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Development and application of a mechanistic model to estimate emission of nitrous oxide from UK agriculture

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Abstract

A mechanistic model of N_2O emission from agricultural soil (DeNitrification-DeComposition—DNDC) was modified for application to the UK, and was used as the basis of an inventory of N_2O emission from UK agriculture in 1990. UK-specific input data were added to DNDC's database and the ability to simulate daily C and N inputs from grazing animals and applied animal waste was added to the model. The UK version of the model, UK-DNDC, simulated emissions from 18 different crop types on the 3 areally dominant soils in each county. Validation of the model at the field scale showed that predictions matched observations well. Emission factors for the inventory were calculated from estimates of N_2O emission from UK-DNDC, in order to maintain direct comparability with the IPCC approach. These, along with activity data, were included in a transparent spreadsheet format. Using UK-DNDC, the estimate of N_2O-N emission from UK current agricultural practice in 1990 was 50.9 Gg. This total comprised 31.7 Gg from the soil sector, 5.9 Gg from animals and 13.2 Gg from the indirect sector. The range of this estimate (using the range of soil organic C for each soil used) was 30.5–62.5 Gg N. Estimates of emissions in each sector were compared to those calculated using the IPCC default methodology. Emissions from the soil and indirect sectors were smaller with the UK-DNDC approach than with the IPCC methodology, while emissions from the animal sector were larger. The model runs suggested a relatively large emission from agricultural land that was not attributable to current agricultural practices (33.8 Gg in total, 27.4 Gg from the soil sector). This 'background' component is partly the result of historical agricultural land use. It is not normally included in inventories of emission, but would increase the total emission of N_2O-N from agricultural land in 1990 to 78.3 Gg.

Keywords: Inventory; Greenhouse gas; Agricultural cropland; Grassland; IPCC

1. Introduction

Signatory states to the United Nations Framework on Climate Change (UNFCC) are required to produce an annual national inventory of nitrous oxide (N_2O) emission from all anthropogenic sources. This inventory is intended to advise the magnitude and change in total emissions and gives an indication of which sectors of activity are responsible for the greatest emissions. Estimates of the contribution of agriculture to the total UK emission have indicated an increase over recent years as industrial sources (particularly adipic and nitric acid manufacture) have declined (Salway et al., 2001). Salway et al. (1999) estimated that in 1990 47% of the

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total UK emission was from agriculture (63.9 Gg N_2O-N). In order to comply with the Kyoto Protocol on greenhouse gas emissions, 1990 levels of N_2O emission from EU countries are required to be reduced by 8% in the period 2008–2012. Mitigation strategies require an agreed inventory against which measures to reduce N_2O emissions from agricultural sources can be judged.

The framework that is used currently to estimate sources of N_2O from UK agriculture is that produced by the Intergovernmental Panel on Climate Change (IPCC, 1997). This approach utilises emission factors (EFs) which specify the proportion of N input that is emitted as N_2O, and are used with activity data (such as animal numbers, fertiliser use and crop areas) to calculate emission. These EFs are derived from field measurements at sites in a variety of countries, with different soil types, climate and crops (IPCC, 1997). Default EF values are provided, but each has a large range, which reflects the contrasting background conditions of the measurements and leads to a large uncertainty in the emission estimate (Brown et al., 2000). An approach is required which assigns some of this variation to its controlling variables by producing an estimate that takes into account factors such as soil, climate and fertiliser type. Possible approaches include the development and application of more detailed empirical relationships, which would account for such factors, or the use of a suitable mechanistic model to estimate emissions. This study used the rainfall-driven process-based model called DNDC (DeNitrification-DeComposition) (Li et al., 1992), originally written for USA conditions, to provide the basis for an improved UK N_2O emission estimate. The development of this model for the UK, and the estimates of N_2O emissions from agricultural land for 1990 derived from it, are discussed in this paper.

2. Model description

The DNDC model (Li et al., 1992) was selected to produce an annual UK emission estimate because it has reasonable data requirements, has produced robust estimates for other countries and is suitable for simulation at appropriate temporal and spatial scales for this exercise. DNDC is a process-oriented simulation model of C and N biogeochemistry in agricultural ecosystems, developed to assess nitrous oxide (N_2O), nitric oxide (NO), dinitrogen (N_2), ammonia (NH_3) and carbon dioxide (CO_2) emissions from agricultural soils. The model contains 4 main sub-models (for full details see Li et al., 1992 and Li, 2000):

1. The soil climate sub-model calculates hourly and daily soil temperature and moisture fluxes in one dimension. The soil is divided into horizontal layers, water fluxes and heat flows between which are determined by soil texture and the gradients of soil moisture potential (for water fluxes) and soil temperature (for heat flows).
2. The crop growth sub-model simulates crop biomass accumulation and partitioning based on thermal degree days and daily N and water uptake. If N or water stress occurs, crop growth will be depressed.
3. The decomposition sub-model calculates decomposition, nitrification, NH_3 volatilisation and CO_2 production on a daily timestep. Decomposition can occur in 3 organic matter pools: decomposable residues, microbial biomass and humads, each of which has a labile and resistant component. The effect of soil properties such as soil temperature, clay fraction and water content is modelled using reduction factors that constrain decomposition rate from the maximum in non-optimum conditions.
4. The denitrification submodel tracks the sequential biochemical reductions from nitrate (NO_3) to NO_2^-, NO, N_2O and N_2 based on soil redox potential and dissolved organic carbon (DOC) concentration. Soil factors such as pH and temperature are taken into account. The growth and death of denitrifier populations are simulated, which enables consumption of C, NO_3^-, NO_2^-, NO and N_2O.

