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Regional modelling of nitrous oxide emissions from fertilised agricultural soils within Europe

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ii Abstract

Agricultural soils are a major source of nitrous oxide (N_2O) emissions within the European Union. The Member States of the European Union are obliged to provide annual inventories of N_2O using a simple statistical model based on default emission factors, described in guidelines produced by the Intergovernmental Panel on Climate Change (IPCC) that relate N_2O emissions to national statistics on inputs such as the total amount of N fertiliser applied to soils. Regional N_2O estimations are not taken into account by the IPCC. A mechanistic model DNDC (DeNitrification and DeComposition) was run using a harmonised database of pan-European data containing data such as soil properties, daily climate, arable crops, mineral and organic N usage and farm management. One-year simulations for 1997 were made for 20 crop types within NUTS level 3 provincial regions.

The accuracy of the input data used to run the DNDC model had a significant impact on the N_2O emission estimates, in particular the spatial distribution of arable crops and scale and accuracy of the SOC data. A simulation for Italy using national fine scale data (NUTS level 3 crop data and 1:250,000 measured soil organic carbon (SOC) data estimated N_2O emissions for Italy in 1997 as **44,700** t N_2O–N yr^{-1}. A second simulation for Italy using European scale SOC data (1:1,000,000 estimated SOC) gave an N_2O estimate of **76,300** t N_2O–N yr^{-1}. A third simulation for Italy using European scale crop data (NUTS level 2) and spatially disaggregated to NUTS level 3 gave an N_2O estimate of **99,500** t N_2O–N yr^{-1}. The scale at which the model

was run produced a large range in SOC values within each unit, thereby, a large range in N_2O estimates.

A comparison was made DNDC estimates of N_2O emissions estimates using the IPCC methodology. The DNDC modelled emission factor of N_2O emission due to N fertiliser of **0.0083** kg N_2O-N kg^{-1} N was lower than the IPCC emission factor of **0.0125** N_2O-N kg^{-1} N. It was shown that the relationship between N_2O emissions and mineral N fertiliser application is not linear. The DNDC model estimates far higher N_2O emissions due to the mineralisation of SOC than the IPCC methodology. The DNDC modelled results showed a significant variation in the estimations of N leached from different regions compared to the IPCC default factor that assumes 30% of all mineral N fertiliser and organic manure is leached.

The pan-European database was used to make an estimation of direct N_2O emissions on a European scale at the NUTS 3 level for the first time. Validation of the European results is difficult due to the paucity of Europe-wide measured N_2O emission data.

This thesis has clearly demonstrated that a mechanistic model and a database containing national and pan-European data can produce regional estimates of direct N_2O emissions from fertilised agricultural soils at the NUTS level 3 across Europe. However, uncertainties in the regional estimates of N_2O emissions remain due to the large uncertainties in both the raw and processed data.

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1 Introduction

This chapter introduces the subject of greenhouse gas (GHG) emissions, how inventory analysis is used to estimate GHG emissions, and highlights the objectives and importance of this study to international GHG policy support. A glossary of common terms, chemicals and S.I. units used in this thesis are shown in the appendices.

1.1 Background

A GHG can be defined as a gas that contributes to the natural greenhouse effect, the role played by a layer of gases, which trap the heat from the sun in the Earth's atmosphere. Without the GHG effect, the planet would be too cold to sustain life, as we know it. Some of the GHG occur naturally (*e.g.* water vapour, carbon dioxide, methane, and nitrous oxide) while others are exclusively human-made and released by modern industry, agriculture and the burning of fossil fuels. The concentrations of GHGs in the atmosphere are increasing (*e.g.* the concentration of carbon dioxide (CO_2) has risen by more than 30% since 1800) and there is a general acceptance that an increase in the levels of these GHGs will cause a rise in the Earth's temperature (IPCC, 1995).

To address the increasing concerns in climate change and global warming the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Kyoto Protocol in 1997. The Kyoto Protocol is an international agreement that outlines targets and timetables for the reduction of anthropogenic sources of global warming. Under the Kyoto Protocol, industrialised countries are required to reduce their emissions of six greenhouse gases (Table 1.1) below the 1990 level during the first commitment period from 2008 to 2012. Article 4 of the UNFCCC requires that all signatories of the Kyoto Protocol produce national inventories of all GHGs not controlled by the Montreal Protocol[1], using a comparable methodology. The Intergovernmental Panel on Climate Change (IPCC), through the Office of Economic Cooperation and Development (OECD) and the International Energy Agency (IEA) coordinates the development and updating of the national inventory methodologies.

To enable direct comparison of the different GHGs emission estimates are expressed in CO_2 equivalents. The GWP potentials of the main GHGs shown in Table1.1 are calculated on the basis of a temporal period of 100 years taking into account the atmospheric lifetime of the substances (IPCC, 1995).

Table 1.1. Global warming potential of the six main GHG considered under the Kyoto Protocol.

Greenhouse gases		**GWP**
Carbon dioxide	CO_2	1
Methane	CH_4	21
Nitrous oxide	N_2O	310
Hydrofluorocarbons	HFCs	Range of 140 – 11,700 depending on molecules (weighted values are 5,435 in 1990, 8,914 in 1993 and 1,732 in 2002)
Perfluorocarbons	PFCs	Range of 6500 – 9200 depending on molecules (weighted values are 7,293 in 1990, 7,828 in 1994 and 7,182 in 2002)
Sulphur hexafluoride	SF_6	23,900

Taking into account the global warming potential of the main GHGs, the global contributions of the main GHGs to enhanced heat trapping are shown in Figure 1.1.

[1] The Montreal Protocols aim is to reduce atmospheric levels of ozone depleting gases Chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC)

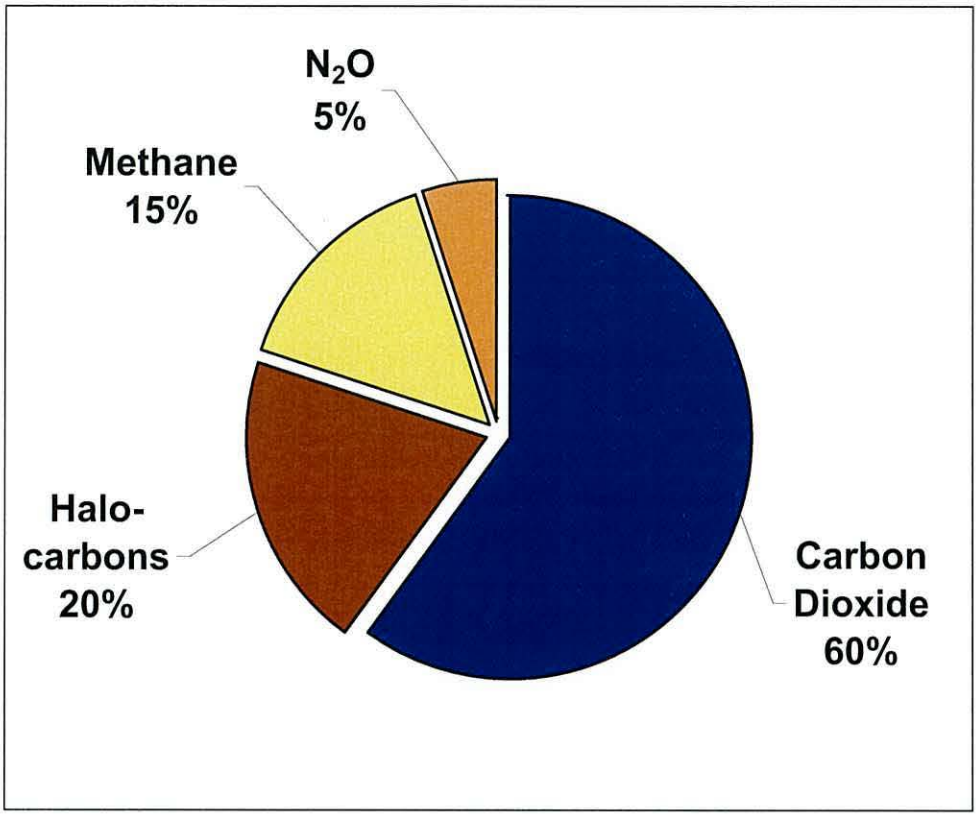


Figure 1.1. Greenhouse gases approximate global contribution to enhanced heat trapping (IPCC, 1995).

Although the contribution of N_2O to enhanced heat trapping is only 5% there is a two-fold uncertainty in the estimations of N_2O emissions from agricultural soils (described later in this thesis). The uncertainty in the estimation of N_2O emissions can make a significant contribution to the uncertainty in total GHG emission estimates and towards the goals of the Kyoto protocol, where the EU reduction target in total GHG emissions is 8% (CEC, 2004).

The contribution of agricultural GHGs emissions towards climate change and global warming has gained greater recognition in recent years (Oenema, 2001). Agricultural GHG emissions within the European Union (EU) in 1990 accounted for approximately 10.1 % of total GHG emissions (Figure 1.2) (EEA 2004).

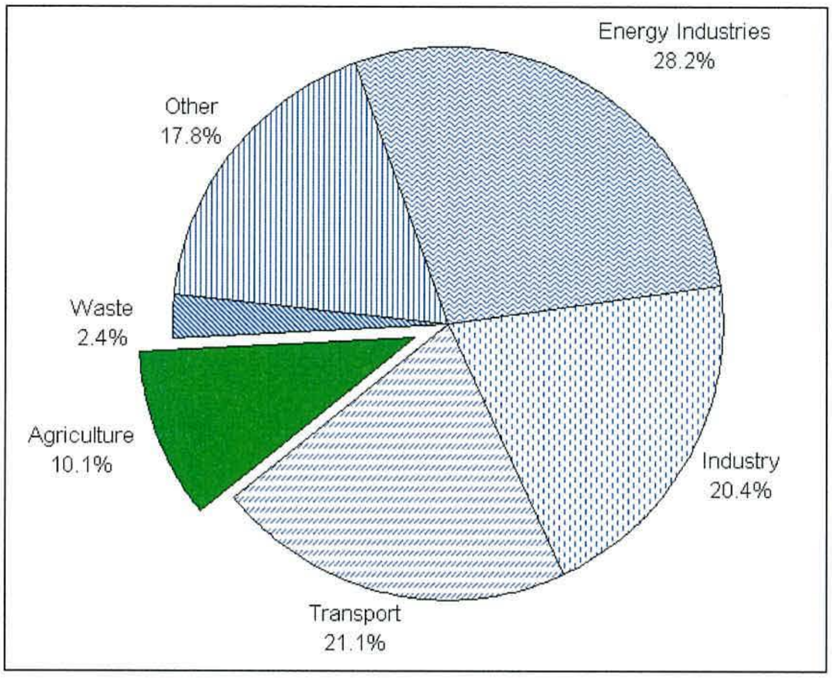


Figure 1.2. Contribution of agriculture to the EU GHG budget.

In Ireland (27 %) and France (18 %) the respective contributions of agricultural emissions to total GHG emissions are significantly higher than the EU average (10.1%) (EEA, 2004). This is due, at least in part, to the relative importance and size of the agricultural sector in these countries as a proportion of the respective total national economic activities. In contrast Luxembourg has the lowest contribution of agriculture to its total national greenhouse gas emissions (3.1 %) (EEA, 2004). The three main sources of GHGs emissions from agriculture in the EU are:

- N_2O emissions from agricultural soils
- CH_4 from enteric fermentation
- CH_4 and N_2O from manure management

N_2O emissions from agricultural soils, occurring by the conversion of nitrogen in the soil (where synthetic fertilisers, animal waste, sewage sludge applications, biological N-fixation and crop residues may be the source), are the largest source of N_2O emissions in the EU-15 accounted for 206 Mt of CO_2 equivalent in 1990 (Bates, 2001). Emissions of N_2O from agricultural soils include emissions from manure after spreading on soils, but exclude emissions due to manure handling, where N_2O emissions are generated during manure storage when manure nitrogen is converted into N_2O. Manure management emissions of CH_4 and N_2O accounted for 46 Mt of CO_2 equivalent in 1990 (Bates, 2001). CH_4 emissions from enteric fermentation, occurring in ruminant animals (*e.g.* cattle and sheep) and some non-ruminant animals (*e.g.* pigs and horses) and from the decomposition of manure under anaerobic conditions, accounted for 194 Mt of CO_2 equivalent in 1990 (Bates, 2001). In comparison to N_2O and CH_4 agricultural emissions of CO_2 are relatively small, with 17 Mt of CO_2 equivalent reported for the EU in 1990 (Bates, 2001).

Several different types of models exist that can be used to estimate GHG emissions from agricultural soils, ranging from simple empirical representations (*i.e.* the IPCC emissions inventory approach) to mechanistic (process-based) models. The majority of mechanistic models work at the plot or field scale level taking into account complex factors such as microbial growth in the soil. The dependency of these field scale models on a large number of input parameters limits their suitability for modelling GHG on sites where detailed data is not available. One of the major advantages of using field scale models is the ability to compare modelled results with measured results and to model the effects of farm management practice changes on emissions. However, undertaking large scale regional assessments of GHG emissions is generally impracticable or impossible due to the need to collect suitable data to run highly detailed models Therefore, simplified models that require fewer inputs are more suitable for regional GHG estimates. Confidence in the results produced by a simplified model will normally be less than in those from a highly detailed model.

Perhaps the greatest impact of climate change on soils will arise from climate-induced changes in land use and management (Rounsevell *et al.* 1999). Any model used to estimate emissions from agricultural soils should therefore have the ability not only to successfully estimate emissions under current conditions but also under various scenarios of land use and climate.

The utilisation of a Geographical Information System (GIS) can greatly improve the understanding of GHG emissions by storing and processing region wide data, required to drive a mechanistic soil emissions model, deriving spatial relationships between datasets, and displaying and analysing the results spatially. The combination of a mechanistic model and GIS can provide an integrated modelling tool that can be used to support EU GHG policy (described in more detail in section 1.2 of this thesis) development by modelling GHG emissions under present agricultural and climatic conditions but also by the application of scenario analyses of changes in agriculture and climate. A graphical overview (see Figure 1.3) shows the structure and role of the integrated policy support tool created by this study.

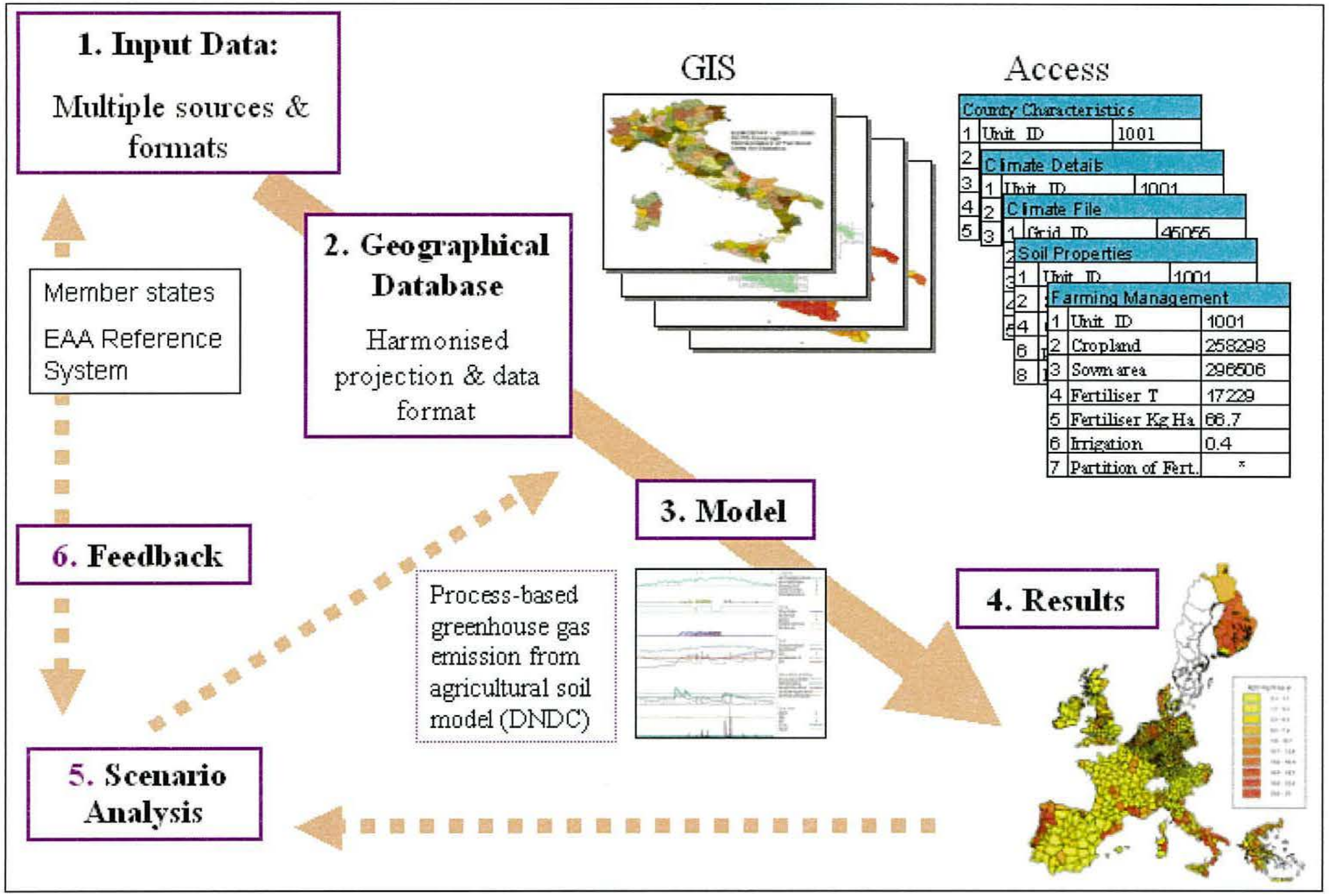


Figure 1.3. Integrated tool combining a pan-European database with a mechanistic model for GHG analysis and policy support.

1.2 Importance of this study to European policy

This thesis was completed at the Soil and Waste unit of the European Commission's Joint Research Centre (JRC) in Ispra, Italy. A category 30 grant was provided by the EC to contribute to research and development of N_2O emissions from agricultural soils.

This study will add to the understanding of the fate of mineral nitrogen (N) and organic fertilisers applied to agricultural systems on a regional scale. The results of the study will make an important contribution towards the European Commission's (EC) Joint Research Centre's (JRC) (www.ei.jrc.it) research into the study of nutrient flow in agricultural systems and ultimately provide support to the EC policy makers within DG Agriculture and DG Environment on matters such as:

- The Nitrate and Water Framework (WFD) Directives 91/676/EEC and 2000/60/EEC.
- Development of agri-environment indicators (IRENA) and reform of the common agricultural policy COM(2001)144.
- The soil thematic strategy for soil protection.

In addition, this study will contribute to the JRC's role within the European Environment Agency's (EEA) GHG monitoring mechanism. The European Commission's Directorate General (DG) for Environment has charged the EEA with the role of collating and monitoring the GHG inventories from Member States (see Figure 1.4). The JRC provides support to the EEA monitoring mechanism through research comprising modelling, inventory estimation and measuring campaigns.

