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Testing DayCent and DNDC model simulations of N_2O fluxes and assessing the impacts of climate change on the gas flux and biomass production from a humid pasture

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ABSTRACT

Simulation models are one of the approaches used to investigate greenhouse gas emissions and potential effects of global warming on terrestrial ecosystems. DayCent which is the daily time-step version of the CENTURY biogeochemical model, and DNDC (the DeNitrification–DeComposition model) were tested against observed nitrous oxide flux data from a field experiment on cut and extensively grazed pasture located at the Teagasc Oak Park Research Centre, Co. Carlow, Ireland. The soil was classified as a free draining sandy clay loam soil with a pH of 7.3 and a mean organic carbon and nitrogen content at 0–20 cm of 38 and 4.4 g kg^{-1} dry soil, respectively. The aims of this study were to validate DayCent and DNDC models for estimating N_2O emissions from fertilized humid pasture, and to investigate the impacts of future climate change on N_2O fluxes and biomass production. Measurements of N_2O flux were carried out from November 2003 to November 2004 using static chambers. Three climate scenarios, a baseline of measured climatic data from the weather station at Carlow, and high and low temperature sensitivity scenarios predicted by the Community Climate Change Consortium For Ireland (C4I) based on the Hadley Centre Global Climate Model ($HadCM_3$) and the Intergovernment Panel on Climate Change (IPCC) A1B emission scenario were investigated. DayCent predicted cumulative N_2O flux and biomass production under fertilized grass with relative deviations of +38% and (−23%) from the measured, respectively. However, DayCent performs poorly under the control plots, with flux relative deviation of (−57%) from the measured. Comparison between simulated and measured flux suggests that both DayCent model's response to N fertilizer and simulated background flux need to be adjusted. DNDC overestimated the measured flux with relative deviations of +132 and +258% due to overestimation of the effects of SOC. DayCent, though requiring some calibration for Irish conditions, simulated N_2O fluxes more consistently than did DNDC. We used DayCent to estimate future fluxes of N_2O from this field. No significant differences were found between cumulative N_2O flux under climate change and baseline conditions. However, above-ground grass biomass was significantly increased from the baseline of 33 t ha^{-1} to 45 (+34%) and 50 (+48%) t dry matter ha^{-1} for the low and high temperature sensitivity scenario respectively. The increase in above-ground grass biomass was mainly due to the overall effects of high precipitation, temperature and CO_2 concentration. Our results indicate that because of high N demand by the vigorously growing grass, cumulative N_2O flux is not projected to increase significantly under climate change, unless more N is applied. This was observed for both the high and low temperature sensitivity scenarios.

1. Introduction

Nitrous Oxide (N_2O), on a kg to kg basis, has a global warming potential of approximately 298–310 times that of carbon dioxide (CO_2) over a 100 year timescale (Watson et al., 1996; IPCC, 2007) with an atmospheric lifetime of approximately 120 years (Prather, 1998). The concentration of N_2O in the atmosphere has

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risen from a pre-industrial level of about 270 ppb–319 ppb in 2005, and is estimated to be rising at a rate of 0.8 ppb per annum (IPCC, 2007). According to the IPCC (2001, 2007) N_2O is responsible for about 6% of the anthropogenic component of radiative forcing.

The complex interaction of microbiological processes and soil conditions, such as water content, carbon (C) and nitrogen (N) content, temperature and pH regulates N_2O dynamics in the soil profile, and determines how and when N_2O is released from the soil surface (Granli and Bockman, 1994). Management practices such as soil tillage, crop type, and the application of nitrogen fertilizers influence the physical and hydrological condition of the soil and the timing and distribution of nutrient inputs. This in turn affects the size, composition and activity of the soil microbial population, and therefore, the extent of N_2O production and emission from agricultural soils.

Worldwide, agricultural soils, particularly grazed pastures, are the major single source of N_2O emissions contributing approximately 46–52% of the global anthropogenic N_2O flux (Mosier et al., 1998; Olivier et al., 1998; Kroeze et al., 1999; IPCC, 2007). In Europe, grasslands are the major contributor to the exchange of greenhouse gases in the biosphere, with fluxes intimately linked to management practices. In Europe, about 40% of the agricultural area is covered by permanent grassland used for livestock farming (FAO, 2004). Grasslands range from intensively fertilized pure grass swards to extensively managed grass-legume mixtures and semi-natural grasslands, which are often found in mountainous areas or on moist lowland soils (FAO, 2004). In Ireland, about 80% of the agricultural area and 58% of the total land area is grassland (Teagasc, 2010; CSO Census of Agriculture, 2010). This includes grazed pasture, silage, hay meadows and rough grazing areas.

Changes in the exchange of greenhouse gases between grassland ecosystems and the atmosphere may significantly impact on global climate change. Consequently, the increase in global mean annual temperature, predicted to be 1.5–4.5 °C over the next 50–100 years, will dramatically affect terrestrial ecosystems (IPCC, 2007). Most biological and chemical soil processes are strongly dependent on temperature (Shaver et al., 2000) including decomposition (Shaw and Harte, 2001), N mineralization and nitrification (Stark and Firestone, 1996), nutrients uptake (BassiriRad, 2000), and consequently emissions of CO_2, N_2O and methane (CH_4) (Malhi et al., 1990; Raich and Schlesinger, 1992; Abdalla et al., 2009a) respond to temperature.

The DayCent (Daily Century) and DNDC (DeNitrification-DeComposition) models are two widely-used ecosystem biogeochemistry models used to estimate greenhouse gas emissions. The DayCent model is the daily time-step version of the CENTURY biogeochemical model (Parton et al., 1994). Comparison of model results and observed data have shown that DayCent reliably simulates crop yield, SOM levels, and trace-gas flux for various native and managed systems (Del Grosso et al., 2002, 2009). The DNDC model was developed to assess N_2O, NO, N_2 and CO_2 emissions from agricultural soils (Li et al., 1992; Li, 2000). The rainfall driven process-based model DNDC (Li et al., 1992) was originally developed for USA conditions. It has been used for simulation at a regional scale for the United States (Li et al., 1996), China (Li et al., 2001), Canada (Smith et al., 2010) and Europe (Kesik et al., 2006). This study is part of an ongoing research programme to measure and model N_2O flux from Irish agriculture (Abdalla et al., 2009a,b,c). The aims of this study were to validate the DayCent and DNDC models for estimating N_2O emissions from fertilized humid grassland in the midlands of Ireland, and to investigate the effect of future climate change on N_2O fluxes and biomass production.

2. Materials and methods

2.1. Field experimental site

A detailed description of the study site can be found in Abdalla et al. (2009a,b). It is located at the Oak Park Research Centre in Carlow 52°86′N and 6°54′W, Ireland. The site area (≈7 ha) has an elevation of 56 m a.s.l, a mean annual rainfall of 824 mm and a mean annual air temperature of 9.4 °C. The soil is classified as a sandy clay loam with a pH of 7.3 and a mean organic carbon and nitrogen content at 0–20 cm of 38, and 4.4 g kg^{-1} dry soil, respectively. The pasture has been permanent grassland for at least the last 80 years, but was ploughed and reseeded in October 2001 with perennial ryegrass (*Lolium perenne L., cv Cashel*) at a density of 13.5 kg ha^{-1} and white clover (*Trifolium repens L., cv Aran*) at a density of 3.4 kg ha^{-1}.

Silage cutting took place once during the experimental period on 15th May 2004 and extensive cattle grazing was from July to November 2003, and then from July to November 2004 with a stocking rate of 2 cattle ha^{-1}. Nitrogen in the form of calcium ammonium nitrate (CAN) was applied at a rate of 200 kg N ha^{-1} y^{-1} in two applications of 128 and 72 kg N ha^{-1} on the 2nd of April and 27th of May 2004, respectively. Grazing and cutting took place on the whole field for both the control and the fertilized plots. Nitrous oxide fluxes were measured from four replicated chambers on the control plots and four replicated chambers on the fertilized plots.