DNDC has been used for simulation at a regional scale for the United States (Li et al., 1996) and China (Li et al., 2001). Some alteration of the database structure and content of DNDC was required in order to improve suitability for use in the UK. To distinguish it from the original DNDC, this version will be referred to as UK-DNDC.

2.1. Input data

UK-specific data on soil characteristics, crops, daily climate, livestock and farming practice for each county were used as input data to the model databases. For each county, the 3 dominant soils were selected on the basis of areal coverage on agricultural land (from databases of Soil Survey and Land Research Centre (SSLRC), Macaulay Land Use Research Institute and the Department of Agriculture and Rural Development, Northern Ireland). The soils accounted for, on average, 60% of the total agricultural area of each county (excluding common rough grazing areas). Soils were classified according to a combination of soil texture (Hodgson, 1976; Clayden and Hollis, 1984) and HOST class (Boorman et al., 1995). HOST (Hydrology of Soil Types) is a system that categorises all UK soils according to the hydrological characteristics of the soil and underlying substrate. The texture/HOST classification gave a total of 23 categories of mineral soils for England and Wales, each having a mean and standard deviation of each of the input data required by UK-DNDC calculated from all soils within the SSLRC database. Wherever the input data were not available for mineral soils from Scotland and Northern Ireland, they were modelled using pedo-transfer functions for saturated hydraulic conductivity (Hollis and Woods, 1989), water holding capacity (Simota and Mayr, 1996) and bulk density (Rawls, 1983). For organic soils, data existed for % soil organic carbon, pH and bulk density (the latter for England and Wales only). Where required input data were not available for Scottish and Northern Ireland organic soils, published data on UK blanket peats (Burton and Hodgson, 1987; Milne and Browne, 1997; Bembridge, 1986) were used together with SSLRC data for the Winter Hill soil series (considered most similar to Northern Ireland blanket peat).

Input data on properties of the 3 dominant soils in each county included (as in DNDC) minimum and maximum soil organic carbon, bulk density, pH, total porosity, clay proportion, water-filled pore space at field capacity and permanent wilting point, and saturated hydraulic conductivity. In an analysis of the sensitivity of DNDC to variability in soil properties, Li et al. (1996) concluded that the majority of the variability in N_2O emission caused by the heterogeneity of soils could be captured by calculating N_2O emissions at minimum and maximum values of soil organic C reported for each state in the USA. For each soil type, therefore, UK-DNDC was run twice, once using the minimum value for soil organic C and a second time with the maximum value. Model runs were undertaken for each of the 3 soil types, and emission per crop per county calculated as

$$E_{ij} = \sum_{k1,3} \left(R_{ij} A_{ij} \frac{\mathrm{SA}_{jk}}{\sum_{k1-3}(\mathrm{SA}_j)} \right), \qquad (1)$$

where E_{ij} is N_2O-N emission from crop i in county j, R_{ij} is emission from crop i in county j (kg N ha^{-1}), A_{ij} is area of crop i in county j and SA_{jk} is area of soil k in county j.

A total of 18 crop types were simulated, which adhered as closely as possible to the categories in the MAFF Agricultural and Horticultural Census (MAFF, 1991a). Crop areas for each county were taken from MAFF (1991a), SOAEFD (1991) and DANI (1991). Parameters for each of these crops were included in the crop library, as in the original DNDC. These included crop height, optimum yield, C:N ratios of grain, root and shoot and water requirement. Fertiliser use for each crop was taken from the Survey of Fertiliser Practice (MAFF, 1991b), with application dates and the total fertiliser proportioned through the year according to MAFF (1994) and Halley and Soffe (1988). Other information on farming practices for each crop included dates of planting, harvest and tillage, yield data (from Halley and Soffe, 1988 and Nix, 1991) and straw disposal information (D. Wilkins, MAFF and Cathy Knott, Processors and Growers Research Organisation, pers. comm.). In UK-DNDC, an extra library file for irrigation was included, which specified irrigation to each crop type in England and Wales using county- and crop-specific statistics (MAFF, 1991c), which were used to establish a 'pool' from which irrigation could be taken. During simulations, irrigation was triggered when the crop suffered water deficiency and water was extracted from this pool according to the crop water demand until the pool was exhausted. It was assumed that no irrigation occurred in Scotland and Northern Ireland. The required weather data for UK-DNDC were daily rainfall, minimum and maximum temperature (supplied by British Atmospheric Data Centre (BADC)) and N in rainfall for each county (from UK Acid Deposition Network) together with longitude and latitude of each county. Weather stations from the BADC were selected on the basis of availability of daily data for each variable for 1990. Proximity analysis was used to assign BADC and UK Acid Deposition Network stations to each county.

