these quantities using scenario-specific spatial allocation rules (Rounsevell et al. 2005). The A and B scenarios represent more economically and environmentally and equity orientated futures, respectively (Rounsevell et al. 2005). The 1 and 2 scenarios represent more globally and more regionally orientated developments, respectively (Rounsevell et al. 2005). For this study, land use in baseline year 2000 and in 2020 and in 2050 A1, A2 and B1 scenarios at a resolution of 10 min. latitude and longitude were aggregated to county scale. A decrease in the area under grasslands was predicted for A1, A2, and B1 scenarios in 2020 and 2050 relative to baseline year 2000 (Table 3). The range of change rate was −17.2 to −30.4 % in 2020 and −36.7 to −42.1 % in 2050 relative to 2000.

#### *Nitrogen fertilizer application rate change*

The N fertilizer application rate in the baseline year 2000 was obtained from the N fertilizer application rate surveyed in 2000 at the regional scale (8 regions in Ireland) (Coulter et al. 2002). It was assumed that counties in the same region have the same N application rate. Therefore, the N application rate in a county follows the N application rate of the region of which that county is part. Nitrogen fertilizer use in the baseline year 2000 was calculated by multiplying the N fertilizer application rate in 2000 by the grassland area in

2000. To predict N fertilizer use in 2020 and 2050 it was assumed that the N fertilizer application rate in 2020 and 2050 would be 100 % compliant with regulated N fertilizer application rates as defined by Irish law (SI 378 of 2006). Since SI 378 was newly launched in 2006, and the actual fertilizer application rate at that time was not known, it was estimated as the N fertilizer application rate (at the regional scale) at Rural Environmental Protection Scheme (REPS) farms. These farms comply with Teagasc nutrient advice (Coulter et al. 2002; Humphreys 2008) (equivalent to SI 378 of 2006) and were separately surveyed in 2000 by Coulter et al. (2002). The fertilizer use in 2020 and 2050 was calculated by multiplying the N fertilizer application rate of REPS farms by land-use area of each scenario in 2020 and 2050. The estimated N fertilizer use was divided into monthly N fertilizer use using percentage levels of N use by month in Irish agricultural lands (Coulter and Lalor 2008; S. Lalor, pers. comm.). A decrease in N fertilizer use in grasslands was predicted for A1, A2, and B1 scenarios in 2020 and 2050 relative to baseline year 2000 (Table 3). The ranges of predicted change were −43.5 to −52.6 % in 2020 and −56.8 to −60.5 % in 2050 relative to 2000.

*Climate change*

Predictions for the future Irish air temperature, rainfall and soil water content were derived from the C4I project (Steele-Dunne et al. 2008; Cochrane 2011). The predictions were generated by downscaling the European Centre Hamburg Model Version 5 (ECHAM 5) general circulation model data (Roeckner et al. 2003) using the Rossby Centre Atmosphere Model Version 3 (RCA3) regional climate model. The RCA3 was developed from the High Resolution Limited Area Model (HIRLAM) (http://hirlam.org/) but includes improvements in the radiation and turbulence schemes and in cloud parameterization (Kjellström et al. 2005). Simulations were run at a resolution of 14 km for a reference period 1961–2000 (Wang et al. 2006) and for future periods 2021–2060 and 2060–2099 under the IPCC SRES A1, A2, and B1 scenarios (Nakicenovic et al. 2000). It was suggested that multi-year weather data would produce more reliable estimates of soil $N_2O$ emissions at regional scale (Butterbach-Bahl et al. 2004). Therefore, in this study, averages of 1971–2000, 2021–2030 and 2045–2054 climate scenarios were used to estimate $N_2O$ emission in the baseline year 2000, 2020 (A1, A2, and B1 scenarios), and 2050 (A1, A2, and B1 scenarios), respectively. Monthly averages of air temperature, rainfall and soil water content at a resolution of 14 km were derived from the C4I project and the data were aggregated by county scale (Cochrane 2011). Since monthly soil temperature scenarios were not provided by the C4I project, monthly soil temperature scenarios were estimated using monthly air temperature scenarios provided by the C4I project and monthly differences between observed air temperature and soil temperature in the recent 30 year period (1971–2000) in each county (http://www.met.ie) as below (Eq. 9):

$$\begin{aligned}&\text{Monthly soil temperature scenarios}\\&\quad = \text{monthly air temperature scenarios}\\&\qquad -(\text{observed monthly average air temperature}\\&\qquad\quad -\text{observed monthly average soil temperature})\end{aligned} \tag{9}$$

Bulk density was derived from soil survey results of the SoilC project (Kiely and Carton 2009). In the SoilC project, soil samples were collected at 71 locations throughout Ireland during 2006–2007 and bulk density in grasslands was selected in each county from this database. Water-filled pore space (WFPS) was calculated (Linn and Doran 1984) using soil water content and bulk density. Predicted soil temperature, WFPS, and rainfall derived from C4I project show future common trends throughout the 26 counties in Ireland. Soil temperature increases and WFPS and rainfall decrease in summer but increase in winter in 2020 and 2050 relative to the baseline year 2000. For example, in County Cork, in the south of Ireland, A1, A2, and B1 scenarios in 2020 and 2050 relative to baseline year 2000 predicted that soil temperature would increase by 1.8–3.2 °C and WFPS would decrease 0.3–2.4 % in summer but increase 0.2–0.5 % in winter. Similarly, rainfall would decrease by 4–28.4 mm $month^{-1}$ in summer but increase by 9.9–38.3 mm $month^{-1}$ in winter.

Estimation of $N_2O$ emissions using emission factors and an empirical model

In this study, three different EF methodologies were used to estimate the direct $N_2O$ emissions under different scenarios: IPCC default Tier 1 EF (IPCC 2006); climate- and crop- responsive EFs (CCREFs) (Flynn et al. 2005); and climate sensitive EF (CSEF) (Flechard et al. 2007). In addition, an Irish grasslands nitrous oxide emissions (IGNE) empirical model has been developed during this study.

## Emission factors methodology

First, the IPCC default EF (IPCC 2006) is a fixed value of 1.0 % regardless of climate or crop type.

Second, the CCREF developed by Flynn et al. (2005) was used to estimate direct $N_2O$ emissions from Irish grasslands. The CCREF is an empirical, multiple-regression model based on direct $N_2O$ measurements in Scottish agricultural lands. The model relates direct $N_2O$ emissions to rainfall around the time of fertilizer application and corrects for soil temperature (Flynn et al. 2005). The model requires monthly rainfall and soil temperature data to simulate monthly EF. The footnote to Table 1 in Flynn et al. (2005, p. 1524) gives the equation for 'climate variable EF'. In fact, the equation should have been divided by fertilizer application rate to give the EF as a percentage (K. A. Smith, pers. comm.). The corrected equations are provided below (Eqs. 1 and 2):

$$\mathrm{CCREF}(\%)_{\mathrm{month\ i}} = \frac{\text{climate variable } \mathrm{N_2O} \text{ emission}_{\mathrm{month\ i}}}{\text{fertilizer application rate}_{\mathrm{month\ i}}} \times 100 \quad (1)$$

$$\text{Climate variable } \mathrm{N_2O} \text{ emission}_{\mathrm{month\ i}} = \frac{(51 \times \mathrm{rainfall}_{\mathrm{month\ i}})-615}{1000} \times 2^{\frac{\text{soil temperature}_{\mathrm{month\ i}}-12}{10}} \quad (2)$$

where, CCREF $(\%)_{\mathrm{month}\ i}$ is CCREF (%) in month $i$, fertiliser application $\mathrm{rate}_{\mathrm{month\ i}}$ is a fertilizer application rate in month $i$ (kg N $ha^{-1}$ $month^{-1}$) for cut and grazed grass, rainfall $_{\mathrm{month}\ i}$ is an amount of rainfall in month $i$ (mm $month^{-1}$) and soil temperature $_{\mathrm{month}\ i}$ is an average soil temperature in month $i$ (°C).