2.2. Field N_2O fluxes and grass biomass

Measurements of N_2O flux were carried out from November 2003 to November 2004. Nitrous oxide fluxes were measured using the methodology of Smith et al. (1995). Large chambers were made from steel and painted with white paint on the outside and black paint on the inside to prevent interior heating. Chambers consisted of two parts: a 52 × 52 × 15 cm^3 square collar inserted permanently into the soil over which a 50 × 50 × 30 cm^3 lid with a plastic septum could be sealed in place for gas sample collection. To reduce spatial variation caused by excreta patches, we chose a part of the field which was deemed to be representative of the whole field, and used four replicated large static chambers that covered 0.25 m^2 at a distance of 100 m apart. Previous studies on grassland fields of similar size used 3–4 replicated chambers to measure N_2O fluxes (Flechard et al., 2007; Allard et al., 2007).

After the lids were in place an initial gas sample was taken and a second was taken at 60 min. Linearity was checked by sampling each half an hour for a closure period of 3 h. In order to cover most of the year we sampled every week, and more intensively (twice a week) following fertilizer application. Previous studies of N_2O fluxes using static chambers have sampled at frequencies ranging from one hour to two weeks (Mogge et al., 1999; Choudhary et al., 2002; Simek et al., 2004; Flechard et al., 2007). Samples were taken in the morning between 9 and 11 am. Samples were taken using a 60 ml gas-tight syringe after flushing of the syringe 3–4 times in the chamber to ensure adequate mixing of air within the chamber. All 60 ml of the sample was then injected into a 3 ml gas-tight vial with a vent needle inserted into the top of the vial to allow the extra air flush out. N_2O concentrations were measured using a gas chromatograph (Shimadzu GC 14B, Kyoto, Japan) with electron capture detection (column and detector temperatures were 30 and 300 °C respectively). The nitrous oxide standard was a 1 +/− 0.02 ppm N_2O in synthetic air. A calibration series was made by proportional dilution of the standard with pure N_2. The daily flux rate for each chamber and the average daily flux rate for the four replicates were calculated using the closed flux chamber technique equation (Smith et al., 1995; Baggs et al., 2003). Above-ground biomass samples were harvested each 1–2 weeks from four circular rings of 50 cm diameter.

2.3. Models descriptions

The DayCent model is the daily time-step version of the CENTURY (Parton et al., 1994) biogeochemical model. DayCent (Del Grosso et al., 2001; Parton et al., 1998) simulates fluxes of C and N between the atmosphere, vegetation, and soil. Plant growth is controlled by nutrient availability, water, and temperature. Nutrient supply is a function of soil organic matter (SOM) decomposition and external nutrient additions. Daily maximum/minimum temperature and precipitation, timing and description of management events and soil texture data are needed as model inputs. Key sub-models include plant production, SOM decomposition, soil water and temperature by layer, nitrification and denitrification, and CH_4 oxidation. Comparison of model results and plot data has shown that DayCent reliably simulates crop yield, SOM levels, and trace gases (Li et al., 2005; Del Grosso et al., 2009).

In this study the DNDC model (version 8.9; http://www.dndc.sr.unh.edu/) was applied. DNDC contains four main sub-models (Li et al., 1992; Li, 2000); the soil climate sub-model calculates hourly and daily soil temperature and moisture fluxes in one dimension, the crop growth sub-model simulates crop biomass accumulation and partitioning, the decomposition sub-model calculates decomposition, nitrification, NH_3 volatilization and CO_2 production, whilst the denitrification sub-model tracks the sequential biochemical reduction from nitrate (NO_3) to NO_2^-, NO, N_2O and N_2 based on soil redox potential and dissolved organic carbon.

Measured values of meteorological parameters and land management records were used as input variables to the DayCent and DNDC models (Abdalla et al., 2009a). Field N_2O flux data were used for DayCent and DNDC models validations by comparing measured and predicted N_2O fluxes. The models accuracies were evaluated by calculating the Root Mean Square Error (RMSE) and relative deviation (RD) between observed and DayCent/DNDC outputs.

$$\text{RMSE} = \left(\sum(\text{modelled} - \text{observed})^2/N\right)^{1/2} \quad (1)$$

$$\text{RD} = (\text{modelled} - \text{observed})/\text{observed} \times 100 \quad (2)$$

where N is the number of data series. Annual cumulative flux for models outputs were calculated as the sum of simulated daily fluxes (Cai et al., 2003). Soil properties and climate input data of both models are summarized in Table 1.

2.4. Climate scenarios

The future climate data used in this research were statistically downscaled by the Irish National Meteorological Service Research Group (C4I, 2008) based on the Hadley Centre Global Climate Model ($HadCM_3$) and the emission scenario (A1B) published by the Intergovernmental Panel on Climate Change (Nakicenovic and Swart, 2000; IPCC, 2001). Two different temperature sensitivity scenarios (high and low) were investigated to estimate the uncertainty in future climate (Collins et al., 2006). A regional climate model, known as RCA_3, was applied to the $HadCM_3$ data in a process which is known as dynamic downscaling. RCA_3 is based on a model initially developed by the Rossby Centre and further developed by the C4I project at Met Éireann. The resultant model data has a horizontal resolution of 25 km. A full description is given in the C4I (2008) report.

Table 1
DayCent/DNDC models input data for the pasture field.

Climate data	
Latitude (degree)	52°86′N
Yearly maximum of average daily temperature (°C)	13.3 (baseline), 15.2 (high scenario) and 12 (low scenario
Yearly minimum of average daily temperature (°C)	5.4 (baseline), 10.3 (high scenario) and 7 (low scenario)
Yearly accumulated precipitation (mm).	794 (baseline), 1472 (high scenario) and 1407 (low scenario)
N concentration in rainfall (mg N l^{-1})	0.001[a]
Atmospheric CO_2 concentrations (ppm)	350[a] (baseline) and 700[a] (future scenarios)
Soil properties (0–10 cm depth)	
Vegetation type	Moist pasture
Soil texture	Sandy clay loam
Bulk density (g cm^{-3})	1.0
Clay fraction	0.34[a]
Soil pH	7.3
Initial organic C content at surface soil (kg C kg^{-1})	0.038
Harvest	Grazing/cutting
WFPS at field capacity	0.87
WFPS at wilting point	0.09
Depth of water-retention layer (cm)	100[a]
Slope (%)	0.0

[a] Default values.

The baseline scenario is a measured daily climate data set (1961–1990) from a nearby weather station in Carlow. The two future climate scenarios (high and low temperature sensitivity) investigated in this study are of daily data and for a period of 30 years (2061–2090) from the $HadCM_4$. Weather input data are maximum and minimum air temperature and precipitation. CO_2 concentrations of 350 and 700 ppmv were suggested and used in the models for the baseline and future scenarios, respectively (IPCC, 1995).

2.5. Statistical analysis

Statistical analyses were carried out using the PRISM (GraphPad, San Diego, USA) and Data Desk (Data Description Inc. New York, USA) software packages. Flux data was checked for normal distribution and log transformed. Regression analysis and both 1- and 2-way analyses of variance (ANOVA) were applied to N_2O flux and biomass production.

3. Results and discussion

3.1. Model validations and results under baseline scenario

Temporal patterns of N_2O for the observed and DayCent modelled fluxes from the fertilized plots were generally similar for most of the measured period. However, DayCent overestimated the influence of added N fertilizer by producing two types of N_2O peaks; a smaller one at the time of N application and a higher one later in August, 2004 (Fig. 1). This second higher peak was not observed for the control plots. Here, as both the fertilized and control plots were subjected to the same climate and extensively grazed, it was clear that N availability in the soil was the only difference between the two, suggesting that this later peak was due to residual effects of applied N fertilizer. The model suggests that applied fertilizer N is retained in the soil for long periods (up to September), where other environmental factors like rainfall and temperature are high (Fig. 2), resulting in a second higher N_2O peak

