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Application of the DNDC model to predict emissions of N_2O from Irish agriculture

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ABSTRACT

Models are increasingly used to examine the potential impacts of management and climate change in agriculture. Our aim in this paper was to assess the applicability of the field-DeNitrification DeComposition (DNDC) model in Irish agriculture. This study provides the results of that evaluation, which is a prerequisite for using the model for assessing management impacts in the future. The DNDC model was tested against seasonal and annual data sets of nitrous oxide flux from a spring barley field and a cut and grazed pasture at the Teagasc Oak Park Research Centre, Co. Carlow, Ireland. In the case of the arable field, predicted fluxes of N_2O agreed well with measured fluxes for medium to high fertilizer input (70–160 kg N ha^{-1}) but poorly described those fluxes from zero fertilizer treatments. In terms of cumulative flux values, the relative deviation of the predicted fluxes from the measured values was a maximum of 6% for the highest N fertilizer inputs but increased to 30% for the medium N and more than 100% for the zero N fertilizer treatments. There is a linear correlation of predicted against measured flux values for all fertilizer treatments ($r^2 = 0.85$) but the model underestimated the seasonal flux by 24%. Incorporation of literature values from a range of different studies on arable and pasture land did not significantly improve the regression. The description by DNDC for measured fluxes of N_2O from reduced tillage plots was poor with underestimation of up to 55%.
For the cut and grazed pasture the relative deviations of predicted to measured fluxes were 150 and 360% for fertilized and unfertilized plots. A sensitivity analysis suggests that the poor model fit is due to DNDC overestimating WFPS and the effect of initial soil organic carbon (SOC) on N_2O flux. As the arable and grassland soils differed only in SOC content, reducing SOC of the grassland field to that of the arable field value significantly improved the fit of the model to measured data such that the relative deviations decreased to 9 and 5% respectively. Sensitivity analysis highlighted air temperature as the main determinant of N_2O flux, an increase in mean daily air temperature of 1.5 °C resulting in almost a 65% increase in the annual cumulative flux. This is interesting as with future global warming, N_2O flux from the soil will have a strong positive feedback. It can be concluded that DNDC is unsuitable for predicting N_2O from Irish grassland due to its overestimation of WFPS and effect of SOC on the flux.

1. Introduction

Nitrous oxide contributes to climate change by virtue of having a global warming potential (GWP) 298 times greater than that of carbon dioxide (IPCC, 2007). The atmospheric concentration of this greenhouse gas has increased from approximately 275 ppb in pre-industrial times to a present day concentration of 314 ppb (Houghton et al., 1996; IPCC, 2007). Agricultural land is the most important 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). Primary reasons for enhanced N_2O emissions from cultivated soils are increased N inputs by mineral fertilizers, animal wastes and biological N fixation (IPCC, 1996, 2007). Other factors which affect N_2O emissions are temperature, moisture, crop type, fertilizer type, soil organic carbon content, soil pH, tillage and soil texture (Dobbie et al., 1999; Stehfest and Bouwman, 2006; IPCC, 2007; Metay et al., 2007).

Management can influence soil fertility directly through fertilizer inputs (Bouwman, 1996; Makarov et al., 2003) and indirectly via management-induced changes in plant composition (Collins et al., 1998; Patra et al., 2006) and consequently increase N_2O flux from soils. For example mowing and grazing accelerate the N cycle (Bardgett et al., 1998; Güsewell et al., 2005) and encourage increased above- and below-ground plant growth (Leriche et al., 2001) and root exudation (Lipson and Schmidt, 2004). Plants in mown grasslands must complete their life cycle relatively early in the season, thus the recycling of roots from early-season species in mown fields boosts soil nutrient contents sooner than

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in un-mown fields (Bardgett et al., 1998). Mowing enables short-lived herbs, that exploit early-season ecological niches (Louault et al., 2005), to flourish, and grazing reduces the dominance of grasses in favor of short-lived rosette species (Bullock et al., 2001).

National inventories of N_2O fluxes from agricultural soils as required by signatory countries to the United Nations Framework Convention of Climate Change (UNFCC), are mainly derived from the use of the default IPCC Tier 1 method, where 0.9–1.25% of applied inorganic nitrogen to agricultural soils is assumed to be released to the atmosphere as nitrous oxide-N (Bouwman, 1996; IPCC, 1997, 2000, 2007). This standard reporting procedure has advantages in collating annual inventories but may mask significant variations in emission factors (EFs) on a regional scale (Schmid et al., 2001; Laegreid and Aastveit, 2002; Flynn et al., 2005). For instance in Ireland, published EFs derived from field measurements of N_2O using either eddy covariance or static chamber methods vary depending on soil type, land management, climate and year and range from 3.4% for a grassland in Cork to 0.7 to 4.9% for Carlow and Wexford grasslands (Hsieh et al., 2005; Hyde et al., 2006; Flechard et al., 2007).

Because of the importance of nitrous oxide emission for global warming, regional or even global emission estimates are needed for policy and decision makers. Given the considerable expense of establishing and maintaining relevant flux measurement sites, the use of simulation models to estimate N_2O fluxes from agricultural soils, using soil and climate data, has obvious benefits. Modelling also allows the complex links between soil physical, chemical and microbial processes that underpin nitrification, denitrification and decomposition to be examined. Models can simulate the processes responsible for production, consumption and transport of N_2O in both the long and short term, and also allow spatial simulation (Willams et al., 1992).

Simulation models range from simple empirical relationships based on statistical analyses to complex mechanistic models that consider all factors affecting N_2O production in the soil (Li et al., 1992; Frolking et al., 1998; Stenger et al., 1999; Freibauer and Kaltschmitt, 2003; Roelandt et al., 2005; Jinguo et al., 2006). These factors include soil moisture, soil temperature, carbon and nitrogen substrate for microbial nitrification and denitrification which are critical to the determination of N_2O emissions (Cho et al., 1979; Batlach and Tiedje, 1981; Frissel and Van Veen, 1981; Tanji, 1982; Leffelaar and Wessel, 1988). One widely used mechanistic model is DeNitrification DeComposition (DNDC) developed to assess N_2O, NO, N_2 and CO_2 emissions from agricultural soils (Li et al., 1992, 1994; 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) and China (Li et al., 2001). Advantages of DNDC are that it has been extensively tested and has shown reasonable agreement between measured and modelled results for many different ecosystems such as grassland (Brown et al., 2001; Hsieh et al., 2005; Saggar et al., 2007), cropland (Li, 2003; Cai et al., 2003, Yeluripati et al., 2006; Pathak et al., 2006; Tang et al., 2006) and forest (Li, 2000; Stange et al., 2000; Kesik et al., 2006). The model has reasonable data requirement and is suitable for simulation at appropriate temporal and spatial scales.