Third, the CSEF developed by Flechard et al. (2007) was used to estimate direct $N_2O$ emissions from Irish grasslands. The CSEF is an empirical, multiple-regression model based on direct $N_2O$ measurements for a 3-year period at 10 grass sites in 8 European countries, including Ireland (Flechard et al. 2007). The model requires monthly soil temperature, water-filled pore space (WFPS) and rainfall data to simulate monthly EF. In Flechard et al. (2007, p. 145) Eq. (3) states the equation for 'a bell membership function B (WFPS)'. The equation is misprinted (C. R. Flechard, pers. comm.), and the corrected form of the equation is provided below as Eqs. 3 and 4 with the constants (A, B, C, D) of Eq. 3 provided in Table 1. The constants were derived from Flechard et al. (2007, p. 145):

$$\ln(\mathrm{CSEF}, \%) = A + B \times soil\ T + C \times B(WFPS) + D \times P \quad (3)$$

where, *soil T* is a monthly average soil temperature (°C), $P$ is a monthly rainfall (mm $month^{-1}$), and $B$ is a bell membership function defined as:

$$B(WFPS) = \frac{1}{1 + \left(\frac{WFPS-c}{a}\right)^{2b}} \quad (4)$$

where, *WFPS* is water-filled pore space (%), and parameters $a$, $b$ and $c$ equal 15 %, 3 % and 75 %, respectively.

In this study, since the coefficients in the CSEF (Eq. 3) have a large range, the CSEF was modified to four different models (CSEF I–IV, Eqs. 3 and 4 and Table 1) to reflect the range of coefficients systematically: the medium (medium level in the range of constants), high 50 % (high 50 % level in the range of constants), high 75 % (high 75 % level in the range of constants) and highest (highest level in the range of

**Table 1** Constants of model CSEF and CSEF I, II, III and IV

| Model | Level in the range of constants | A | B | C | D |
|---|---|---|---|---|---|
| CSEF | Whole range | −5.52 (± 1.75) | 0.18 (± 0.10) | 2.40 (± 1.21) | 0.01 (± 0.01) |
| CSEF I | Medium level | −5.52 | 0.18 | 2.4 | 0.01 |
| CSEF II | High 50 % level | −4.65 (−5.52+0.875) | 0.23 (0.18+0.05) | 3.01 (2.40+0.605) | 0.015 (0.01+0.005) |
| CSEF III | High 70 % level | −4.21 (−5.52+1.313) | 0.26 (0.18+0.075) | 3.31 (2.40+0.907) | 0.018 (0.01+0.0075) |
| CSEF IV | Highest level | 3.77 (−5.52+1.75) | 0.28 (0.18+0.10) | 3.61 (2.40+1.21) | 0.02 (0.01+0.01) |

constants) constants were applied in the modified models CSEF I, CSEF II, CSEF III and CSEF IV respectively. It is noted that less than medium-level constants were not used since CSEF with constants in this range produced very low EFs (less than 0.1 %), which has not practically happened (see observed Irish grassland $N_2O$ EF in Table 2).

### Irish grassland nitrous oxide emissions (IGNE) empirical model

In this study, an Irish grasslands nitrous oxide emissions (IGNE) empirical model was newly developed using annual direct $N_2O$ emissions in Irish grasslands, climate factors such as cumulative annual rainfall and annual average soil temperature, and N input reported in referred literature (24 data-set from 5 studies; Table 2). Multiple regressions of variables such as cumulative annual rainfall, annual average soil temperature, soil C and N, and N input with the dependent variable N input-derived annual $N_2O$ emissions (total $N_2O$ emission—background $N_2O$ emission) were performed under the linear, exponential, quadratic and mixed forms using SigmaPlot® ver. 11.0 (Systat Software Inc., San Jose, CA, USA). The results indicated that N input can be a significant variable to predict N input-derived annual $N_2O$ emissions ($P$<0.001), showing a significant exponential relationship (Fig. 1). However, rainfall, soil temperature and soil C and N did not significantly add to the ability to predict annual $N_2O$ emissions ($P$>0.5). Considering the results, the IGNE model was determined as follows (Eq. 5).

$$\text{N input-derived annual } N_2O \text{ emissions} \left(\text{kg N ha}^{-1}\right) = e^{a*N} \left(R^2 = 0.38\right) \quad (5)$$

where, N is N input (kg N $ha^{-1}$), a=0.0057±0.0003 ($P$<0.0001).

The low level (a=0.0057−0.0003=0.0054), medium level (a=0.0057), and high level (a=0.0057+0.0003=0.006) constants were applied in the modified models IGNE I (Eq. 6), IGNE II (Eq. 7), and IGNE III (Eq. 8).

IGNE I (low-level constant)

$$\text{N input-derived annual } N_2O \text{ emissions} = e^{0.0054*N} \quad (6)$$

IGNE II (medium-level constant)

$$\text{N input-derived annual } N_2O \text{ emissions} = e^{0.0057*N} \quad (7)$$

IGNE III (high-level constant)

$$\text{N input-derived annual } N_2O \text{ emissions} = e^{0.006*N} \quad (8)$$

### Estimation of direct $N_2O$ emissions

In this study, direct $N_2O$ emissions in the baseline year 2000, 2020 and 2050 scenarios were determined by IPCC EF, CCREFs, CSEF I–IV, and IGNE I–III. The direct $N_2O$ emissions were determined for each county since the N fertilizer application rate and the agricultural land use in the baseline year 2000 were only available at the county scale. Therefore, the amount of direct $N_2O$ emissions in Irish grasslands reported in this study is a summation of the emissions of all of 26 counties in Ireland.

For the CCREF and the CSEF methods, a three-step process was used to estimate the direct $N_2O$ emission by county. The first step was to determine the monthly N fertilizer use for each county in the baseline year 2000, 2020 and 2050 scenarios (see Nitrogen fertilizer application rate change section, Table 3). The second step was to determine monthly EFs for each county in baseline year 2000, 2020 and 2050 scenarios for the CCREF and CSEF methods using climate data in the baseline year 2000 and for the 2020 and 2050 climate change scenarios. The third step was to calculate the direct $N_2O$ emission in the baseline year 2000, 2020, and 2050 scenarios by multiplying the monthly N fertilizer obtained in the first step by monthly EFs obtained in the second step.

For the IPCC EF method, the yearly N fertilizer use rate (kg N $ha^{-1}$ $y^{-1}$) for each county in the baseline year 2000, 2020 and 2050 scenarios was determined then multiplied by IPCC EF (1 %) to find the total yearly $N_2O$ emissions of each county.

For the IGNE method, the yearly N fertilizer use rate (kg N $ha^{-1}$ $y^{-1}$) for each county in the baseline year 2000, 2020 and 2050 scenarios was used to calculate yearly direct $N_2O$ emissions rates (kg $N_2O$−N $ha^{-1}$ $y^{-1}$) and then multiplied by the grassland area (ha) of the county to find the total yearly $N_2O$ emissions of each county.

t2.1 **Table 2** Observed climate factors, nitrogen (N) input, direct nitrous oxide ($N_2O$) emissions and $N_2O$ emission factor (EF) in Irish grasslands