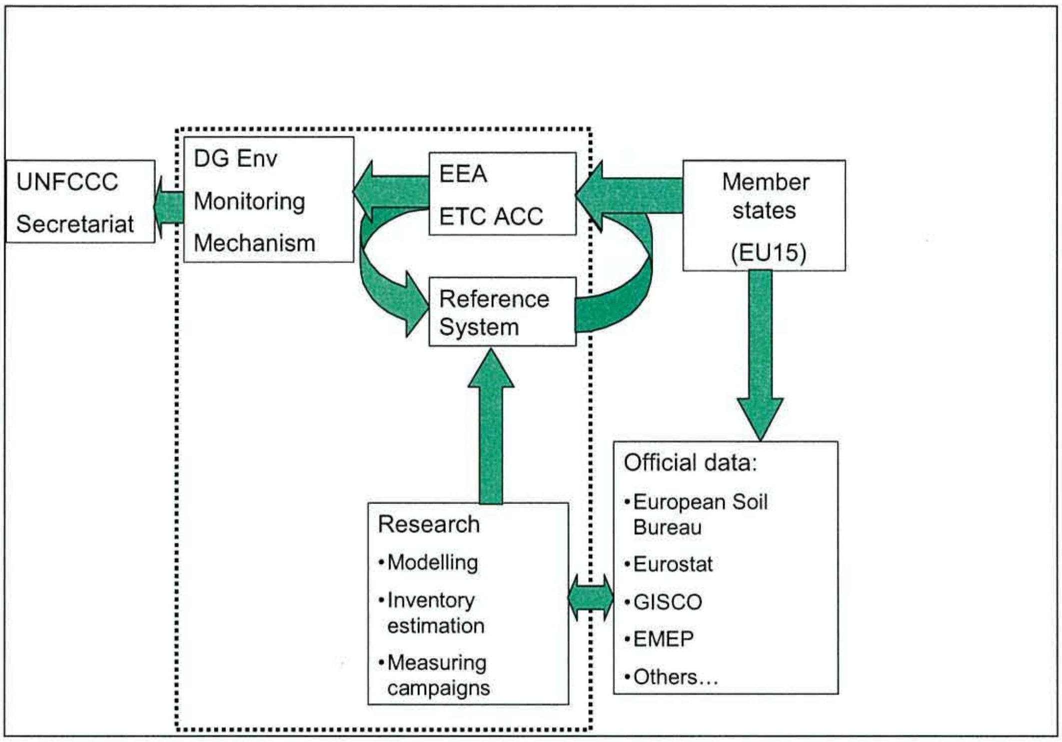


Figure 1.4. The role of GHG modelling within the GHG monitoring mechanism.

This study will contribute to the development of agri-environment indictors, within the aims of IRENA (Indicator Reporting on the integration of Environmental concerns into agricultural policy) that considers the environmental consequences of N_2O with regards to agricultural policies of the EC Commission communication COM (2001)144. Scenarios of agricultural practices and changes in policy can be readily applied using the modelling tool, created within this study, allowing immediate regional results and analysis, a precision of emission estimates that are not possible using the simple national IPCC statistical approach or via measurements.

1.3 Objectives

The hypothesis of the study is to show that a mechanistic model that takes into account climate, soil and farm management conditions can be used to estimate N_2O emissions at the regional scale and can be used to replace the current statistical approach used by member states to calculate N_2O inventories.

The principal objective of this thesis is to show that a tool, coupling a mechanistic flux model with a harmonised pan-European database containing relevant, and readily available environmental and agricultural data, can be used effectively in the estimation of N_2O emissions from fertilised agricultural soils on a regional scale. To satisfy the principal objective it was necessary to achieve the following goals:

1. Identification of a suitable 'state of the art' mechanistic model for estimating N_2O fluxes from agricultural soils.
2. Performance of a sensitivity analysis of the model within the constraints of input parameters available on a European scale.
3. Development of a harmonised European scale database containing GIS coverages and tabular data relevant to the assessment of nitrous oxide emissions in soils, including meteorological, soil, crop, livestock, and farm practice parameters.
4. Identification of uncertainties and data gaps within the input data.
5. Alteration of the model data input structures where necessary to suit particular regional input data structures and availability.

6. Identification of an optimum scale of geographical unit at which to run the model.
7. Regional modelling of N_2O estimates for Italy using different combinations of soil organic carbon content values and crop data.
8. Comparison of modelled and IPCC estimates of direct and indirect N_2O emissions and evaluation of IPCC emission factors.
9. Estimation of N_2O emissions from agricultural soils on a European scale (EU15)[2] (see figure 1.5).

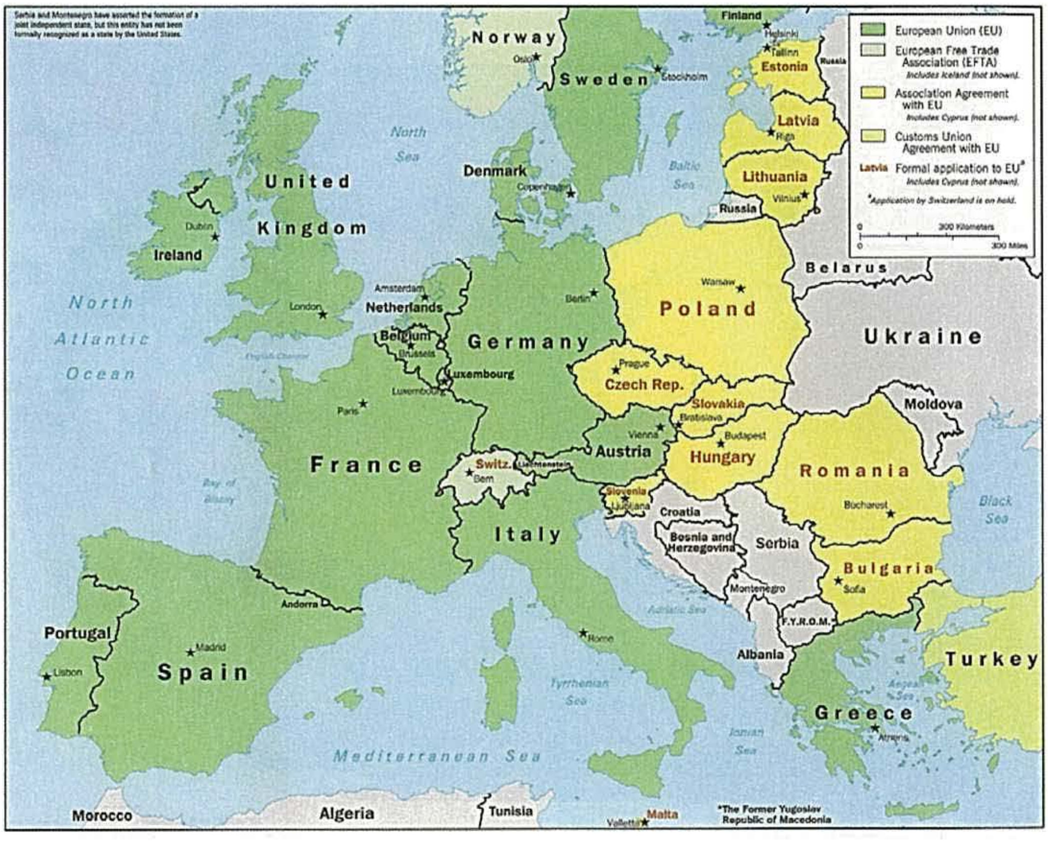


Figure 1.5. European Member States.

[2] EU15: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Spain, Portugal, Sweden and the United Kingdom.

2 N_2O emissions and agricultural soils

This chapter describes the importance of estimating N_2O emissions, the soil processes of the nitrogen cycle that are involved in the production of N_2O emissions, and the agricultural and climatic processes that can affect N_2O emissions. In addition, the complex methods used to measure N_2O emissions are detailed.

2.1 Nitrous Oxide (N_2O) and sources

The atmospheric concentration of N_2O is higher at present than at any time in the past one thousand years. The concentration has increased by 17% from 270 ppb in the period of 1000–1750 to 316 ppb in the year 2000 (IPCC, 2001a). With 60% of N_2O emissions occurring in the Northern Hemisphere, the concentration is about 0.8 ppb greater in the Northern Hemisphere than in the Southern Hemisphere (IPCC, 2001b). The global mean atmospheric lifetime of N_2O is approximately 114 years indicating that any mitigation strategies will have long-term consequences (IPCC, 2001b). The major sink for N_2O is photolysis[3] in the stratosphere, leading to the production of nitrogen oxide products that can affect stratospheric ozone levels (Crutzen, 1981).

Natural sources of N_2O in 1990 were estimated to be approximately 10 Tg N yr^{-1} with soils representing about 65% of the sources and oceans about 30% (IPCC,

[3] Phytolysis is the chemical change caused by radiant energy and results in the following change: $N_2O \rightarrow NO$ and $O_3 + NO \rightarrow O_2 + NO_2$

2001a). Anthropogenic sources (agriculture, biomass burning, industrial activities, and livestock management) for 1990 were estimated to be approximately 7 Tg N yr^{-1} (IPCC, 2001a). Globally 70% of anthropogenic N_2O emissions are attributable to agriculture (IPCC, 1995a) whilst within the EU15 agriculture accounts for just 52% of N_2O emissions (see Figure 2.1) (UNFCCC, 2003). The large uncertainties in the estimates of N_2O emissions from agriculture will be described later in this thesis.

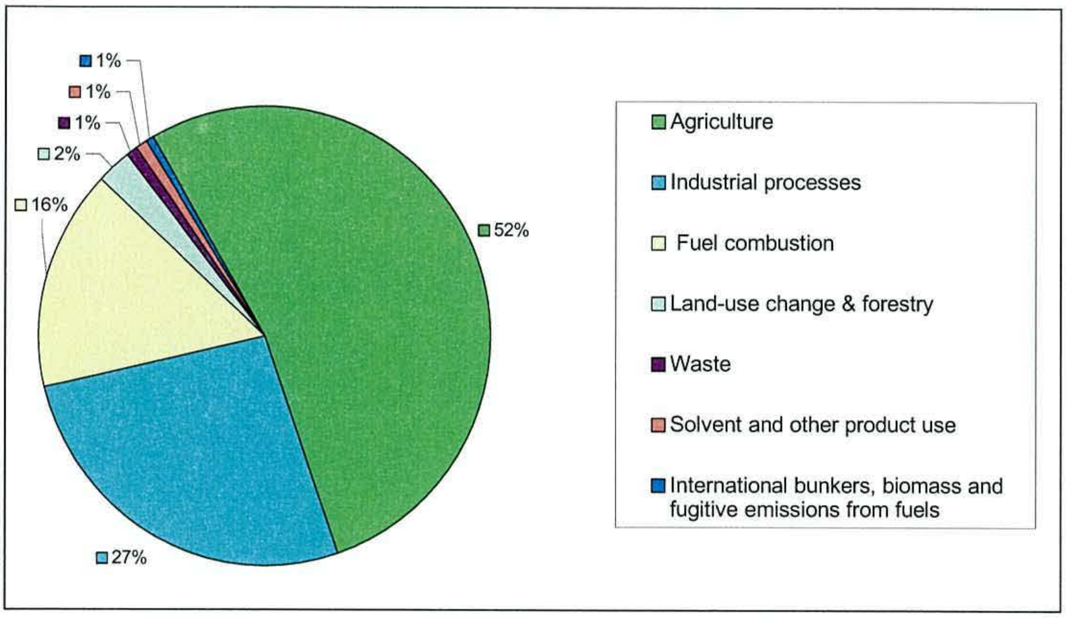


Figure 2.1. Anthropogenic N_2O sources in Europe (EU15).

The IPCC methodology describes agricultural emission sources as including fertilised agricultural soils, manure management, field burning and rice cultivation. In recent years, agricultural N_2O emissions reported by EU15 Member States have fallen by approximately 6% principally due to changes in agricultural practices and production following the reform of the Common Agricultural Policy (CAP) (Bates, 2001). Agricultural N_2O emissions, reported by the EU15 Member States between

1990 and 1997,using the IPCC estimation methodology are shown in Figure 2.2, where the annual variation in totals can be seen (UNFCCC, 2003). It should be noted that the IPCC estimations are reported in Gg (000 t) of N_2O and not CO_2 equivalent.

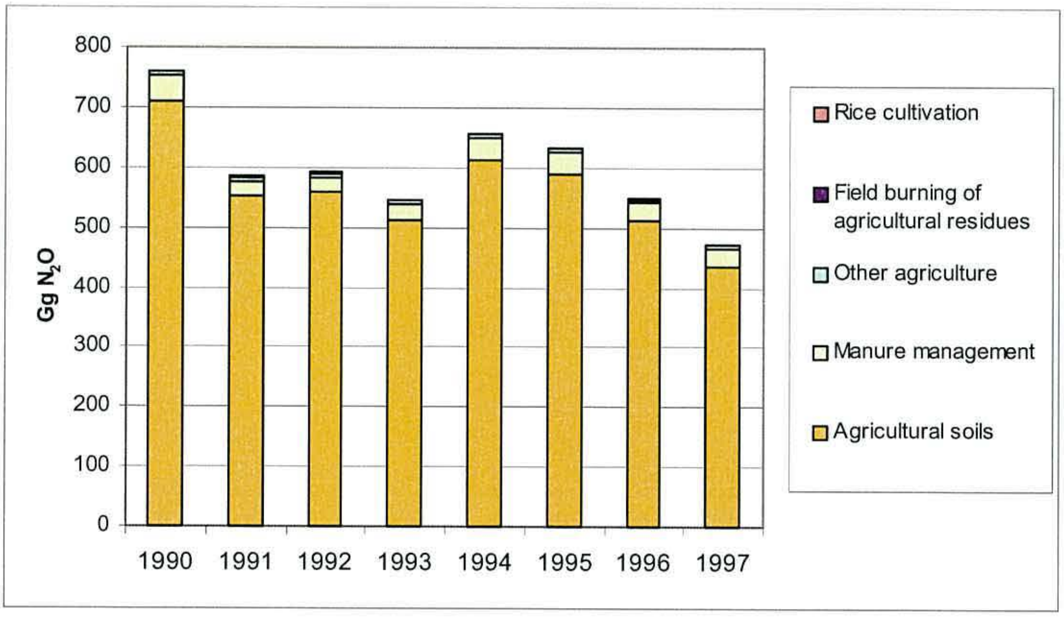


Figure.2.2. EU15 agricultural N_2O emissions (Gg) 1990 - 1997.

The current IPCC guidelines include methodologies to account for N_2O emissions from both direct and indirect sources associated with agriculture (described in more detail in chapter 3).

2.2 Measurements of N_2O

Measurements of N_2O are important for deriving emission factors (the fraction of N inputs emitted as N_2O), understanding the soil processes driving emissions, monitoring the effect of changes to farm management practices, developing models and for the validation of models. The IPCC emission factor, calculates N_2O emissions as 1.25 ± 1% of the N applied and was derived by Bouwman (1996) using the relationship between observed fertiliser N inputs and measured N_2O emissions for 20 grassland and maize fields. Measurements of emissions can be very time consuming and complex and therefore can only give a limited account of emissions, both temporally and spatially.

Aulakh *et al.* (1984) measured N_2O emissions using a methodology where undisturbed soil cores were taken in aluminium cylinders and sealed in jars containing sodium hydroxide (NaOH) to absorb the CO_2. After the injection of acetylene (C_2H_2) and incubation for 24 hours, the gas samples were measured using a chromatograph and N_2O fluxes derived. Ball *et al.* (1999) and Smith *et al.* (1998) measured N_2O with manually and automatic closed chambers, which enclosed the atmosphere immediately above the soil surface. Hourly samples taken from the chambers allowed remote collection of gas samples to be carried out at programmed time intervals. Borjesson and Svensson (1997) measured soil gas concentrations by chambers and permanent probes installed at 0.5 m, 0.7 m and 0.9 m depths. Soil temperatures were measured by thermisters, whilst soil moisture, expressed as percentage wetness, was measured gravimetrically by drying the soil at 105°C.

In different measurement campaigns Kaiser *et al.* (1998b) observed that temporal changes in N_2O emissions were influenced in descending order by the year of observation, the crop type and the N-application, whereas Mogge *et al.* (1999) found that predictors of the temporal changes in N_2O emissions were nitrate, pH and temperature, indicating heterogeneity of management. Spatial variation of N_2O emissions at the plot scale can be high due to hot spots and therefore to achieve a representative estimation of N_2O, measurement techniques should integrate fluxes over a large area (Rover *et al.* 1999).

To understand patterns in emissions and derive emission factors, datasets containing multiple measurements covering a wide range of climate, soil types, crop types and forms of N are essential. The International Fertilizer Association (IFA) and the Food and Agriculture Organisation of the United Nations (FAO) collated a dataset, described in Bouwman *et al.* (2002a), comprising global measurements for estimating N_2O-N emissions induced by mineral N fertilisers. The data includes 468 measurements for various crops, soil types and management practices in European countries based on an extensive literature review (IFA/FAO, 2001). However, a summary of data for a few select major crop types (see Table 2.1) shows that N_2O measurement data are sparse across Europe. This makes direct regional level comparison of emissions difficult. No daily measurements of N_2O or climate data are provided within the dataset, which can be a problem for comparison of daily results produced by many mechanistic models. From the data, Bouwman *et al.* (2002a) identified that longer measurement periods yielded more of the strong fertilization effect on N_2O emissions, intensive measurements ($\geq$1 per day) yielded lower emissions than less intensive measurements (2–3 per week) and higher N_2O emissions occurred from soils with high organic-C content than from less fertile soils. Bouwman *et al.* (2002b) used the data to derive a new emission factor for global mean fertilizer-induced emissions of N_2O at 0.9% of the N applied, which is lower than the default IPCC emission factor of 1.25%. The IFA/FAO (2001) concluded from the data shown that the potential impact of imposing regulations of mineral N fertiliser use would be modest from a global emission perspective.

Comparing emissions in Table 1, it can be seen that the highest emission occurs from soils under rye cropping in Germany (56 kg N_2O-N ha^{-1} yr^{-1}) grown on an organic soil. In contrast N_2O emissions from a rye cropping system grown on a sandy loam soil in Denmark were only 0.5 kg N_2O-N ha^{-1} yr^{-1}. Emissions from grassland are highest on an organic soil in Germany (19.8 kg N_2O-N ha^{-1} yr^{-1}) and lowest on sandy loam soils in Belgium (0.08), Germany (0.01) Spain (0.001) and the UK (0.02). From these results it can be determined that soil type has a large affect on N_2O emissions.

Table 2.1. Measured emissions of N_2O-N ha^{-1} yr^{-1} from major crop types in Europe

		Barley	Grass	Maize	Oats	Potato	Rape	Rye	Silage maize	Sugar beet	Sunflower	Winter wheat
BE	Min		0.08	2.25								
	Max		8.40	2.25								
DE	Min	1.09	0.01	1.34	5.00	1.62		56.40	2.20	1.50	9.36	0.84
	Max	1.18	19.80	15.60	5.70	8.64		56.40	4.80	3.60	12.93	0.90
DK	Min	0.54	0.67				1.26	0.50				0.18
	Max	1.31	9.35				1.26	0.50				0.18
ES	Min		0.00	0.36								
	Max		0.08	0.50								
FR	Min			11.00			0.01					
	Max			11.00			5.87					
IT	Min			0.65								
	Max			1.84								
NL	Min		0.45									
	Max		41									
SE	Min	0.24										
	Max	1.4										
UK	Min	0.30	0.02			1.20						0.30
	Max	0.864	18.4			4.5						0.9

The U.S. Trace Gas Network (TRAGNET) provides another dataset containing daily N_2O measurement data (Ojima *et al.* 2000). This network was set up to collate and distribute detailed data on field conditions and N_2O measurements (TRAGNET, 2000). The principal aim of the TRAGNET network was to increase the understanding of GHG emissions from soils by including comparable data on trace gas flux measurements, ecosystem measurements, interaction between measurement and modelling groups, testing and comparing gas flux models and the establishment of a long-term data archive for trace gas flux and associated data. However, the measurements are limited to only a few sites. For instance, the only European measurement data within the network are from a pasture in Scotland that cannot be considered representative of all the agricultural, soil and climate conditions within Europe.

Variability of N_2O flux measurements in individual studies is large (Langeveld *et al.* 1997) and can be attributed to scale dependent controlling factors and partly to random noise (Syring and Benckiser, 1990). Given the complexity of making measurements there is a paucity of measurement data, both temporally and spatially. Thus, N_2O emissions from many possible combinations of crop, climate, and management combinations are unknown.

2.3 Soils and N_2O emissions

Fertilisation, climate and soil characteristics are the key factors determining N_2O formation and losses from agricultural soils (Freibauer and Kaltschmitt, 2000). This section describes the natural processes in soils involved in N_2O production whilst section 2.4 discusses the anthropogenic influences on emissions. Despite considerable research on N_2O production processes and its controlling factors the fate of a unit of N that is fertilised on a specific arable field is still very difficult to predict (Mosier *et al.* 1996).