The Field-DNDC model 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.

This paper presents a field evaluation of DNDC for an Irish sandy loam soil under both arable and grassland crops with different fertilizer and tillage regimes. Results are discussed in terms of the suitability of this model for estimating annual and seasonal fluxes of N_2O from Irish agriculture.

2. Materials and methods

2.1. Experiments

Measurements of N_2O flux were carried out for a spring barley field from April to August for two consecutive seasons (2004/05), and for a cut and grazed pasture from October 2003 to November 2004. Both fields were located at the Oak Park Research Centre, Carlow, Ireland (52°86' N, 6°54' W). The arable field was seeded with spring barley (cv. Tavern) at a density of 140 kg ha^{-1} and managed under two different tillage regimes; conventional tillage where inversion ploughing to a depth of 22 cm was carried out in March, 5 weeks prior to planting, and reduced tillage to a depth of 15 cm which was carried out in September of the year before. The field has been used for cereals production for the past 15 years and as cropland for the past 50 years.

The cut and grazed pasture had been permanent grassland for at least the past 80 years and 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}. Daily minimum and maximum air temperature (°C) and rainfall in (mm) were recorded at the Teagasc Research Centre Weather Station (Met Eireann). Initial soil properties and climate factors of both sites are summarized in Table 1.

For the spring barley, in 2004, three rates of N-fertilization zero: (N_0), 70 (N_1) and 140 (N_2) kg N ha^{-1}, were applied once on the 27th of April. In 2005, two fertilizer applications took place on the 12th of April zero (N_0), 53 (N_1) and 106 (N_2) kg N ha^{-1}, and on the 10th of May zero (N_0), 26 (N_1) and 53 (N_1) kg N ha^{-1}. The total amount of N-fertilization applied in 2005 was therefore zero (N_0), 79 (N_1) and 159 (N_2) kg N ha^{-1}. Nitrogen fertilizer was split in the second year to cover all possible N application management recommended for the field. Application of zero fertilizer started from 2003 until now but the field had received the recommended field rate of fertilizer 140–160 kg N ha^{-1} before 2003. Experimental design was a complete randomized plot design with four replicates.

For the cut and grazed pasture, nitrogen fertilizer was applied at a total rate of 200 kg N ha^{-1} y^{-1} divided into two applications of 128 and

Table 1
DNDC model input data for both the spring barley and the pasture fields.

	Spring barley field	Pasture field
Climate data		
Latitude (degree)	52°86' N	52°86' N
Yearly maximum of average Daily temperature (°C)	13	13
Yearly minimum of average Daily temperature (°C)	4.0	4.0
Yearly accumulated precipitation (mm).	792	792
N concentration in rainfall (mg N l^{-1})	0.001*	0.001*
Atmospheric CO_2 concentrations (ppm)	380*	380*
Soil properties (0–10 cm depth)		
Vegetation type	Barley crop	Moist pasture
Soil texture	Sandy loam	Sandy loam
Bulk density (g cm^{-3})	1.4	1.0
Clay fraction	0.19*	0.34*
Soil pH	7	7.3
Initial organic C content at surface soil (kg C kg^{-1}).	0.019	0.038
Harvest	Grain harvest, mulch/till	Grazing/cutting
Soil tillage	Conventional and reduced	None
WFPS at field capacity	0.68	0.87
WFPS at wilting point	0.12	0.09
Depth of water-retention layer (cm)	100*	100*
Slope (%)	0.0	0.0

*Default values.

72 kg N ha^{-1} on the 2nd of April and the 27th of May respectively. Separate areas of the field were kept unfertilized as control plots. Fertilizer was applied in the form of calcium ammonium nitrate (CAN). Fertilized plots were replicated four times while control plots were replicated three times. Silage cutting took place once, on the 15th of May and cattle (beef) grazing (extensive) was from July to November 2003, and then from July to November 2004 with stocking rate of 2 cattle ha^{-1}.

2.2. Field N_2O fluxes

Nitrous oxide fluxes were measured using the methodology of Smith et al. (1995). Chambers consisted of three parts: a 52×52×15 cm high square collar inserted permanently in the soil over which a 50×50×30 cm high lid with a plastic septum could be sealed in place for gas sample collection. After the lids were in place an initial gas sample was taken and then a second and third at 30 and 60 min, respectively. In order to cover most of the crop growth period/year we sampled every week and more intensively (twice/week) following fertilizer application. Previous studies of N_2O fluxes using static chambers have sampled at frequencies ranging from 1 h to 2 weeks (Moge 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 a.m. Samples were taken using a 60 ml gas-tight syringe after flushing of the syringe to ensure adequate mixing of air within the chamber. All 60 ml of the sample was then injected into a pre-evacuated 3 ml gas-tight vial with a vent needle inserted into the top, and stored until analysis. N_2O flux was measured using a gas chromatograph (Shimadzu GC 14B, Kyoto, Japan) with electron capture detection (column and detector temperatures were 30 and 300 °C respectively).

2.3. Soil moisture

For both fields and each treatment, four soil samples were taken at a depth of 0–20 cm at every gas-sampling occasion. Samples were weighed, oven dried to constant mass at 105 °C, and reweighed again. The dry weight and differences between fresh and dry weight were used to calculate the both gravimetric and volumetric water content. Average