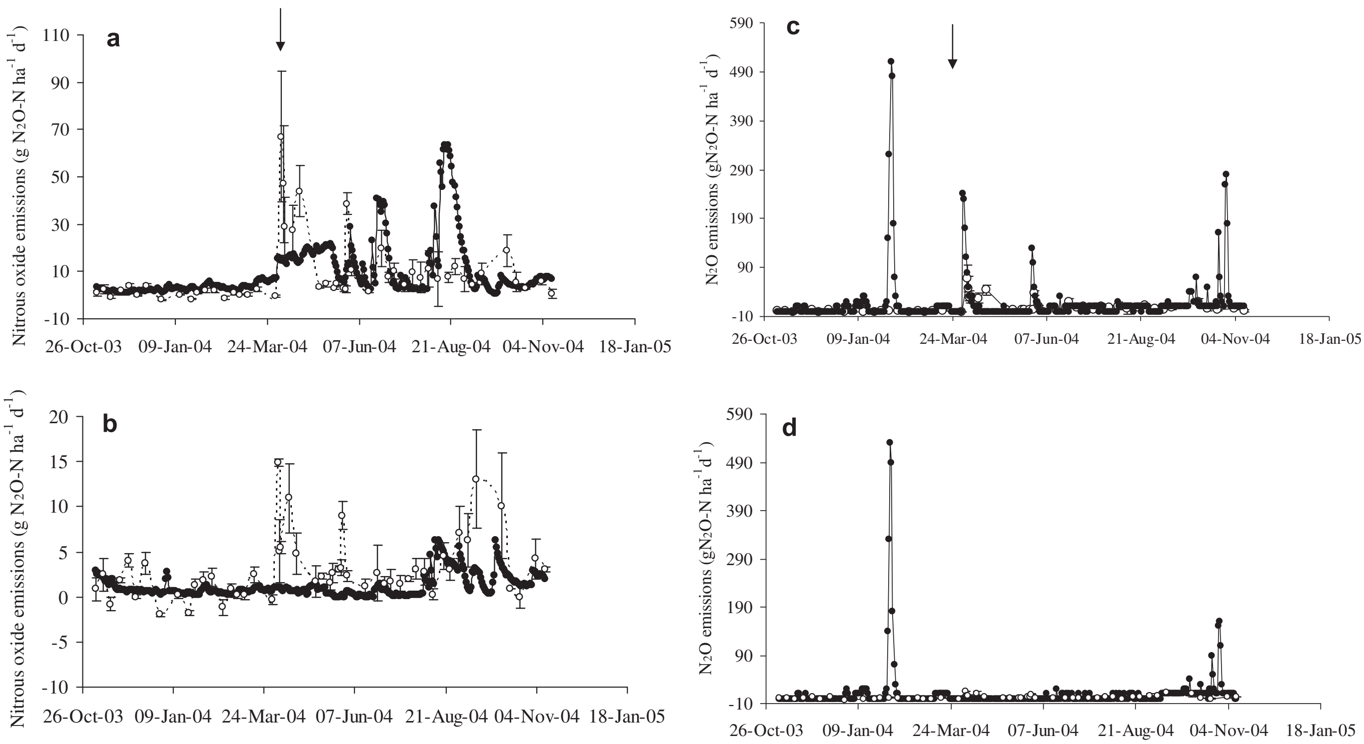

Fig. 1. Comparisons of DayCent (a and b) and DNDC (c and d) model-simulated (●) and field measured (○) N_2O fluxes from the fertilized (a and c) and control (b and d) pasture treatments in 2003/2004. (Error bars for measured values are ± standard error.) Arrow show time of fertilizer application.

(Fig. 1). Comparisons over many years showed that the height and time of this later peak depends on the combined effects of higher rainfall and temperature (Fig. 2). Rainfall increases soil moisture and stimulates denitrification by temporarily reducing the oxygen diffusion into the soil (Dobbie and Smith, 2001) and increasing the solubility of organic carbon and nitrate in the soil (Bowden and Bormann, 1986). High temperature increases both soil organic matter decomposition and microbial response to other perturbations, such as fertilization and rainfall (Stanford and Epstein, 1974; Bramley and White, 1990; Antonopoulos, 1999; Wennman and Katterer, 2006). The model also overestimated the measured soil water filled pore space values (WFPS; Fig. 3). This overestimation may result in significant flux discrepancies between the measured and modelled data since WFPS is a critical determinant of N_2O flux (Keller and Reiners, 1994; Ruser et al., 1998; Dobbie and Smith, 2001). This parameter is a key requirement for a reliable simulation of N_2O (Frolking et al., 1998), as increasing WFPS may reduce the contribution of nitrification, and increase denitrification (Li, 2000; Li et al., 2001).

The second simulated peak resulted in a higher cumulative N_2O flux of 3.6 kg ha^{-1} compared with the measured flux of 2.6 kg ha^{-1}, which corresponds to a relative deviation of +38% from the measured flux (Table 2). The regression between observed and modelled fluxes ($y = 0.41x + 0.57$) accounted for 32% of the variation in the data (RMSE = 2) (Fig. 4). However, by excluding this peak, the model gave approximately similar cumulative N_2O flux to that observed, with a deviation of only +1%. This is not the case for the control plots where, although this second peak was not observed, the model performed poorly compared to observed data with a relative deviation of (−57%) RMSE = 0.5 (Table 2 and Fig. 1). In contrast to Del Grosso et al. (2008), DayCent underestimated the flux at zero N fertilizer with a cumulative flux of 0.5 kg ha^{-1} compared with a cumulative measured flux of 1 kg ha^{-1}. The comparison with field data suggests that, for applications on unfertilised Irish grasslands, DayCent could be improved by increasing the background emissions of N_2O (Del Grosso et al., 2008).

The pattern of simulated grass biomass by the DayCent model agreed well with the measured results and the model underestimated observed biomass by (−23%). The relationship between the weekly simulated above-ground grass biomass and the weekly field observed biomass is illustrated in Fig. 5. Here, the regression ($y = 0.47x + 0.5$) accounted for 38% of the variation in the data (RMSE = 0.15). Comparable results using DayCent were also reported for wheat, rice, maize and soybean (Stehfest et al., 2007; Del Grosso et al., 2008). Simulated soil temperature by DayCent and DNDC compared favourably with measurements (Fig. 6); for DayCent $r^2 = 0.64$ and RMSE = 0.57 whilst for DNDC $r^2 = 0.88$ and RMSE = 0.44.

Simulated emissions of N_2O flux by the DNDC model showed similar patterns as the field measured flux for most of the measured period. However, DNDC predicted a significantly higher peak, from both the fertilized and control plots in February. This higher peak resulted in an annual cumulative N_2O flux of 6.04 and 3.58 kg N_2O–N ha^{-1}, with annual differences between the measured and modelled flux of 3.44 and 2.58 kg N_2O–N ha^{-1}, for fertilized and control plots respectively (Table 2 and Fig. 1). Due to this peak, estimation of annual emissions was very poor with relative deviations of +132% (RMSE = 5.2; for fertilized plots) and +258% (RMSE = 4; for the control plots) from the measured flux. DNDC also significantly underestimated the observed above-ground biomass by 75% (RMSE = 0.22) (Fig. 5). The model (DNDC) is very sensitive to soil organic carbon content (SOC; Li et al., 1996, 2001; Beheydt et al., 2007; Abdalla et al., 2009a); a 20% increase in SOC corresponds to a 58% increase in N_2O flux (Abdalla et al., 2009a). Similar overestimates of the effects of initial SOC by DNDC have also been reported by Li et al. (1992), Brown et al. (2002) and Hsieh et al. (2005). DNDC also significantly overestimates observed