The major soil processes (reactions) of the nitrogen cycle involved in the production of N_2O (Figure 2.3) include:

- Mineralisation-immobilization: Organic nitrogen from decaying plant and animal residues (proteins, nucleic acids, amino sugars, urea) is converted to ammonia (NH_3) and ammonium (NH_4^+). The resultant ammonium can be converted back to organic N (immobilization) where it is taken up by microbes and plants (assimilated) or nitrified to nitrate (NO_3^-).
- Nitrogen Fixation - the microbial conversion of molecular nitrogen (N_2) to ammonia (NH_3).
- Nitrification - The first oxidation product of the nitrification process produced by *Nitrosomonas* bacteria is nitrite (NO_2^-) that is further oxidised by *Nitrobacter* bacteria to produce nitrate (NO_3^-).
- Denitrification - the microbial reduction of NO_3^- to NO and N_2O.
- Nitrate loss: Assimilation by crops and soil leaching

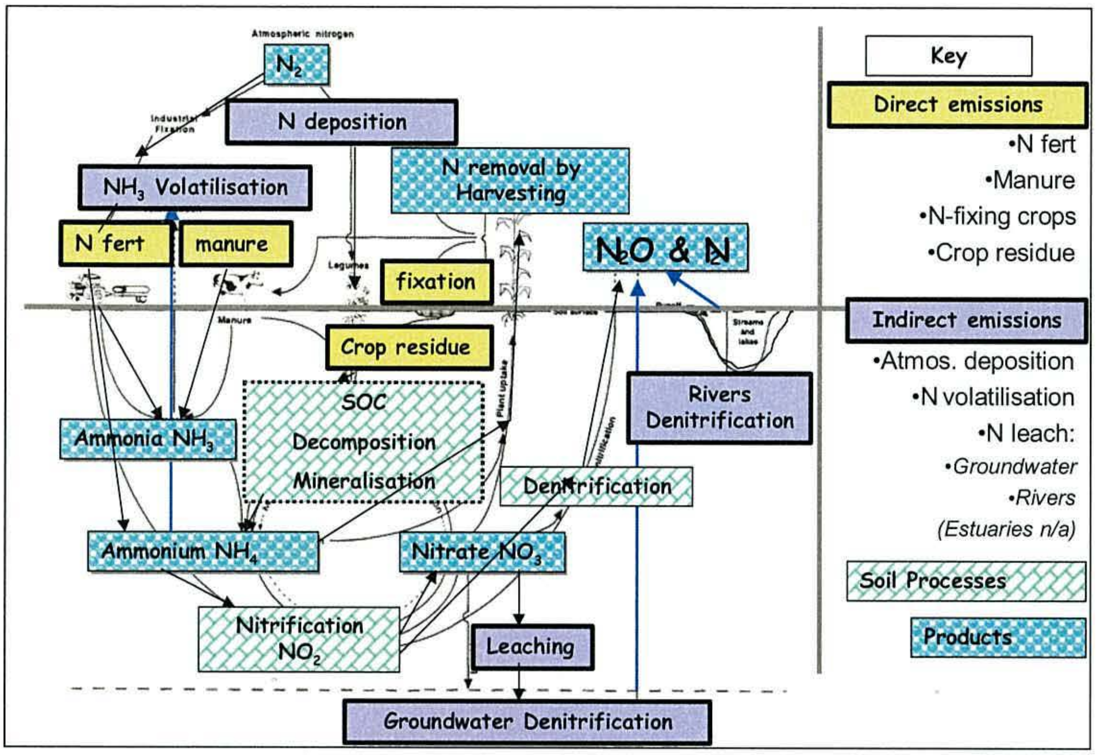


Figure 2.3. Soil processes involved in the production of direct and indirect N_2O emissions.

N_2O is predominantly emitted from soils as a result of denitrification in anaerobic soil conditions and to a lesser extent, by nitrification in aerobic soil conditions. For denitrification to occur the general requirements, as described by Smith (1990) are:

- The presence of micro-organisms possessing the metabolic capacity
- Suitable electron donors
- Anaerobic conditions
- Availability of nitrate, nitrite, nitric oxide and/or nitrous oxide.

Van Beek *et al.* (2004) found that annual N losses through denitrification, from intensively managed grassland on peat soil in the Netherlands, averaged 87 kg N ha^{-1} with almost 70% of the N losses originating deeper than 20 cm below the soil surface. The N losses through denitrification, accounted for 16% of the N surplus at farm-level (including mineralisation of peat), were not wholly related to the total N input of 280 kg N ha^{-1} yr^{-1}, of which 220 kg N ha^{-1} yr^{-1} was applied as mineral fertiliser, but also to the mineralisation of peat (263 kg N ha^{-1} yr^{-1}). Van Beek *et al.* (2004) concluded that NO_3^- contents of the soil largely governed the magnitude of N losses through denitrification, whilst the groundwater level controlled the depth where denitrification occurred.

Nitrification refers to the oxidation of ammonium to nitrite and then nitrate. Nitrite is a transient compound that is not readily taken up by plants or microbes. For nitrification to occur the presence of aerobic chemoautotrophs called nitrifiers is required. While some low levels of heterotrophic nitrification can occur, rates of nitrification are generally low and the quantities of nitrate produced are relatively small, in comparison to the quantities of nitrate produced by the chemoautotrophs. All nitrifiers are aerobic, and nitrification occurs at C: N ratios of less than 20 where N is abundant. In some settings, such as forest litter layers, nitrification occurs by saprophytic fungi rather than chemoautotrophic bacteria.

The nitrification process can have various impacts on the environment by contributing to:

- The decomposition of nitrogenous material
- The fixation of carbon into organics (albeit a relatively small contribution due to the inefficiency of the microbes that perform nitrification)[4]

[4] The fixation of one mole of carbon requires the oxidation of 35 moles of ammonia to nitrite and 100 moles of nitrite to nitrate.

In turn, the nitrification process can be affected by environmental conditions. For instance, if an excessive amount of nitrogen is added to an environment where nitrification occurs, metabolisation of the nitrogen to nitric acid can deplete the acid-sensitive microbes that perform nitrification. Moreover, the aerobes can be further depleted if the introduction of wastes leads to excessive growth of other species that deplete oxygen.

Various soil environmental factors regulate both the nitrification and denitrification processes and, thereby, the rate of N_2O emissions. These include soil water content, soil temperature, aeration, ammonium and nitrate concentrations, the amount of mineralisable carbon and pH (Sahrawat and Keeny, 1986; Granli and Bockman, 1994). Denitrification generally increases with increased soil moisture (Ball *et al.* 1999). Where soil mineral N is not a limiting factor, exponential relationships between N_2O flux and both water-filled pore space and temperature have been observed. Emissions of N_2O increase with an increase in temperature, attributed to increases in anaerobic volume fraction, brought about by an increased respiratory sink for O_2 (Smith *et al.* 2003). The temperature dependence is expressed in terms of the $Q10$ value. Observed values for the $Q10$ for N_2O emissions range up to 10 or more compared with a general range of 2-4 for most biochemical processes (Smith *et al.* 2003). Temporal changes in N_2O emissions can be attributed to temporal changes in temperature resulting from freezing and thawing cycles affecting microbial activity (Rover *et al.* 1998).

Diurnal fluctuations in emissions can be associated with diurnal cycles affecting soil temperature at different layers. The time lag in soil temperature changes affects the time that N_2O is produced at different depths and hence the timing of emissions from the surface layer. N_2O emissions can vary from year to year and are highly dependent on the intensity of rainfall at the time of fertiliser application.

Henault *et al.* (1998) showed that N_2O emissions are strongly affected by soil type. In soils at the same latitudes, Henault *et al.* (1998) observed that N_2O emissions were highest in soils with high clay content, organic matter content and alkaline pH. N_2O emissions are strongly related to the available soil organic carbon (SOC) with N_2O emissions generally increasing with an increase in SOC (Li *et al.* 1997). In an estimation of N_2O emissions from agricultural soils in Germany, Bareth *et al.* (1999) estimated that N-fertilised soils with a high content of organic matter have a 'high' potential for N_2O emissions (6 - 8 kg N_2O-N ha^{-1} yr^{-1}). Natural peatlands contain large amounts of organic carbon and nitrogen and if they are drained for agriculture the enhanced mineralisation can result in considerable losses of carbon and nitrogen (Flessa *et al.* 1998). Mogge *et al.* (1999) found that long-term application of farmyard manure enhanced distinct carbon pools in soils available for mineralisation and consequently N_2O emissions.

SOC is generally derived from the soil organic matter (SOM) content, and is estimated to make up 58% of the SOM with the rest of the SOM comprising other elements (*e.g.* 5% N, 0.5% Phosphorus (P) and 0.5% Sulphur (S)). A conversion to SOC from a given SOM requires that the SOM be divided by a factor of 1.72

(1.00/0.58). Globally SOM represents a major pool of carbon in the biosphere. It has been estimated that there is more than twice the amount of carbon (1400 teragrams[5] (Tg)) stored in the top metre of soil than in the atmosphere (Post *et al.* 1982). Moreover, global vegetation models predict that high latitude areas (*e.g.* above 50°N), representing about 23% of the vegetated global land area, are currently accumulating about 0.4 petagrams[6] (Pg) C yr^{-1} (30% of the estimated global terrestrial sink) and that this sink could increase to 0.8-1.0 Pg by 2050 (White *et al.* 2000). The objective of many CO_2 mitigation strategies planned to meet the Kyoto Protocol obligations is to utilise the carbon sequestration potential of soil. Smith *et al.* (2000) showed that no single land-management change in isolation can mitigate all of the CO_2 required for Europe's commitments to the Kyoto Protocol and that to fully exploit the full potential of arable land for carbon sequestration the highest importance should be given to the implementation of policies which encourage surplus land to be put into alternative long-term land-use such as bio-energy crops or reversion to natural vegetation. While the rate of accumulation of SOM is often higher on fertilised fields this has to be offset by CO_2 emissions emitted during the industrial fertiliser production process and the consumption of fossil fuels and CO_2 emitted by the mechanical application of the fertiliser (Schlesinger, 2000). Any calculations regarding the mitigation of CO_2 by increasing SOM should take into account the effect of increasing N_2O emissions (Smith *et al.* 2001).

[5] teragram = $g \times 10^{12}$
[6] petagram = $g \times 10^{15}$

It has been shown that N_2O is enhanced by the increase in available mineral N, which can enhance nitrification and denitrification rates (Mosier *et al.* 1998). Thus addition of mineral fertiliser N, can directly lead to an increase in N_2O emissions. The IPCC methodology of estimating direct N_2O emissions from agricultural soils is based on this assumption. Other agricultural practices that affect N_2O emissions are described in the next chapter.

2.4 Agricultural practices and N_2O emissions

Emissions of N_2O are influenced by a number of factors in addition to soil type including land use change and land use, fertiliser type, manure or plant residue incorporation, irrigation and crop type.

Land use conversion may increase the availability of soil organic matter, temperature, levels of inorganic N and O_2 concentration, as well as increasing N_2O emissions (Chao *et al.* 2000). Conversion of forests to pasture and agricultural land results in large emissions of soil N_2O (Mosier *et al.* 1991). In addition, conversion from one form of agricultural land use to another also affects N_2O emissions. Kaiser *et al.* (1998a) found that conversion (ploughing, applying 40 kg N ha^{-1} and growing barley) of uniform grassland and grassland mixed with clover increased N_2O emissions respectively by 6.1 and 3.3 kg N_2O-N ha^{-1} yr^{-1}. Draining wetlands for agricultural use, thereby lowering the groundwater table can also increase emissions of N_2O. Klemedtsson *et al.* (1999) found that following the drainage of a peat bog and fen in Scandinavia, for cereal crops, the N_2O emissions were 15 kg N_2O-N ha^{-1} yr^{-1} compared to an undrained peat bog and fen where the

N_2O emissions were not detectable (due to N_2O produced during denitrification being reduced to N_2). Average N_2O emissions for European fertilised peatlands are estimated to be 7.3 kg N_2O-N ha^{-1} yr^{-1} (Klemedtsson *et al.* 1999).

In a comparison of land use types Smith *et al.* (1998) found that N_2O emission rates were higher from grazed grassland than from cereal crops and that emissions from both were higher than those from temperate natural ecosystems. Vermoesen *et al.* (1996) found that emissions from mown grassland, grazed grassland and a maize field were 3.3, 12.0 and 2.7 kg N_2O-N ha^{-1} yr^{-1} respectively. Annual emissions from arable lands in Belgium measured by Goossens *et al.* (2001) ranged from 0.3 to 1.5 kg N_2O-N ha^{-1} yr^{-1} representing N losses of 0.3 to 11%. In contrast emissions from intensively managed grasslands ranged from 15 to 32 kg N_2O-N ha^{-1} yr^{-1} representing N losses of 3 to 11%. Goossens *et al.* (2001) found that land use was more influential on the results than soil properties, and that the majority of emissions occurred during the winter period, highlighting the need for year round measurements.

The rate of N_2O production and emission depends primarily on the availability of mineral N in the soil. Thus, the application of mineral N fertilisers in agricultural systems increases N_2O emissions greatly, if there is a population of active nitrifying or denitrifying microorganisms present (Bouwman, 1990). In a German peatland Augustin *et al.* (1998) noted that low and moderate N fertilisation (60 or 120 kg N ha^{-1} yr^{-1}) caused a slight increase in N_2O emissions whilst high application rates (480 kg N ha^{-1} yr^{-1}) caused drastically enhanced N_2O emission rates within a very short period of time. N_2O emission rates ranged from 5.3 to 14.0 kg

N_2O-N ha $^{-1}$ yr^{-1} comparable with bog rice systems. However, the relationship between N_2O emissions and fertiliser application is not always strong. Flessa *et al.* (1998) recorded annual N_2O-N fluxes of 4.2, 15.6, 19.8 and 56.4 kg N_2O-N ha^{-1} yr^{-1} from a fertilised meadow, a fertilised field, an unfertilised meadow and an unfertilised field on cultivated peaty soil in Germany. The largest emission occurred on the unfertilised field on the peaty soil with a low pH of 4.0 although the relation to pH was weak when compared for the other systems. The seasonal variation in N_2O emissions was explained by Flessa *et al.* (1998) to be caused by changes in the groundwater level and soil nitrate content. One interesting conclusion from this example was that although the amount of organic carbon and nitrogen stored in the peaty soils was 20 times larger than that of nearby cultivated mineral soils, N_2O losses were not always larger from the organic soils. The reason for this was that the peaty soils has been intensively drained and cultivated for many decades. C and N mineralisation rates are assumed to be much higher on recently drained fen sites (Flessa *et al.* 1998). Mean background emissions of 0.5 kg N_2O-N ha^{-1} yr^{-1} were recorded by Flessa *et al.* (2002a) from sites in southern Germany with no N input whilst emissions from fertilised sites ranged from 1.3 to 16.8 kg N_2O-N ha^{-1} yr^{-1}. The highest emission was from a wheat field with emissions occurring between December and March during frequent freezing and thawing events. The relationship between emissions and N input was highly variable (0.7 to 5.9% of N input) giving a mean emission of 2.5% attributed to local soil properties (fine silty texture), soil management and climatic conditions that favour denitrification (Flessa *et al.* 2002a).

In another German site, Kaiser *et al.* (1998a) found that N_2O losses from applied N-fertiliser ranged from 0.7 and 4.1%.

Clayton *et al.* (1997) found that the type of fertiliser applied to soils has a clear affect on N_2O emissions as shown in Table 2.2.

Table 2.2. Fertiliser type and N_2O emissions

Fertiliser type	**N emitted as N_2O-N from fertilised grassland (%)**
Cattle slurry	2.2
Urea	1.4
NH_4NO_3	1.2
$Ca(NO_3)_2$	1.1
$(NH_4)_2SO_4$	0.4

Boeckx and Van Cleemput (2001) noted that the results of Clayton *et al.* (1997) indicate that the IPPC emission factor is in good agreement with the observed N_2O emission factor for urea, NH_4NO_3 and $Ca(NO_3)_2$, but underestimates emissions from slurry and over estimates emissions from $(NH_4)_2SO_4$. Dobbie and Smith (2003) found that applying urea instead of NH_4NO_3 to wet soils in cool conditions reduced N_2O emissions from N-fertilised grasslands in Scotland. Applying urea with a nitrification inhibitor could further reduce emissions. The N_2O fluxes measured by Dobbie and Smith (2003) peaked soon after N fertiliser, tailing off and remaining low until the next N application. Peak fluxes of 560 ± 57 g N_2O-N ha^{-1} d^{-1} were highest after application of NH_4NO_3. Moreover, there was a greater response to rainfall around the time of application of NH_4NO_3. This example shows that N_2O emissions are strongly influenced by the timing, quantity and type of fertiliser applied to agricultural soils. Kammann (1998) found that on an experimental grassland site where the management regimes differed in the total amount of mineral

N fertilisers applied, the cutting frequency and in the mean annual ground water table height, N_2O emissions occurred mainly just after fertiliser application and during freeze-thaw periods. Merino *et al.* (2001) found that N_2O production by slurry-amended soil (N_2O mainly due to nitrification) was twice as high as that of the mineral amended soil (N_2O from denitrification). An addition of nitrification inhibitor dicyandiamide to the slurry and mineral fertiliser produced a decrease in N_2O emissions from the slurry but not from the mineral fertiliser. Incorporation of manure (to reduce NH_3 volatilisation) greatly increases N_2O emissions depending on soil type as well. Chadwick *et al.* (1999) found that if the manure was injected instead of surface applied NH_3 loss was reduced, but emissions of N_2O increased from 1.6 to 6.1% of N applied on a clayey loamy soil and from 0.05 to 0.1% on a sandy soil. Velthof *et al.* (2002) found that high N_2O emissions were associated with manures with high contents of inorganic N, easily mineralisable N and C, such as liquid pig manure with emission rates of 7.3-13.9% of N input.

In the Netherlands, on grasslands and silage maize with a high slurry application rate of 250 kg N ha^{-1} yr^{-1}, Van Groenigen *et al.* (2004) observed N_2O fluxes of 1.92 and 6.81 kg N_2O-N ha^{-1} yr^{-1} for sandy and clay soils respectively. The emissions from slurry applied on the sandy soil were five times higher than when mineral fertiliser was applied. On clay soils the difference in emissions between mineral fertiliser and slurry was minimal. Background emissions were observed as being 0.14 and 1.52 kg N_2O-N ha^{-1} yr^{-1}. Van Groenigen *et al.* (2004) concluded that N_2O emissions were not linearly related to N application rates and varied with type and application rate of fertiliser.

Incorporation of crop residues is a potentially important source of N_2O, though poorly quantified (Velthof *et al.* 2002). Kaiser *et al.* (1998a) found that a crop rotation with subsequent incorporation of wheat residues gave the lowest emission factor of 0.7% of applied N, whereas the highest emission factor of 4.1% came from incorporation of sugar beet. Emissions attributed to the incorporation of legume residues, in leguminous cropping systems with no fertiliser application, were observed by Flessa *et al.* (2002a) to range from 7.4 to 12.9 kg N_2O-N ha^{-1} yr^{-1}. Flessa *et al.* (2002a) also noted increased emissions from sunflower fields following incorporation of legume cover cops. Kaiser *et al.* (1998b) found that crop type significantly influenced N_2O emissions mainly due to the different amounts of fertiliser applied to the crops. However, Kaiser *et al.* (1998b) observed that sugar beet showed the highest emissions despite having the lowest application of N-fertiliser, mainly due to the incorporation of the sugar beet residues. Velthof *et al.* (2001) suggest that the IPCC factor for estimating N_2O emissions from crop residues should define crop specific emission factors, instead of one emission factor for all the crop residues.

The timing and method of soil tillage can affect N_2O emissions. Soil loosening by tillage can decrease N_2O emissions while soil compaction can increase emissions (Flessa, 2002b). Ball *et al.* (1999) observed that no-tillage systems can increase N_2O emissions due to increased soil compaction (related to a lack of soil disturbance) and increased crop residue incorporation (related to increased SOC available for mineralisation and therefore increased available N). These factors make the no-tillage soil less aerobic than under conventional tillage. No-tillage systems are increasing where there is a need to reduce crop production costs, erosion from wind and water, a need to improve water efficiency and importantly as part of CO_2 mitigation strategies to increase the rate of carbon sequestration in soils. In a two to three month period after the sowing of a wheat crop, Aulakh *et al.* (1984) observed N_2O emissions under a conventional tilled system to range from 3 to 7 kg N ha^{-1} yr^{-1} whilst emissions from the same crop under a no-tillage system ranged from 12 to 16 kg N ha^{-1} yr^{-1}. On a fallow site (no crop rotation or fertiliser application) the N_2O emissions under a conventional tillage system ranged from 12 to 14 kg N ha^{-1} yr^{-1} whilst under a no-tillage system they were 34 kg N ha^{-1} yr^{-1}.