| | Study site | Measurement periods | Cumulative annual rainfall, mm | Annual average soil temperature, °C | Fertilizer type | Total N-input (A), kg ha$^{-1}$ | Background $N_2O$ emissions (B)[b], kg ha$^{-1}$ | Total $N_2O$ emissions (C), kg ha$^{-1}$ | N input-derived $N_2O$ emissions (C-B), kg ha$^{-1}$ | $N_2O$ EF [(C−B)/A], % | References | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| t2.2 | | | | | | | | | | | | |
| t2.3 | Wexford (52.0 °N, 6.0 °W) | Nov. 2001 – Nov. 2002 | 1209.8[d] | 11.8[d] | Urea, CAN[a] | 279.7 | [c] | [c] | 2.7 | 1.0 | Hyde et al. 2006 | |
| | | | | | | 321.3 | [c] | [c] | 3.2 | 1.0 | | t2.4 |
| | | | | | | 329.6 | [c] | [c] | 0.8 | 0.2 | | t2.5 |
| | | | | | | 429.5 | [c] | [c] | 6.2 | 1.4 | | t2.6 |
| | | | | | | 468.4 | [c] | [c] | 8.9 | 1.9 | | t2.7 |
| | | | | | | 489.2 | [c] | [c] | 10.0 | 2.0 | | t2.8 |
| t2.9 | | Dec. 2002 – Nov. 2003 | 1133.7[d] | 12.2[d] | | 287.2 | [c] | [c] | 14.0 | 4.9 | | |
| | | | | | | 312.0 | [c] | [c] | 11.0 | 3.5 | | t2.10 |
| | | | | | | 311.1 | [c] | [c] | 16.6 | 5.3 | | t2.11 |
| | | | | | | 475.7 | [c] | [c] | 34.4 | 7.2 | | t2.12 |
| | | | | | | 464.7 | [c] | [c] | 16.7 | 3.9 | | t2.13 |
| | | | | | | 538.0 | [c] | [c] | 21.8 | 4.1 | | t2.14 |
| t2.15 | Carlow (52.86 °N, 6.54 °W) | Oct. 2003 – Nov. 2004 | 964.7[d] | 11.1[d] | CAN | 200 | 0.93±0.16[e] | 2.4±0.3[e] | 1.47 | 0.83 | Abdalla et al. 2009 | |
| t2.16 | Cork (52.14 °N, 8.66 °W) | 2003 | 1178.2 | 9.8 | Organic, inorganic fertilizer | 342.8 | [c] | 11.5±2.1[f] | [c] | [c] | Kim et al. 2010 | |
| t2.17 | | 2004 | 1341.0 | 9.8 | | 316.2 | [c] | 6.4±2.4[f] | [c] | [c] | | |
| t2.18 | | 2005 | 1448.6 | 10.0 | | 243.2 | [c] | 4.0±0.8[f] | [c] | [c] | | |
| t2.19 | | 2007 | 1382.6 | 10.1 | | 269.1 | [c] | 4.8±0.7[f] | [c] | [c] | | |
| t2.20 | | 2008 | 1630.5 | 9.9 | | 175.0 | [c] | 2.9±0.6[f] | [c] | [c] | | |
| t2.21 | Cork (51.47 °N, 9.59 °W) | Sep. 2007 – Aug. 2008 | 980.4 | 11.0 | CAN, Organic-N | 153.4 | −1.8±2.0 | 2.0±3.5 | 3.8 | 2.5 | Rafique et al. 2011a | |
| t2.22 | Cork (51.36 °N, 10.17 °W) | Sep. 2007 – Aug. 2008 | 1001.0 | 12.3 | Urea, CAN, Organic-N | 377.5 | 1.2±1.9 | 9.1±2.7 | 7.9 | 2.1 | | |
| t2.23 | Cork (51.58 °N, 10.12 °W) | Sep. 2007 – Aug. 2008 | 1500.3 | 10.2 | Urea, CAN, pasture sward, Organic-N | 404.7 | 2.3±1.6 | 8.1±2.8 | 5.8 | 1.4 | | |
| t2.24 | Cork (51.58 °N, 9.55 °W) | Sep. 2007 – Aug. 2008 | 1220.9 | 10.9 | CAN, Organic-N | 327.7 | 2.5±1.8 | 8.2±2.5 | 5.7 | 1.7 | | |
| t2.25 | Limerick (51.44 °N, 10.17 °W) | Sep. 2007 – Aug. 2008 | 1040.7 | 11.0 | Urea, CAN, sweet grass, Organic-N | 341.1 | 0.8±2.8 | 11.6±3.1 | 10.8 | 3.2 | | |
| t2.26 | Cork (51.37 °N, 9.40 °W) | Sep. 2007 – Aug. 2008 | 960.1 | 11.0 | Urea, CAN, Organic-N | 355.9 | 2.4±2.7 | 9.1±2.9 | 6.7 | 1.9 | | |
| t2.27 | Tipperrary (51.35 °N, 9.43 °W) | Sep. 2007 – Aug. 2008 | 1370.4 | 10.2 | Organic-N | 340.7 | 0.2±2.1 | 4.2±2.6 | 4.0 | 1.2 | | |
| t2.28 | Tipperrary (51.35 °N, 9.38 °W) | Sep. 2007 – Aug. 2008 | 1370.4 | 10.2 | Urea | 121.0 | 1.0±3.1 | 2.7±2.2 | 1.7 | 1.4 | | |

t2.30 **Table 2** (continued)

| | Study site | Measurement periods | Cumulative annual rainfall, mm | Annual average soil temperature, °C | Fertilizer type | Total N-input (A), kg ha$^{-1}$ | Background $N_2O$ emissions (B)[b], kg ha$^{-1}$ | Total $N_2O$ emissions (C), kg ha$^{-1}$ | N input-derived $N_2O$ emissions (C-B), kg ha$^{-1}$ | $N_2O$ EF [(C−B)/A], % | References |
|---|---|---|---|---|---|---|---|---|---|---|---|
| t2.29 | Cork (51.47 °N, 9.59 °W) | Sep. 2008 – Aug. 2009 | 1060.5 | 10.6 | CAN, Organic-N | 232.0 | 0.9±2.4 | 3.3±3.5 | 2.4 | 1.0 | |
| t2.30 | Cork (51.36 °N, 10.17 °W) | Sep. 2008 – Aug. 2009 | 1050.5 | 11.0 | Urea, CAN, Organic-N | 432.2 | 1.7±3.6 | 10.2±3.2 | 8.5 | 2.0 | |
| t2.31 | Cork (51.58 °N, 10.12 °W) | Sep. 2008 – Aug. 2009 | 1580.1 | 9.7 | Urea, CAN, pasture sward, Organic-N | 446.6 | 2.0±2.2 | 7.0±2.4 | 5.0 | 1.1 | |
| t2.32 | Cork (51.58 °N, 9.55 °W) | Sep. 2008 – Aug. 2009 | 1350.4 | 8.5 | CAN, Organic-N | 417.5 | 2.2±3.2 | 12.4±2.8 | 10.2 | 2.4 | |
| t2.33 | Limerick (51.44 °N, 10.17 °W) | Sep. 2008 – Aug. 2009 | 1040.6 | 10.3 | Urea, CAN, sweet grass, Organic-N | 277.2 | 0.8±2.6 | 9.2±2.9 | 8.4 | 3.0 | |
| t2.34 | Cork (51.37 °N, 9.40 °W) | Sep. 2008 – Aug. 2009 | 1100.2 | 10.4 | Urea, CAN, Organic-N | 334.9 | 2.0±1.8 | 8.6±2.7 | 6.4 | 1.9 | |
| t2.35 | Tipperrary (51.35 °N, 9.43 °W) | Sep. 2008 – Aug. 2009 | 1320.6 | 10.3 | Organic-N | 176.5 | 0.5±2.3 | 3.7±3.0 | 3.2 | 1.8 | |
| t2.36 | Tipperrary (51.35 °N, 9.38 °W) | Sep. 2008 – Aug. 2009 | 1320.6 | 10.3 | Urea | 140.6 | 0.3±2.1 | 2.4±1.9 | 2.1 | 1.5 | |

Q2 [a] *CAN* calcium ammonium nitrate

[b] Background $N_2O$ emissions: $N_2O$ emissions from no N fertilizer treatment

[c] No data

[d] Obtained from closest weather stations

[e] Mean ± standard error

[f] Mean ± standard deviation

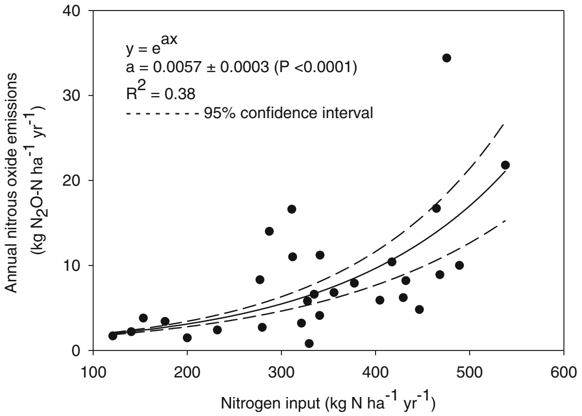


**Fig. 1** Observed relationship between nitrogen (N) input-derived annual direct nitrous oxide ($N_2O$) emission and N input in Irish grasslands ($n$=19) (see detail information in Table 2)

### Determination of contributions of N fertilizer, and land use and climate changes to direct $N_2O$ emission

The contribution of each parameter including N fertilizer, land use and climate change to direct $N_2O$ emissions in 2020 and 2050 was determined. The 2020 and 2050 emissions were determined with CCREFs, CSEF II and IGNE II methodologies under the following three conditions: 1) only N fertilizer application rate changes (no land-use and no climate changes); 2) only land-use changes (no N fertilizer application rate and no climate changes); and 3) only climate changes (no land-use change and no N fertilizer application rate changes). CSEF II and IGNE II were used since the EFs determined by CSEF II (Table 5) are similar to observed ones (Table 2) and IGNE II represents IGNE models showing a relatively narrow range of variation in estimated N2O emissions (Table 6).