The livestock element of the database and model was changed significantly from DNDC. Six types of animal were considered (dairy cattle, non-dairy cattle, pigs, 'upland' sheep, 'lowland' sheep and poultry), maintaining consistency with the IPCC approach. N excretion values, based on the dietary N balance calculations of Smith et al. (2000b) and Smith and Frost (2000) for each class of animal in the Agricultural Census (MAFF, 1991a), were used to calculate representative excretion rates for the 6 classes of animals used. The number of animals in each county contributing to each livestock N source (excretion while grazing, FYM and slurry) was calculated using data from the Agricultural Census (MAFF, 1991a; SOAEFD, 1991), assuming a 180 day grazing season (Julian day 91–272). It was assumed that during the grazing period, dairy cows would be indoors for 4 h per day during milking, so one-sixth of the daily N excretion contributed to the FYM or slurry components, rather than grazing. It was assumed that ca. 5% of pigs grazed outdoors all year, all poultry were kept indoors and sheep were kept outdoors, with the exception of 30 days (Julian days 1–30) when they were assumed to be indoors during lambing (as Chadwick et al., 1999; Misselbrook et al., 2000). When not contributing to the 'grazing' pool, animal excreta were allocated to the slurry or FYM waste management systems according to the ratios assumed in the inventories of Chadwick et al. (1999) and Misselbrook et al. (2000).

It was assumed that applications of FYM and slurry were made four times a year. The timing of these was taken to be the mid-point of the year-quarters presented in Smith et al. (2000) and Smith et al. (2001a, b), with the proportions of the annual application taking place on these dates also taken from this source. For each animal class, the proportion of excretal N as urine and dung was specified using data from Jarvis et al. (1989), van Vuuren and Meijs (1987), Orr et al. (1995) and Whitehead (1995). For N deposited while grazing, N was 'applied' on a daily basis, with N as urine immediately entering the available N pool in the top 2 layers of soil and N in dung declining linearly over 200 days. Values for the rate of disappearance of dung pats range from 100 days (Wall and Strong, 1987) to 21 months for 75% disappearance (Lumaret and Kadiri, 1995).

Before N was 'applied' as FYM or slurry, the emission of N as N_2O, NO_x and NH_3 during animal housing and storage of animal waste was calculated, using the housed livestock N_2O emission inventory calculations of Chadwick et al. (1999) and the NH_3 inventory of Misselbrook et al. (2000). This loss of N was subtracted from the manure N before its application was simulated. The division of spread FYM and slurry between arable and grassland sectors was also taken from Chadwick et al. (1999).

2.2. Model validation

Satisfactory validation of the model is essential if a confident estimate is to be established. UK-DNDC output was compared, at the field scale, with 16 datasets from contrasting soil, crop and fertiliser types, as well as sources of N from applied animal waste, urine and dung. Although the estimate reported in this inventory was annual, comparisons with observations were made on a daily rather than annual basis because the interpolation between observations, required to produce an annual estimate, would be of questionable accuracy.

2.3. Model estimates

In order to be consistent with the IPCC (1997) approach, model estimates were converted into emission factors from each N source. In order to do this, 'background' runs were undertaken, which assumed the absence of animals and N input, except that from the atmosphere. Emission factors were then calculated as:

$$\mathrm{EF} = \frac{\text{emission with N source-emission without N source}}{\text{total N input from source}}, \quad (2)$$

where N source may be fertiliser, FYM, slurry or N deposited while grazing.

The results were then displayed in a transparent manner in a spreadsheet (Microsoft Excel 97). Emission summaries were presented using the framework of IPCC (1997) sectors: soil (emission from fertilizer, applied animal wastes, N deposited while grazing and N from crop residues), animals (housing and storage) and indirect (emission of N from leached nitrate and re-deposited NH_3). Activity data (e.g. animal numbers, crop areas, fertiliser rates) from which N inputs were calculated, together with the EFs which were used to calculate emission of N as N_2O, were presented in the spreadsheet. Since DNDC and UK-DNDC do not simulate N_2O emission during the housing of animals or the storage of animal manures, the emissions of N_2O from these sources from the inventory of Chadwick et al. (1999) were added to the spreadsheet output, in order to include an estimate of emission from the 'animal' sector.

The IPCC (1997) methodology produces an estimate of emission from 'indirect' sources (i.e. from leached N and deposited volatilised NH_3), using EF5 (0.025 kg N_2O-N/kg N leached) and EF4 (0.01 kg N_2O-N/kg N deposited), respectively to calculate emission. UK-DNDC estimates N leached and volatilised and to these pools EF5 and 4, respectively, were applied to calculate N_2O-N emission from the indirect sector. In order to be consistent with the IPCC approach, the total N leached was included in the estimate (i.e. the 'background' leached N was not subtracted from the total). While the use of EF5 for leached N is far from satisfactory, due to its large uncertainty, it was used in the absence of a suitable alternative, because of the lack of data on N_2O emission from nitrification and denitrification in water-bodies.

2.4. Sensitivity analysis

Sensitivity of the model output to variation in the input values was investigated by changing the value of the single input variable and holding all others at baseline values. The analysis concentrated on weather variables (temperature and precipitation) and changes in farming practice (e.g. timing, rate and form of N fertiliser). The baseline scenario for this analysis was a grass crop in Bedfordshire receiving 177 kg N ha^{-1} as ammonium nitrate, with daily weather for this county in 1990.