Irrigation can also increase N_2O emissions. Jambert *et al.* (1997) found that an intensively irrigated maize field emitted 11 kg N ha^{-1} yr^{-1}.

Atmospheric deposition of N can also make a significant contribution to N_2O emissions and in areas of low fertiliser application and high rainfall (*i.e.*. upland pastures) atmospheric deposition of N (NO_3^-, NH_4^+ and NH_3) can exceed that applied directly to the soils as mineral N fertiliser. In the UK for instance, significant atmospheric deposition of N can be found in the uplands of Wales, northern England and western Scotland where rates of 30 kg N ha^{-1} have been measured annually (DETR, 1994).

2.5 Agricultural soils and other GHGs

In addition to N_2O and CO_2, agricultural soils can be a significant source of CH_4. Flooded rice fields cover 11% of the world's arable area and account for 8% of total CH_4 emissions (IRRI, 2002). On the European scale, CH_4 emissions from rice fields are less significant as the rice fields cover less than 380,000 ha (0.35%) of the total arable area (Eurostat, 2003) and account for far less CH_4 emissions than from enteric sources. Estimations of enteric CH_4 emissions are generally compiled by statistical approaches based on livestock totals. On a regional scale, CH_4 emissions from rice production can be significant sources in parts of Italy, Spain and Greece. In northern Europe only soils with a very high water table are considered to be sources of CH_4, whilst all others are sinks (Smith *et al.* 2000). Rice fields can have very high emission rates of N_2O where the soil aeration regimes are changing rapidly (*i.e.*, flooding and drying out) (Li *et al.* 2004). Therefore any data gathered on the management of rice fields is mutually important to both CH_4 and N_2O emissions.

3 Regional estimations of N_2O emissions and mechanistic models

Whilst many N_2O measurements have been made at the field scale using some of the complex procedures, described in section 2.5, there still remains a great need for estimates of N_2O production at the regional scale. This regional level information is required for GHG inventory analysis and for further understanding of the factors that drive N_2O emissions at the regional scale. This chapter highlights the techniques currently used to extrapolate field-scale N_2O measurements to the regional scale and the methodology developed by the IPCC to produce national inventories of N_2O emissions from agricultural soils. In addition, the role of mechanistic models in estimating N_2O emissions at the regional scale and their contribution to inventory analysis is discussed.

3.1 Scaling and uncertainties

N_2O emissions from soils can be estimated at many different spatial levels. Langeveld *et al.* (1997) distinguished six main spatial scales related to N_2O emissions.

- The microbe (μm) scale: used to study the biological processes involved in transformations of dissolved gases and nutrients. Modelling at this scale requires a detailed mechanistic model (Leffelaar, 1998).
- The aggregate scale (mm to cm): The geometric shapes of aggregates (soil particles cohered together) are used as functional units with respect to transport and transformation of substances. In the denitrification process,

Arah and Smith (1989) identified that the aggregate radius and oxygen demand were the main factors affecting the ratio of N_2O to (N_2O + N_2) evolving from the aggregates.

- The soil column (0.1-1 m) and the rhizotron scale (metres) take into account gaseous transport through macropores in soil columns as well as between aggregates. In addition, at the rhizotron scale the vegetation or crop growth can be taken into account and can be useful for developing or testing field scale models (Langeveld *et al.* 1997). Rolston and Marino (1976) modelled NO_3^- dynamics at the rhizotron scale but found that N_2O could not be successfully modelled at this scale due to the high sensitivity of N_2O to factors outside the aggregate scale.
- The field scale (10 to 1000 m): Deterministic regression models are used at this scale that develop relationships between N_2O emissions and field scale parameters, or mechanistic models that describe the processes that drive N_2O emissions (*i.e.* Soil structure, nutrient availability, agricultural practices, climate). Mechanistic models will be reviewed in more detail in section 3.3.
- The regional scale: Generally, estimations at this scale are extrapolations of measurements made at the soil column or field scale. Mechanistic models are increasingly being used to generate regional emissions, often involving aggregation of multiple field scale runs.

The technique used for extrapolating GHG measurement results between different temporal and spatial scales is known as scaling. The large spatial heterogeneity and temporal variability of the factors that control N_2O emissions from agricultural soils, described in chapter 2, ensure that there will be many uncertainties in the estimations when N_2O measurements results are extrapolated (up-scaled) to the regional scale. Bouwman (1999) identified that the main goals of any investigative approach to reduce uncertainties in GHG emission estimates between terrestrial ecosystems and the atmosphere at the landscape, regional and global scale are:

- Identification of data gaps in scaling approaches between field, landscape, regional and global scales.
- Development of procedures to bridge process-level information between different scales.
- Assessment of methods for integration, aggregation and other data operations.
- Assessment of approaches to uncertainty analysis in bottom-up and top-down scaling.

An important step in the scaling of N_2O emissions is the delineation of functional soil/land use types where distinct differences in soil structure; composition or properties are correlated with functions or soil processes relevant for N_2O production (Bouwman, 1999). A bottom-up scaling approach can be used whereby statistical or mechanistic models can be used to calculate N_2O emissions for regions where measurement data is insufficient (spatially and temporally) or not available. Such models should ideally integrate known properties or variables at the larger regional scale, whilst accounting for the spatial and temporal variability of processes involved at the smaller field scale.

Bouwman (1994) based a global model on the strong relationship between measured N_2O emission and the amount of N being cycled through the soil. A regression equation resulting from the correlation of an N_2O index (based on the combination of five factors representing major regulators of N_2O production: soil fertility, organic matter input, soil moisture status, temperature and soil oxygen status) and actual field measurements was used to calculate emissions on a 1° longitude × 1° latitude grid using the Mercator projection. Minor differences in the measurements caused significant shifts in the correlation coefficient and a lack of validatory measurement data made this approach unsuitable for a number of important ecosystems (Bouwman, 1994).

A top-down scaling approach, such as inverse modelling, may also be used whereby the atmospheric concentrations of N_2O are related back to their sources. The bottom-up scaling approach is perhaps the more suitable approach for scaling N_2O emissions, as this approach can take immediately into account changes in agricultural practices and/or climate. In contrast, atmospheric concentrations of N_2O are subject to a significant time lag and cannot be easily related to changes in agricultural practice or climate.

Further uncertainties in up scaling may be identified when data are used in an extrapolation process or to drive mechanistic models. Uncertainties can be caused by the disaggregation; generalisation or aggregation of the data such as can be found in many soil maps. All maps, whether digital or analogue, are generalised representations of reality. Generalisation is an inherent characteristic in all geographic data (Joao, 1998) and can cause significant transformations of the original data. For instance if a GIS is used to process many datasets uncertainties in the datasets rather than the real world values will induce errors in all subsequent interpretations and actions based on the generalised data. This indicates that a great deal of uncertainty will occur in any modelling exercise that requires many different map-based datasets and GIS procedures to process the data. 'Ground-truthing' the datasets or results is vitally important to validate any results produced by modelling and up-scaling exercises.

Bareth *et al.* (2001) used a GIS to develop a soil-land-use-system approach developed to estimate N_2O emissions from a dairy farm system in Southern Germany. The environmental information system (EIS) combined soil, land-use, topography, long-term N_2O measurements and farm management data to predict an annual potential for N_2O emissions for around 775 km^2 of about 3.0 kg N_2O-N ha^{-1}.

3.2 Inventory analysis and the Kyoto Protocol

To understand the relative importance of N_2O discharges from agricultural soils to the total GHG emissions from all sources, comprehensive inventories of N_2O emissions must be compiled. In addition, all of the EU Member States are obliged, as signatories to the Kyoto protocol, to produce annual inventories of GHGs and their sources. The first phase of the methodology for reporting GHG estimations, including N_2O emissions from agricultural soils, was developed in 1995 (IPCC, 1995). These guidelines relate direct N_2O emissions to agricultural soils that have been fertilised with mineral N fertiliser. The IPCC 1995 approach can best be described as a simplistic statistical model where a basic formula equates N_2O

emissions to the nitrogen input, at the national scale, multiplied by a conversion factor of 1.25 ± 1.0 %.

The 1995 IPCC emission formula did not account for indirect N_2O emissions that could eventually evolve back to the atmosphere from N leaching or runoff from agricultural fields. To compensate for this omission, Cole *et al.* (1996) suggested the use of an additional emission factor of 0.75% of N applications. The IPCC emission factors were derived from a limited number of measurements, mostly coming from field studies in temperate agro ecosystems in North America and Europe. The emission factors account for 90% of the range of the published field data used (Bouwman, 1994; Mosier *et al.* 1998).

The IPCC phase II methodology of 1997 extended the phase I methodology by including direct N_2O emissions from animal production (including waste management) and indirect agricultural emissions. Direct sources include N_2O emissions emitted directly to the atmosphere from

- Synthetic fertilizers: related to N input from the mineral N fertilizers.
- Animal wastes Applied to Soils: related to N input from organic manure applied to soils.
- N-fixing Crops: related to the total dry biomass produced by pulses and soybeans.
- Crop Residue: Dry production of other crops.
- Cultivation of histosols: related to the area of cultivated organic soils

All of the direct emissions are calculated using the IPCC recommended N_2O emission rate of 1.25 % (±1.0 %) of N applications with the exception of the cultivation of organic soils (2-5 % in temperate zones and 10 % in the tropical zones) (IPCC, 1997). The IPCC estimate of N_2O emissions from organic soils provides an estimate of enhanced background emissions (unfertilized soils). However, because of enhanced mineralisation of soil organic matter due to historical agricultural practices, actual background emissions may be higher than natural emissions. Background emissions may also be lower where soil organic carbon depletion has occurred (Groffman *et al.* 1999).

Indirect sources of N_2O emissions include:

- Nitrogen leaching and run-off: related to N from fertilizers and animal wastes that are lost through leaching and run off.
- Atmospheric deposition: related to the volatilized N (NH_3 and NO_x) from mineral N fertilizers and organic manure (IPCC, 1997).

N_2O emissions associated with leaching and runoff play an important role in determining both the magnitude and the uncertainty of the agricultural N_2O source, as estimated by the 1996 revised IPCC methodology. According to the methodology, leaching/runoff emissions account for over 1/4 of the total agricultural N_2O source and nearly 1/2 of the range of uncertainty in the total source (IPCC, 1997). There are several areas of uncertainty in the IPCC estimate of N leaching and runoff related to N_2O emissions. First, in the current methodology, a default-leaching fraction for fertilizer and animal waste of 30% is recommended for all countries, despite large variations within individual watersheds and agricultural systems. Second, the N_2O emission factor associated with groundwater may be overestimated by an order of magnitude. Currently, groundwater accounts for 60% of leaching-related N_2O emissions, with the remainder assumed to occur from rivers and estuaries.

The equations used by the IPCC 1997 methodology to produce the article 4 inventories of direct and indirect N_2O emissions from agricultural soils are shown in appendix 2. The IPCC methodology requires national statistics on mineral N fertiliser use, livestock populations, and crop residue management. No account is taken for crop areas, soils, climate, fertiliser types or agricultural practices (*e.g.*, in crop planting, harvesting, tillage, irrigation). The IPCC methodology does not require the data to be geo-referenced and regional differences in agricultural practices and climate are not accounted for.

In a comparison between measured N_2O emissions from arable soils and emissions estimated using the IPCC methodology Freibauer *et al.* (2003) found a highly significant, but relatively weak correlation of N_2O emissions with N-input (see Figure 3.1). Freibauer *et al.* (2003) concluded that approximately half of the variation in N_2O emissions could not be explained by N input alone and that the emissions must be as a result of site-specific factors.

Regressions

Temperate West

$y = 1.08 \pm 0.13\ N_2O$, $r^2 = 0.63$***

Sub-boreal Europe

$y = 0.38 \pm 0.04\ N_2O$, $r^2 = 0.64$***

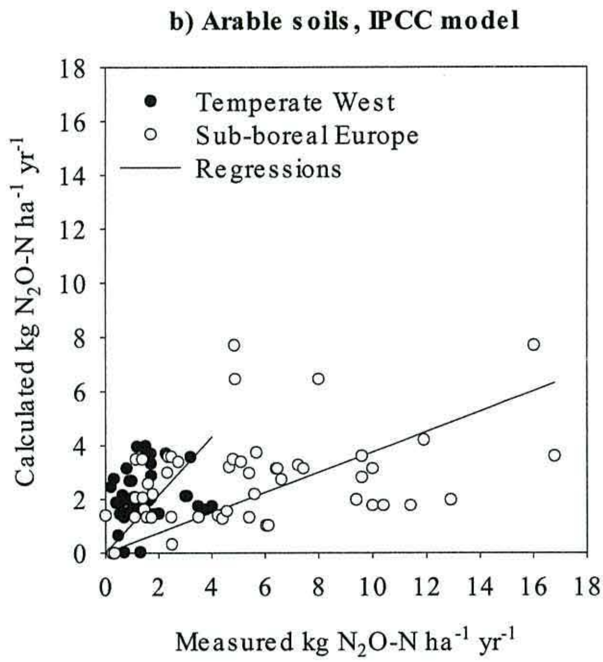


Figure 3.1. Correlation between measured N_2O emissions and IPCC-based estimates. Arable soils show lower mean and maximum emissions in oceanic temperate climate (Temperate West) than in pre-alpine temperate and sub-boreal climate (Sub-boreal Europe) (Freibauer and Kaltschmitt, 2003).

Estimating N_2O emissions on a regional scale is important for developing an understanding of the interactions between crop types, soil properties, climate, agricultural management and N_2O emissions. To make both significant improvements in the methodology used to produce N_2O emission estimates from agricultural soils and to produce regional estimations, the next step forward in inventory analysis is the utilisation of mechanistic models (Mosier *et al.* 1998)

3.3 Mechanistic models

Mechanistic models can fulfil the role needed for up-scaling N_2O emissions from the field scale to a regional scale by undertaking multiple crop/soil/climate scenarios at large spatial scales and over large temporal periods. If an accurate simulation of N_2O emissions is to be modelled, reflecting real conditions, then the mechanistic model must take into account all of the major components of the nitrogen cycle (as described in section 2.1). These components include mineralisation, assimilation by plants and microbes, leaching, and microbial-driven transformations, as well as the interaction between the nitrogen cycle and the carbon cycle and ecosystem biophysical drivers. An example of a simple conceptual mechanistic model developed by Paul and Domsch (1972) for modelling nitrification only, is shown in Figure 3.2. Many complex models have been developed in the past years that take into account many more processes than just nitrification. Some of these will be described in section 3.4.

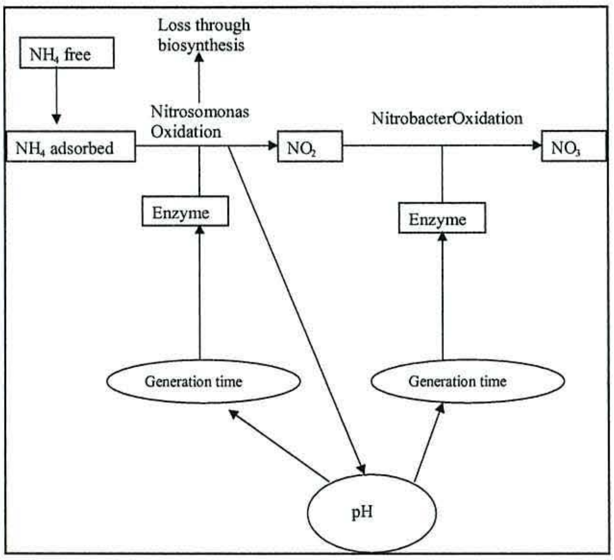


Figure 3.2. A simple mechanistic model for nitrification.

The results produced by mechanistic models must be validated against N_2O measurement data to test if the results represent real conditions. The modelled results may also show where measurement data are lacking and future measurement campaigns should be targeted.

Mechanistic model results can be used to identify agricultural practices or geographical areas that enhance high N_2O emissions. Thus the modelled results can be used to target particular areas where measurement campaigns or policy targeted mitigation strategies would be most effective. In addition, mechanistic models can be used to evaluate the IPCC emission factors and to produce regional emission estimates that take into regional differences in agricultural practices, soils and climate.

The benefits of undertaking regional estimates of N_2O are that emissions are strongly affected by differences in environmental conditions (*i.e.* climate or soil type) or agricultural practices (*i.e.* timing of planting or harvesting). The influence of climate and agricultural practices on N_2O emissions was illustrated in section 2.2. Thus, regional N_2O emissions can be related to the changes in agricultural practice, soil type or climate than national estimates. One of the limitations with mechanistic models is the availability of data to validate model estimates. The paucity of data has been a concern for many areas in Europe. A study such as this can be used to identify data gaps in both measurements and data required for regional modelling efforts.

3.4 Evaluation of mechanistic models for estimating N_2O emissions

There have been many mechanistic models developed for modelling N_2O emissions from agricultural soils that can contribute to the improvement of the IPCC methodology. The majority of the mechanistic models only account for direct emissions that are just one part of the total N_2O budget estimated by the IPCC methodology. One model that accounts for indirect emissions is the N-model developed by Kroeze and Seitzinger (1998). The N-model was primarily developed to account for N_2O emissions from aquatic systems (rivers, estuaries and continental shelves) and has been applied to 177 watersheds worldwide on a grid of 1 ° longitude by 1 ° latitude using the Mercator projection. One of the major limitations with the N-model, with regard to quantifying the total agricultural N_2O budget is the lack of groundwater estimates.

Frolking *et al.* (1998) made a comparison of four mechanistic models CENTURY-NGAS (Parton *et al.* 1994), Denitrification and Decomposition (DNDC) (Li *et al.* 1992a and Li *et al.* 1992b), Expert-N (Engel and Priesack, 1993) and the Carnegie-Ames-Stanford Approach (CASA) (Potter *et al.* 1996). The four models contain several common features namely plant growth, nutrient uptake, litter fall, decomposition of soil organic matter, and nitrogen mineralisation. Frolking *et al.* (1998) determined that accurate simulation of soil moisture was determined to be the key requirement for the reliable simulation of N_2O emissions. Whilst Frolking *et al.* (1998) observed that the N_2O emissions estimates produced by the models were close to measured N_2O emissions, the different approaches and structures of the models resulted in differing estimates of other gaseous N losses including nitric oxide (NO), dinitrogen (N_2) and ammonia (NH_3).

Many other different approaches to mechanistic modelling of N_2O emissions have been explored where models have been based on simplified processes (Potter *et al.*1996), soil structure (Arah and Smith, 1995; Smith, 1980; Tenreiro, 2000) or detailed microbial growth in the soils (Li *et al.* 1992a).

An example of a simplified process model, the CASA model developed in the United States by the National Aeronautics and Space Administration (NASA), used the soil microbial community as an index and calculated the process rates directly as a function of environmental parameters. CASA is a monthly time-step model and has been used to simulate global N_2O fluxes, driven in part by satellite remotely sensed data, at a global resolution. A major inherent limitation of the CASA model is its inability to take into account changes in agricultural management.

Soil structural models use physical processes as limiting factors where soil structure (aggregate and pore size distribution) are used to calculate the availability of substrates and oxygen, taking into account the diffusion of oxygen and substrates to the active sites within the soil (Arah and Smith, 1989; Smith, 1980). Though soil structure controls the processes involved in N_2O formation at the micro-scale, soil structure can be controlled at a higher scale, for instance by climate. According to Tenreiro (2000), this makes the soil structure approach suitable for both field and regional scale estimates.

More complex mechanistic models consider oxygen diffusion into individual soil micro-aggregates to determine the fractional volume of the soil that is anaerobic at any instant such as the model developed by (Smith, 1980). The more deterministic mechanistic models are the microbial growth models that calculate specific process rates per unit of active microbial biomass. The amount of microbial biomass in the soil is calculated using appropriate relationships connecting microbial biomass with the content of organic carbon (Li *et al.* 1992a). DNDC has been developed specifically to look at the nitrogen biogeochemistry in agro ecosystems and is therefore able to easily incorporate a variety of agricultural management activities such as manure application, planting, harvesting, weeding, tillage and irrigation.