### Statistical analysis

The normality of the distribution of the model outputs was analyzed using the Shapiro-Wilk normality test (Shapiro and Wilk 1965). One-way analysis of variance (ANOVA) was used to evaluate the differences in means of determined EFs by month and year. When the standard assumptions of normality were violated, non-parametric Kruskal-Wallis one-way ANOVA on ranks (Kruskal and Wallis 1952) was used. Dunn's test was used for all pairwise comparisons following Kruskal-Wallis one-way ANOVA on ranks. Differences were considered significant at the $P$<0.05 level. These statistical analyses were conducted using SAS® ver. 9.2 (SAS Institute, Cary, NC, USA) and SigmaPlot® ver. 11.0 (Systat Software Inc., San Jose, CA, USA).

## Results

### Predicted EFs and fertilizer-derived $N_2O$ emission in grasslands

*Prediction from IPCC 2006 emission factors*

Through applying agricultural land-use and N fertilizer application rate changes to the IPCC default EF (1 %), a decrease in N fertilizer-derived direct $N_2O$ emission was estimated for A1, A2, and B1 scenarios in 2020 and 2050 relative to 2000 (Table 4). The predicted change rate ranges from −43.5 to −52.6 % in 2020 and from −56.8 to −60.5 % in 2050 relative to 2000.



**Table 3** Area (ha) and nitrogen (N) fertilizer use (tonnes N) in grasslands and their change rates (%) scenarios in Ireland for baseline year 2000 and IPCC A1, A2, and B1 scenarios in 2020 and 2050

| Year | Scenario | Grassland | | N fertilizers | |
|---|---|---|---|---|---|
| | | Area, ha | Change rate, % | Use, t N | Change rate, % |
| 2000 | Baseline | 3 535 443 | – | 365 012 | – |
| 2020 | A1 | 2 456 994 | −30.5 | 173 135 | −52.6 |
| | A2 | 2 928 607 | −17.2 | 206 150 | −43.5 |
| | B1 | 2 928 607 | −17.2 | 206 150 | −43.5 |
| 2050 | A1 | 2 047 651 | −42.1 | 144 085 | −60.5 |
| | A2 | 2 073 907 | −41.3 | 145 935 | −60.0 |
| | B1 | 2 239 333 | −36.7 | 157 589 | −56.8 |

**Table 4** Estimated nitrous oxide ($N_2O$) emission by IPCC default emission factor (EF) (IPCC 2006) and climate- and crop-responsive EF (CCREFs) (Flynn et al. 2005) and change rates of direct $N_2O$ emission (relative to 2000) in grasslands for baseline year 2000 and IPCC A1, A2, and B1 scenarios in 2020 and 2050. It is noticed that the amount of $N_2O$ emitted from Irish grasslands reported in this study is a summation of 26 counties at the county scale

| Year | Scenario | IPCC default EF | | | CCREFs | | |
|---|---|---|---|---|---|---|---|
| | | EF, % | $N_2O$ emission, t $N_2O$–N | Change rate, % | EF, % | $N_2O$ emission, t $N_2O$–N | Change rate, % |
| 2000 | Baseline | 1 | 3650 | – | 5.6±0.4[a] | 31 201 | – |
| 2020 | A1 | 1 | 1731 | −52.6 | 6.1±0.5 | 14 709 | −52.9 |
| | A2 | 1 | 2062 | −43.5 | 6.2±0.6 | 18 401 | −41.0 |
| | B1 | 1 | 2062 | −43.5 | 6.1±0.5 | 18 066 | −42.1 |
| 2050 | A1 | 1 | 1441 | −60.5 | 6.4±0.4 | 12 946 | −58.5 |
| | A2 | 1 | 1459 | −60.0 | 6.7±0.6 | 13 638 | −56.3 |
| | B1 | 1 | 1576 | −56.8 | 6.2±0.6 | 13 823 | −55.7 |

[a] Mean ± standard error

*Prediction from climate- and crop- responsive emission factors (CCREFs)*

Through applying agricultural land-use, N fertilizer application rate and climate changes to CCREFs, it was predicted that EFs will increase but N fertilizer-derived direct $N_2O$ emissions will decrease in Irish grasslands for A1, A2, and B1 scenarios in 2020 and 2050 relative to 2000 (Table 4). The emissions predicted by the CCREF method are about 8 times higher than the default 1 % IPCC values. The predicted EFs show two common temporal trends (Fig. 2). Firstly, on an annual scale, EFs show seasonal variation: EFs in July–September (mean values 8.0–9.0) are significantly (all $P<0.001$) higher than in December–February (4.5–4.6). Secondly, on a decadal scale, EFs in 2020 and 2050 (6.0–6.8) are significantly higher than in 2000 (5.8–6.2) (all $P<0.01$). The predicted change rate of direct $N_2O$ emissions ranges from −41.0 to −52.9 % in 2020 and from −55.7 to −58.5 % in 2050 relative to 2000.



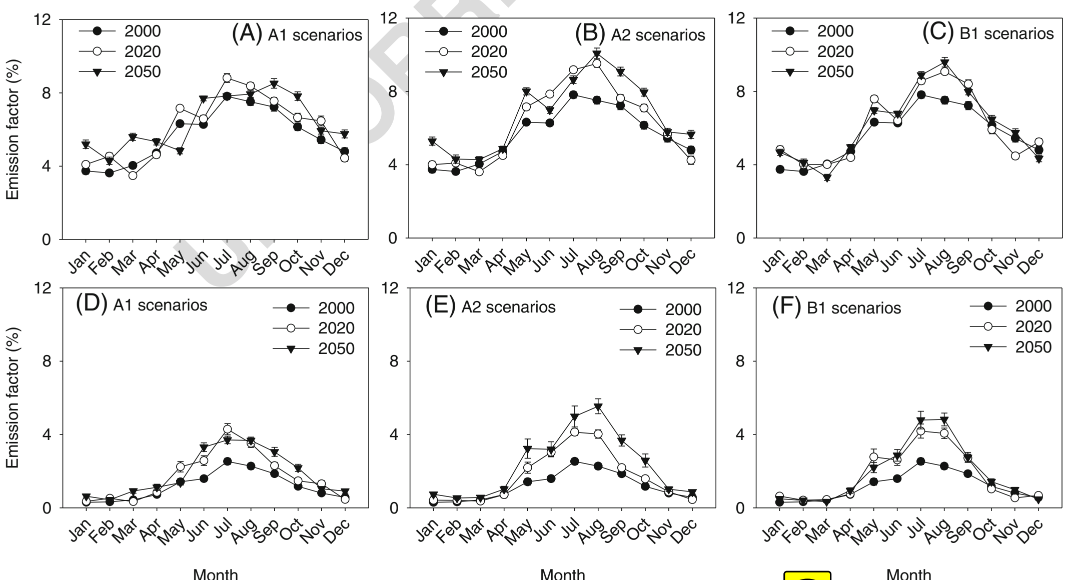


**Fig. 2** Temporal variation of emission factors (EFs) determined by climate- and crop-responsive EFs (CCREFs; Flynn et al. 2005) **(a, b, and c)** and climate sensitive EF (CSEF II, Flechard et al. 2007) **(d, e, and f)** with climate change scenarios in Ireland for the baseline year 2000 and A1, A2, and B1 scenarios in 2020 and 2050

*Prediction from climate sensitive emission factors (CSEFs)*

Through applying agricultural land-use, N fertilizer application rate and climate changes to CSEF I–IV, it was predicted that EFs will increase (Table 5, Fig. 2) but N fertilizer-derived direct $N_2O$ emissions will decrease (Table 5) in Irish grasslands for A1, A2, and B1 scenarios in 2020 and 2050 relative to 2000. As with the results from the CCREFs methodology, the estimated EFs show common temporal trends (high in July–September and low in December–February), and EFs in 2020 and 2050 are higher than the EFs in 2000 (Fig. 2). CSEF I–IV predicts that direct $N_2O$ emissions decrease from 4.8 to 38.8 % by 2020 and from 12.7 to 43.5 % by 2050 relative to 2000 depending on scenarios. For instance, CSEF II predicts that $N_2O$ emissions decrease from 4199 tonnes N in 2000 to 2766–3569 tonnes N in 2020 (a 15.0–34.1 % decrease relative to 2000) and 2541–3122 tonnes N (a 25.6–39.5 % decrease relative to 2000) in 2050.