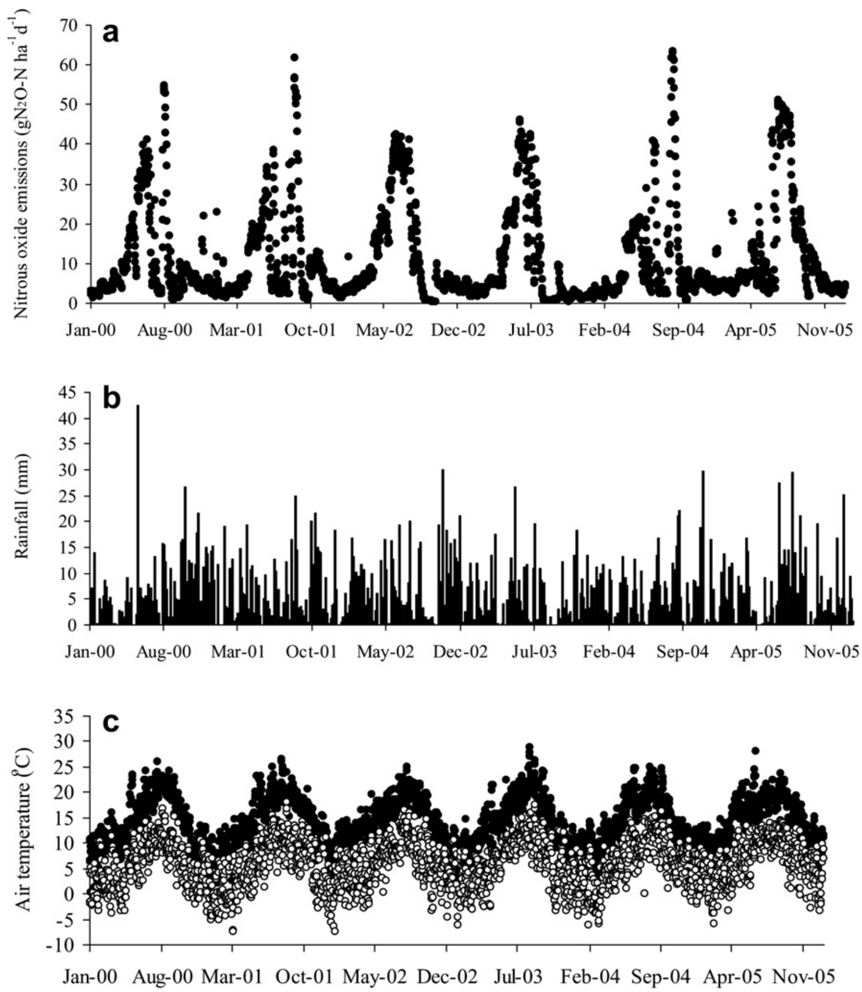

Fig. 2. Simulated nitrous oxide fluxes (a), measured precipitation (b) and maximum (●) and minimum (○) temperature (c) during 2000–2005.

WFPS (Fig. 3), leading to a higher than observed predicted flux (Beheydt et al., 2007; Abdalla et al., 2009a).

Although the DayCent model needs to be better parameterised for application in Irish grasslands, both cumulative total N_2O emission, and the general pattern of emissions agree quite well with measured data, and were better than equivalent estimates from the DNDC model, which significantly overestimated the observed flux and underestimated the observed biomass. Improving the parameterisation of DayCent for Irish grasslands will make the model a useful tool for testing different mitigation scenarios, and will enhance the quality of the reporting to the United Nations Framework Convention on Climate Change (UNFCCC) through use of an IPCC tier 3 methodology (IPCC, 2006). In this study, depending on the results of model validations, we considered that using DayCent for estimating the magnitude and seasonal trends of N_2O fluxes and above-ground biomass was more suitable than DNDC.

3.2. Model results under climate change scenarios

Because the DNDC model significantly overestimated observed N_2O fluxes and significantly underestimated observed above-ground biomass, the impacts of future climate change were investigated using the DayCent model only. Two climate scenarios from the C4I, low and high temperature sensitivity, to provide the highest and lowest impacts of climate change, were investigated. For each scenario, the DayCent model was run for a period of 30 years. Simulated patterns of N_2O fluxes, under both scenarios, were similar to that at the baseline scenario during most of the year (Table 3; Fig. 7). Here, average height of the first peak at baseline was approximately similar to that of 2004 but, under climate change scenarios, DayCent predicted a significant increase for this peak. The reason was the higher temperature and rainfall, expected due to climate change during fertilizer application, compared with the baseline. The average height for the second peak at baseline was decreased because time for this peak was different from one year to another. However, under climate change, the second peak disappeared, mainly due to the decrease in available N later in the season. No statistically significant difference ($p > 0.05$) between the annual cumulative fluxes for the three scenarios was found. Under climate change, the high temperature sensitivity scenario produced slightly higher cumulative nitrous oxide fluxes (4.4 kg ha^{-1}) whilst the low temperature sensitivity scenario produced slightly lower cumulative nitrous oxide fluxes (4.1 kg ha^{-1}) compared with the baseline fluxes (4.2 kg ha^{-1}). This is different from the significant increases in N_2O flux predicted for a nearby cropland field, using DNDC, where climate change was projected to increase the flux by 55–88% depending on the N fertilizer application rate. However, in the cropland field, most of the fluxes took place during the post crop harvesting period, where straw was incorporated and no crops were present (Abdalla et al., 2009c).

For both future scenarios, predicted biomass production was significantly higher ($p < 0.05$) than in the baseline (Fig. 8).

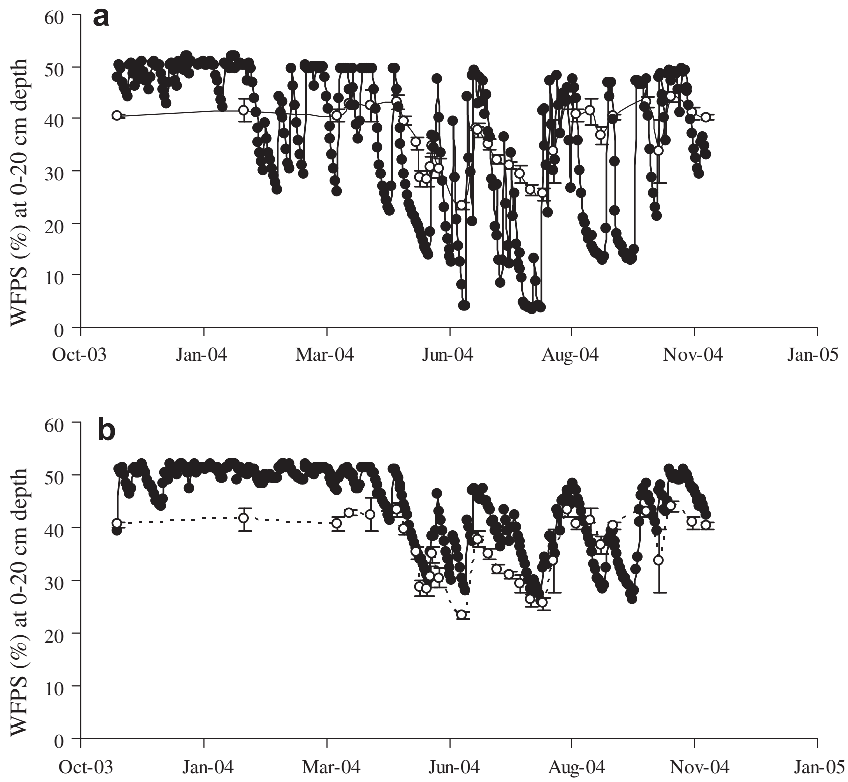

Fig. 3. Comparisons between the simulated (●) and field measured (○) WFPS from the cut and grazed pasture for DayCent (a) and DNDC (b) models in 2003/04. (Error bars for measured values are ± standard error.)

This increase was due to the overall effect of increasing rainfall, temperature and CO_2 concentration. Under baseline conditions, annual above-ground grass biomass (dry matter) was about 33 t ha^{-1} whilst under climate change this value was increased to 45 (+34%) and 50 (+48%) t ha^{-1} for the low and high temperature sensitivity scenario. An increase in grass dry matter production in Ireland due to climate change was also predicted by Fitzgerald et al. (2009). Here, changes in precipitation (Rosenzweig and Tubiello, 1997; Izaurralde et al., 2003; Mearns, 2003) and temperature (Fiscus et al., 1997) can affect crop productivity. Higher temperatures may increase plant carboxylation and stimulate higher photosynthesis, respiration, and transpiration rates. Plant growth and development would continue to increase, because of enhanced metabolic rates at higher temperatures, combined with increased carbon availability (Reddy and Hodges, 2000). Changing atmospheric carbon dioxide concentrations could also have positive effects on plants (Mitchell et al., 1993; Curtis and Wang, 1998; Anwar et al., 2007). Several factors may be responsible for this effect (i) increasing CO_2 has a direct effect on C availability by stimulating photosynthesis and reducing photorespiration (Akita and Moss, 1973) (ii) increasing CO_2 concentrations decrease stomatal conductance (Moss et al., 1961; Akita and Moss, 1973; Wong, 1979; Rogers et al., 1983; Morison and Gifford, 1984) which reduces the transpiration rate per unit leaf area. Reduced transpiration will also increase the leaf temperature which can further increase photosynthesis (Acock, 1990). Both an increase in photosynthesis and a decrease in transpiration result in an increase in the grass water use efficiency. (iii) Increases in CO_2 decrease the crop N concentration (Schmitt and Edwards, 1981; Hocking and Meyer, 1991).