Most of the models described have been developed to run on the field scale. One of the major problems in applying field scale models at the regional scale is the limited regional data availability. Therefore, a tool that can store all the spatially and temporally continuous data must is required sought. This role can be fulfilled by the use of a Geographical Information System (GIS) (described in more detail in chapter 5).

3.5 Mechanistic models and GIS

The use of a GIS that can hold and analyse spatial data, linked to a mechanistic model has been shown to provide a useful platform for undertaking N_2O emissions estimates on a regional scale (Muller *et al.* 1997). Recent progresses in spatial sciences in GIS and remote sensing (RS) have enabled the set up of soil, land use, climate and agricultural management information systems (Doluschitz *et al.* 2002). Where regional data required for modelling is lacking GIS and RS technologies can be used for interpolating data. Integrating GIS with mechanistic models is increasing and Hartkamp *et al.* (1999) identified four main methods that are used:

- Interface: a user interface communicates independently with a GIS and mechanistic model,
- Link: a GIS is used to process data for use by a mechanistic model,
- Combine: processing of data and automatic exchange of data,
- Integrate: fully integrating a GIS and a mechanistic model into one system,

The DNDC model includes a regional model that uses a database containing spatially referenced data. However, the database is not directly integrated with a GIS. The DNDC database must be previously processed in a GIS and the data exchanged with the model database. Spatial parameters including soil and land use are not considered by the DNDC model in their spatial relation (Doluschitz *et al.* 2002).

3.6 Model criteria for an EU-wide regional estimation of N_2O

The model requirements for this study were that the model should take into account most of the physical processes that drive N_2O emissions and the factors described in the IPCC methodology. The chosen model also needed the ability to incorporate agricultural practices and climate change scenarios, to operate on both field and regional scales. To undertake a regional estimate of N_2O emissions the model needed to be able to be linked to a GIS database that contained all of the relevant parameters for N_2O emissions.

Based on the review of models undertaken in section 3.4, and suitability to this study of regional emissions (Brown *et al.* 2002; Grant *et al.* 2003; Li and Aber, 2000) the DNDC model was identified as the most appropriate model for this study. The DNDC model is freely available on the Internet at the University of New Hampshire website (www.dndc.sr.unh.edu) with a user guide (Li, 2002). The DNDC model (version 77) was downloaded for this study, and is described in more detail in chapter 4. Dr. Changsheng Li of the University of New Hampshire provided the source code for the DNDCv77 model.

Changes were made to the model database structure, with the author's cooperation to fit the pan-European data available resulting in a new DNDC version 79b created specifically for this study.

4 DNDC (denitrification/decomposition) model

This chapter describes the structure of the DNDC model, the inputs required to run the model and highlights the most sensitive parameters identified following a sensitivity analysis of the mathematical model.

4.1 Introduction to the DNDC model

The DNDC model is a detailed mechanistic model that takes into account processes controlling C and N cycling in soils (Li *et al.* 1992a). It has been widely used for predicting C, N and CH_4 dynamics within agricultural soils.

The structure of the DNDC model (see Figure 4.1) shows the ecological drivers, soil environmental variables and sub-models of mechanistic processes that simulate the fluxes of GHGs from agricultural soils. DNDC was developed to simulate N_2O fluxes produced by nitrification and denitrification and CO_2 fluxes produced by decomposition and root respiration. The model also simulates the dynamic behaviour of a variety of C and N pools in the soil.

A soil climate sub-model uses daily meteorological data to predict soil temperature and moisture profiles, soil water flow (based on Fourier's law) and soil water uptake by plants for every hour of the simulation. One limiting factor in the accuracy of the DNDC thermal hydraulic model is the exclusion of surface flow. All rainfall is presumed to percolate into the soil. This limits the DNDC model's ability to accurately model indirect emissions due to run-off. However, the IPCC methodology bases indirect emissions due to leaching and run-off solely on the amount of N leached from the soils. In this situation, the DNDC model can be used to compare the IPCC estimate of N losses due to leaching.

A crop/vegetation growth sub-model simulates the growth of various crops from planting to harvest, predicting biomass and N-content of grain, stalk and root. Crop growth is limited by nitrogen and water availability in the root zone. Transpiration water losses are calculated from crop growth and a crop-specific water-use-efficiency parameter.

A decomposition sub-model partitions the soil organic carbon content into four soil pools: litter, labile humus, passive humus, and microbial biomass. Each pool has a fixed decomposition rate and a fixed C: N ratio. Decomposition rates are influenced by soil texture, and soil temperature, soil moisture and N limitations.

Nitrogen mineralised during decomposition enters the inorganic nitrogen pool as NH_4^+, where it accumulates and is nitrified to NO_3^- (with losses as NO and N_2O) or is lost via plant uptake, leaching, transformation to NH_3 and volatilisation, or adsorption onto clay minerals. Soluble carbon levels, which fuel both nitrification and denitrification, are related to the fraction of carbon released by the decomposition of litter, labile humus and dead microbial biomass that is re-assimilated by the microbial biomass each day.

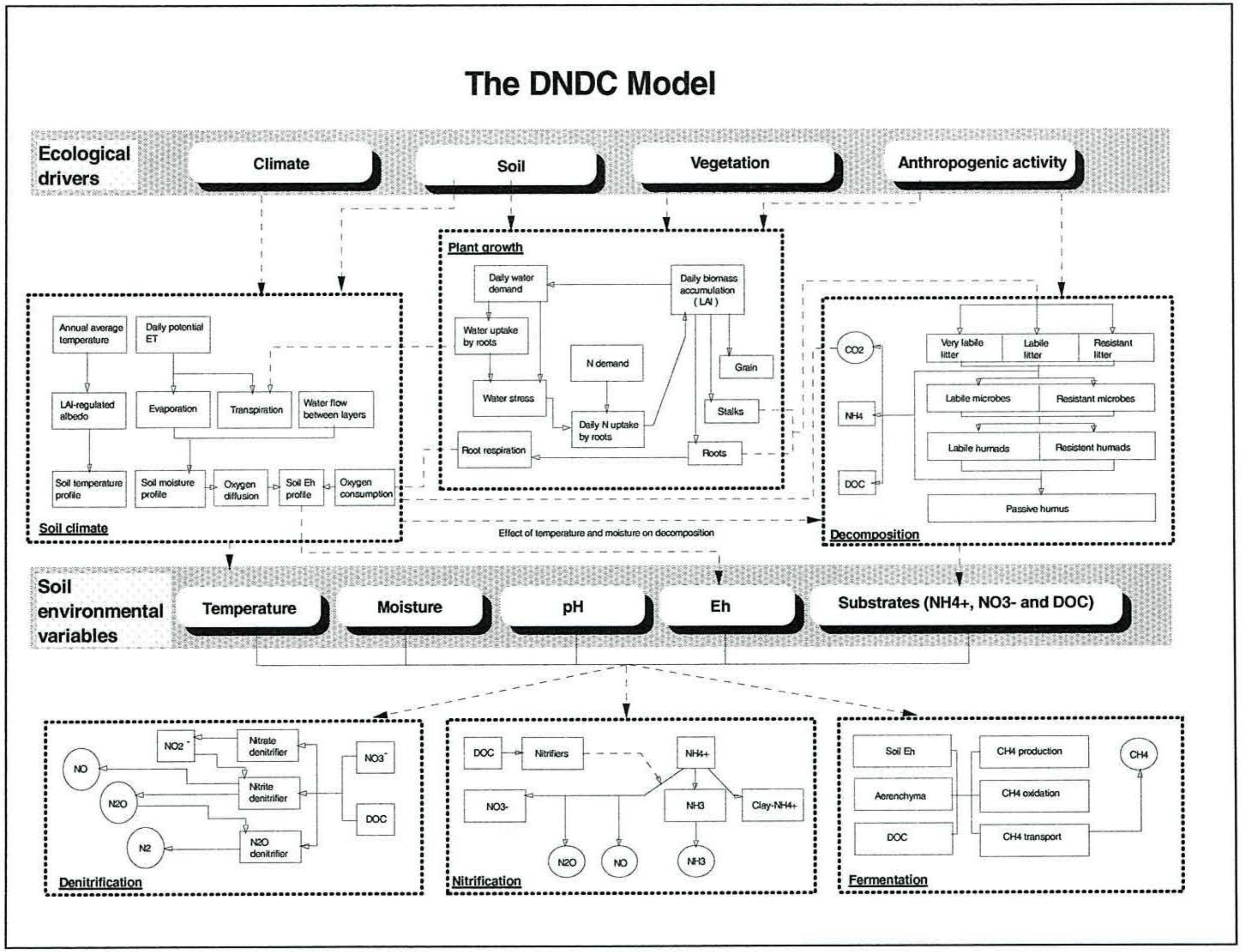


Figure 4.1. DNDC model structure (Li *et al.* 2000)

The crop growth and decomposition sub-models both operate on a daily time step. However, the denitrification is modelled on an hourly time-step activated by rainfall events (causing the soil moisture to increase and/or soil oxygen availability to decrease), irrigation or flooding practices and cold temperatures. Air temperatures below -5 °C are assumed to freeze the soil and thus inhibit oxygen diffusion into the soil. The decomposition sub-model provides the initial status of available NO_3^- and soluble carbon pools required for the initiation of denitrification. The rates for each step in the denitrification reduction sequence ($NO_3^- \rightarrow NO_2^- \rightarrow N_2O \rightarrow N_2$) are a function of soluble C, soil temperature (or redox potential (Eh) for 'frozen' soils), soil pH, N-substrate availability, and denitrifier biomass. As the soil dries following a rainfall event, the denitrifying portion of each model layer decreases proportionally with soil water content. The denitrification sub-model predicts consumption of nitrate and soil fluxes of NO, N_2O and N_2 associated with individual rain events. Eh is calculated depending on the soil organic matter content as a substitute for oxygen consumption, and an Eh multiplier for the denitrification rate is computed. DNDC does not simulate soil freeze/thaw and the associated impact on soil water content, even though this has been shown to be a major contributor to N_2O emissions (see Section 2.3).

4.2 Running the DNDC model and inputs/outputs.

To evaluate the data input requirements and outputs of the DNDC model a series of field scale runs, recording daily soil temperature and moisture flows and N_2O emissions, were undertaken using baseline data taken from published sources and climatic data for 1993 from the TRAGNET and JRC's Monitoring Agriculture and Regional Information Systems (MARS) database (described in more detail in chapter 5). With any modelling exercise, the model should be suited to the scale of the data available but once a suitable model and data sources have been identified the model can be modified to best use the data available. Likewise, the data need to be modified to the needs of the model. An overview of the inputs required by DNDC is shown in Figure 4.2.

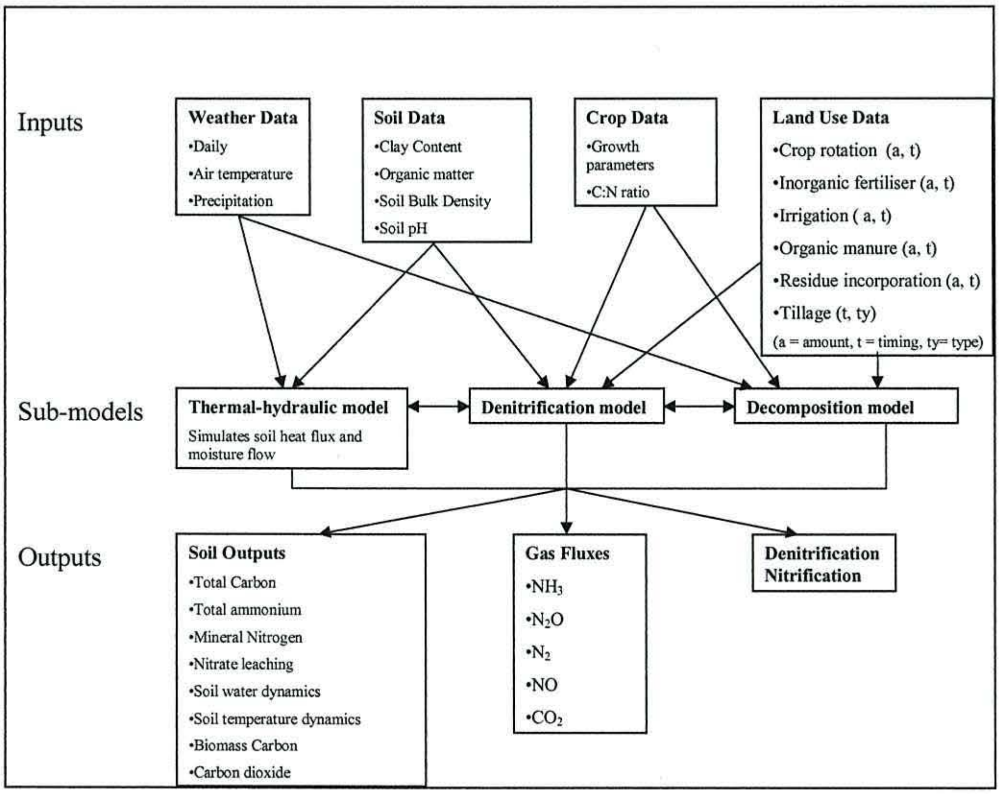


Figure 4.2. Inputs and output parameters used in the DNDC model.

In order to evaluate the inputs, sub model processes and outputs of the DNDC model, before undertaking the collation of regional data and estimations, a series of test runs were made using the field scale mode of the model. The field mode of the DNDC model is both time and data intensive requiring detailed input parameters to be entered via a user interface. The large number of input parameters is an advantage when making a comparison with measured data. The field mode also enables the recording of daily gaseous emissions as well as soil temperature and moisture flows. These daily soil flows and estimates were used to make a comparison with daily measured data. For undertaking regional runs (described in chapter 6) the regional mode of the DNDC model simulates exactly the same processes as the field scale mode using a reduced number of input parameters. These input parameters are stored in and delivered to the model from a series of databases prepared in advance (described in chapter 5). To compare the modelled estimates with field site measurements required a site that had sufficient data to run the DNDC model (daily meteorological, soil data, crop data and farm management data) and daily or year-round N_2O measurement data. For the purpose of this comparison, the baseline conditions were derived from the field and soil characteristics for a fertilised grass ley cut in Scotland described by Clayton *et al.* (1997) (see Table 4.1.). The site has a fairly low annual average temperature of 10°C coupled with fairly high rainfall of 977 mm per year. Fertilisation is high 360 kg N ha^{-1} yr^{-1} and the site has a no-tillage regime. The soil is clay loam with a low SOC carbon content of 2.8%. The Scottish field data used in this evaluation were previously used in a comparison of N_2O emissions reported for various sites within the TRAGNET network (described in section 2.2) and to run four different N_2O flux models by Frolking *et al.* (1998) described in section 3.4. The main aim of this field scale exercise was to show the necessity of daily meteorological data in estimating N_2O emissions.

The meteorological data for 1993 consisting of minimum temperature (°C) and maximum temperature (°C) and precipitation (mm) for the Scottish field site were derived from the TRAGNET network data (TRAGNET, 2000). The TRAGNET meteorological data was not complete for the entire year and only gave the data for 57 days. The TRAGNET database reports measurements of N_2O at the Scottish site taken daily, or every second day, for ten days following fertilisation and weekly during the rest of the growing season and less frequently during the winter (Frolking *et al.* 1998).

Table 4.1. Field site characteristics. (Clayton *et al.* 1997)

a. Fertilisation: 120 kg NH_4NO_3 derived N ha^{-1} on 29/4, 8/6 and 10/8.
b. Harvesting (t dry matter ha^{-1}): 28/5 (5200 t), 29/7 (3.5 t), 6/10 (2.5 t).

Field site characteristics	
Mean annual air temp (°C)	10.3
Mean annual ppt (mm)	977
Vegetation	perrenial ryegrass
Soil type	Gleysol (FAO-UNESCO classification)
Soil texture	clay loam
Surface soil carbon	0.028
Fertilisation	360 (a)
Tillage	none
Harvest	3 cutting yr^{-1} (b)
Annual N_2O flux (kg N/ha/yr)	1.6-5.2
Surface soil properties	
Sand/silt/Clay	34/37/22
Bulk density (g/cm3)	1.48
pH	6.15
SOC (kg C/kg soil)	0.028
Crop Properties	
Above ground NPP (kg dry matter/ha)	14,000
Rooting depth (m)	0.25
LAI Leaf are index (m^2/m^2)	4
Grain/shoot/root biomass fractions (%)	0/67/33
Grain/shoot/root biomass C:N ratios	-/18/40
Water requirement (mm/kg C fixed above ground)	0.144

The modelled emissions, at the Scottish site using the baseline site data and TRAGNET meteorological data (see Figure 4.3) show peak emissions occurring in the summer period following most of the fertiliser applications (in agreement with Dobbie and Smith (2003)) and episodes of precipitation, in accordance with Ball *et al.* (1999). Clayton *et al.* (1997) also observed periods of high N_2O emission in the summer following some but not all the fertilisations. The high emissions following precipitation can be attributed due to the wet soils increasing the oxygen-deficient conditions that are suitable for the denitrification process to occur (Li *et al.* 1992). The peak emissions highlight the need for daily meteorological data to drive the mechanistic sub-models of DNDC, but also the need for frequent N_2O

measurements. Infrequent N_2O measurements could omit peak emission events thereby underestimating the annual N_2O emission.

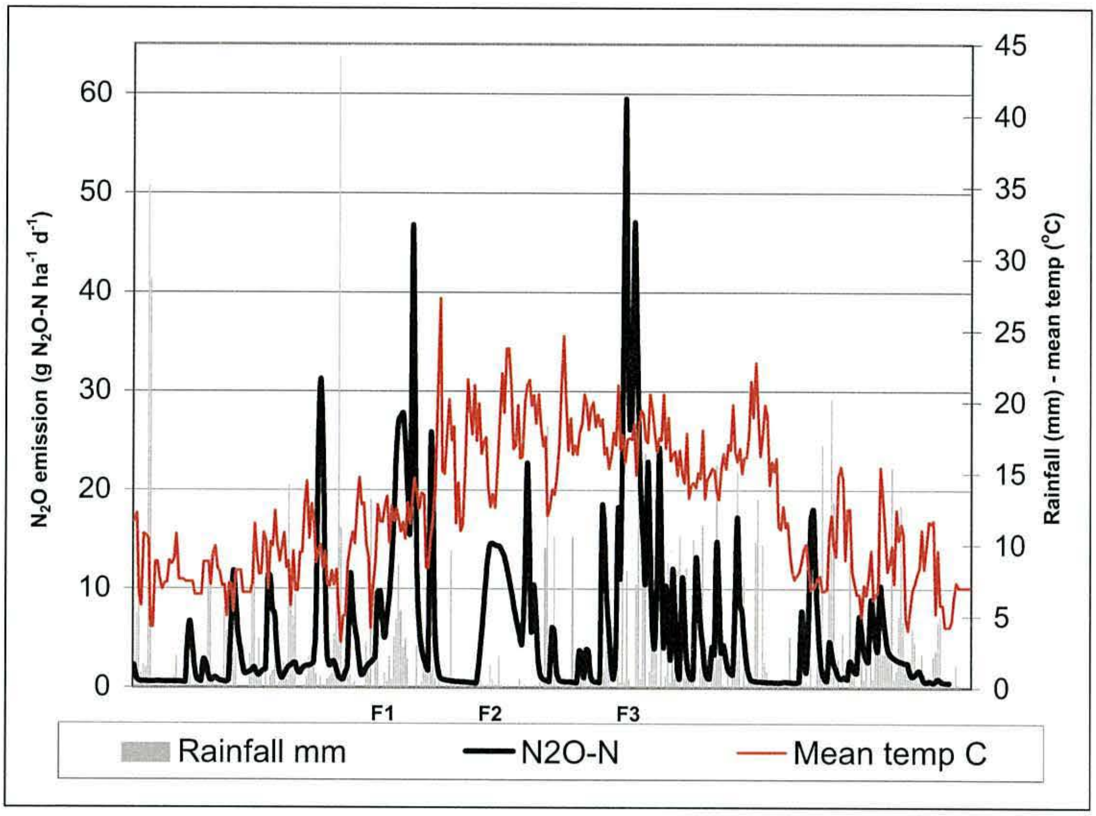


Figure 4.3. Daily N_2O emission (in black) related to the TRAGNET daily meteorological data for Edinburgh. Mineral fertiliser application times are indicated by the figures F1, F2 and F3.