*Prediction from Irish grasslands nitrous oxide emission (IGNE) model*

Through applying agricultural land-use and N fertilizer application rate change scenarios to IGNE I–III, it was predicted that N fertilizer-derived direct $N_2O$ emissions decrease 32–44 % by 2020 and 48–53 % by 2050 relative to 2000 depending on scenarios (Table 6) (The EFs for this model are not given). For instance, IGNE II predicts that direct $N_2O$ emissions decrease from 6,648 tonnes N in 2000 to 3745–4459 tonnes N in 2020 (a 33–44 % decrease relative to 2000) and 3117–3409 tonnes N (a 49–53 % decrease relative to 2000) in 2050.

Contributions of N fertilizer, land-use, and climate changes to N fertilizer-derived $N_2O$ emission

By applying N fertilizer application rate (land-use and climate remain unchanged), land-use (N fertilizer use and climate remain unchanged) and climate changes (N fertilizer use and land-use remain unchanged) to CCREF and CSEF II and IGNE II, it was found that the changes in N fertilizer application rate and land use tend to decrease the direct $N_2O$ emissions, but climate change tends to increase $N_2O$ emissions, resulting in a net decrease in direct $N_2O$ emissions at both 2020 and 2050 for all scenarios (Table 7). Land-use changes

**Table 5** Estimated nitrous oxide ($N_2O$) emissions by climate sensitive emission factors I–IV (CSEF I–IV) (Flechard et al. 2007) and change rates of direct $N_2O$ emission (relative to baseline year 2000) in Irish grasslands for the baseline year 2000 and IPCC A1, A2, and B1 scenarios in 2020 and 2050. It is noticed that the amount of $N_2O$ emitted from Irish grasslands reported in this study is a summation of 26 counties at the county scale

| Year | Scenario | CSEF I | | | CSEF II | | | CSEF III | | | CSEF IV | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | EF[a] % | $N_2O$ emission, t $N_2O$–N | Change rate, % | EF[a] % | $N_2O$ emission, t $N_2O$–N | Change rate, % | EF[a] % | $N_2O$ emission, t $N_2O$–N | Change rate, % | EF[a] % | $N_2O$ emission, t $N_2O$–N | Change rate, % |
| 2000 | Baseline | 0.13±0.01 | 464 | – | 1.2±0.1 | 4199 | – | 3.6±0.4 | 12 755 | – | 11.0±1.3 | 38 993 | – |
| 2020 | A1 | 0.17±0.01 | 284 | −38.8 | 1.7±0.2 | 2766 | −34.1 | 5.4±0.6 | 8741 | −31.5 | 17.4±2.0 | 27 838 | −28.6 |
| | A2 | 0.17±0.01 | 344 | −25.7 | 1.7±0.1 | 3458 | −17.6 | 5.5±0.5 | 11 102 | −13.0 | 18.0±1.6 | 35 916 | −7.9 |
| | B1 | 0.17±0.01 | 356 | −23.3 | 1.7±0.2 | 3569 | −15.0 | 5.6±0.6 | 11 461 | −10.1 | 18.4±2.4 | 27 838 | −4.8 |
| 2050 | A1 | 0.19±0.01 | 262 | −43.5 | 1.9±0.1 | 2541 | −39.5 | 6.0±0.5 | 7979 | −37.4 | 19.2±1.7 | 25 186 | −35.4 |
| | A2 | 0.2 1±0.02 | 298 | −35.8 | 2.3±0.2 | 3122 | −25.6 | 7.8±0.9 | 10 260 | −19.6 | 26.5±3.6 | 34 048 | −12.7 |
| | B1 | 0.18±0.01 | 282 | −39.2 | 1.9±0.2 | 2828 | −32.6 | 6.1±0.7 | 9084 | −28.8 | 20.2±2.6 | 29 434 | −24.5 |

[a] Mean ± standard error

**Table 6** Estimated direct nitrous oxide ($N_2O$) emissions by Irish grassland $N_2O$ emission model (IGNE I–III; this study) and change rates of $N_2O$ emission (relative to baseline year 2000) in Irish grasslands for the baseline year 2000 and IPCC A1, A2, and B1 scenarios in 2020 and 2050. It is noticed that the amount of $N_2O$ emitted from Irish grasslands reported in this study is a summation of 26 counties at the county scale

| Year | Scenario | IGNE I | | IGNE II | | IGNE III | |
|---|---|---|---|---|---|---|---|
| | | $N_2O$ emission, t $N_2O$–N | Change rate, % | $N_2O$ emission, t $N_2O$–N | Change rate, % | $N_2O$ emission, t $N_2O$–N | Change rate, % |
| 2000 | Baseline | 6431 | – | 6648 | – | 6874 | – |
| 2020 | A1 | 3665 | −43.0 | 3745 | −43.7 | 3827 | −44.3 |
| | A2 | 4363 | −32.2 | 4459 | −32.9 | 4556 | −33.7 |
| | B1 | 4363 | −32.2 | 4459 | −32.9 | 4556 | −33.7 |
| 2050 | A1 | 3050 | −52.6 | 3117 | −53.1 | 3185 | −53.7 |
| | A2 | 3090 | −52.0 | 3157 | −52.5 | 3226 | −53.1 |
| | B1 | 3336 | −48.1 | 3409 | −48.7 | 3486 | −49.3 |

result in direct $N_2O$ emissions changes of −11 to −50 % in 2020 and −20 to −60 % in 2050; climate change produced increases of up to 50 % in 2020 and up to 80 % in 2050, and N fertilizer application rate change reduced emissions by 19.0 and 32.1 % in 2020 and 2050 respectively, relative to 2000.

**Table 7** Change rate (%) of direct nitrous oxide ($N_2O$) emissions from Irish grasslands in 2020 and 2050 relative to baseline year 2000 under only land-use change [nitrogen (N) fertilizer application rate and climate remain unchanged], only climate change (land use and N fertilizer application rate remain unchanged) and only N fertilizer application rate change (land-use and climate changes remain unchanged) scenarios. The emissions were determined by climate- and crop- responsive emission factors (CCREFs) (Flynn et al. 2005), climate sensitive emission factor (CSEF II) (Flechard et al. 2007) and Irish grassland $N_2O$ emission model (IGNE II, this study)

| Methodology | Year | IPCC scenario | Change rate of $N_2O$ emission (%) relative to 2000 | | |
|---|---|---|---|---|---|
| | | | Land-use change | Climate change | N fertilizer application rate change[a] |
| CCREFs | 2020 | A1 | −20.2 | +2.1 | −33.7 |
| | | A2 | −11.4 | +7.6 | |
| | | B1 | −11.4 | +5.5 | |
| | 2050 | A1 | −28.2 | +8.7 | −33.7 |
| | | A2 | −27.5 | +12.3 | |
| | | B1 | −24.4 | +5.5 | |
| CSEF II | 2020 | A1 | −52.6 | +38.6 | −32.1 |
| | | A2 | −43.7 | +46.1 | |
| | | B1 | −44.6 | +49.0 | |
| | 2050 | A1 | −60.8 | +53.9 | −32.1 |
| | | A2 | −60.5 | +82.7 | |
| | | B1 | −56.8 | +55.7 | |
| IGNE II | 2020 | A1 | −30.4 | NA[b] | −19.0 |
| | | A2 | −17.2 | NA | |
| | | B1 | −17.2 | NA | |
| | 2050 | A1 | −42.1 | NA | −19.0 |
| | | A2 | −41.4 | NA | |
| | | B1 | −36.7 | NA | |

[a] Nitrogen fertilizer application rate change has a scenario.

[b] Not available to determine since IGNE models do not include climate factors.

## Discussion

### Predicted $N_2O$ emission factors and N fertilizer-derived direct $N_2O$ emissions in future Irish grasslands

The estimated EFs by CCREF and CSEF II commonly show that EFs in summer (July–September) are higher than the EFs in winter (December–February). The pattern can be explained by the fact that EFs are commonly driven by soil temperature (section Emission factors methodology) and soil temperature is higher in summer than in winter in Ireland (section Study area). They also commonly show that EFs in 2020 and 2050 are higher than the EFs in 2000. This can be explained by the prediction that soil temperature will increase in Ireland in the future (section Climate change).

Estimated EFs (1.2±0.1 %) in 2000 by CSEF II and the IPCC default EF (1 %) are in the lower range of the observed EFs in Irish grasslands (2.6±0.4 %, lower quartile 1.2 %, upper quartile 3.8 %; Table 2). In contrast, estimated EFs (5.6±0.4) by CCREFs in 2000 (Table 4) are above the higher range of those observed EFs in Irish grasslands. Estimated direct $N_2O$ emissions in 2000 by both IPCC default EF and CSEF II are lower than the estimations by IGNE. These results suggest that IPCC EF and CSEF II methodology may underestimate direct $N_2O$ emissions, and CCREFs may overestimate them.