3. Results

3.1. UK-DNDC-based estimates of N_2O emission

The total N_2O-N emission from UK current agricultural practice in 1990 was estimated to be 50.9 Gg, comprising 31.7 Gg from soil, 5.9 Gg from animals (this does not include emission from N deposited while grazing or from applied slurry and FYM, which are included in the soil sector) and 13.2 Gg from the indirect sector (Table 1). Of the emission from soil in the UK, 77% was attributed to fertiliser, 17% from applied animal waste and 5% due to emission from N deposited while grazing. The large emission estimate from fertiliser reflects, in part, the relatively large emission factor from

Table 1
UK-DNDC emission estimates for soil, animal and indirect sectors in UK countries in 1990

Source of emission	UK-DNDC estimate (Gg N_2O-N)				
	England	Wales	Scotland	N. Ireland	UK
Emissions from soil:					
Fertiliser	18.91	1.93	1.95	1.77	24.56
Applied animal waste	3.86	0.13	0.37	1.08	5.43
N deposited while grazing	0.83	0.26	0.50	0.14	1.73
Soil total	23.60	2.32	2.82	2.99	31.73
Total soil emission from:					
Grassland	16.75	2.26	2.47	2.78	24.27
Cereals	4.10	0.04	0.22	0.13	4.50
Other crops	2.75	0.02	0.13	0.08	2.97
Total emission from 'Animals' (i.e. from housing and waste storage)	3.89	0.53	0.87	0.63	5.93
Total Indirect	7.59	0.93	2.95	1.76	13.23
Background emission	14.38	2.39	14.22	2.82	33.80
Overall total (current agricultural practice + soil background)	46.50	5.83	18.45	7.55	78.32

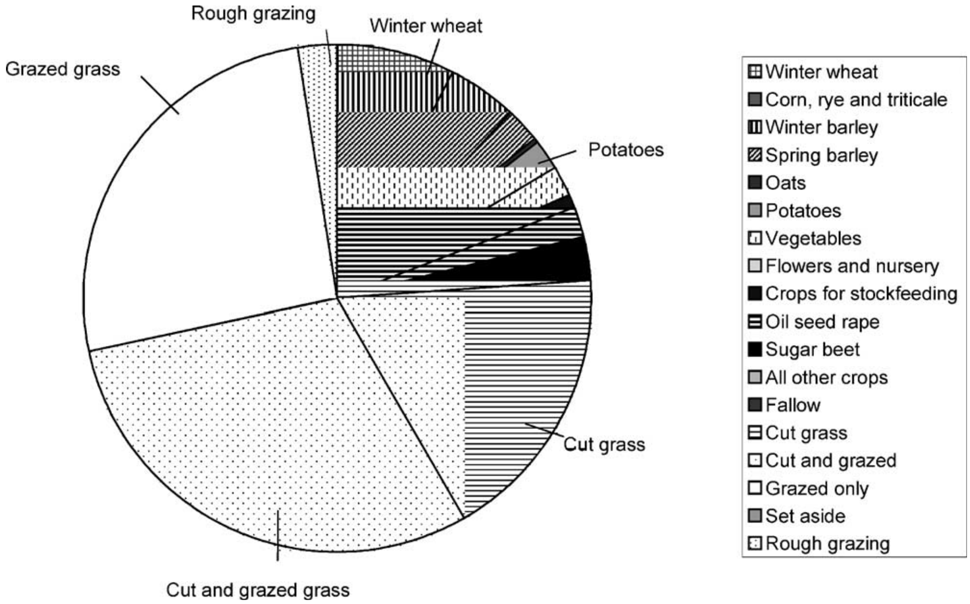

Fig. 1. Contribution of each of the 18 simulated crops to the total estimate (50.9 Gg N_2O-N) of N_2O emission from UK agriculture in 1990. (Emissions from corn, rye and triticale, flowers and nursery, all other crops, fallow and set-aside too small to be visible).

this source (see below) but mainly the large input of N via fertiliser.

Emission factors for each N source showed a large range across soil and crop types. In the case of fertiliser, for example, the mean predicted EF was 1% with a range of 0.1–14.8%, although over 90% of values were below 2%. Large EFs were calculated, for example, for potatoes, vegetables and sugar beet. UK emissions from soils under grassland, cereals and all other crops (Table 1) equate to 2.0, 1.2 and 2.2 kg N ha^{-1}, respectively, on average across all counties. Annual total UK emissions (i.e. including indirect losses) from grassland, cereals and all other crops were 35.1, 5.7 and 4.2 Gg, respectively (Fig. 1), reflecting differences in both area and emission between these crop groups. These emissions equate to 2.9, 1.6 and 3.1 kg N ha^{-1} on average across all counties for grassland, cereals and other crops, respectively. The latter class includes some crops which have relatively small areal coverage but large estimated emission rates, such as potatoes, vegetables and sugar beet.