In another example (see figure 4.4) the Scottish site data (Clayton *et al.* 1997) was used in conjunction with daily meteorological data for 365 days, provided by the School of Agriculture and Forest Sciences at the University of Wales, Bangor, UK, for an upland pasture site in Aber, Wales UK. This site was considered to have a similar land-use and climate to that of the Scottish pasture site. The peak emissions in summer following fertiliser application (shown in figure 4.4) display a similar pattern to the results using the TRAGNET data. What is of interest is the increased frequency of peak N_2O emissions, due to the more detailed meteorological data. The N_2O emissions also drop to zero when the mean temperature drops below freezing (see figure 4.4). Although DNDC assumes frozen soils inhibit oxygen diffusion, the model does not simulate soil freeze/thaw, a major contributor to N_2O emissions.

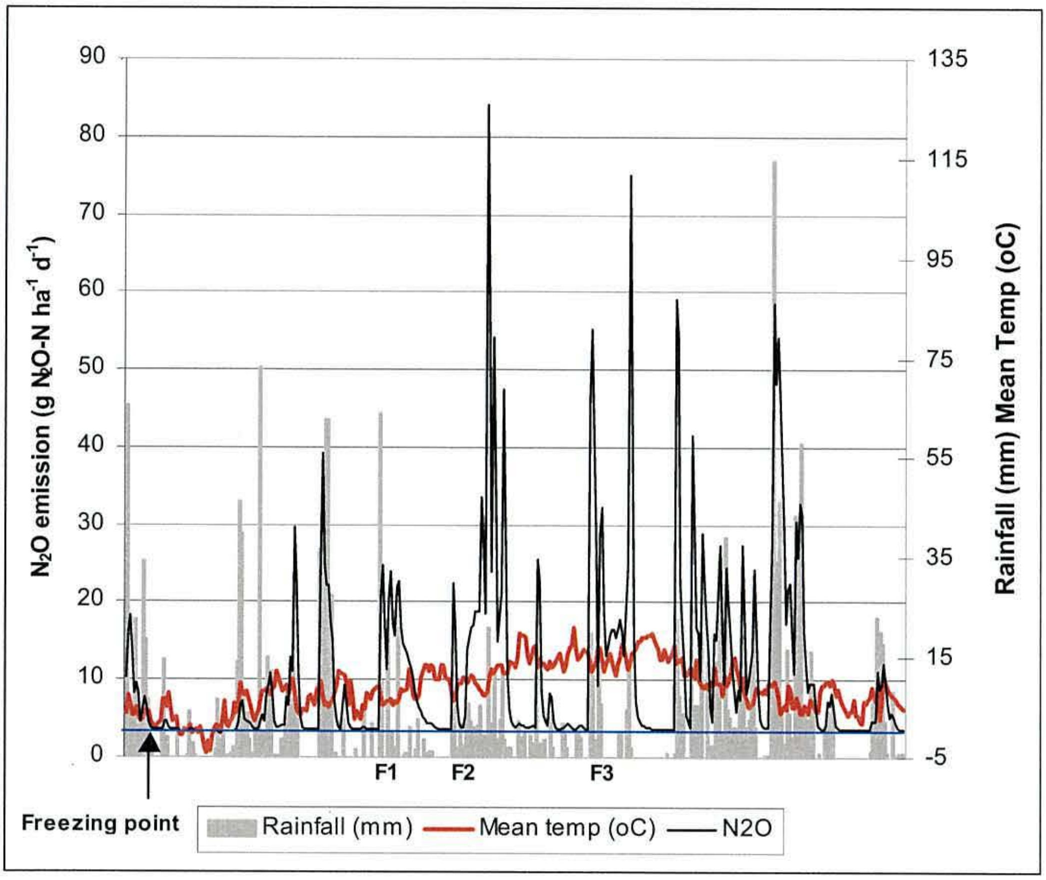


Figure 4.4. Daily N_2O emissions related to daily meteorological data for Aber, North Wales. Mineral fertiliser application times are indicated by the figures F1, F2 and F3.

To further demonstrate the necessity of daily meteorological data for estimating N_2O emissions a scenario using the Scottish site baseline date and the long-term climate database of the JRC's MARS database (described in more detail in section 5) was undertaken. The long-term climate data consists of average values for

30 years. From the results, shown in Figure 4.5, it can be seen that the long-term averaged rainfall data set cannot be used to represent daily conditions for specific years. Rainfall events may change significantly from year to year with heavy daily rainfall events occurring at different periods of the year. The peaks in N_2O emissions account for the fertilisation events but the peaks due to rainfall events are not modelled effectively.

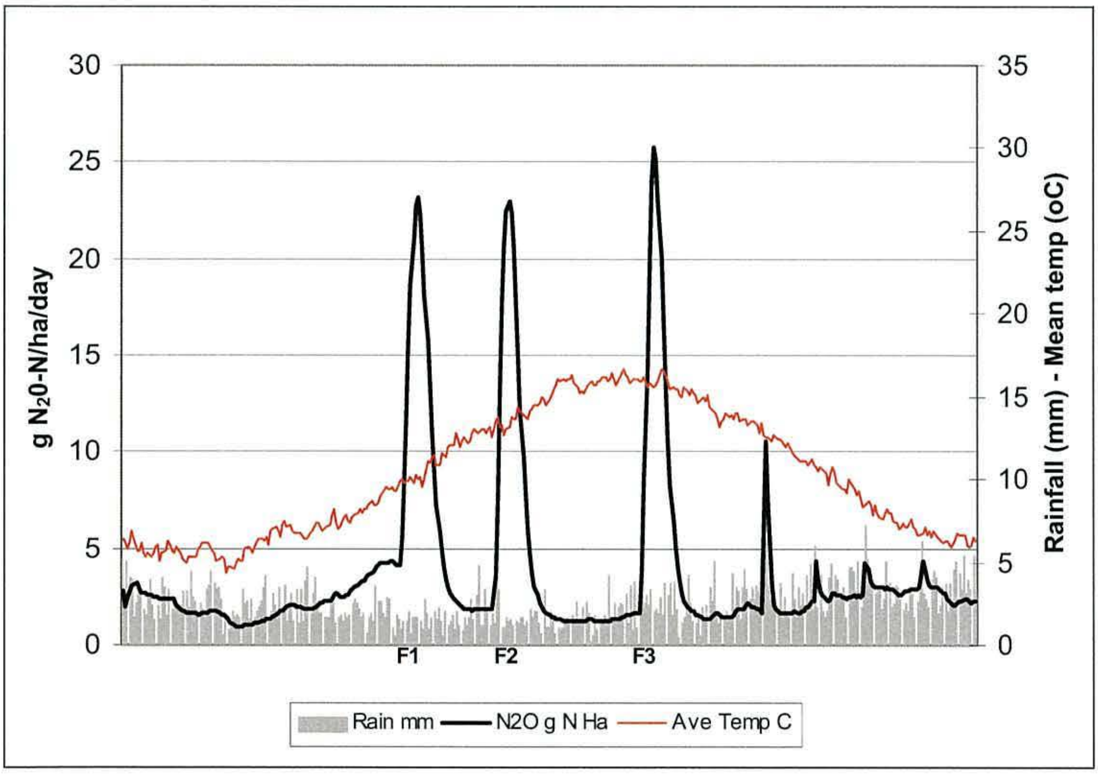


Figure 4.5. Modelled N_2O emission estimates using the MARS long-term database. Mineral fertiliser application times are indicated by the figures F1, F2 and F3.

The results of the climate comparison, shown in Table 4.2, indicate that with increased annual rainfall there is a significant increase in N_2O emissions. The increase in N_2O between the Aber and Edinburgh exercises can also be attributed to the increased meteorological events due to the more detailed daily meteorological used in the Aber exercise. The main impact of increased rainfall would be on increased soil moisture and therefore increased N_2O emissions (Ball *et al.* 1999).

Table 4.2. Test run results calculated in this study using the various climate data sets and the DNDC model.

Site	Average temp	Total annual Precipitation	Rain-N deposition	NO_3^- available for leaching	NH_3 volatilisation	N_2O	NO	N_2
	(°C)	(mm)	(Kg N ha^{-1})					
Edinburgh	12.4	977.1	17.59	163.52	10.09	2.49	27.01	5.30
Long-term	10.3	800.9	14.42	300.52	2.64	1.65	20.72	0.58
Aber	9.0	1598.9	28.78	195.76	3.48	4.50	16.92	6.19

To identify the relationship between climate and N_2O emissions it is essential that sites providing daily N_2O measurements also record daily climate data. This data is also important for evaluating the performance of daily time step mechanistic models.

A comparison between the modelled DNDC outputs of soil temperature and soil moisture and experimentally derived data from Aber, North Wales was undertaken. In comparison to the field measurements of soil moisture, the modelled soil moisture values (see Figure 4.6) tended to generally over-estimate soil water content. In comparison, with the experimentally measured soil temperature readings (see Figure 4.7), the DNDC model tended to overestimate soil temperature at a soil depth of 5 cm but underestimate it at 30 cm. The accuracy of the measured temperature data from the Aber site is unknown, but these differences in soil temperature and moisture would have considerable effect on N_2O estimates.

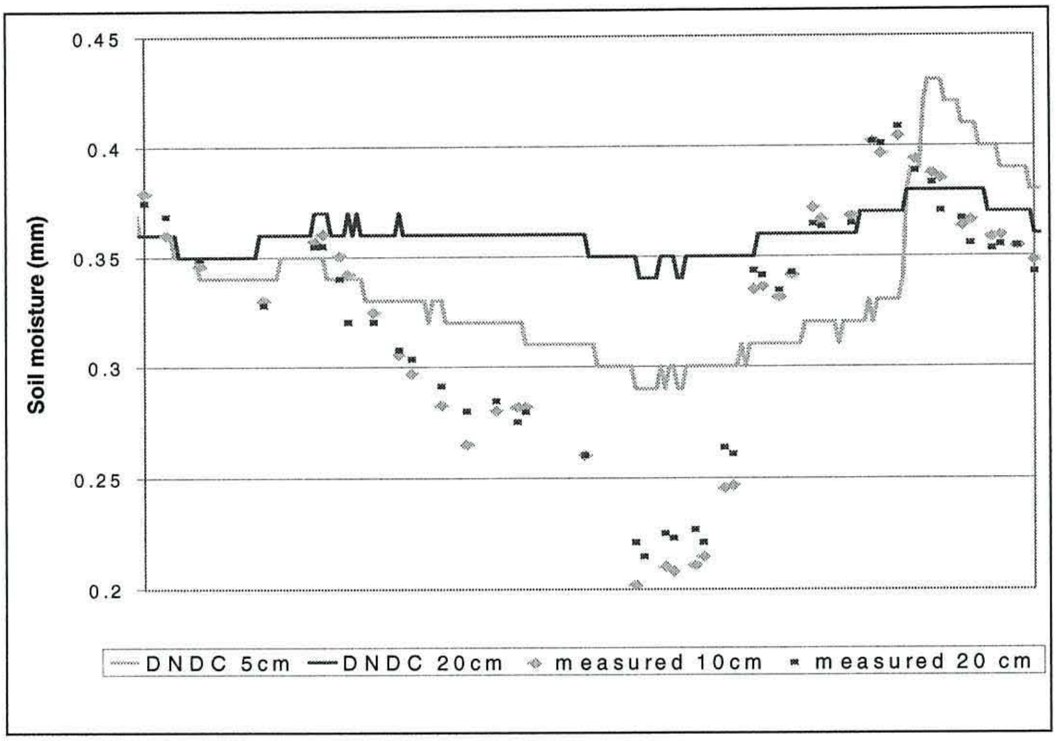


Figure 4.6. Modelled and measured soil moisture for two soil depths (10 and 20 cm) at the Aber site located in North Wales.

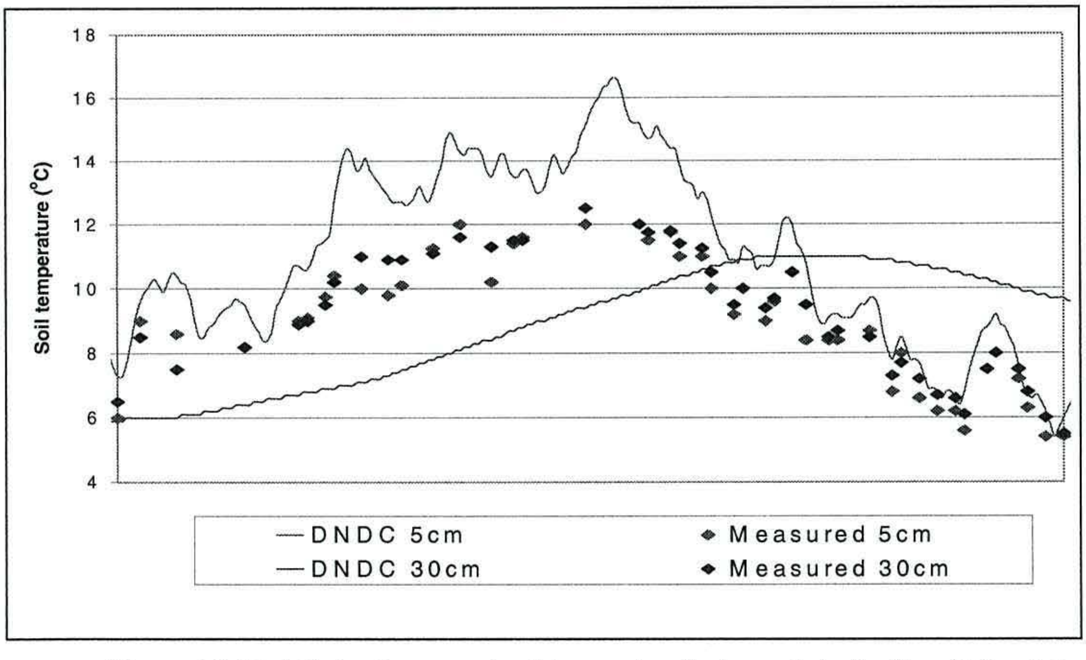


Figure 4.7. Modelled and measured soil temperature for two soil depths (5 and 30 cm) at the Aber site located in North Wales.

4.3 Sensitivity analysis

The sensitivity analysis took the form of a standard one-at-a-time (OAT) screening design, also known as *ceteris paribus* (Saltelli *et al.* 2000) where input values were changed, one at a time, from the standard baseline conditions of the Scottish site described in section 4.2. Sensitivity analysis was undertaken for all the major input factors required for running the regional mode of DNDC. Brown *et al.* (2002) and Li *et al.* (1992b) have also previously undertaken a sensitivity analysis of the DNDC model. However, the DNDC model has been under continuous development and many versions of the model exist. Therefore, a sensitivity analysis was undertaken for the DNDC version 79b used in this study. The sensitivity analysis results of the model to soil texture (see Figure 4.8) indicate that N_2O emissions increase with an increase in clay content. This is most likely due to the increased soil moisture with increased clay content, in accordance with Ball *et al.* (1999).

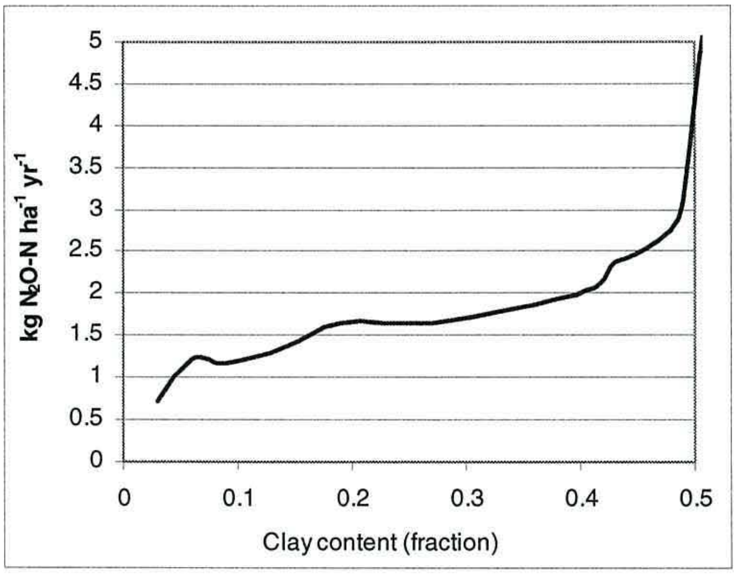


Figure 4.8. Sensitivity of DNDC modelled N_2O emissions in response to changes in soil texture.

The sensitivity analysis of the DNDC model to SOC content in soils (Figure 4.9) indicates a significant increase in N_2O emissions with increasing SOC. Brown *et al.* (2002) also found that the DNDC model was very sensitive to soil organic carbon content. However, in the sensitivity analysis other environmental factors were held constant. This may account for the non-linear curve shown in figure 4.9. Measured N_2O emissions (IFA/FAO, 2001) support the premise that N_2O emissions are highest on soils with a high SOC content. Bouwman *et al.* (2002b) noted that N_2O emissions for the same fertilizer rate tend to increase with higher soil carbon content. Although the SOC values of fertilised agricultural soils are generally low (see Section 5.2), the sensitivity of the model to SOC indicates that any regional emission estimates produced with the DNDC will be highly sensitive to any uncertainties in the SOC input data.

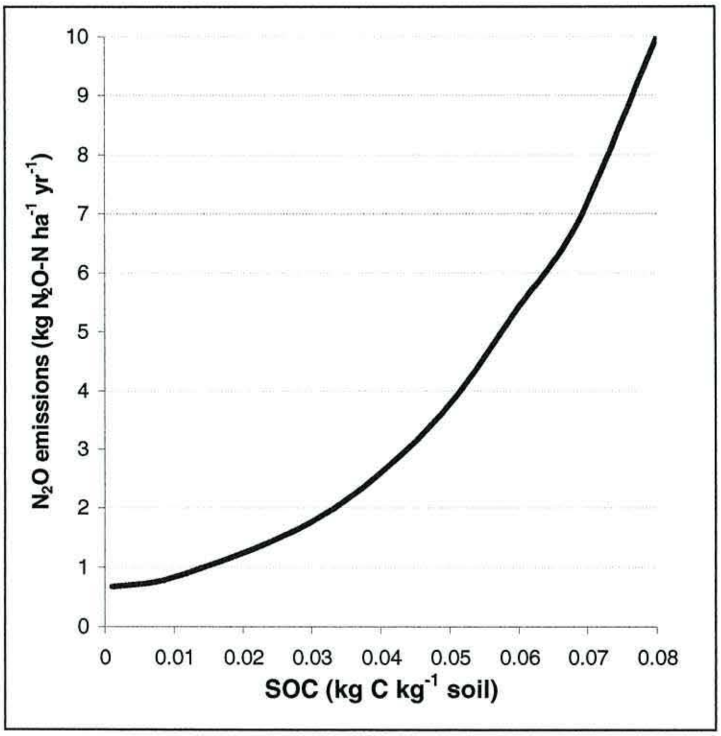


Figure 4.9. Sensitivity of DNDC modelled N_2O emissions in response to changes in soil organic carbon (SOC) levels.

In comparison to the effects of soil texture and SOC the factors shown in Figures 4.10 to 4.15 show less effect on N_2O emissions.

The DNDC model showed an upward trend in N_2O when the pH increased from 4.5 to 7.0, then a decrease above a pH of 7.0 (Figure 4.10). However, the changes in N_2O are relatively small (1.4 to 1.65 kg N_2O-N ha^{-1} yr^{-1}). Flessa *et al.* (1998) observed high N_2O emissions on a soil with a pH of 4 but found the relation to pH was weak in other systems.