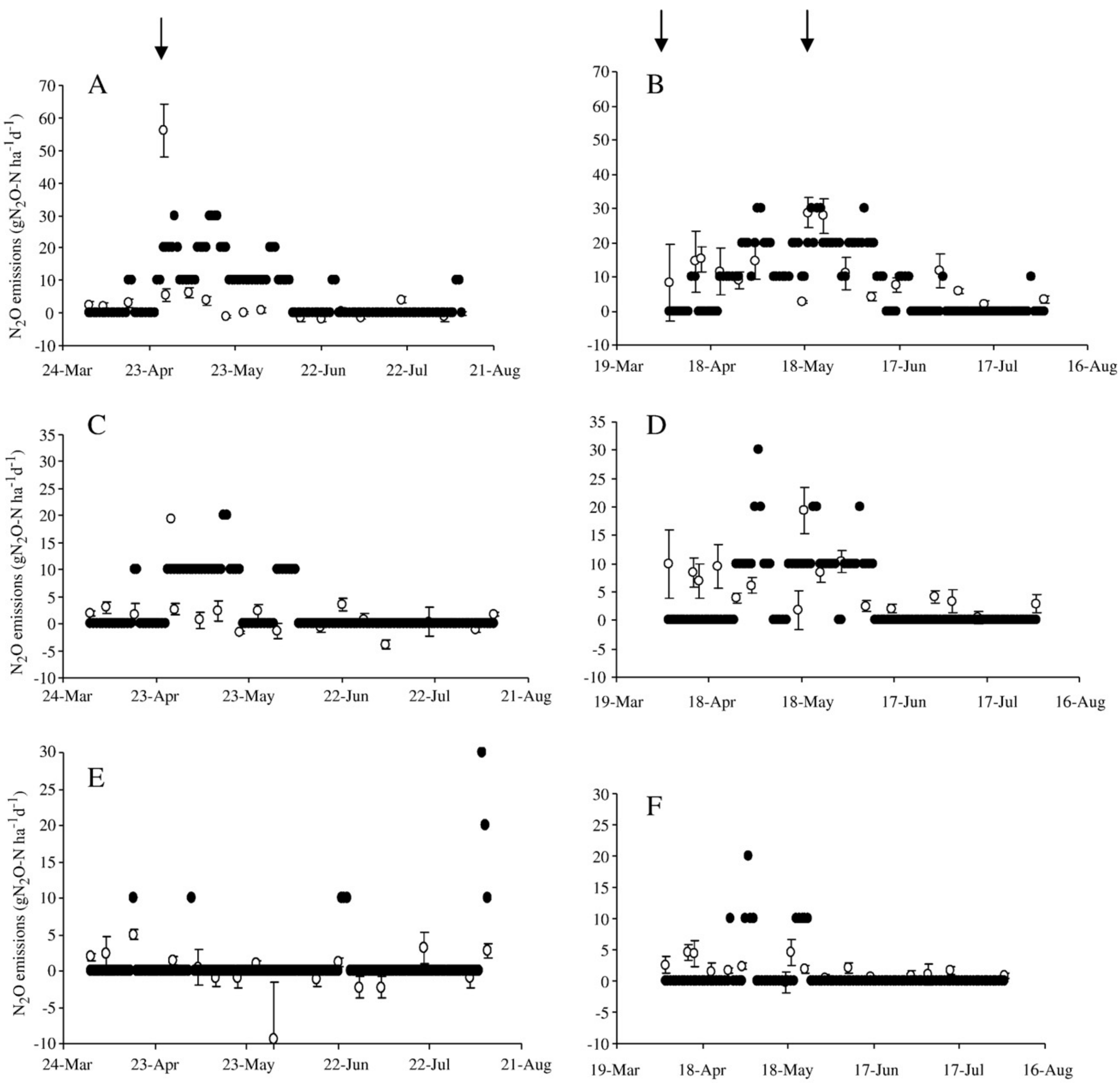

Fig. 1. Comparison of model-simulated (●) and field measured (○) N_2O flux from the high (upper), medium (bottom) and low (lower) fertilized conventional tillage in 2004 (A, C, E) and 2005 (B, D, F). (Error bars for measured values are ±standard error). Arrows show time of fertilizer application.

bulk density was 1.4 g cm^{-1}. Water filled pore space (WFPS) is calculated by WFPS = (soil gravimetric water content × bulk density) / [1 − (bulk density / particle density)] (Linn and Doran, 1984).

2.4. DNDC model

In this study the DNDC model (version 9.2; http://www.dndc.sr.unh.edu/) was tested for both the arable field and the cut and grazed pasture. All field management variables, including grain yield, fertilizer application and tillage system (where reduced tillage was defined as disk or chisel ploughing to 10 cm) were input into the model. Soil properties and climate input data are summarized in Table 1. For the arable field model testing was possible only for the growth period of the crop, whilst for the cut and grazed pasture 12 months of data were used. The model testing was carried out by (1) comparing the measured and modelled temporal pattern of weekly N_2O flux values, (2) comparing the measured and modelled cumulative N_2O fluxes (using weekly values), and (3) comparing the measured and modelled emission factors.

The relative deviation (y) of the modelled flux from measured flux values was calculated by the following equation:

$$Y = (X_S - X_O) / X_O \times 100,$$

where X_O and X_S are the measured and modelled fluxes respectively. Annual and seasonal cumulative fluxes for DNDC outputs were calculated as the sum of simulated daily fluxes (Cai et al., 2003). EFs for the modelled data were calculated by subtracting cumulative DNDC flux data for unfertilized soils from that of the fertilized soils and dividing by the N fertilizer input. Sensitivity analysis was carried out by varying a single determinant factor whilst keeping other factors constant for one annual cycle of the model.

3. Results and discussion

Climate and soil input variables for DNDC are listed in Table 1. Field data measurements were used for all of the variables listed except for