The counties with the largest emissions of N_2O-N per hectare were, in decreasing order, Devon, Cumbria, Norfolk, North Yorkshire and Shropshire (Fig. 2). The high emissions from these counties are attributed in part to a greater-than-average proportion of the total agricultural area in these counties that is used for grass (Devon, Shropshire, Cumbria), potatoes (Norfolk, Shropshire) and sugar beet (Norfolk, Shropshire). These are crops that were found to have high soil emissions, on average across the UK (grass (excluding rough grazing) was 3.5 kg N ha^{-1}, potatoes 3.7 kg N ha^{-1}, sugar beet 4.1 kg N ha^{-1} and oilseed rape 1.6 kg N ha^{-1}). These emissions reflect, in part, the relatively high fertiliser applications to these crops (MAFF, 1994) and the high N content of their residues. Sugar beet residue, for example has a C:N ratio of 19.8, compared with 72.8 for wheat (C. Rahn, HRI, pers. comm.).

Model runs to provide the 'background' emission for Eq. (2) estimated that 27 Gg of N_2O-N was emitted from the soil in the absence of fertiliser and animal manures; almost as much as was predicted to occur from soil as the result of the application of these N sources (32 Gg).

3.2. Model validation

The agreement between simulated and measured data was generally good. Examples are given in Fig. 3a–c. For the 2-yr grassland dataset of Clayton et al. (1997) (Fig. 3a) UK-DNDC simulated 3 strong peaks in each year associated with fertiliser application of 120 kg N ha^{-1} as ammonium nitrate. In the first year, the measured and modelled peak from the first application agreed well, while no real peak was measured for the second application and a small peak for the third application, despite rainfall having occurred in the days previous on both occasions. In the second year, measured and simulated peaks are apparent for the first and second applications, but no peak was observed in the field for the third application, despite 7 mm of rainfall occurring on the day before and day of application combined. The observed peak for the second application was greater than the model-simulated peak. The baseline emissions (i.e. emission between peaks) of

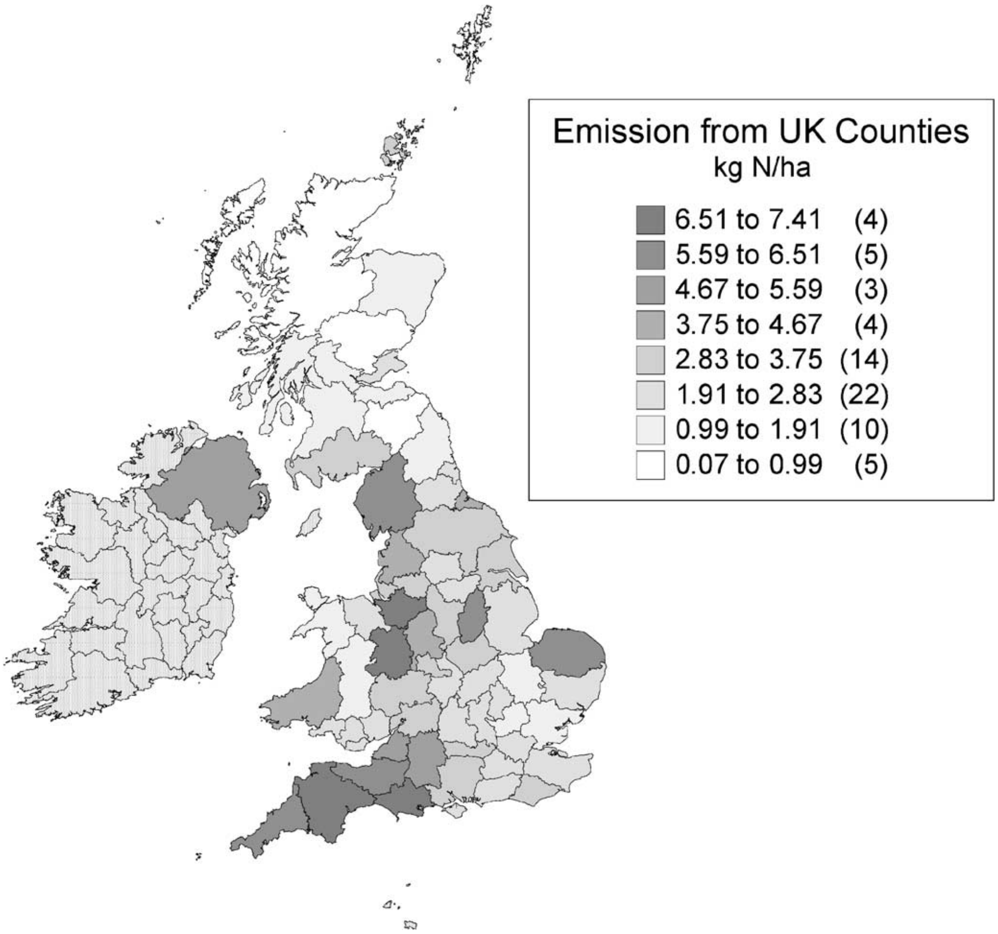

Fig. 2. Estimated emission (kg N ha^{-1}) of N_2O from agriculture in each county of Great Britain and overall average emission for Northern Ireland.