Climate feedback could have significant impacts on N_2O fluxes from soil. Soil nitrogen increases due to increasing mineralization with changing temperature and precipitation (Waksman and Gerretsen, 1931; Kirschbaum, 1995; Wennman and Katterer, 2006; Abdalla et al., 2009c). However, in this simulation, climate change showed no significant effect on N_2O flux from the soil. In our simulations, there was a considerably greater demand for N from enhanced grass growth under climate change (Fig. 8). The amount of

Table 2
Annual measured flux, DayCent predicted flux, DNDC predicted flux and differences between predicted and measured fluxes of N_2O (kg N_2O–N ha^{-1}).

Treatment	Measured flux	DayCent	DNDC	Flux difference (DayCent-measured)	Flux difference (DNDC-measured)
Control	1.0	0.5	3.58	−0.5	+2.58
Fertilized	2.6	3.6	4.06	+1.0	+3.44

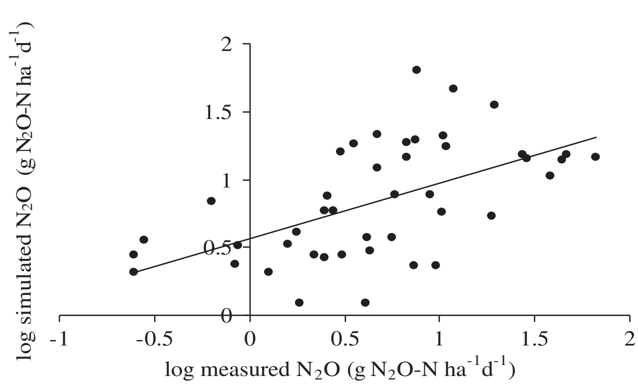

Fig. 4. Correlation between the DayCent model-simulated and field measured N_2O fluxes for the grass field. $y = 0.41x + 0.57$ ($r^2 = 0.32$).

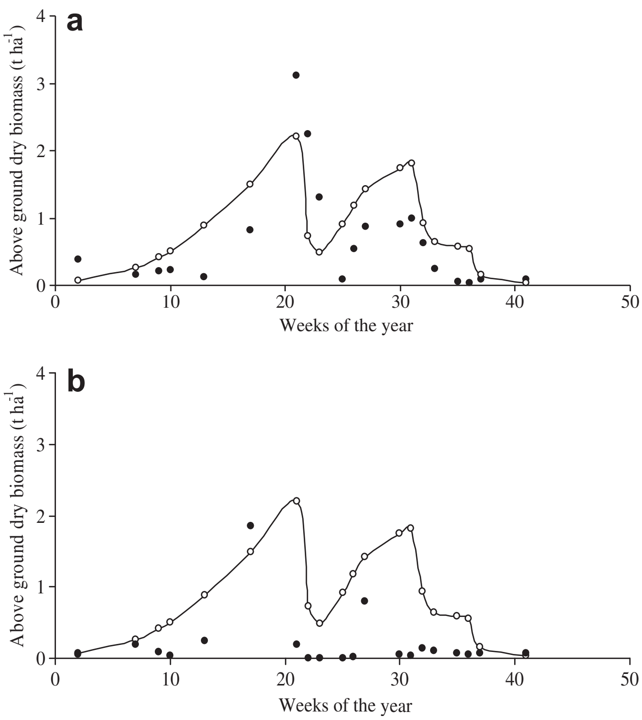

Fig. 5. Weekly DayCent (a) and DNDC (b) simulated (●) and field measured (○) grass biomass in 2004.

Table 3
DayCent simulated soil ammonium, nitrate, annual above-ground biomass and cumulative N_2O fluxes at different climate scenarios. Values with different letters for the same column are significantly different from each other ($p < 0.05$).

Climate scenario	Average soil ammonium ($g\ kg^{-1}$)	Average soil nitrate ($g\ kg^{-1}$)	Average biomass ($t\ ha^{-1}\ y^{-1}$)	Cumulative flux ($kg\ N_2O{-}N\ ha^{-1}\ y^{-1}$)
Baseline	35a	3a	33a	4.2a
High sensitive	14b	2a	50b	4.4a
Low sensitive	19c	2a	45c	4.1a

available soil N, in excess of the N requirement of the grass decreased, resulting in low N_2O flux. Here, N_2O flux has a threshold response to N, and the amount of N lost to atmosphere depends on the amount of N taken by the crop (McSwiney and Robertson, 2005; Abdalla et al., 2010). Soil mineral nitrogen and N mineralization are the main sources of N_2O production (Bouwman, 1990; Granli and Bockman, 1994; Abdalla et al., 2010). Nitrogen has a direct influence on N_2O production by provision of N for both nitrification and denitrification (Baggs and Blum, 2004). This is in agreement with many other studies over a range of different soils and crop systems (McSwiney and Robertson, 2005-arable; Abassi and Adams, 2000; Maddock et al., 2001; Ball et al., 2002 and Maljanen et al., 2002-forest and grasslands). However, the soil type under investigation is a sandy loam that has relatively low mineralization. Soil characteristics and environmental conditions affect mineralization (Schoenau and Campbell, 1996), and the extensive grazing had no significant effect on N_2O flux. Compared to the baseline, a significant decrease

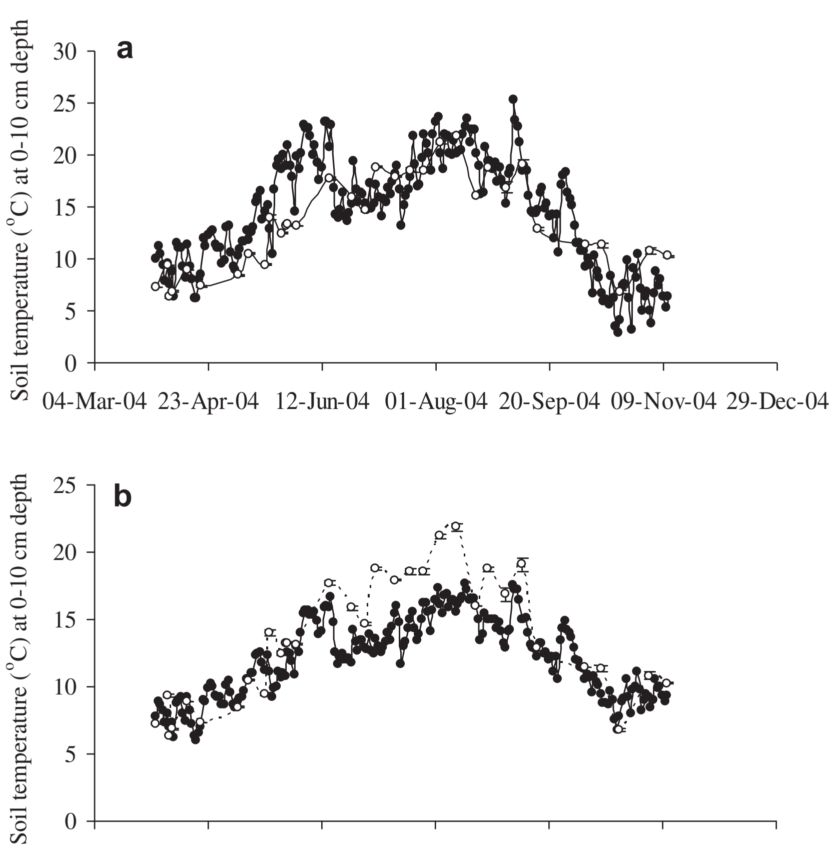

Fig. 6. Comparison between the DayCent (a; $r^2 = 0.64$; RMSE = 0.57) and DNDC (b; $r^2 = 0.88$; RMSE = 0.44) simulated (●) and field measured (○) soil temperature (0–10 cm depth) from the cut and grazed pasture in 2004. (Error bars for measured values are ± standard error.)