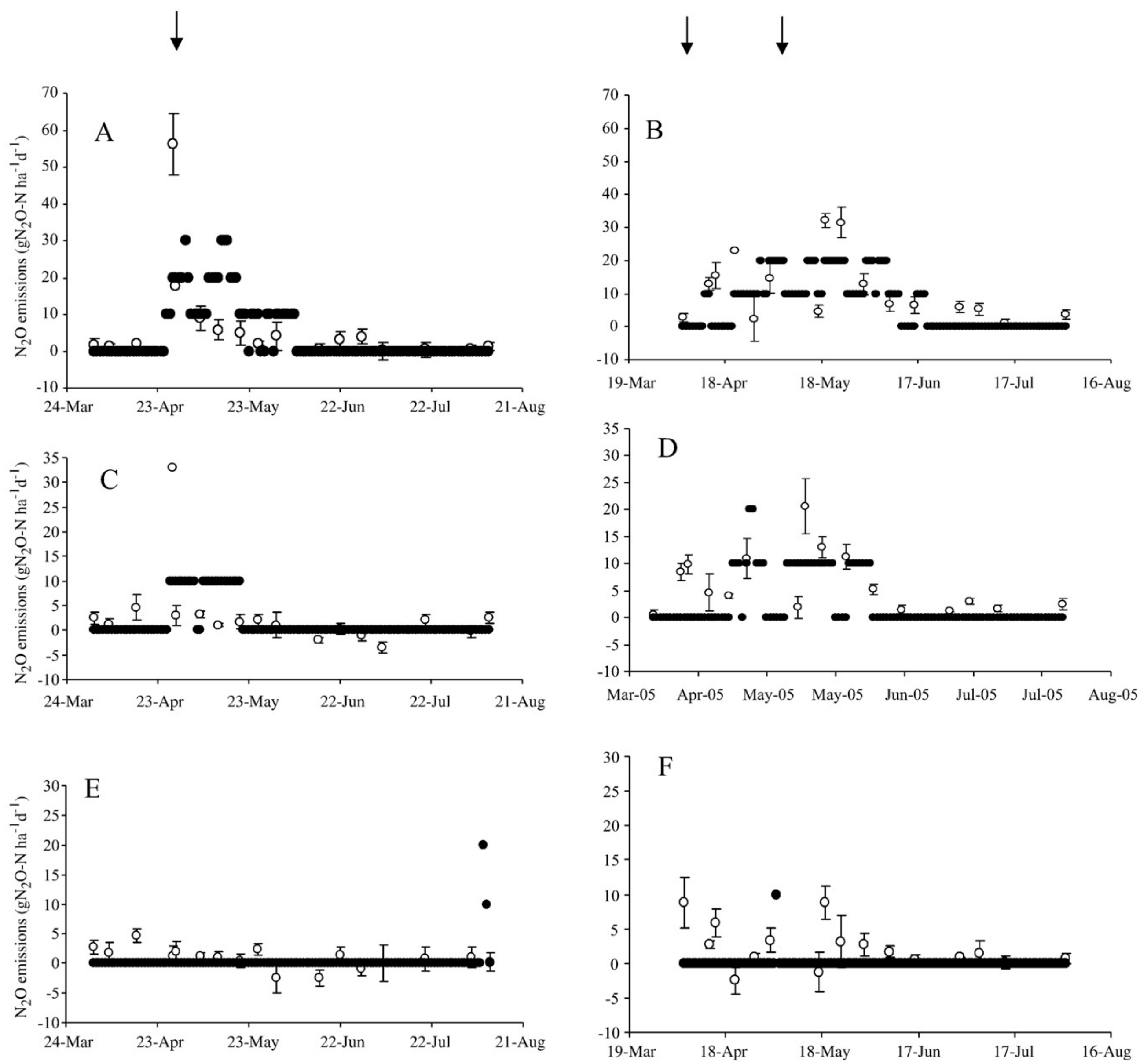

Fig. 2. Comparison of model-simulated (●) and field measured (○) N_2O flux from the high (upper), medium (bottom) and low (lower) fertilized reduced tillage in 2004 (A, C, E) and 2005 (B, D, F). (Error bars for measured values are ± standard error). Arrows show time of fertilizer application.

atmospheric CO_2, rainfall N, clay fraction and depth of the soil water retention layer. Here default values were used. Collectively, DNDC was better at predicting N_2O fluxes for high inputs of N fertilizer (>140 kg N ha^{-1}) than for zero or low N input treatments (0–70 kg N ha^{-1}). In addition the model appeared to be unduly sensitive to the influence of soil organic carbon content.

3.1. Arable field

Measurements of N_2O flux were limited to the growth period of the barley crop hence annual estimates of flux were not produced. Figs. 1–3 relate to a comparison of the modelled and measured fluxes for 2004/05 as either daily values (Figs. 1 and 2), or cumulative flux (Fig. 3). At limited mineral N in the soil, DNDC had no response to rainfall distribution (Fig. 4). This was clear for 2004 where early N_2O flux peaks were missed (Fig. 3). However, at high mineral N, some flux peaks were coincided with high rain events (Dobbie et al., 1999), though the relationship was inconsistent. In general the temporal pattern of N_2O flux was different between modelled and measured data, DNDC extending the influence of added fertilizer over a wider time period and producing smaller peaks. This is more pronounced for the higher fertilizer treatments in 2004 than in 2005 (Figs. 1A, 2A and C) and can be clearly seen in the cumulative flux plots (Fig. 3A and B). This discrepancy between the years may be related to DNDC overestimating the water filled pore space (WFPS) in 2004 as opposed to 2005, WFPS being a critical determinant of N_2O flux at the time of fertilizer application (Keller and Reiners, 1994; Ruser et al., 1998; Dobbie and Smith, 2001). According to Frolking et al. (1998) WFPS is a key requirement for a reliable simulation of N_2O. Here, increasing WFPS may reduce the contribution of nitrification and increase denitrification (Li, 2000; Li et al., 2000). This is illustrated in Fig. 5A where modelled WFPS values were consistently higher than measured values in 2004, with maximum differences of 25–30% being recorded. In comparison, modelled values for 2005 (Fig. 5B) were closer to measured values with maximum differences of only 13–16%.

The tillage options provided by DNDC do not allow the reduced, non-inversion tillage used in our study to be fully described. In contrast to the conventional tillage plots, DNDC significantly under-estimated the N_2O flux from the reduced tillage plots for the medium and higher fertilizer treatments by up to 55% (Fig. 3B and D). This may not be critical for modelling N_2O fluxes from Irish agriculture as reduced cultivation and direct drilling of cereal crops represents less than 10% of arable land, <40,000 ha (Fortune et al., 2003; ECAF, 2004).

Cumulative fluxes from sowing to harvest are given in Table 2. Modelled fluxes for the high fertilizer inputs agreed with field measured values, giving the smallest relative deviations from field data of −1 and −6%. These deviations increase significantly as fertilizer input is reduced. The largest % deviation, and hence the worst fit was obtained for the zero fertilizer treatments, with relative deviations of −35 to more than 5000% calculated. Clearly DNDC is best suited for medium to high N input treatments and does not account for negative flux values that can occur in low to zero N input treatments where the soil may act as a sink for N_2O (Ryden, 1981; Clayton et al., 1997). Similar DNDC results for high and medium N fertilizer inputs have been reported for rice fields by Zheng et al. (1999) (381 kg N ha^{-1}; 8% deviation), for maize fields by Crill et al. (2000) (181 kg N ha^{-1}; 3.5% deviation), for grass by Hsieh et al. (2005) (337 kg N ha^{-1}; 33% deviation) and for barley fields by Flessa et al. (1995) (50 kg N ha^{-1}; 36% deviation). However, these observations are not consistent in the literature. In contrast to our results far better agreements between modelled and measured flux values have