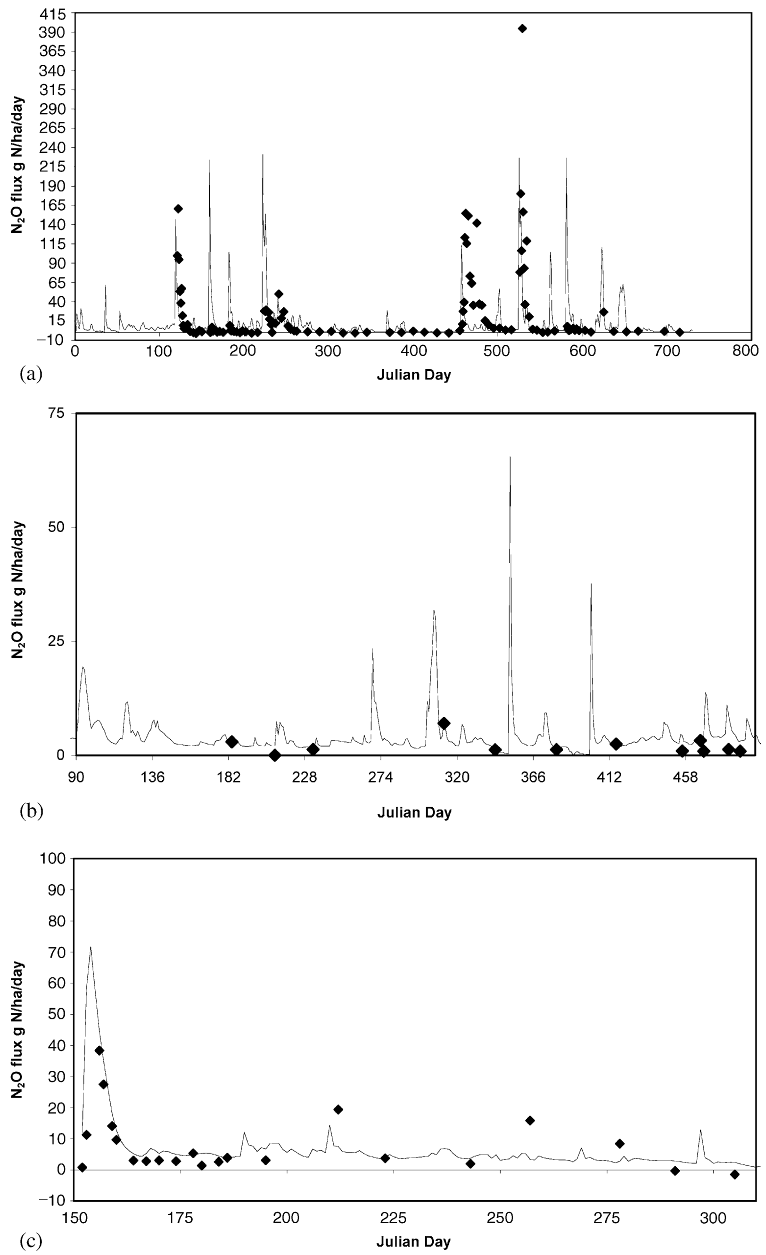

Fig. 3. Comparison of modelled (——) and measured (◆)N_2O-N emission from (a) a grassland site near Edinburgh with clay loam soil, receiving 360 kg N ha^{-1} as ammonium nitrate (Clayton et al., 1997). (b) A winter wheat site in SE England with a silty-loam soil, receiving 225 kg N ha^{-1} as farmyard manure (Harrison et al., 1995) and (c) a grassland site in SW England with clay loam soil, receiving urine (equivalent to 528 kg N ha^{-1}) (Yamulki et al., 1998).

the model and the observations accorded well. The dataset of Harrison et al. (1995) (Fig. 3b) had far smaller emissions than that of Clayton et al. (1997), and offers a contrast of both crop (winter wheat) and N source (farmyard manure). Although there is good agreement between modelled and measured values, especially when it is considered that the error associated with the measurements is ± 5 g N ha^{-1} day^{-1} (S. Yamulki pers. comm.), there are many simulated peaks on days on which no measurements were taken (Fig. 3b). This is a shortcoming of many measurement campaigns due to financial and practical constraints. The dataset of Yamulki et al. (1998) shows emission from grassland on application of urine patches (Fig. 3c). Although observed emissions in this dataset are generally <10 g N ha^{-1} day^{-1}, the model predicted the emissions well.

The simulated peak associated with the application of urine was greater than the observed peak, but measurements were not made on the 3rd and 4th days after application of urine, when the highest and third highest simulated emissions occurred.

3.3. Sensitivity analysis

As Li et al. (1992) demonstrated for DNDC in the United States, the model estimate of N_2O emission was highly sensitive to soil clay content and soil organic C, producing a 3.2% and 9.3% increase, respectively, in UK-DNDC-estimated emission for a 10% increase in value of input variable (Table 2). Sensitivity to changes in climate was even more pronounced: a 1°C increase in annual average temperature (9.7% increase) and 10% increase in precipitation led to increases in N_2O-N emission of 18% and 23.8%, respectively.