While the different methodologies had a wide range of estimated direct $N_2O$ emissions in the baseline year 2000, they all predicted that the emissions in Irish grasslands would be reduced in 2020 (by 30–50 %) and 2050 (by 40–60 %) relative to 2000. These results are similar to the previous studies conducted in Scotland (Flynn et al. 2005) and Belgium (Roelandt et al. 2007): an average decrease of 63 % in direct $N_2O$ emission by 2080 was predicted in Scottish grasslands (Flynn et al. 2005) and a decrease of 14 % in direct $N_2O$ emission by 2050 was predicted in scenario in agricultural land in Belgium (Roelandt et al. 2007).

### The impact of N fertilizer application rate, land-use and climate changes

In this study, it was found that the reduction in N fertilizer application rate would result in a 19–34 % decrease of direct $N_2O$ emission, if land use and climate remain unchanged. This result is similar to the findings of a previous study (Hsieh et al. 2005) that predicted reduced N fertilizer use in Ireland to comply with the EU Water Quality Directive would decrease direct $N_2O$ emissions. China has implemented a soil testing and fertilizer recommendation program to reduce the over usage of synthetic N fertilizer on cereal crops and it resulted in reduction of direct $N_2O$ production in cereal crops by 241±4 Gg $N_2O$−N in 2001–2008 relative to the means for 1998–2000 (Sun and Huang 2012). These suggest the expected decrease in fertilizer use driven by the implementation of SI 378 of 2006 can substantially contribute to mitigating $N_2O$ emissions. The SI 378 of 2006 was originally set up for the protection of water from pollution caused by nitrates and phosphates from agricultural sources (Department of Environment, Heritage and Local Government 2006). These results therefore suggest that current efforts to manage and optimize N fertilizer use can contribute to the mitigation of $N_2O$ emission as well as to the protection of water resources (Leip et al. 2011; Sun and Huang 2012).

The results of this study show that if N fertilizer application rate and climate remain unchanged, land-use change reduces N fertilizer-derived direct $N_2O$ emission by up to 60 % by 2050 relative to 2000. This indicates that land-use change can also be a factor mitigating direct $N_2O$ emission, which is consistent with previous studies conducted in Scotland (Flynn et al. 2005), Belgium (Roelandt et al. 2007) and the Netherlands (Nol et al. 2011). In Scotland, reductions in agricultural land use have the potential to mitigate the increase of direct $N_2O$ emissions and may even reduce emissions to below current levels (Flynn et al. 2005). Similarly, direct $N_2O$ emissions from Belgian agricultural soils will be markedly affected by changes in agricultural land areas (Roelandt et al. 2007). Furthermore, in our efforts to mitigate GHG emissions it is suggested that land-use management plans should be constructed to prevent any potential problems. Afforestation in abandoned agricultural land can increase C sequestration by vegetation and soil (e.g. Eaton et al. 2008; Laganière et al. 2010). Therefore afforestation in predicted abandoned agricultural land caused by future land-use change may provide opportunities to enhance C sequestration. On the other hand, an increase in abandoned agricultural areas may cause urban sprawl (e.g. Antrop 2004) and the degradation of environmental quality in rural areas (e.g. Tang et al. 2005), which may negatively affect our current efforts to mitigate GHG emissions (Bart 2010).

The results of this study show that climate change can increase direct $N_2O$ emissions from 5 % to 80 % by 2050, depending on applied methodologies and scenarios, since the predicted future climate scenarios commonly include increases in both summer temperatures and winter precipitation in Ireland. This result indicates future climate change can increase direct $N_2O$ emissions and is consistent with the results of previous studies (Flynn et al. 2005; Hsieh et al. 2005; Eckard and Cullen 2011). In south-eastern Australia, climate change scenarios suggest increasing temperatures, declining rainfall and longer dry summer seasons and it was found that direct $N_2O$ emissions will increase in the future projected climate (Eckard and Cullen 2011). In this study, the increase in direct $N_2O$ emissions due to climate change is not large enough to compensate for the decrease in direct $N_2O$ emissions by fertilizer reduction use and land-use changes. However, the large variation of the contribution rate depending on scenarios suggests that the potential impact of climate change on direct $N_2O$ emission should not be ignored.

Uncertainties and further studies

This study shows that climate variable EF and N variable empirical $N_2O$ emission models developed with regionally observed climate factors and direct $N_2O$ emission data are useful for estimating direct $N_2O$ emission and for predicting future emission changes (Flynn et al. 2005; Flechard et al. 2007; Roelandt et al. 2007). It is suggested that region-specific climate variable EF and empirical emission models can be an intermediate methodology for regions where a region-specific process-based model (e.g. DAYCENT, Parton et al. 2001; DNDC, Rafique et al. 2011b) has not been developed (IPCC 2006; Skiba et al. 2012). However, it is recognized that uncertainties exist in the climate variable EF and N variable empirical $N_2O$ emission models used in this study that may affect its results. First, the climate variable EF methodology may have limitations in its ability to estimate direct $N_2O$ emission from N input; it assumes a linear relationship between N input and direct $N_2O$ emission exists in various N managed agricultural areas (e.g. Bouwman 1996). However, there is a growing body of literature showing a nonlinear relationship between N input and direct $N_2O$ emission (e.g. Cardenas et al. 2010; Kim et al. 2013), and the direct $N_2O$ EF was not a constant value but was dependent on N input (e.g. Cardenas et al. 2010; Kim et al. 2013). In Irish grasslands, the annual direct $N_2O$ emission abruptly increased after passing optimal N fertilization rate, and this increase caused a higher ratio of direct $N_2O$ emission to N input (Kim et al. 2010; Rafique et al. 2011a). In this study, a nonlinear exponential relationship was found between N input and direct $N_2O$ emission in Irish grasslands (Fig. 1). The results suggest that the EF methodology may have an uncertainty in its estimation of direct $N_2O$ emissions in N managed soils: underestimation in intensive N input areas and overestimation in extensive N input areas. Also, if N input decreases, the EF methodology may underestimate the mitigated direct $N_2O$ emission since the emissions may decrease in an exponential scale while the methodology estimates the decrease in a linear scale (Millar et al. 2010). In this respect, the newly developed IGNE may be better for estimating direct $N_2O$ emissions since the model considers N application rate when estimating direct $N_2O$ emissions. Second, the climate variable EF and N variable empirical $N_2O$ emission models used in this study may be limited when reflecting the effect of future climate change on direct $N_2O$ emissions. The N variable empirical $N_2O$ emission model IGNE does not include climate variables. While the two climate variable EFs are able to consider climate change, they also have limitations. Climate change models commonly predict increasing episodic events such as long-term droughts following heavy rainfall as well as variations of temperature or precipitation (e.g. Meehl et al. 2007). It has been found that episodic peak $N_2O$ emissions after the rewetting of dry soils significantly affect annual $N_2O$ budgets in agricultural lands (e.g. Kim et al. 2012). In Irish grassland, it was found that large, direct $N_2O$ emission events often follow heavy rainfall after a long dry period (Hyde et al. 2006; Kim et al. 2010; Rafique et al. 2012). Q4 While other studies showed reduced $N_2O$ fluxes during drying periods, the abruptly increased fluxes following rewetting did not compensate for the reduced or nil uptake rates during the dry period at the seasonal scale (Borken and Matzner 2009; Goldberg and Gebauer 2009). The climate variable EF methodology used in this study does not reflect the effect of the episodic events on direct $N_2O$ emission. Therefore, there are uncertainties in the predicted impact of climate change on direct $N_2O$ emission.

In addition, the IGNE model developed in this study did not include climate variables such as rainfall and soil temperature since they did not significantly add to the ability to predict annual $N_2O$ emissions. With newly available Irish $N_2O$ emission data in future, the IGNE model can be assessed and improved to include climate variables. The inclusion of the episodic nature of $N_2O$ emissions in IGNE model can also improve the results. The long term data may also provide a better explanation of the IGNE model and improve the $R^2$ value as shown in Fig. 1.

Furthermore, land use changes into the future may not comply with the ATEAM predictions as Ireland may well become more dependent on agriculture (Department of Agriculture, Fisheries and Food 2011). It is also recognized that the limited number of bulk density data used for CSEF potentially caused uncertainties in the projected $N_2O$ emissions. With newly available data in future, the issue can be assessed and the results will be improved.