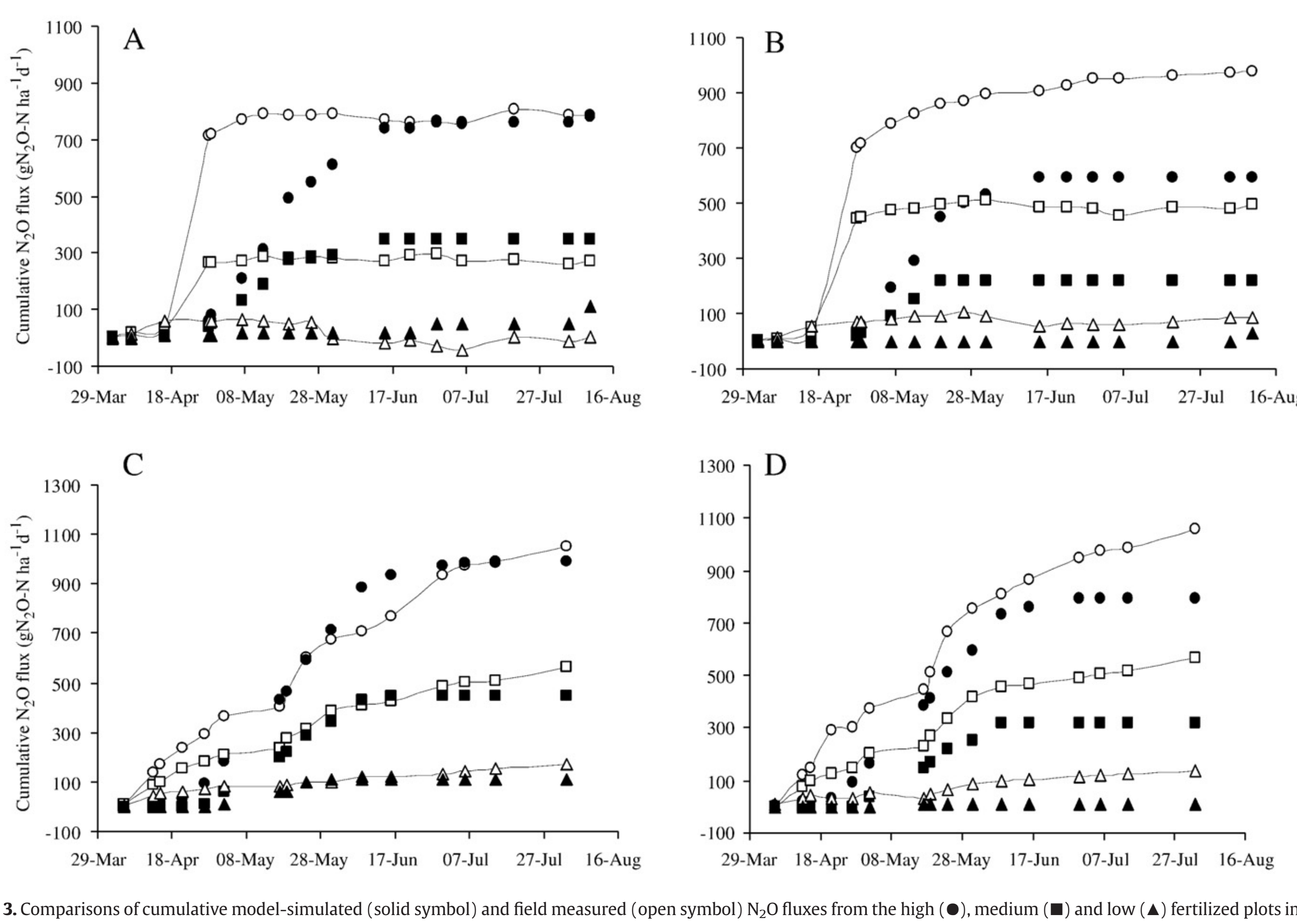

Fig. 3. Comparisons of cumulative model-simulated (solid symbol) and field measured (open symbol) N_2O fluxes from the high (●), medium (■) and low (▲) fertilized plots in 2004 and 2005 for conventional (A and C) and reduced (B and D) tillage system.

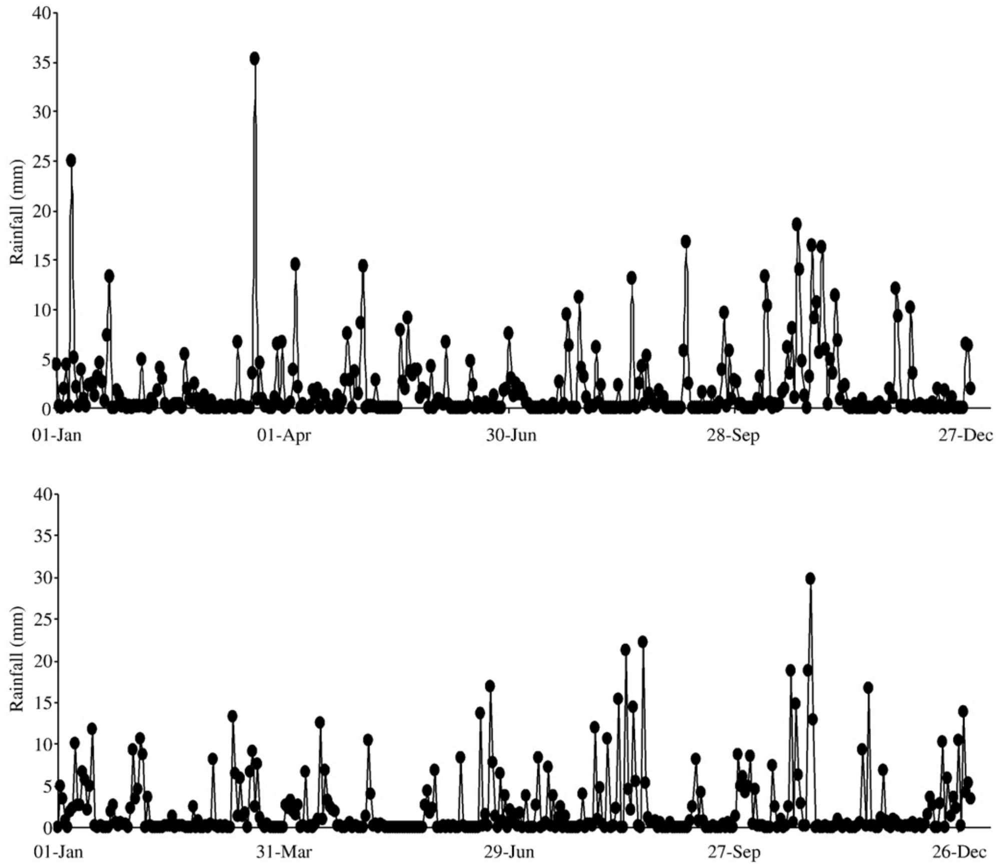

Fig. 4. Rainfall (mm) distribution in the year 2004 (upper) and 2005 (lower).

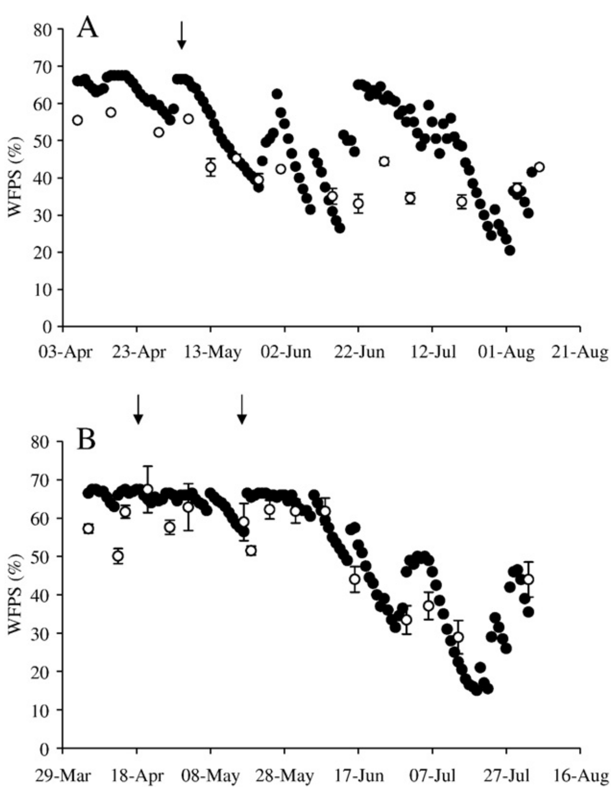

Fig. 5. Comparison between the measured (○) and modeled (●) WFPS from CN_2 treatment in 2004 (A) and 2005 (B). (Error bars for measured values are ± standard error). Arrows indicate time of N fertilizer application.

been obtained for low to zero N inputs by Terry et al. (Pahokee muck soil; rainy season; 1981), Beheydt et al. (Belgium; sandy loam soil; rainy season; 2007) and Qiu et al. (China; paddy soil; low precipitation; 2009).