Estimates of emission were highly sensitive to aspects of farming practice, particularly the type, rate, timing and depth of fertiliser application. Increasing the depth of fertiliser placement may not be a practical option in grassland, but model estimates suggest this would significantly reduce emission of N_2O. Delaying each of the 3 fertiliser applications by one month produced a large increase in emission. This would be expected because of the sensitivity to temperature, which increases through the period in which applications were simulated. The effect of fertiliser type was very significant, but the effect was found to vary according to baseline conditions. The sensitivity of the model to changing farming practices would make it suitable for investigation of potential mitigation strategies for N_2O emission.

4. Discussion

4.1. Comparison with IPCC estimate

The total emission estimate from current agricultural practice using UK-DNDC (50.9 Gg N_2O-N) was smaller than the emission estimate of 87 Gg N_2O-N obtained using the IPCC (1997) methodology with default values (Brown et al., 2000) (hereafter referred to as the IPCC (1997) methodology), and the 63.9 Gg N_2O-N estimated by Salway et al. (1999). In the soil sector, emission from fertiliser represented a larger proportion and amount of the soil total than was predicted by the IPCC (1997) methodology. The mean emission factor for fertiliser was 0.01 kg N_2O-N/kg N applied, compared with the IPCC EF1 of 0.0125 kg N_2O-N/kg N. Emissions from applied animal waste and N deposited while grazing were smaller than those of IPCC because of the use of UK-specific N excretion data and, especially in the case of emission from N deposited while grazing, smaller emission factors, on average. The UK-DNDC-estimated EF for N deposited while grazing was, on average across all counties, 0.005 kg N_2O-N/kg N, compared with 0.02 kg N_2O-N/kg N with the IPCC methodology. The former accords more closely with measurements by Yamulki and Jarvis (1997) of 0.0068 kg N_2O-N/kg N for cattle urine and 0.0026 kg N_2O-N/kg N for dung.

There are few datasets with which to validate the large estimates of emissions from vegetables. In southwest Scotland, Dobbie et al. (1999) measured large N_2O losses from brassicas (9.1 kg N_2O-N ha^{-1} between March and October, following application of 130 kg fertiliser N ha^{-1} and 12.2 kg N_2O-N ha^{-1} following application of 230 kg fertiliser N ha^{-1}) and from potatoes (4 kg N_2O-N ha^{-1} following application of 170 kg N ha^{-1} and 4.7 kg N_2O-N ha^{-1} following application of 180 kg N ha^{-1}). Ryden and Lund (1980) recorded losses of 41.8 kg N_2O-N ha^{-1} yr^{-1} from celery (fertiliser application of 336 kg N ha^{-1}) and 26.6 kg N ha^{-1} from cauliflower (fertiliser application of 528 kg N ha^{-1}) in California. These crops, although generally of a relatively small area, have a large effect on emission from some counties.

The estimate of emission from the animal sector (animal waste during storage and housing) (5.9 Gg N_2O-N) was greater than that using the IPCC (1997) methodology (4.2 Gg N_2O-N) primarily because the EFs used in the UK-DNDC methodology (derived from Chadwick et al., 1999) for 'solid', 'liquid' and 'other' categories of animal waste management system were greater than those of the IPCC (1997) methodology.

The estimate of emission from the indirect sector was very much smaller from UK-DNDC than from IPCC (1997), and represents a smaller proportion of the total emission from agriculture. Since N_2O emission from leached N was calculated using the original IPCC EF5, the difference between the two methodologies is mainly attributable to the calculation by UK-DNDC of a smaller proportion of the total N that is leached, and the subtraction from the 'applied' waste in the UK-DNDC methodology of N emitted as N_2O, NH_3 and NO_x. The estimate of the proportion of N that is leached (FracLEACH) from the UK-DNDC-based methodology had a large range, but the mean value across all soils and crops was 0.14, compared with the value of 0.3 used in the IPCC (1997) methodology. Other information sources corroborate the finding that the value of FracLEACH assumed by IPCC may be too high for most UK conditions (Brown et al., 2000).

4.2. Estimate of 'background' emission

In order to make comparisons on the same basis, the estimate of emission from 'background' sources was excluded from the emission estimate in the same way that occurs in the IPCC (1997) methodology, i.e. the

Table 2
Sensitivity of N_2O emission estimate of UK-DNDC to soil, climate and management practice (baseline scenario in italics)

Input variable	Value	% change from baseline	N_2O emission ($kg\,ha^{-1}$)	% change in emission estimate
Organic C				
($kg\,kg^{-1}$ soil)	0.031	−5	2.39	−3.6
	0.033	*0*	*2.48*	*0*
	0.035	5	2.60	4.8
	0.036	10	2.71	9.3
Clay fraction	0.351	−10	2.58	−4.03
	0.371	−5	2.55	−2.82
	0.390	*0*	*2.48*	*0*
	0.410	5	2.43	2.02
	0.429	10	2.40	3.23
N in rainfall (ppm)				
	1.808	−10	2.44	−10
	1.909	−5	2.46	−5
	2.009	*0*	*2.48*	*0*
	2.109	5	2.49	5
	2.21	10	2.50	10
Average annual temperature (°C)	8.28	−19.4	2.11	−14.9
	9.28	−9.7	2.25	−9.3
	10.28	*0*	*2.48*	*0*
	11.28	9.7	2.93	18.1
	12.28	19.4	3.16	27.4
Annual average precipitation (cm)	47.33	−20.8	3.22	29.8
	53.54	−10.4	3.09	24.6
	59.74	*0*	*2.48*	*0*
	65.95	10.4	3.07	23.8
	72.15	20.8	3	21.0
Fertiliser amount ($kg\,N\,ha^{-1}$)	117	−33.9	2.14	−13.7
	147	−16.9	2.34	−5.6
	177	*0*	*2.48*	*0*
	207	16.9	2.63	6.0
	237	33.9	2.77	11.7
Fertiliser depth (cm)	*0*		*2.48*	*0*
	10		2.15	−13.3
	20		1.71	−31.0
	30		1.63	−34.3
Fertiliser timing			2.48	0
	+1 month		2.85	14.9
	+2 months		2.97	19.8
Fertiliser type	NH_4NO_3		*2.48*	*0*
	KNO_3, $Ca(NO_3)_2$		1.81	−27
	NH_4HCO_3		1.01	−59
	Urea		2.52	2
	$(NH_4)_2SO_4$		2.47	0