Overall, the predicted direct $N_2O$ emission in this study may have certain uncertainties and it is suggested that there is a need for additional studies to understand how direct $N_2O$ emission responds to N input and to develop a new EF methodology to reflect the response. Further studies are also needed to better understand the effect of the episodic climate events (Kim et al. 2012) and timing of fertilizer application (Rees et al. 2013) on direct $N_2O$ emission and to develop EF and emission models reflecting these effects.

## Conclusion

In this study, through applying changes in N fertilizer application rate, land-use and climate scenarios to the IPCC EF, two different climate variable EFs and an Irish grassland $N_2O$ emission empirical model (IGNE), it was found that there were large differences in the predicted absolute level of N fertilizer-derived direct $N_2O$ emissions between methodologies, however the models consistently predicted the direction of change in emissions. N fertilizer-derived direct $N_2O$ emissions were predicted to decrease 30–50 % by 2020 and by 40–60 % by 2050 in Irish agricultural land relative to 2000. While the predicted decrease in N fertilizer application rate reduces direct $N_2O$ emissions by up to 34 %, and land-use change reduces N fertilizer-derived direct $N_2O$ emissions by 20–40 %, climate change increases direct $N_2O$ emission by 5–80 % by 2050. These results indicate that N fertilizer application rate and land-use changes can contribute to the mitigation of direct $N_2O$ emissions, but climate changes may increase direct $N_2O$ emission in a future Irish agricultural landscape. It is suggested that current efforts to manage N fertilizer use can enhance the mitigation of N fertilizer-derived direct $N_2O$ emissions. The results of this study also provide an example of positive feedback on climate change on direct $N_2O$ emissions and it is suggested that further studies are needed to understand the feedback better.

**Acknowledgments** The authors are grateful to Keith Smith and Chris Flechard for their comments on the EF methodologies. We are also grateful to: Nicolas Dendoncker and Mark D. A. Rounsevell for providing data of the ATEAM project; Tido Semmler and Noreen Brennan of Met Eireann for data on the C4I project and Irish weather stations. We appreciate discussions with Mikhail Mishurov, Stan Lalor, James Humphreys, Bernard Hyde, Ute Skiba and Donna Giltrap, and for GIS and computing support from Xianli Xu and Ciaran Lewis and Anne Austin for editing. We acknowledge the support of the Irish Department of Agriculture under Research Stimulus Fund Programme (RSF 06 372) and the Environmental Protection Agency of Ireland under CelticFlux Programme (2001-CC/CD-(5/7)).

## References

Abdalla M, Jones M, Smith P, Williams M (2009) Nitrous oxide fluxes and denitrification sensitivity to temperature in Irish pasture soils. Soil Use Manag 25:376–388. doi:10.1111/j.1475-2743.2009.00237.x

Antrop M (2004) Landscape change and the urbanization process in Europe. Landsc Urban Plan 67:9–26. doi:10.1016/S0169-2046(03)00026-4

Bart IL (2010) Urban sprawl and climate change: a statistical exploration of cause and effect, with policy options for the EU. Land Use Policy 27:283–292

Black K, Byrne KA, Mencuccini M, Tobin B, Nieuwenhuis M, Reidy B et al (2009) Carbon stock and stock changes across a Sitka spruce chronosequence on surface-water gley soils. Forestry 82:255–272 Q6

Bodirsky BL, Popp A, Weindl I, Dietrich JP, Rolinski S, Scheiffele L, Schmitz C, Lotze-Campen H (2012) $N_2O$ emissions from the global agricultural nitrogen cycle – current state and future scenarios. Biogeosciences 9:4169–4197

Borken W, Matzner E (2009) Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. Global Change Biol 15:808–824

Bouwman AF (1996) Direct emission of nitrous oxide from agricultural soils. Nutr Cycl Agroecosyst 46:53–70

Butterbach-Bahl K, Kesik M, Miehle P, Papen H, Li C (2004) Quantifying the regional source strength of N-trace gases across agricultural and forest ecosystems with process based models. Plant Soil 260:311–329. doi:10.1023/B:PLSO.0000030186.81212.fb

Cardenas LM, Thorman R, Ashleee N, Butler M, Chadwick D, Chambers B, Cuttle S, Donovan N, Kingston H, Lane S, Dhanoa MS, Scholefield D (2010) Quantifying annual $N_2O$ emission fluxes from grazed grassland under a range of inorganic fertiliser nitrogen inputs. Agric Ecosyst Environ 136:218–226

Cochrane M (2011) Scenario generation and climate change modelling of nitrous oxide emissions from grasslands in Ireland. M.Sc thesis. Cork Institute of Technology. Cork. Ireland. 153p

Coulter BS, Lalor S (2008) Major and micro nutrient advice for productive agricultural crops. Teagasc, Johnstown Castle

Coulter BS, Murphy WE, Culleton N, Finnerty E, Connolly L (2002) A survey of fertilizer use in 2000 for grassland and arable crops. Teagasc, Johnstown Castle Research Centre, Wexford

Crutzen P (1970) The influence of nitrogen oxides on the atmospheric ozone content. QJR Meteorol Soc 96:320–325

de Klein CAM, Eckard RJ, van der Weerden TJ (2010) Nitrous oxide emissions from the nitrogen cycle in livestock agriculture: estimation and mitigation. In: Smith K (ed) Nitrous Oxide and Climate Change. Earthscan Ltd, London, pp 107–142

Denman KL, Brasseur G, Chidthaisong A, Ciais P, Cox PM et al (2007) Couplings between changes in the climate system and biogeochemistry. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 663–745

Department of Agriculture, Fisheries and Food (2008) Compendium of Irish Agricultural Statistics 2008. Dublin, Ireland. Available at http//www.agriculture.gov.ie/publications/2008/compendiumofirishagriculturalstatistics2008/ (Last Accessed, 01-08-2010)

Department of Agriculture, Fisheries and Food (2011) Food Harvest 2020. Dublin, Ireland. Available at http://www.agriculture.gov.ie/agri-foodindustry/foodharvest2020/ (Last Accessed, 19-02-2012)

Department of Environment, Heritage and Local Government (2006) European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2006. S.I. No. 378 of 2006. The Stationary Office, Dublin, Ireland, 49 pp. Available at http://www.irishstatutebook.ie/2006/en/si/0378.html (Last Accessed, 01-08-2011)

Dunne S, Hanafin J, Lynch P, McGrath R, Nishimura E, Nolan P, et al. (2008) Ireland in a warmer world: Scientific predictions of the Irish climate in the twenty-first century. Community Climate Change Consortium for Ireland (C4I). p.109. Available at http://www.c4i.ie/docs/IrelandinaWarmerWorld.pdf (Last Accessed, 18-01-2011)

Eaton J, McGoff N, Byrne K, Leahy P, Kiely G (2008) Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. Clim Chang 91:317–334. doi:10.1007/s10584-008-9412-2

Eckard RJ, Cullen BR (2011) Impacts of future climate scenarios on nitrous oxide emissions from pasture based dairy systems in south eastern Australia. Anim Feed Sci Technol 166–167:736–748

Environmental Protection Agency (2011) Ireland national inventory report 2011: Greenhouse gas emissions 1990 – 2009 reported to the United Nations framework convention on climate change, Johnstown Castle, Wexford, Ireland. Available at http://coe.epa.ie/ghg/nirdownloads.jsp (Last Accessed, 20-02-2012)

FAOSTAT (2013) Statistics of the Food and Agriculture Organisation of the United Nations. http://faostat.fao.org (Last accessed, 29-03-2013)

Fay D, McGrath D, Zhang C, Carrigg C, O'Flaherty V, Kramers G et al (2007) National soils database. Johnstown Castle Research Centre Wexford, Ireland

Flechard CR, Ambus P, Skiba U, Rees RM, Hensen A, van Amstel A et al (2007) Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe. Agric Ecosyst Environ 121:135–152. doi:10.1016/j.agee.2006.12.024

Flynn HC, Smith J, Smith KA, Wright J, Smith P, Massheder J (2005) Climate- and crop-responsive emission factors significantly alter estimates of current and future nitrous oxide emissions from fertilizer use. Global Change Biol 11:1522–1536. doi:10.1111/j.1365-2486.2005.00998.x

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW et al (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB et al (eds) Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York

Goldberg SD, Gebauer G (2009) Drought turns a Central European Norway spruce forest soil from an $N_2O$ source to a transient $N_2O$ sink. Global Change Biol 15:850–860