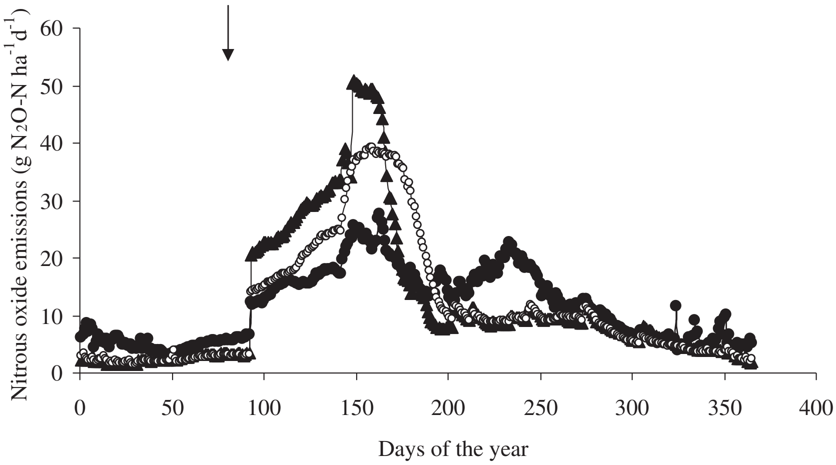

Fig. 7. Effects of climate change on N_2O emissions from the grass field for the high (▲) and low (○) temperature sensitive climate data compared with measured baseline climate (●). Arrow shows time of fertilizer application.

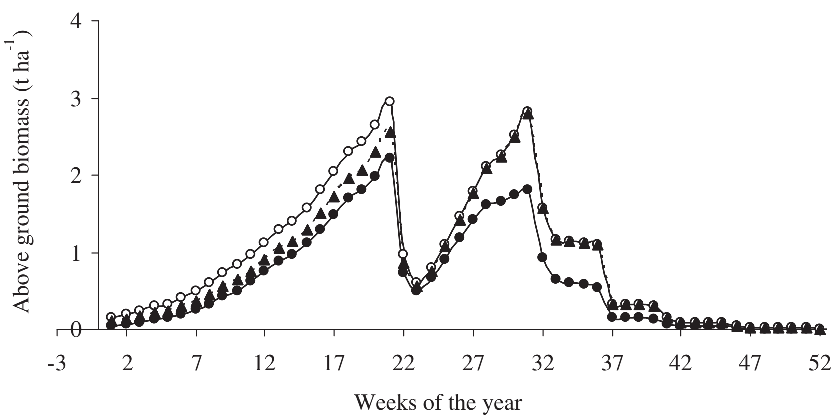

Fig. 8. Effects of climate change on above-ground grass biomass production for the high (○) and low (▲) temperature sensitive climate scenarios compared with measured baseline climate (●).

($p < 0.05$) was observed for the daily soil ammonium at 15 cm depth, from 35 to 14 and 19 mg kg^{-1} for the high and low temperature sensitivity scenarios, respectively (Table 3). Therefore, future N_2O flux from this field will not be significantly affected by climate change, unless more N fertilizer is applied.

Considering that the grass area in Ireland is about 4 M ha (CSO, 2010), sandy loam soil make up >30% of Irish soil types and the nitrogen fertilizer application rates used by the farmers at the time of this work were 200 kg ha^{-1} N, DayCent predicted large increase in above-ground grass biomass due to climate change. Under climate change, for the high and low temperature sensitivity scenarios, above-ground grass biomass could increase by approximately 68 and 48 Mt dry matter, respectively. However, the increase in N_2O flux due to climate change under this low N input grass is negligible, suggesting that future climate change will favour Irish low N input grasslands, with more biomass but no significant change in N_2O flux.

DayCent model was run assuming that the current field management will remain the same in the future. However, the predicted future higher above-ground biomass production by DayCent would encourage farmers to increase grazing intensity. This would increase emissions of methane (CH_4) and excretal N deposition from grazing animals. Alternatively, farmers could apply less N fertilizer to the pasture to achieve the current amount of above-ground biomass production without making significant change on N_2O or CH_4 fluxes.

4. Conclusions

Although further improvement is possible, the DayCent model effectively estimates the N_2O fluxes and biomass production from the Irish grasslands compared with DNDC model. DNDC significantly overestimates the measured N_2O flux, with relative deviations of +132% (RMSE = 5.2) and 258% (RMSE = 4) for the fertilized and control plots. DayCent predicted N_2O flux and biomass production from fertilized grass with relative deviations of +38% (RMSE = 2) and (−23%) (RMSE = 0.15) compared with the observed values, respectively. DayCent predicts a significantly higher peak coinciding with higher temperature and rainfall in August–September, associated with fertilizer N still held in the soil later in the season. The model fit under control plots was not good with a relative deviation of (−57%) (RMSE = 0.5). Under climate change, grass biomass was projected to increase from the baseline value of 33 t ha^{-1} to 45 (+34%) and 50 (+48%) t ha^{-1} for the low and high temperature sensitivity scenarios, respectively. Our results suggest, that due to significant grass growth and higher N demand by the grass, climate change is not expected to significantly affect N_2O fluxes from this low N input pasture, unless more N is applied in the future. This was projected for both the high and low temperature sensitivity scenarios. Our results suggest that future climate change will favour the Irish, low N input grasslands with more biomass but with no significant change in N_2O flux.

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References

Abdalla, M., Wattenbach, M., Smith, P., Ambus, P., Jones, M., Williams, M., 2009a. Application of the DNDC model to predict emissions of N_2O from Irish agriculture. Geoderma 151, 327–337.

Abdalla, M., Jones, M., Smith, P., Williams, M., 2009b. Nitrous oxide fluxes and denitrification sensitivity to temperature in Irish pasture soils. Soil Use Management 25, 376–388.

Abdalla, M., Jones, Williams, M., 2009c. Simulation of nitrous oxide emissions from Irish arable soils: effects of climate change and management. Biology and Fertility of Soils. doi:10.1007/s0037-009-0424-5.

Abdalla, M., Jones, M., Ambus, P., Williams, M., 2010. Emissions of nitrous oxide from Irish arable soils: effects of tillage and reduced N input. Nutrient Cycling in Agroecosystems 86, 53–65.

Abassi, M.K., Adams, W.A., 2000. Gaseous N emissions during simultaneous nitrification/denitrification associated with mineral N fertilisation to a grassland soil under field conditions. Soil Biology and Biochemistry 32, 1251–1259.

Acock, B., 1990. Effects of carbon dioxide on photosynthesis, plant growth, and other processes. In: Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture. American Society of Agronomy, Madison WI ASA especial pub. No. 53.

Akita, S., Moss, D.N., 1973. Photosynthetic responses to CO_2 and light by maize and wheat leaves adjusted for constant stomatal apertures. Crop Science 13, 234–237.

Allard, V., Soussana, J.-F., Falcimagne, R., Berbigier, P., Bonnefond, J.M., Ceschia, E., D'hour, P., Henault, C., Laville, P., Martin, C., Pinares-Patino, C., 2007. The role of grazing management for the net biome productivity and greenhouse gas budget (CO_2, N_2O and CH_4) of semi-natural grassland. Agriculture. Ecosystem and Environment 121, 47–58.

Antonopoulos, A.Z., 1999. Comparison of different models to simulate soil temperature and moisture – effects on nitrogen mineralisation in the soil. Journal of Plant Nutrition and Soil Science 162, 667–675.

Anwar, M.R., O'Leary, G., McNeil, D., Hossain, H., Nelson, R., 2007. Climate change impact on rain fed wheat in south-eastern Australia. Field Crops Research 104, 139–147.

Baggs, E.M., Blum, H., 2004. CH_4 oxidation and emissions of CH_4 and N_2O from *Lolium perenne* swards under elevated atmospheric CO_2. Soil Biology and Biochemistry 36, 713–723.

Baggs, E.M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H., Cadisch, G., 2003. Nitrous oxide emissions following application of residues and fertilizer under zero and conventional tillage. Journal of Plant Soil 254, 361–370.

Ball, B.C., McTaggart, I.P., Watson, C.A., 2002. 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. Agriculture, Ecosystems and Environment 90, 305–317.

BassiriRad, H., 2000. Kinetics of nutrient uptake by roots: responses to global change. New Phytologist 147, 155–169.

Beheydt, D., Boeckx, P., Sleutel, S., Li, C., Van Cleemput, O., 2007. Validation of DNDC for 22 long-term N_2O field emission measurements. Atmospheric Environment 41, 6196–6211.