The wide range of CAN fertilizer addition in this study allowed a linear regression of modelled *vs.* measured cumulative fluxes which suggest for the overall data set that DNDC is reflecting observed values. This is illustrated in Fig. 6, where observed and modelled data from Table 2 have been plotted. Here, because there is no significant difference between conventional and reduced tillage, flux data of both tillage were pooled together. The regression ($y = 0.78x - 6.5$) accounts for 85% of the variation in the data, but with the simulated values (y) underestimating measured values (x) by 24%. Similar data cited by De Vries et al. (2005), from a range of published studies on grasslands and cereal systems, are also presented in Fig. 6. Data from our study fit well within this group and improve the slope of the regression to $y = 1.1x + 0.35$, ($r^2 = 0.76$).

3.2. Pasture field

Our results suggest that DNDC is unduly sensitive to initial soil organic carbon content. Measured and modelled cumulative fluxes of N_2O from the cut and grazed pasture are shown in Table 3 (annual) and highlight the poor fit of the model where high relative deviation values were calculated. This poor fit of DNDC for grassland was also observed by Beheydt et al. (2007) where 22 long-term measurements of direct N_2O emissions from soils in an intensive agriculture were used to validate DNDC. The only major difference between our arable and the cut and grazed pasture soils is that the latter has significantly higher organic carbon content (0.038 as opposed to 0.019 kg C kg^{-1} dwt). Changing the initial soil organic C content for the model to the lower values of the arable soil greatly improved the fit of the model to

Table 2
Observed and modelled seasonal N_2O emissions from the arable conventional and reduced tillage plots.

Cumulative emissions for cropping season (g N_2O N ha^{-1})					Relative deviation (%)
2004 season	Treatment	Observation	Model	Difference	
Conventional tillage	140 kg N ha^{-1}	788	780	−8	−1
	70 kg N ha^{-1}	269	350	+81	30
	0 kg N ha^{-1}	2	110	+108	5400
Reduced tillage	140 kg N ha^{-1}	978	590	−388	−40
	70 kg N ha^{-1}	494	220	−274	−55
	0 kg N ha^{-1}	87	30	−57	−66
2005 Season					
Conventional tillage	159 kg N ha^{-1}	1053	993	−60	−6
	79 kg N ha^{-1}	563	450	−113	−20
	0 kg N ha^{-1}	170	110	−60	−35
Reduced tillage	159 kg N ha^{-1}	1058	793	−265	−25
	79 kg N ha^{-1}	567	320	−247	−44
	0 kg N ha^{-1}	135	10	−125	−93

the observed values (Fig. 7). By doing so, initial concentration of soil nitrate is changed from 11.4 to 5.82 mg N kg^{-1} and that of ammonium is reduced from 1.14 to 0.582 mg kg^{-1}. Soil denitrification was reduced and consequently N_2O flux for the fertilized plots was reduced to 2797 g N_2O N ha^{-1} (a relative deviation of 9%) and that for the control plots to1110 g N_2O N ha^{-1} (a relative deviation of 5%) as shown in Table 3. This would question the present algorithms in the model describing the effect of soil organic carbon content on N_2O flux. The model is very sensitive to SOC (Li et al., 1996, 2001; Beheydt et al., 2007); a 20% increase in SOC corresponds to a 58% increase in N_2O flux (see below). Soil organic matter enhances the soil's physical, chemical

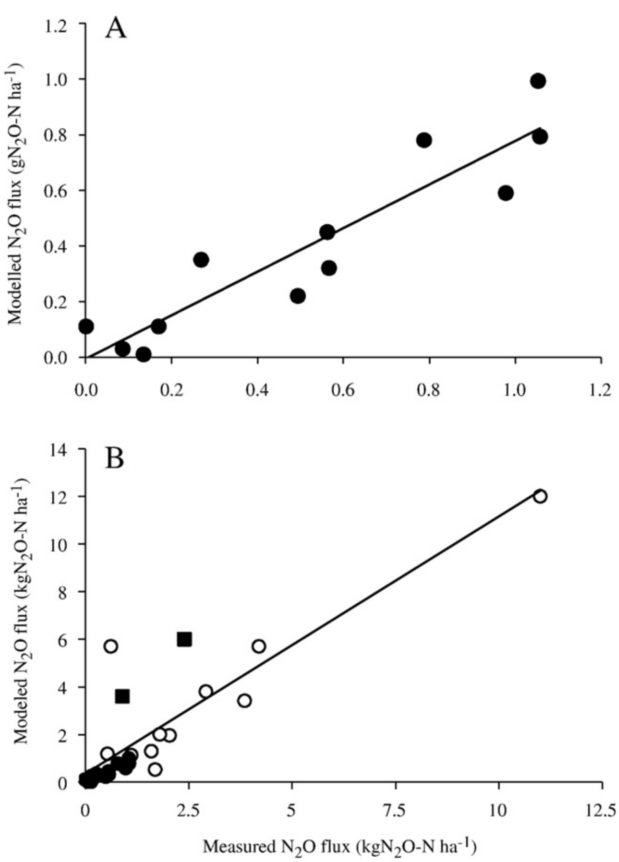

Fig. 6. (A) Correlation between the model-simulated and field measured N_2O fluxes for the arable field. $y = 0.78x - 6.5$ ($r^2 = 0.85$). Data of conventional and reduced tillage were pooled together. (B) Correlation between the model-simulated and field measured N_2O fluxes from our arable (●), pasture (■) and other literature DNDC studies (○)— De Vries et al. (2005). $y = 1.1x + 0.35$, ($r^2 = 0.76$).

and biological properties in a complex way. The increase of soil organic matter has a great effect on N_2O flux because certain organic matter pools correlate with microbial activity. For example, the availability of carbon in soils is known to strongly influence the activity of micro-organisms and as a consequence has a major effect on the cycling and turnover of nutrients (Jandl and Sollins, 1997; Magill and Aber, 2000; Marschner and Bredow, 2002; McDowell, 2003).