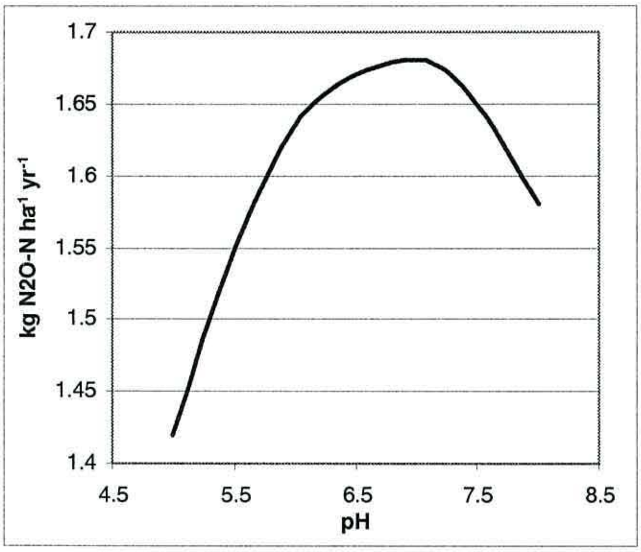


Figure 4.10. Sensitivity of DNDC modelled N_2O emission in response to changes in soil pH.

The sensitivity analysis showed that an increase in bulk density resulted in an increase in N_2O emissions (Figure 4.11). This is supported by Flessa *et al.* (2002b) and Ball *et al.* (1999) who also noted that soil compaction increases N_2O emissions. The sensitivity analysis was carried out within the range of values (1.4 to 1.8 g cm^{-3}) provided by the European soil data. However, a more appropriate scale that reflects values common in agricultural soils would start at 0.9 or 1.0 g cm^{-3}.

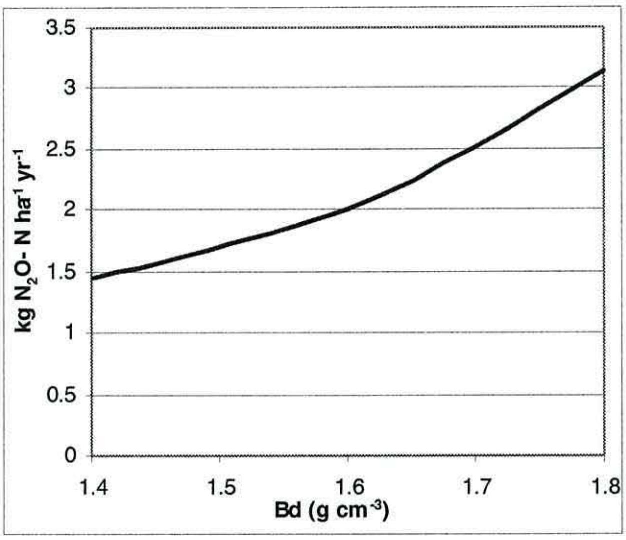


Figure 4.11. Sensitivity of DNDC modelled N_2O emissions in response to changes in soil bulk density (BD).

The sensitivity analysis for temperature was performed by changing the temperature in increases of 1 °C from the baseline conditions. Figure 4.12 shows that increasing the temperature increases N_2O emissions, in accordance with Smith *et al.* (2003).

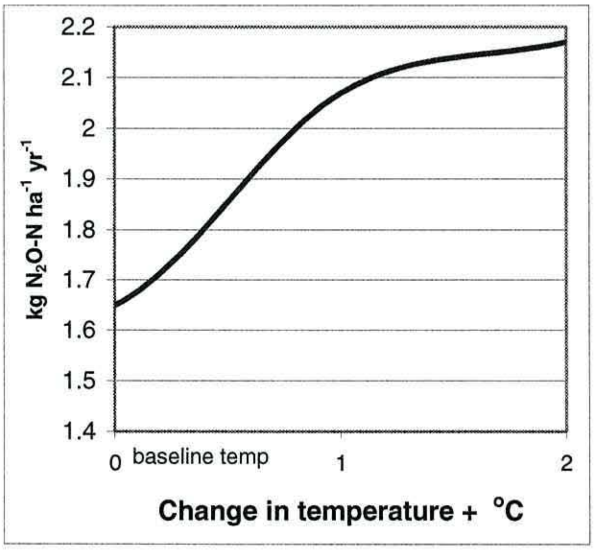


Figure 4.12. Sensitivity of DNDC modelled N_2O emissions in response to a change in temperature from baseline conditions.

N_2O emissions increased with an increase in annual precipitation from the baseline conditions (Figure 4.13), in agreement with Ball *et al.* (1999).

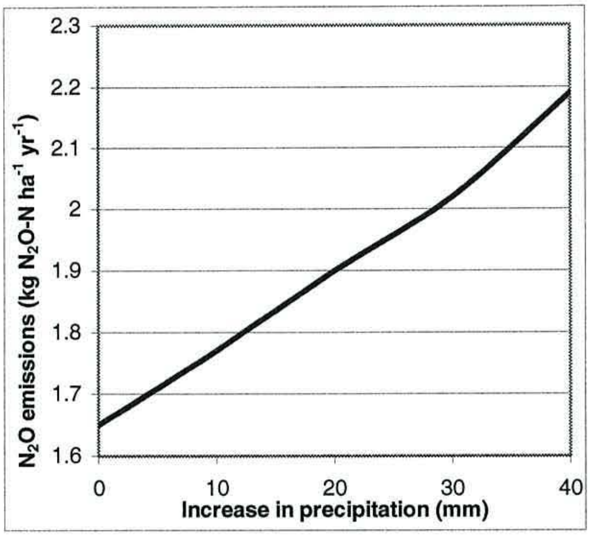


Figure 4.13. Sensitivity of DNDC modelled N_2O emissions in response to a change in precipitation from baseline scenario.

Sensitivity analysis showed that N_2O emissions increased with ploughing depth (Figure 4.14) in accordance with Kaiser *et al.* (1998b).

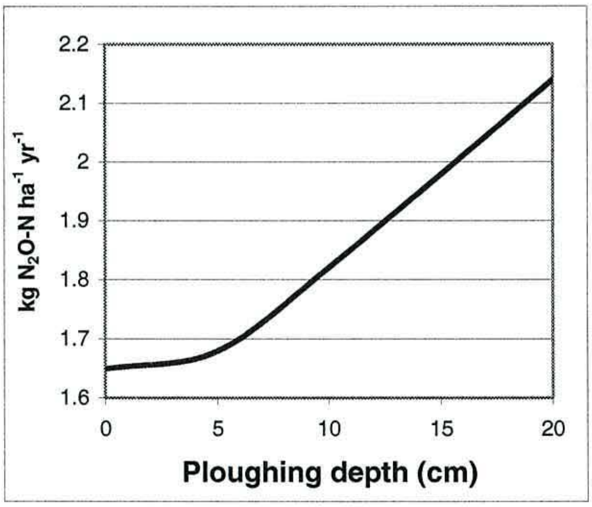


Figure 4.14. Sensitivity of DNDC modelled N_2O emissions in response to changes in ploughing depth.

The DNDC model showed a linear increase in N_2O emissions with increased application of urea fertiliser (Figure 4.15) in agreement with Bouwman (1990). In the modelling situation where all other factors remain static within the one site this is expected. However, in reality other climatic and soil factors would affect this linear relationship.

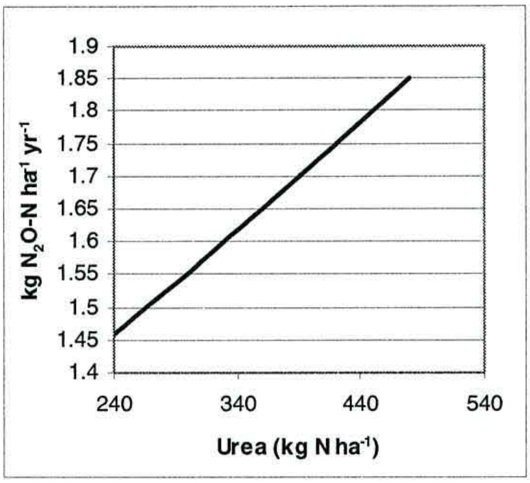


Figure 4.15. Sensitivity of DNDC modelled N_2O emissions in response to changes in the application rate of urea fertiliser.

Sensitivity analysis (Figure 4.16) showed that the type of fertiliser also significantly affects N_2O emissions. Most nitrate based fertilisers show lower N_2O emissions than urea, with the exception of ammonium nitrate, in agreement with Clayton *et al.* (1997).

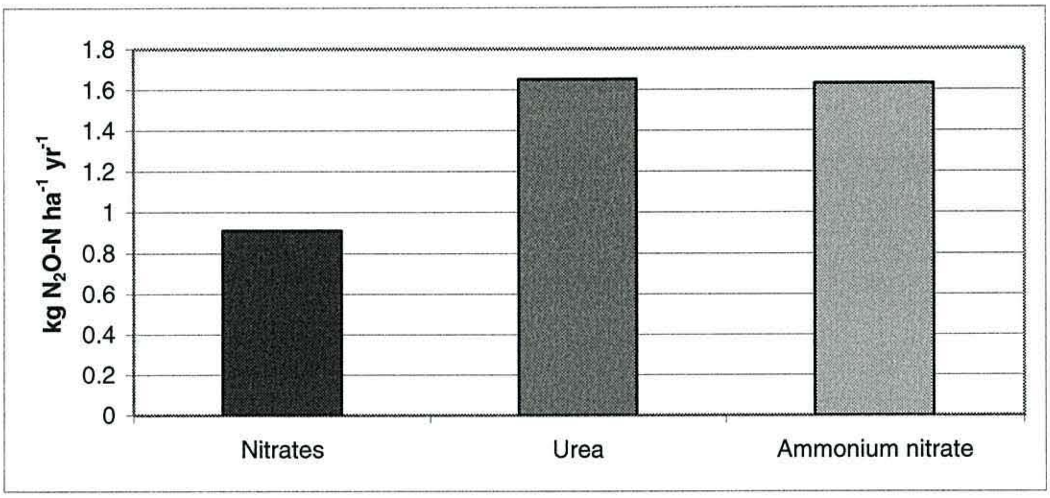


Figure 4.16. Sensitivity of DNDC modelled N_2O emissions in response to changes in fertiliser type.

The sensitivity analysis showed that N_2O emissions also changed with crop type (Figure 4.17). This effect can be attributed to the modelled crops having different biomass production and N uptake rates in the crop characteristic files of the DNDC model. The sensitivity analysis also provided unlikely combinations of crop, soil and climate conditions that would effect N_2O emissions. For example the N_2O emissions are greatly effected by the timing of flooding. In reality the change in crop type changes the management (i.e. fertiliser application, timing) that will also greatly affect N_2O emissions (Kaiser *et al.*, 1998b).

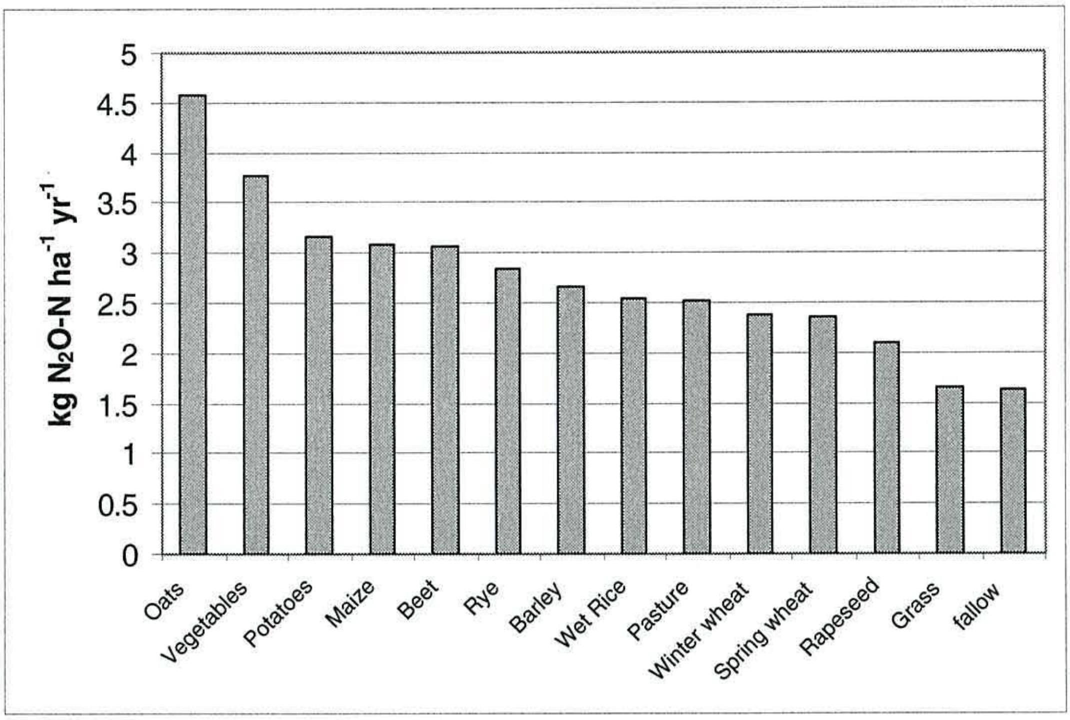


Figure 4.17. Sensitivity of DNDC modelled N_2O emissions in response to changes in crop type.

4.4 Conclusion of the sensitivity analysis

The sensitivity analysis of the DNDC model carried out here showed that modelled N_2O emissions were most affected by changes in SOC, soil texture, precipitation and fertiliser type. None of these factors are directly taken into account by the IPCC methodology. IPCC indicates that high N_2O emissions are attributed with histosols (highly organic soils without texture) associated with agriculture. However, histosols do not account for all agricultural soils with a high organic carbon content that could be a potential source of high N_2O emissions.

The sensitivity analysis carried out in this study corresponds favourably with the sensitive factors of the DNDC sub-models described by Li *et al.* (1992a) shown in Table 4.3. This indicates that the fundamental processes within the DNDC model have not changed between versions.

Table 4.3. Highly sensitive factors affecting predicted N_2O emissions within each of the DNDC sub-models.

DNDC Model	Item	Highly Sensitive Factor
Thermal-hydraulic submodel	Soil moisture	Rainfall patterns
		Soil Texture
Decomposition submodel	Soluble C	Initial organic C
		Soil temperature
		Soil moisture
		Dry period duration
	Nitrate	Initial organic C
		Dry period duration
		Soil temperature
		Soil moisture
Denitrification	N_2O	Precipitation
		Soil soluble C
		Soil nitrate
		Soil Texture

5 Regional database (methods and materials)

A major part of this study was involved or concerned with the sourcing of suitable data and subsequent processing of the collated data. Many datasets relevant to this modelling exercise exist but due to various reasons (economic, political, or scientific exclusivity) are not freely available in their complete form. Moreover, various datasets are not targeted directly towards the modelling community and data are aggregated (*e.g.* Eurostat crop data) before being made available to third parties. A number of datasets suitable for this study were available within the JRC. As data are continuously being updated, a decision was taken to use the most up-to-date and available data for Italy and at the Europe-wide scale, at the time of collation for this study within the time constraints of the thesis period. Italy was selected, as this was where the study was undertaken and detailed up-to-date datasets were available.

This chapter describes the data sources and data requirements needed to undertake this study and the methodology employed to process the data to create a harmonised database suitable for input into a mechanistic model.

5.1 GIS and regional nomenclature

This study made extensive use of a Geographic Information System (GIS). A GIS can be defined as an integrated system for capturing, storing, checking, integrating, manipulating, analysing and displaying data, which are spatially referenced to the Earth. This is normally considered to involve a spatially referenced computer database and appropriate applications software (DOE, 1987).

Real world information or spatial data are represented in a GIS as points, lines (arcs), polygons or as cells (a grid). These spatial features are stored in a coordinate system (*e.g.* latitude/longitude, The Universal Transverse Mercator (UTM), UK National Grid), which references a particular place on the earth. Descriptive attributes in tabular form can then be associated with the spatial features. Spatial data and associated attributes in the same coordinate system can then be layered together for mapping and analysis.

The GIS software used in this thesis was Arc View 3.2 produced by ESRI Inc. (www.esri.com). ESRI software uses a series of internal data formats to hold spatial information: the coverage, the shapefile and the grid.

- A coverage is a data format developed by ESRI for the Arc Info GIS in the early 1980s for storing the location, shape and attributes of vector data (points, lines and polygons) using a sub-directory containing a number of files only readable by ESRI software.
- A shape file is an alternative data format for vector data, also developed by ESRI. Unlike coverages, features are represented by five shapefiles with the attributes being held in a dbf file that can be viewed and manipulated by other third party software (*e.g.* MS-Access).
- Grid is ESRI's format for raster data, the representation of the world as an array of equally sized square cells arranged in rows and columns. Each cell

contains a value representative of the surface that it covers (*e.g.* albedo, code for land cover type, population density).

For statistical purposes, the European Commission uses a standard nomenclature for geo-referencing the administrative divisions of countries called Nomenclature of Territorial Units for Statistics (NUTS). However, the NUTS divisions do not correspond exclusively to administrative divisions within the country. The NUTS acronym is derived from the French name for the scheme, 'nomenclature des unités territoriales statistiques'. A NUTS identifier begins with a two-letter code referencing the country. The subdivision of countries is then referred with one number. A second or third subdivision level is referred with another number each. Each numbering starts with one as zero is used for the upper level. In case it has more than nine entities, capital letters are used to continue the numbering. For example, the province of Varese (NUTS Level 3) is referred to as IT201 while the region of Lombardia (NUTS 2) is coded IT2. These GIS and NUTS terms are used extensively throughout the remainder of the chapter.

Large amounts of spatial data were made available for Europe within the GISCO database (Geographic Information System for the European Commission) (Eurostat, 2003). This database contains spatial data collected and maintained by the Statistical Office of the European Communities (Eurostat), the body responsible for official statistics within the European Union. Datasets relevant for nitrogen modelling include land cover, a Digital Elevation Model (DEM), climate, major watersheds, soil and administrative boundaries.

These data are available as coverages in a Lambert-Azimuthal Equal-Area projection. This projection was considered the most suitable for this study because the area of individual polygons are preserved while simultaneously maintaining a true sense of direction from the centre. Other datasets (described in this chapter) that were not available in this projection were converted to the Lamberthal Azimuthal projection using the parameters shown in Table 5.1. All subsequent GIS maps shown in this thesis were based on GISCO coverages.

Table 5.1. Lamberthal Azimuthal projection parameters

Projection	Lambert Azimuthal
Datum	None
Z units	No
Units	Meters
Xshift	0.0
Yshift	0.0
Radius of the sphere of reference	6378388.0
Longitude of centre of projection	9
Latitude of centre of projection	48
False easting (meters)	0.0
False northing (meters)	0.0

Eurostat maintains a macro-economic statistical database (New Cronos) that contains over 100 million statistical data covering the living conditions and the economic situation of the EU member states and candidate countries (European Commission, 2003). The data are available at various spatial (*i.e.* NUTS levels) and temporal scales (*i.e.* monthly or annual), depending on the statistical field covered. The nine major themes are divided into several domains covering a specific statistical sector.

For nitrogen modelling the themes of most interest are:

- Theme 5 (Agriculture, forestry and fisheries) provides data on economic accounts for agriculture and forestry, structure of agricultural holdings, agricultural production, agricultural products and database on orchards.
- Theme 8 (Environment and Energy) provides statistics on the environment such as agricultural data on nitrogen balance.

5.2 Geographical unit

The DNDC model estimates regional emissions within a predetermined geographical unit by linking all the data stored in a geographical database via a unit identifier (Li and Aber, 2000). The geographical database contains data on geographical location, meteorological cell location, soil parameters, crop area and manure input, and is linked to a library containing non-spatial daily meteorological data, farm management data and crop physiological properties. The geographical unit within DNDC can be either delineated by administrative boundaries (*e.g.* NUTS) or a grid of any required size. The size of the unit used in the modelling exercise is very much determined by the scale of the source data. For this study, the climate and soil data were available on a 50 km × 50 km and 10 km × 10 km grid respectively whereas the crop data were reported within administrative boundaries at either the NUTS 2 or 3 levels. These NUTS vary in area considerably but are predominantly larger than both the soil and climate grids as shown in figure 5.1.