intercept value of the equation on which EF1 is based (flux = 1 + 0.0125 fertiliser) is not counted (see Eq. (2)). The UK-DNDC prediction of an overall emission of 78.3 Gg N_2O-N per year includes 33.8 Gg N_2O-N due to background emission. This makes an important contribution to the overall emission (43%) and although this background emission is not due to current applications of fertiliser and manure, it cannot be considered to be unaffected by agriculture. Emission of N_2O from the soil will be influenced by the past land-use of the site. Further evidence for a 'background' emission of this magnitude was derived from experimental data from 'control' sites used in the validation exercise, which accorded well with model simulations. There was also further corroboration from a statistical analysis of UK emission data (including 54 data points from measurements made over 9 months or longer), which suggested that the intercept of a regression between fertiliser input and emission (as used in IPCC, 1997) would be 1.7 kg N_2O-N ha^{-1}.

4.3. Datasets for validation

There are a limited number of datasets with which daily models such as DNDC can be validated. This is a reflection of the paucity of datasets of appropriate length, variety and frequency rather than of the input requirements of DNDC. In addition to the restricted range of crops available, measurements are seldom recorded every day in a measurement period. In cases where there is poor agreement between measured and model-predicted values it is rarely possible, therefore, to ascertain whether the model's predicted time of emission, or actual emission magnitude is at fault. Compounding this potential lack of synchrony of measured and modelled peaks, strong diurnal patterns in N_2O emission have been observed where continuous measurements have been made (Yamulki et al., 2000). For example, the measured N_2O flux from a urine treatment in Yamulki et al. (2000) was approximately 50 ng N m^{-2} s^{-1} at 12 noon, compared to approximately 200 ng N m^{-2} s^{-1} at its peak, which occurred, in this example, at 4–5 a.m. Measurement time within the day therefore may have a significant effect on the emission estimate if a single hour's measurement is used to extrapolate to daily emissions.

An additional means of gauging the possible accuracy of the model estimate is comparison of model output with large-scale measurements such as that of Fowler et al. (1999). The value of this comparison is limited by the confidence with which the total emission estimated by these measurements can be allocated to agricultural and non-agricultural sources.

5. Conclusions

1. Development and application of DNDC (Li et al., 1992) to the UK produced a model capable of simulating the application of and N_2O emission from both fertiliser and different forms of animal manures in agricultural land in the UK.
2. This attempt to provide a national inventory of N_2O emission based on the UK-DNDC model has a number of advantages over an IPCC-type approach. The greater detail of its calculations allows the effect of contrasting soils, crops, climates and farming practices to be reflected in the emission estimate. The estimate of emission from a given input of N is thus governed by more than N source alone, and more information is available to highlight scenarios of large emission. The sensitivity of UK-DNDC to farm management practices such as timing and type of fertiliser application makes it ideal for investigation of the effect of many management practices that are suggested as options for mitigation of N_2O emission. The approach may be applied at scales from field or farm to county. Because UK-DNDC simulates the processes of N and C cycling within the soil, interaction between different components allows the effects of a given input to be propagated through the system. This is not true of a more simplistic approach, such as IPCC, in which, for example, N input has no effect on crop N uptake or yield.
3. Comparison of UK-DNDC output with 16 datasets showed that model estimates of emission generally agreed closely with those measured in field experiments. This exercise also highlighted the need for more and better datasets, particularly more frequent measurements of N_2O in field campaigns. It identified a requirement for measurements from particular crop types from which the occurrence of large emissions were suggested. Emission of N_2O from leached nitrate constituted a large component of the total emission and a superior method with which to estimate this component is required.
4. The estimate of N_2O-N emission from UK current agricultural practice in 1990 was 50.9 Gg, with a range of 30.5–62.5 Gg. This comprised 31.7 Gg from soil, 5.9 Gg from animals and 13.2 Gg from indirect sources. The largest component of emission in the soil sector was fertiliser (77%). Emission was smaller from cereals than grassland and other crops, on average across all counties. This was reflected in high emission per hectare from counties with a large proportion of their area under crops such as grassland, potatoes, sugar beet and oilseed rape. A total estimate of emission from agricultural land should include that which is not attributable to current farming. Including this component, the estimate of total emission from agricultural land was 78.3 Gg N_2O-N.

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