Similar over-estimates 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). The high simulated N_2O peaks, for both the control and fertilized plots, observed around February 2004, after changing SOC (Fig. 7), may be mainly because of the model overestimating WFPS (Beheydt et al., 2007) as shown in Fig. 8. Water filled pore space leads to high microbial activity by affecting the population of aerobic and anaerobic micro-organisms in the soil (Linn and Doran, 1984).

In, this study, however, the soil types of both the arable and pasture fields were very similar physically and chemically, except for soil organic carbon, and were both free draining soils, over the same period, higher cumulative N_2O fluxes were released from the pasture compared with the arable field. These were observed from the field measurements and predicted by DNDC. Differences in fluxes here, were attributed to land use which is an important driving factor for carbon and nitrogen dynamics of landscape ecosystems (Priess et al., 2001) and therefore can have a significant impact on N_2O flux (IPCC, 2000). Our aim in this paper was to assess the applicability of the DNDC model in Ireland so that in the future, it can be used to assess the impact of various alternative management strategies under future climate. This study provides the results of that evaluation, which is a prerequisite for using the model for assessing management impacts. A detailed description of management impacts on N_2O emissions in Ireland can be found in Abdalla et al. (2009).

3.3. Sensitivity analysis

Given the reasonable fit of the model to the conventional tillage data, the sensitivities of the model outputs for the arable field to changes in soil characteristics, fertilizer N and climate were also investigated. The following scenarios were chosen:

(1) changes in bulk density
(2) changes in initial SOC
(3) changes in fertilizer use
(4) changes in rainfall and air temperature.

The DNDC model appears highly sensitive to changes in bulk density and as mentioned previously, SOC. Increasing the bulk density of the soil from 1.4 to 1.8 g cm^{-1}, an increase of 29%, resulted in a more than equivalent increase in both the apparent rate of N released by denitrification (42%) and the predicted N_2O flux (62%) (Table 4). Bulk density reduces macro pore space and increase WFPS and consequently leads to high microbial activity (Abassi and Adams, 2000). Thus, according to DNDC, any management treatment that increases the bulk density of the soil, such as reduced tillage, would also significantly increase N_2O flux, as has been observed by Aulakh et al. (1984), Baggs et al. (2003) and Six et al. (2004). Reduced tillage is also associated with increases in SOC

Table 3
Observed and modelled annual N_2O emissions from the cut and grazed pasture (2004).

Seasonal emissions (g N_2O N ha^{-1})				Relative deviation (%)
Treatment	Observation	Model	Difference	
Before adjusting SOC				
200 kg N ha^{-1}	2573	6613	4040	157
0 kg N ha^{-1}	1054	3970	2926	360
After adjusting SOC				
200 kg N ha^{-1}	2573	2797	224	9
0 kg N ha^{-1}	1054	1110	56	5

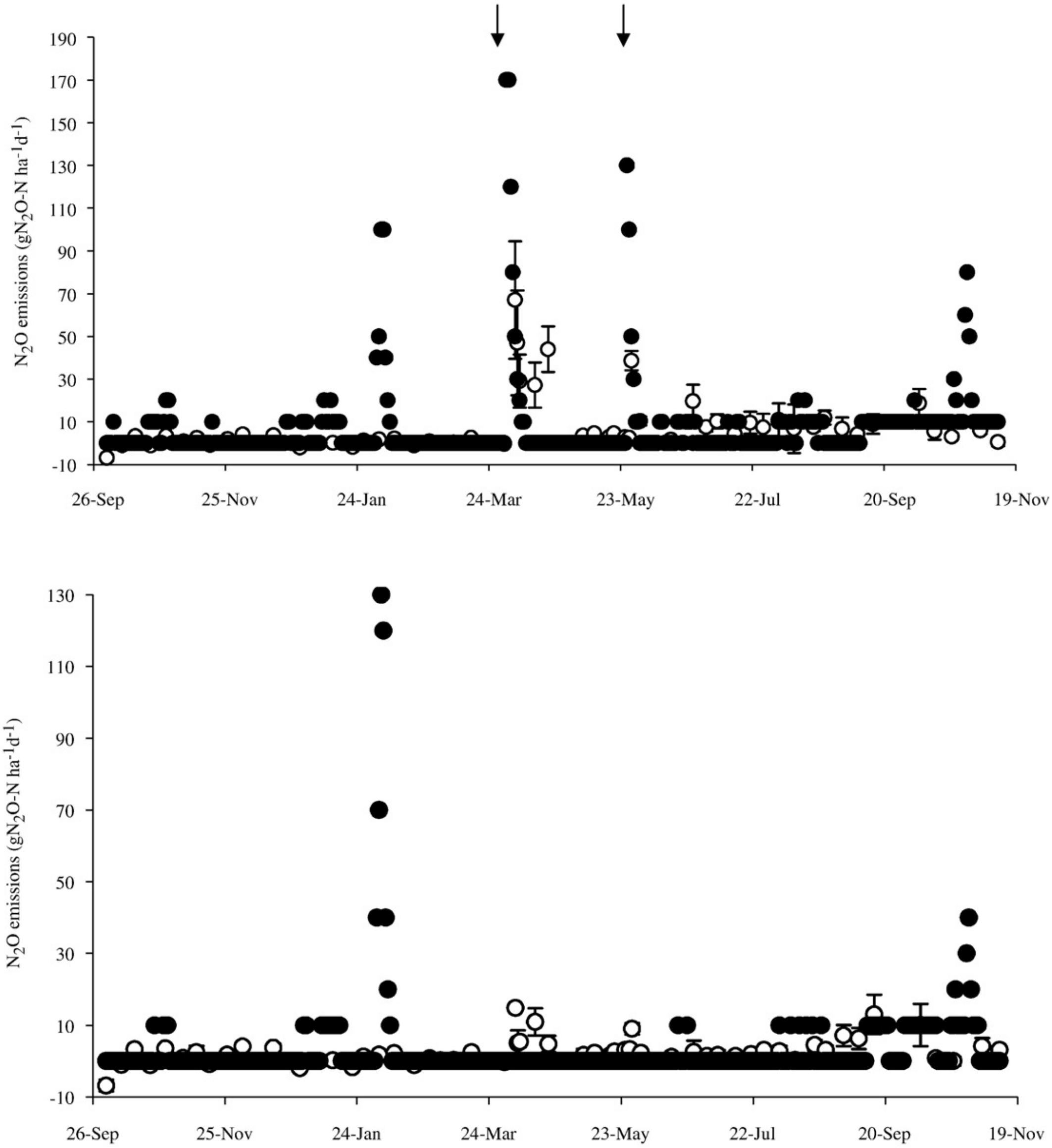

Fig. 7. Comparison of model-simulated (●) and field measured N_2O (○) flux from the fertilized (upper) and control pasture (lower) treatments in 2003/04 after the correction of SOC. (Error bars for measured values are ± standard error). Arrows show time of fertilizer application.