Bouwman, A.F., 1990. Exchange of greenhouse gas between terrestrial ecosystems and atmosphere. In: Bouwman, A.F. (Ed.), Soil and the Greenhouse Effects. Wiley, Chichester, UK, pp. 61–127.

Bowden, W.B., Bormann, F.H., 1986. Transport and loss of nitrous oxide in soil water after forest clear cutting. Science 233, 867–869.

Bramley, R.G.V., White, R.E., 1990. The variability of nitrifying activity in field soils. Plant Soil 126, 203–208.

Brown, L., Syed, B., Jarvis, S.C., Sneath, R.W., Phillips, V.R., Goulding, K.W.T., Li, C., 2002. Development and application of a mechanistic model to estimate emission of nitrous oxide from UK agriculture. Atmospheric Environment 36, 917–928.

Cai, Z., Swamoto, T., Li, C., Kang, G., Boonjawat, J., Mosier, A., Wassmann, R., Tsuruta, H., 2003. Field validation of the DNDC-model for greenhouse gas emissions in East Asian cropping systems. Global Biogeochemical Cycles 17, 1107.

Choudhary, M.A., Akramkhanov, A., Saggar, S., 2002. Nitrous oxide emissions from a New Zealand cropped soil: tillage effects, spatial and seasonal variability. Agriculture, Ecosystems and Environment 93, 33–43.

Collins, W.D., Ramaswamy, V., Schwarzkopf, M.D., Sun, Y., Portmann, R.W., Fu, Q., Casanova, S.E.B., Dufresne, J.-L., Fillmore, D.W., Forster, P.M.D., Galin, V.Y., Gohar, L.K., Ingram, W.J., Kratz, D.P., Lefebvre, M.-P., Li, J., Marquet, P., Oinas, V., Tsushima, Y., Uchiyama, T., Zhong, W.Y., 2006. Radiative forcing by well-mixed greenhouse gases: estimates from climate models in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4. Journal of Geophysical Research 111, D14317.

C4I, 2008. Community Climate Change Consortium for Ireland. Ireland in a Warmer World, World. Scientific Predictions of the Irish Climate in the Twenty-first Century. Final Report. Access at: http://www.c4i.ie/docs/IrelandinaWarmerWorld.pdf.

CSO, 2010. Irish Central Statistics Office. Access at: www.cso.ie.

Curtis, P.S., Wang, X., 1998. A meta analysis of elevated CO_2 effects on woody plant mass, forms and physiology. Oecologia 113, 299–313.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, L., Ojima, D.S., Schimel, D.S., 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In: Schaffer, M., et al. (Eds.), Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press, Boca Raton, FL, pp. 303–332.

Del Grosso, S.J., Ojima, D.S., Parton, W.J., Mosier, A.R., Peterson, G.A., Schimel, D.S., 2002. Simulated effects of dryland cropping intensification on soil organic matter and greenhouse gas exchanges using the DAYCENT ecosystem model. Environmental Pollution 116, S75–S83.

Del Grosso, S.J., Halvorson, A.D., Parton, W.J., 2008. Testing DayCent model simulations of corn yields and nitrous oxide emissions in irrigated tillage systems in Colorado. Journal of Environmental Quality 37, 1383–1389.

Del Grosso, S.J., Ojima, D.S., Parton, W.J., Stehfest, E., Heistemann, M., DeAngelo, B., Rose, S., 2009. Global scale DayCent model analysis of greenhouse gas emissions and mitigation strategies for cropped soils. Global and Planetary Change 67, 44–50.

Dobbie, K.E., Smith, K.A., 2001. The effects of temperature, water filled pore space and land use on N_2O emissions from imperfectly drained gleysol. European Journal of Soil Science 52, 667–673.

FAO, 2004. Food and Agriculture Organization. FAOSTAT Database Collections. FAO, Rome, Italy. http://www.apps.fao.org 2004.

Fiscus, E.L., Reid, C.D., Miller, J.E., Heagle, A.S., 1997. Elevated CO_2 reduces O_3 flux and O_3-induced yield losses in soybeans: possible implications for elevated CO_2 studies. Journal of Experimental Botany 48, 307–313.

Fitzgerald, J.B., Brereton, A.J., Holden, N.M., 2009. Assessment of the adaptation potential of grass-based diary systems to climate change in Ireland – the maximized production scenario. Agricultural and Forest Meteorology 149, 244–255.

Flechard, C., Ambus, P., Skiba, U., Rees, R.M., Hensen, A., Van den Pol, A., Soussana, J.F., Jones, M., Clifton-Brwon, J., Raschi, A., Horvath, L., Van Amstel, A., Neftel, A., Jocher, M., Ammann, C., Fuhrer, J., Calanca, P., Thalman, E., Pilegaard, K., Di Marco, C., Campbell, C., Nemitz, E., Hargreaves, K.J., Levy, P., Ball, B., Jones, S., Van de Bulk, W.C.M., Groot, T., Blom, M., Gunnink, H., Kasper, G., Allard, V., Cellier, P., Laville, P., Henault, C., Bizouard, F., Jolivot, D., Abdalla, M., Williams, M., Baronti, S., Berretti, F., Grosz, B., Dominques, R., 2007. Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe. Agriculture, Ecosystems and Environment 121 (1–2), 135–152.

Frolking, S.E., Mosier, A.R., Ojima, D.S., Li, C., Parton, W.J., Potter, C.S., Priesack, E., Stenger, R., Haberbosch, C., Dorsch, P., Flessa, H., Smith, K.A., 1998. Comparisons of N_2O emissions from soils at three temperate agricultural sites: simulations of year-round measurements by four models. Nutrient Cycling in Agroecosystems 52, 77–105.

Granli, T., Bockman, O.C., 1994. Nitrogen oxide from agriculture. Norwegian Journal of Agricultural Sciences 12, 7–127.

Hocking, P.J., Meyer, C.P., 1991. Carbon dioxide enrichment decreases critical nitrate and nitrogen concentrations in wheat. Journal of Plant Nutrition 14, 571–584.

Hsieh, C.I., Leahy, P., Kiely, G., Li, C., 2005. The effect of future climate perturbations on N_2O emissions from a fertilized humid grassland. Nutrient Cycling in Agroecosystems 73, 15–23.

IPCC, 1995. Climate change 1995: The science of climate change. Contribution of Working Group 1 to the Second Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK.

IPCC, 2001. Climate Change 2001, Third Assessment Report of the IPCC. Cambridge University Press, UK.

IPCC, 2006. IPCC 2006 Revised Guidelines for National Greenhouse Gas Inventories. In: Agriculture, Forestry and Other Land Use (AFOLU), vol. 4. NGGIP, Institute for Global Environmental Strategies. 2108-11, Kamiyamaguchi, Hayama, Kanagawa, Japan 240-0115.

IPCC, 2007. Changes in Atmospheric Constituents and in Radiative Forcing. Cambridge University Press, UK and New York USA.

Izaurralde, R.C.C., Rosenberg, N.J., Brown Jr., R.A., Thomson, A.M., 2003. Integrated Assessment of Hadley Centre (HadCM2) climate-change impacts on agricultural productivity and irrigation water supply in the conterminous United States. Part II. Regional agricultural production in 2030 and 2095. Agricultural and Forest Meteorology 117, 97–122.

Keller, M., Reiners, W.A., 1994. Soil–atmosphere exchange of nitrous oxide, nitric oxide, and methane under secondary succession of pasture to forest in the Atlantic lowlands of Cost Rica. Global Biogeochemical Cycles 8, 399–409.

Kesik, M., Bruggemann, N., Forkel, R., Kiese, R., Knoche, R., Li, C., Seufert, G., Simpson, D., Butterbach-Bahl, 2006. Future scenarios of N_2O emissions from European forest soils. Journal of Geophysical Research 111, G02018. doi:10.1029/2005JG000115. 2006.