Hsieh CI, Leahy P, Kiely G, Li CS (2005) The effect of future climate perturbations on $N_2O$ emissions from a fertilized humid grassland. Nutr Cycl Agroecosyst 73:15–23. doi:10.1007/s10705-005-7129-4

Humphreys J (2008) Nutrient issues on Irish farms and solutions to lower losses. Int J Dairy Technol 61:36–42. doi:10.1111/j.1471-0307.2008.00372.x

Hyde B, Hawkins M, Fanning A, Noonan D, Ryan M, O'Toole P et al (2006) Nitrous oxide emissions from a fertilized and grazed grassland in the South East of Ireland. Nutr Cycl Agroecosyst 75:187–200. doi:10.1007/s10705-006-9026-x

IFADATA (2013) International Fertilizer Industry Association database. http://www.fertilizer.org/ifa/Home-Page/STATISTICS (Last accessed, 29-03-2013)

IPCC (2001) Climate Change 2001: The scientific basis. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X et al (eds) Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, 881 pp Q7

IPCC (2006) IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan

IPCC (2007) Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Kiely G, Carton O (2009) SoilC – Measurement and modelling of soil carbon stocks and stock changes in Irish soils. Datasets Available at http://erc.epa.ie/safer/iso19115/display?isoID=107 (Last Accessed, 01-03-2012)

Kim D-G, Mishurov M, Kiely G (2010) Effect of increased N use and drought on $N_2O$ emission in a fertilized grassland. Nutr Cycl Agroecosyst 88:397–410. doi:10.1007/s10705-010-9365-5

Kim D-G, Vargas R, Bond-Lamberty B, Turetsky MR (2012) Effects of soil rewetting and thawing on soil gas fluxes: a review of current literature and suggestions for future research. Biogeosciences 9:2459–2483

Kim D-G, Hernandez-Ramirez G, Donna G (2013) Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: A meta-analysis. Agric Ecosyst Environ 168:53–65. doi:10.1016/j.agee.2012.02.021

Kjellström E, Bärring L, Gollvik S, Hansson U, Jones C, Samuelsson P, et al. (2005) A 140-year simulation of European climate with the new version of the Rossby Centre regional atmospheric climate model (RCA3). In: SMHI Reports Meteorology and Climatology 108, SMHI, SE–60176. Norrköping, Sweden, 54 pp.

Kruskal W, Wallis W (1952) Use of ranks in one-criterion variance analysis. J Am Stat Assoc 47:583–621

Laganière J, Angers DA, Parè D (2010) Carbon accumulation in agricultural soils after afforestation: a meta-analysis. Global Change Biol 16:439–453

Leip A, Busto M, Winiwarter W (2011) Developing spatially stratified $N_2O$ emission factors for Europe. Environ Pollut 159:3223–3232

Linn D, Doran J (1984) Effect of water–filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Sci Soc Am J 48:1267–1272

Meehl G, Stocker T, Collins W, Friedlingstein P, Gaye A, Gregory J et al (2007) Global Climate Projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB et al (eds) Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge and New York

Millar N, Robertson G, Grace P, Gehl R, Hoben J (2010) Nitrogen fertilizer management for nitrous oxide ($N_2O$) mitigation in intensive corn (Maize) production: an emissions reduction protocol for US Midwest agriculture. Mitig Adapt Strateg Glob Chang 15:185–204. doi:10.1007/s11027-010-9212-7

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S et al (2000) Special Report on Emissions Scenarios. A special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York

Nol L, Verburg PH, Moors EJ (2011) Trends in future $N_2O$ emissions due to land use change. J Environ Manage 94:78–90. doi:10.1016/j.jenvman.2011.1006.1053

Parton WJ, Holland EA, Del Grosso SJ, Hartman MD, Martin RE, Mosier AR et al (2001) Generalized model for NOx and $N_2O$ emissions from soils. J Geophys Res 106:17403–17419. doi:10.1029/2001JD900101

Rafique R, Hennessy D, Kiely G (2011a) Nitrous oxide emission from grazed grassland under different management systems. Ecosystems 14:563–582. doi:10.1007/s10021-011-9434-x

Rafique R, Peichl M, Hennessey D, Kiely G (2011b) Evaluating management effects on nitrous oxide emissions from grasslands using the process based model DNDC. Atmos Environ 45:6029–6039. doi:10.1016/j.atmosenv.2011.07.046

Rafique R, Anex R, Henessy D, Kiely G (2012) What are the impacts of grazing and cutting events on the $N_2O$ dynamics in humid temperate grasslands? Geoderma 181:36–44

Rees RM, Baddeley JA, Bhogal A, Ball BC, Chadwick DR, Macleod M, Lilly A, Pappa VA, Thorman RE, Watson CA, Williams JR (2013) Nitrous oxide mitigation in UK agriculture. Soil Sci Plant Nutr 59:3–15

Roeckner E, Bäuml G, Bonaventura L, Brokopf R, Esch M, Giorgetta M, et al. (2003) The Atmospheric General Circulation Model ECHAM5. Part I: Model description. Max–Planck Institute for Meteorology, Report No. 349, Hamburg, Germany

Roelandt C, van Wesemael B, Rounsevell M (2005) Estimating annual $N_2O$ emissions from agricultural soils in temperate climates. Global Change Biol 11:1701–1711. doi:10.1111/j.1365-2486.2005.01025.x

Roelandt C, Dendoncker N, Rounsevell M, Perrin D, Van Wesemael B (2007) Projecting future $N_2O$ emissions from agricultural soils in Belgium. Global Change Biol 13:18–27. doi:10.1111/j.1365-2486.2006.01273.x

Rounsevell MDA, Ewert F, Reginster I, Leemans R, Carter TR (2005) Future scenarios of European agricultural land use II: projecting changes in cropland and grassland. Agric Ecosyst Environ 107:117–135. doi:10.1016/j.agee.2004.12.002

Shapiro SS, Wilk MB (1965) An analysis of variance test for normality (complete samples). Biometrika 52:591–611. doi:10.1093/biomet/52.3-4.591

Skiba U, Jones SK, Dragosits U, Drewer J, Fowler D, Rees RM, Pappa VA, Cardenas L, Chadwick D, Yamulki S, Manning AJ (2012) UK emissions of the greenhouse gas nitrous oxide. Phil Trans R Soc B 367:1175–1185

Steele-Dunne S, Lynch P, McGrath R, Semmler T, Wang SY, Hanafin J et al (2008) The impacts of climate change on hydrology in Ireland. J Hydrol 356:28–45. doi:10.1016/j.jhydrol.2008.03.025

Sun W, Huang Y (2012) Synthetic fertilizer management for China's cereal crops has reduced $N_2O$ emissions since the early 2000s. Environ Pollul 160:24–27

Tang Z, Engel B, Pijanowski B, Lim K (2005) Forecasting land use change and its environmental impact at a watershed scale. J Environ Manage 76:35–45. doi:10.1016/j.jenvman.2005.01.006

The Irish Meteorological Service (2013) Climate of Ireland. http://www.met.ie/climate/climate-of-ireland.asp (Last accessed, 29-03-2013).

Wang W, Yung Y, Lacis A, Mo T, Hansen J (1976) Greenhouse effects due to man-mad perturbations of trace gases. Science 194:685–690

Wang S, McGrath R, Semmler T, Sweeney C (2006) Validation of simulated precipitation patterns over Ireland for the period 1961–2000. Int J Climatol 26:251–266. doi:10.1002/joc.1246

# AUTHOR'S PROOF

## AUTHOR QUERIES

**AUTHOR PLEASE ANSWER ALL QUERIES.**

Q1. "IPCC 1996" is cited in text but not given in the reference list. Please provide details in the list or delete the citation from the text.
Q2. Please check table footer presentation in Tables 2, 4, 5, 7 if correct.
Q3. Section citation "N fertilizer application rate change" was changed to "Nitrogen fertilizer application rate change". Please check if correct.
Q4. The citation "Rafique et al. 2012c" (original) has been changed to "Rafique et al. 2012". Please check if appropriate.
Q5. Please provide complete bibliographic details for references (Kjellström et al. 2005; Roeckner et al. 2003).
Q6. Black et al. (2009) was not cited anywhere in the text. Please provide a citation. Alternatively, delete the item from the list.
Q7. IPCC (2001) was not cited anywhere in the text. Please provide a citation. Alternatively, delete the item from the list.
Q8. Please check equations if captured and presented correctly.