(Smith, 2004, 2005; Alvaro-Fuentes et al., 2008). Increasing the baseline SOC value by 20% increases N_2O flux by 65%. Hence for at least two associated aspects of reduced tillage, N_2O flux has been predicted to increase significantly, questioning the use of this management technique as a means of lowering total greenhouse gas emissions in the soil we studied here.

Model outputs were also highly sensitive to changes in fertilizer type, with a switch from the principal form of N fertilizer used in cereal production in Ireland (CAN) to urea or ammonium sulphate fertilizers resulting in predicted increases in N_2O flux of 50 and 55%, respectively. These flux increases from ammonium-based fertilizer and urea are in agreement with Clayton et al. (1997), but in contrast to other studies done by Velthof et al. (1997) and Thornton et al. (1998). In our situation, where the soil pH is very high (7), application of ammonium-based fertilizer and urea may increase soil nitrification (Harrison and Webb, 2001) and consequently the N_2O flux. Model outputs, however, proved the most sensitive to changes in air temperature. Here, an increase of 1.5 °C in the daily average air temperature resulted in a 62% increase in N_2O flux and a 57% increase in the rate of total N released by soil denitrification. Temperature increases soil microbial population response to other perturbations such as fertilization and rainfall (Bramley and White, 1990). This is interesting as with the future global warming, N_2O flux from soil will have strong positive feedback. In contrast, changes in rainfall of ± 20% resulted in changes in N_2O flux of 10–15% (Table 4).

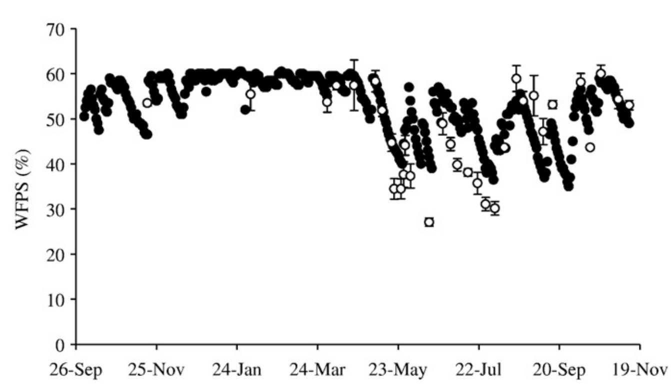

Fig. 8. Comparison between the measured (○) and modeled (●) WFPS from the cut and grazed pasture in 2003/04. (Error bars for measured values are ± standard error). Arrows indicate time of N fertilizer application.

Table 4
Sensitivity of DNDC to changes in soil characteristics, management and climate for the spring barley field (conventional tillage, 2004).

Scenario	Mineralization (kg N ha^{-1} y^{-1})	Annual N_2O flux (kg N ha^{-1} y^{-1})	Denitrification (kg N ha^{-1} y^{-1})
*Baseline	257.4	*1.64*	*5.31*
Bulk density (g cm^{-1})			
1	194	0.67	2.72
1.4	290.8	2.11	5.67
1.8	324.2	2.65	7.53
Initial soil organic carbon			
+20%	305.8	2.59	7.52
−20%	211.1	0.69	2.79
Fertilizer type			
Urea	257.4	2.46	7.04
Ammonium sulphate	257.4	2.54	7.14
Rainfall			
+20%	267.1	1.76	5.78
−20%	244.5	1.41	4.25
Air temperature			
+20%	269.9	2.65	8.36
−20%	243.2	0.93	3.49

*Baseline scenario: bulk density 1.4 g cm^{-3}, SOC 0.0194 kg C kg^{-1}, fertilizer applied and timing (140 kg N/ha CAN, on the 27th of April), annual average max. and min. air temperature 13.7 and 4.8 °C and average daily precipitation 2.2 mm and soil tillage to 22 cm depth carried in March 5 weeks before planting.

For the arable field, emission factors for the modelled data calculated on daily flux ranged from 0.3 to 0.6% of the fertilizer N applied, whereas measured EFs ranged from 0.4 to 0.7% of the fertilizer N applied. Modelled and measured EFs are comparable, but are both significantly lower than the IPCC default value of 1–1.25% (Bouwman, 1996; IPCC, 2006). Here, due to our system limitation, the post harvest flux of N_2O is not included in this calculation, which would change the flux budget and values of EFs (Smith et al., 1998; Syväsalo et al., 2004). Literature measured EF values for cereal crops are extremely variable, ranging from 0.2 to 8% (Eichner, 1990; Kaiser et al., 1998; Smith et al., 1998, Dobbie et al., 1999; Crutzen et al., 2008) and are dependent upon temperature, moisture and soil type (Flechard et al., 2007). For the pasture, a higher annual EF of 1.37% was calculated from the simulated flux before SOC correction; however a value of 0.88% was calculated following SOC correction. This is comparable to the calculated EF of 0.83% for the measured flux.

4. Conclusions

In its present form DNDC is suitable for simulation of C and N dynamics in medium to high N input systems, but less suitable for low input systems, with the accuracy of the prediction being highly dependent on the level of fertilizer application. High fertilizer inputs produce low relative deviations between modelled and measured fluxes (~1–6%) for the arable field under conventional tillage. Prediction of N_2O fluxes from reduced tillage plots however, was poor, with DNDC consistently underestimating measured field values. Here relative deviations ranged from −20 to −93%. One major disadvantage of the model was the limited choice of tillage input options available, none describing the reduced tillage treatment used in this study. Prediction of N_2O fluxes from the cut and grazed grassland was also poor with model outputs significantly overestimating measured field values giving relative deviations of 150–360%. The high simulated N_2O peaks, for both the control and fertilized plots, observed around February 2004, after changing SOC, were considered to be because of the model overestimating WFPS. Our sensitivity analysis suggests that DNDC overestimates the effect of SOC content on nitrification and denitrification. By reducing the SOC input values to those of the cereal field we could significantly improve the fit of the model, reducing relative deviation scores to approximately 5–10%. Sensitivity analysis also highlighted air temperature as the main determinant of N_2O flux, an increase in mean daily air temperature of 1.5 °C resulting in almost 65% increase in the annual cumulative flux. This is interesting as with the future global warming, N_2O flux from soil will have strong positive feedback. If the DNDC model is to be used for greenhouse gas accounting in Ireland, or for examining the impact of management and climate change in Irish agriculture, model performance will need to be improved for grassland and low input systems.

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