Kirschbaum, M.U.F., 1995. The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biology and Biochemistry 27, 753–760.
Kroeze, C., Mosier, A., Bouwman, L., 1999. Closing the global N_2O budget. A retrospective analysis 1500–1994. Global Biochemical Cycles 12, 1–8.
Li, C., Frolking, S., Frolking, T.A., 1992. A model of nitrous oxide evolution from soil driven by rainfall events.1. Model structure and sensitivity. Journal of Geophysical Research Atmosphere 97, 9759–9776.
Li, C., Narayanan, V., Harriss, R., 1996. Model estimate of N_2O emissions from agricultural lands in the United States. Global Biogeochemical Cycles 10, 297–306.
Li, C., 2000. Modelling trace gas emissions from agricultural ecosystems. Nutrient Cycling in Agroecosystems 58, 259–276.
Li, C., Zhuang, Y., Cao, M., Crill, P., Dai, Z., Frolking, S., Moore, B., Salas, W., Song, W., Wang, X., 2001. Comparing a process-based agro ecosystem model to the IPCC methodology for developing a national inventory of N_2O emissions from arable lands in China. Nutrient Cycling in Agroecosystems 60, 1–3.
Li, Y., Chen, D., Zhang, Y., Edis, R., Ding, H., 2005. Comparison of three modeling approaches for simulating denitrification and nitrous oxide emissions from loam-textured arable soils. Global Biogeochemical Cycles 19, GB3002.
Maddock, J.E.L., Dos Santos, M.B.P., Prata, K.R., 2001. Nitrous oxide emission from soil of the Mata Atlantica, Rio De Janeiro State, Brazil. Geophysical Research Atmosphere 106, 23055–23060.
Malhi, S.S., McGill, W.B., Nyborg, N., 1990. Nitrate losses in soils: effect of temperature, moisture and substrate concentration. Soil Biology and Biochemistry 22, 733–737.
Maljanen, M., Martikainen, P.J., Aaltonen, H., 2002. Short term variation in fluxes of carbon dioxide, nitrous oxide and methane in cultivated and forested organic boreal soils. Soil Biology and Biochemistry 34, 577–584.
McSwiney, C.P., Robertson, G.P., 2005. Non-linear response of N_2O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system. Global Change Biology 11, 1712–1719.
Mearns, L.O., 2003. Issues in the impacts of climate variability and change on agriculture. Climatic Change 60, 1–6.
Mitchell, R.A.C., Mitchell, V.J., Driscoll, S.P., Franklin, J., Lawlor, D.W., 1993. Effects of increased CO_2 concentration and temperature on growth and yield of winter wheat at two levels of nitrogen application. Plant Cell and Environment 16, 521–529.
Mogge, B., Kaiser, E.A., Munch, J.C., 1999. Nitrous oxide emissions and denitrification N-losses from agricultural soils in the Bornhoved Lake region: influence of organic fertilizers and land-use. Soil Biology and Biochemistry 31, 1245–1252.
Morison, J.I.L., Gifford, R.M., 1984. Plant growth and water use with limited water supply in high CO_2 concentrations. 1. Leaf area, water use and transpiration. Australian. Journal of Plant Physiology 11, 361–374.
Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., Van Cleemput, O., Abrahamsen, G., Bouwman, L., Bockman, O., Drange, H., Frolking, S., Howarth, R., Smith, K., Bleken, M.A., 1998. Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutrient Cycling in Agroecosystems 52, 225–248.
Moss, D.N., Musgrave, R.B., Lemon, E.R., 1961. Photosynthesis under field conditions. III. Some effects of light, carbon dioxide, temperature and soil moisture on photosynthesis, respiration, and transpiration of corn. Crop Science 1, 83–87.
Nakicenovic, N., Swart, R. (Eds.), 2000. Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, 570 pp.
Olivier, J.G.J., Bouwman, A.F., Van Der hoek, K.W., Berdowski, J.J.M., 1998. Global air emission inventories for anthropogenic sources of N_x, NH_3 and N_2O in 1990. Environmental Pollution 102, 135–148.
Parton, W.J., Ojima, D.S., Cole, C.V., Schimel, D.S., 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Quantitative Modelling of Soil Forming Processes. Soil Science Society of America, Madison, WI, pp. 147–167.
Parton, W.J., Hartman, M.D., Ojima, D.S., Schimel, D.S., 1998. DAYCENT and its land surface sub-model: description and testing. Global and Planetary Change 19, 35–48.
Prather, M.J., 1998. Time scales in atmospheric chemistry: coupled perturbations to N_2O, NO_y, and O_3. Science 279, 1339–1341.
Raich, J.W., Schlesinger, W.H., 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus 44B, 81–99.
Reddy, K.R., Hodges, H.F. (Eds.), 2000. Climate Change and Global Crop Productivity. CAB International, Wallingford, UK.
Rogers, H.H., Bingham, G.E., Cure, J.D., Smith, J.M., Surano, K.A., 1983. Responses of selected plant species to elevated carbon dioxide in the field. Journal of Environmental Quality 12, 569–574.
Rosenzweig, C., Tubiello, F.N., 1997. Impacts of global climate change on Mediterranean agriculture: current methodologies and future directions: an introductory essay. Mitigation and Adaptation Strategies for Global Change 1, 219–232.
Ruser, R., Flessa, H., Schilling, R., Steidl, H., Beese, F., 1998. Soil compaction and fertilization effects on nitrous oxide and methane fluxes in potato fields. Soil Science Society of America Journal 62, 1587–1595.
Schoenau, J.J., Campbell, C.A., 1996. Impact of crop residues on nutrient availability in conservation tillage systems. Canadian Journal of Plant Science 76, 621–626.
Shaver, G.R., Canadell, J., Chapin III, F.S., Gurevitch, J., Harte, J., Henry, G., Ineson, P., Jonasson, S., Melillo, J., Pitelka, L., Rustad, L., 2000. Global warming and terrestrial ecosystems: a conceptual framework for analysis. Bioscience 50, 871–882.
Schmitt, M.R., Edwards, G.E., 1981. Photosynthetic capacity and nitrogen use efficiency of maize, wheat and rice: a comparison between C_3 and C_4 photosynthesis. Journal of Experimental Botany 32, 459–466.
Shaw, M.R., Harte, J., 2001. Control of litter decomposition in a subalpine meadow-sagebrush steppe ecotone under climate change. Ecological Applications 11, 1206–1223.
Simek, M., Elhottova, D., Klimes, F., Hopkins, D.W., 2004. Emissions of N_2O and CO_2, denitrification measurements and soil properties in red clover and ryegrass stands. Soil Biology and Biochemistry 36, 9–21.
Smith, K.A., Clayton, H., McTaggart, I.P., 1995. The measurement of nitrous oxide emissions from soil by using chambers. Philosophical Transactions of the Royal Society of London, Series A 351, 327–337.
Smith, W.N., Grant, B.B., Desjardins, R.L., Worth, D., Li, C., Boles, S.H., Huffman, E.C., 2010. A tool to link agricultural activity data with the DNDC model to estimate GHG emissions factor in Canada. Agriculture, Ecosystems and Environment 136, 301–309.
Stanford, G., Epstein, E., 1974. Nitrogen mineralization-water relations in soils. Soil Science Society of America – Proceedings 38, 103–107.
Stark, J.M., Firestone, M.K., 1996. Kinetic characteristics of ammonium-oxidizer communities in a California oak woodland-annual grassland. Soil Biology and Biochemistry 28, 1307–1317.
Stehfest, E., Heistermann, M., Priess, J.E., Ojima, D.S., Alcamo, J., 2007. Simulation of global crop production with the ecosystem model DayCent. Ecological Modeling 209, 203–219.
Teagasc, 2010. The Irish Agriculture and Food Department Authority. Access at. www.teagasc.ie.
Waksman, S.A., Gerretsen, F.C., 1931. Influence of temperature and moisture upon the nature and extent of decomposition of plant residues. Ecology 12, 33–60.
Watson, R.T., Zinyowera, M.C., Moss, R.H., Dokken, D.J., 1996. Climate change (1995), impacts, adaptation and mitigation of climate change. Scientific Technical Report Analysis. In: Watson, R.T., Zinyowera, M.C., Moss, R.H. (Eds.), Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change, p. 880. Cambridge, New York.
Wennman, P., Katterer, T., 2006. Effects of moisture and temperature on carbon and nitrogen mineralisation in mine tailing mixed with sewage sludge. Journal of Environmental Quality 35, 1135–1141.
Wong, C.S., 1979. Carbon input to the atmosphere from forest fires. Science 204, 210.