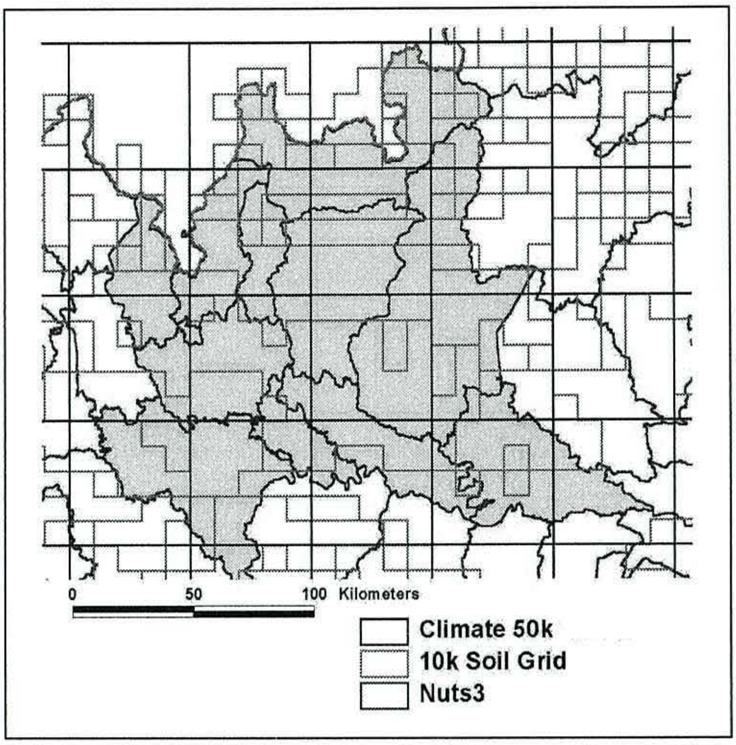


Figure 5.1. The relative scales of input data themes.

Climate (50 km × 50 km), soil (10 km × 10 km), and administrative boundaries (NUTS level 2 and 3). The shaded area, shown here, is the NUTS 2 polygon for Lombardia, Italy, sub-divided into the NUTS level 3 indicated by the blue polygons.

For this study the NUTS level 3 was deemed the most appropriate scale for the geographic unit at which the DNDC model would be run. This decision was taken because the crop data for the EU 15 Member States was available predominantly at NUTS level 2 and the present methodology of disaggregation (described in 5.5) could produce greater uncertainties in the spatial location of crops if a scale smaller than NUTS level 3 was chosen. Moreover, the meteorological data were only available at a 50 km × 50 km resolution, and it was assumed that a modelling scale smaller than NUTS level 3 would not necessarily reflect the true meteorological conditions. To make better use of modelling scales smaller than

NUTS level 3 a finer resolution of meteorological data would be required that could take into account adiabatic lapse rates (decrease in temperature with altitude) and more localised conditions.

The geographic parameters (see Table 5.2), required by the DNDC GIS database file No. 1 of 'county characters', provides the link via the unit ID to all the other geographic parameters needed to run the DNDC model at the regional scale.

Table 5.2. Geographic information and example data required by the DNDC GIS database.

Grid Characteristics		
1	Unit ID	*1001*
2	Name *	*IT201*
3	Region *	*Varese*
4	Longitude	*8.764*
5	Latitude	*45.734*

NUTS level 3 polygons were derived from the GISCO coverage of NUTS regions version 7 (Eurostat, 2003). The resultant coverage containing 1077 polygons (Figure 5.2) shows clearly that the NUTS level 3 administrative units are heterogeneous in both size and shape. This is important to note, as these differences in size and shape can produce significant differences in the ranges of statistical data depending on location and the type of data derived (in particular the range of soil parameters described in section 5.5). Longitude and latitude coordinates, in digital degrees, are used to drive the day length function of the crop growth model within the DNDC model. These parameters were derived the centroid of each NUTS level 3 polygon.

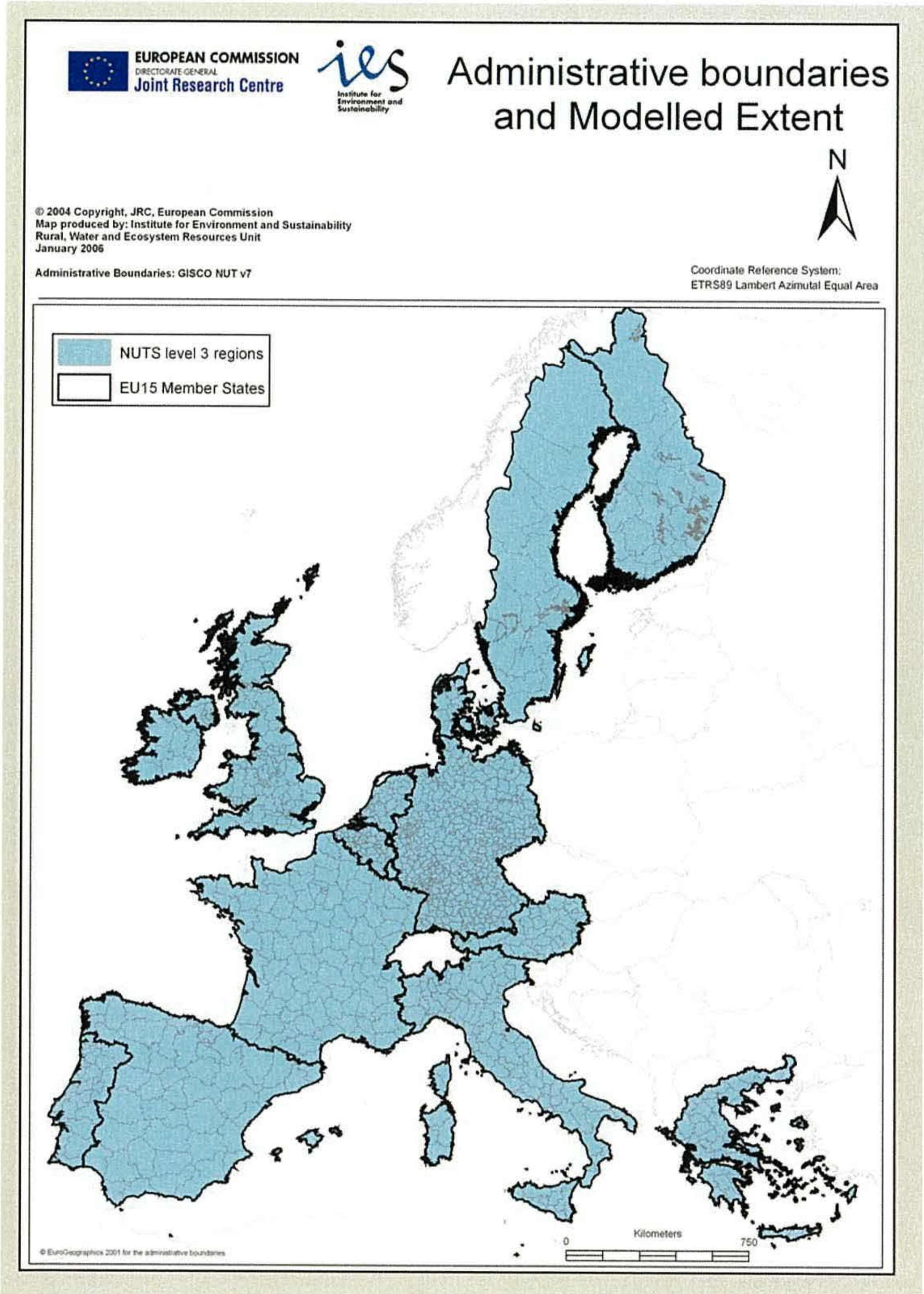


Figure 5.2. Geographic modelling unit coverage (NUTS level 3) for the EU15.

5.3 Meteorological data

The Monitoring Agriculture and Regional Information Systems unit (MARS) of the JRC possess an archive of daily surface meteorological measurements (shown in Table 5.3) from more than 1500 weather stations across Europe. The MARS unit have spatially interpolated the meteorological data onto a 50 km × 50 km grid by selecting the best combination of surrounding meteorological stations for each grid (see Figure 5.3).

Table 5.3. MARS database daily meteorological data

Climate parameter	Unit
Minimum air temperature	^{o}C
Maximum air temperature	^{o}C
Precipitation	mm
Mean windspeed (at 10m height)	m/s
Mean vapour Pressure	hPa
Calculated potential evaporation	mm
Calculated global radiation	KJ/m^2

In addition to the daily dataset, a long-term reference weather data set for Europe is available consisting of a long-term average values calculated on all the years of the archive (from 1975 to last full year) on a Julian day basis (366 days). The long-term dataset can be used for identifying a correlation between annual rainfall patterns and annual N_2O emissions. However, for this study the daily meteorological data was used due to the strong relationship between daily rainfall, temperature and N_2O emissions.

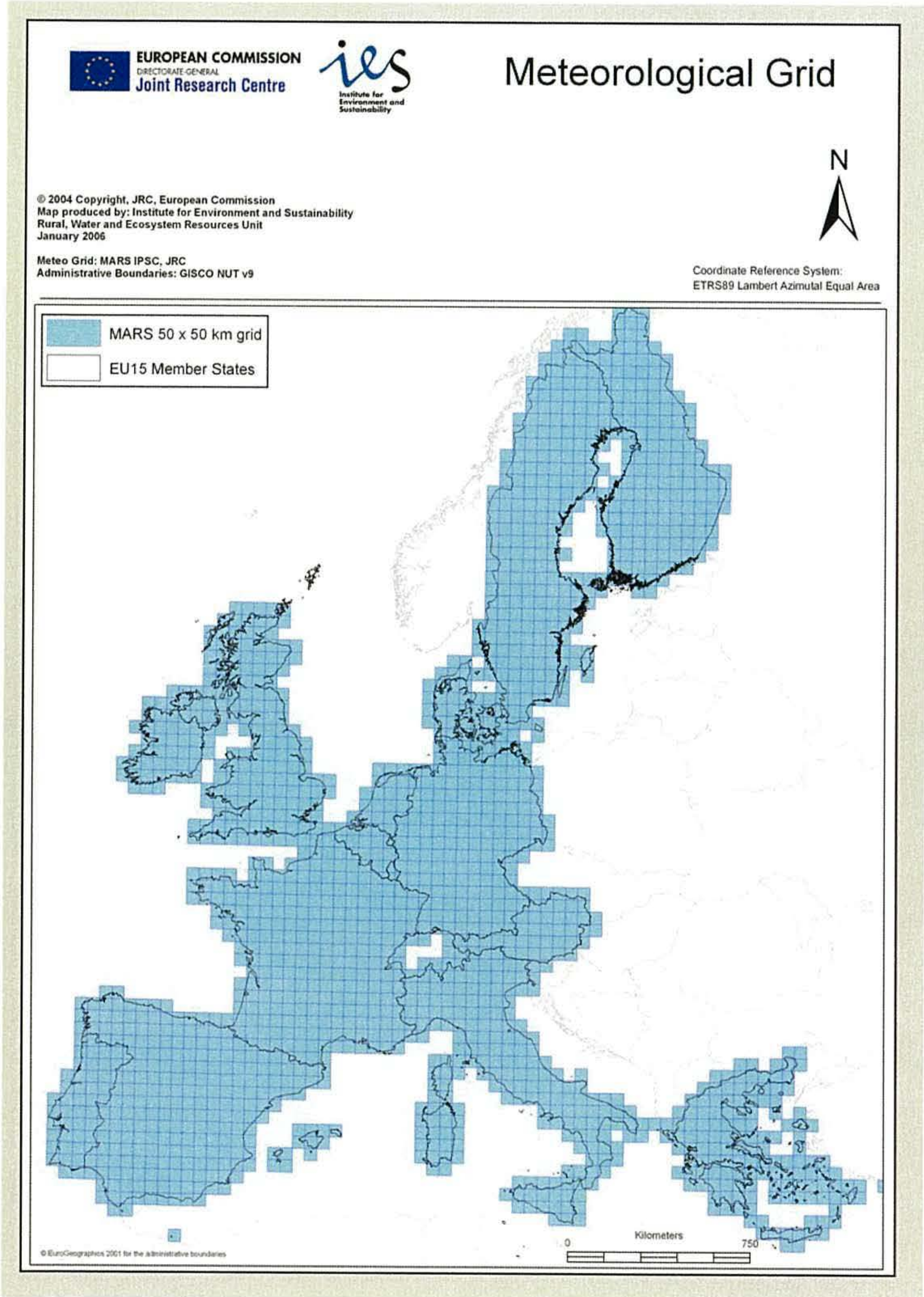


Figure 5.3. Meteorological grid (50 km × 50 km cells) for the EU15.

The DNDC GIS database file No. 2 of 'climate information' provides the link between the modelled unit with the individual meteorological text files that contain the parameters of Julian day; minimum and maximum temperature (°C) and precipitation (cm) for 365 days as shown in Table 5.4. In addition, the atmospheric N deposition values (described in section 5.4) for each modelled unit were added to the climate information file.

Table 5.4. Climate information required by the DNDC GIS database and example data. The climate-details file contains the N concentration data and the spatial link between the modelled unit (unit ID) and the climate file. The climate library file holds the daily climate data to run DNDC.

	Climate details	
1	Unit ID	*1001*
2	Climate file	*45055*
3	N concentration	*0.95*
	Climate library file	
1	Climate file	*45055*
2	Julian day	*1 - 365*
3	Max temp	*4.1*
4	Min temp	*2.3*
5	Rainfall (cm)	*0.5*

By using data overlay techniques in the GIS software the spatial link between the MARS 50 km grid and the centre point of each modelled unit was calculated. The 1077 individual text files containing the climate parameters for each modelled unit were stored in the DNDC climate library.

The Pan-European soil erosion risk assessment (PESERA) project (Kirkby and Jones, 2004) computed a monthly interpolated version of the MARS 50 km data at 1 km resolution using an inverse-spline mathematical procedure. However, this procedure did not produce what was considered to be an accurate representation of rainfall commensurate with the resolution of 1 km. The necessity for daily data, as shown in section 4.2 of this study, precluded the use of this 1 km rainfall data.

5.4 Nitrogen deposition in rainfall

The Co-operative Programme for the Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP) has been carrying out measurements of air quality in Europe since 1977 (EMEP, 2001). The DNDC required parameter of annual N (dissolved nitrate and ammonium) concentration in rainfall (mg N/l or parts per million (ppm)) was derived from the EMEP Precipitation Chemistry Database that contains wet deposition measurement data of:

- NH_4^+ mg N/l (ammonium)
- NO_3^- mg N/l (nitrate)

EMEP measuring stations (see Figure 5.4) report the data as precipitation weighted arithmetic mean values in mg N/l. The data have been obtained by multiplying the weighted mean concentration by the total amount of precipitation in the period. The concentrations for days with missing precipitation data have consequently been assumed equal to the weighted average of the period. Due to paucity of the measurement data, it was necessary to create a European coverage in Arc View where each measurement station was represented by a theissen polygon

The values within each theissen polygon were thus spatially related to each modelled unit and added to the 'climate information' file.

Alternative N deposition data held by EMEP is based on the Eulerian acid deposition model 50 km × 50 km EMEP grid that contains NH_4^+ and NO_3^- concentration data in μg N m^{-3} available for 1999. However, these data were not available for this study.

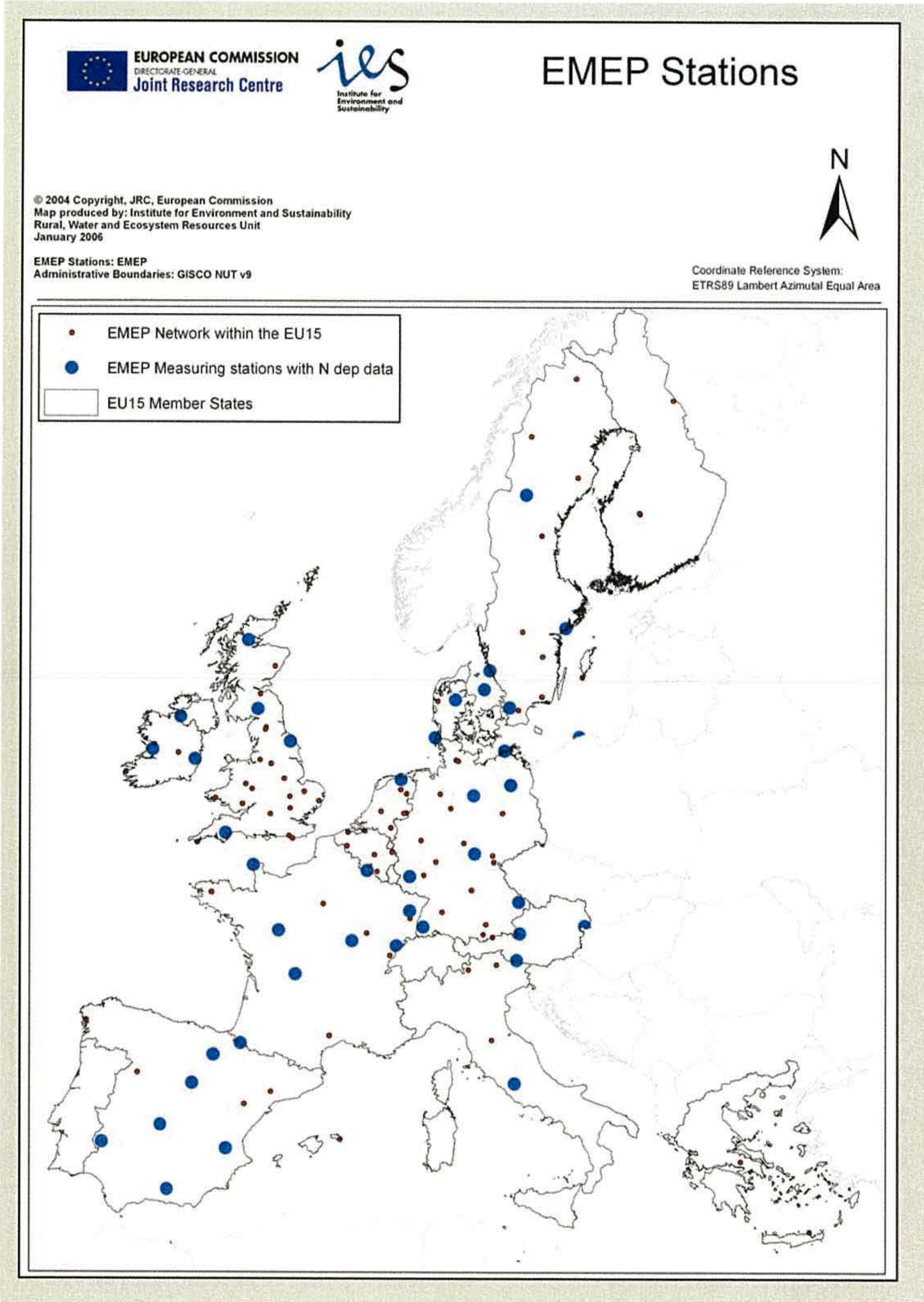


Figure 5.4. EMEP nitrogen deposition stations and theissen polygons in the EU15 used in the DNDC predictions of N_2O emissions..

5.5 Soil parameters

Pan European soil data were available from the Soil and Waste Unit of European Commission's JRC through the activities of the European Soil Bureau Network (ESB). The European Soil Database (ESBD) v1.0 described by Montanarella and Jones (1999) incorporates the following datasets:

- Soil Geographical Database of Europe (SGBDB) v 3.2.8.0.
- Soil Profile Analytical Database of Europe (SPADE) v 2.0.
- Hydraulic Properties of European Soils (HYPRES) database linked to the 1:1,000,000 (1:1 M) SGDBE v 1.0.
- Pedo-transfer Rules (PTR) database derived from an expert system for the estimation of several additional parameters needed for environmental interpretations of the soil map.

The ESB database provides an important source of information for the EC in the monitoring of soil quality, soil organic matter, degradation, contamination, and for assistance in the formation and evaluation of policies towards sustainable agriculture. Van Ranst and Gellinck (1998) produced a list of the soil parameters within the ESB database considered suitable for the input parameters required by many nitrogen flux, organic matter and soil hydraulic models.

The SGBDB uses a soil mapping units (SMU) polygon at a scale of 1:1 M that can be related to the Soil Typological Units (STU) that holds the soil parameters. However, because each SMU within the SGBDB consists of one or more STUs, the data must be processed before the soil parameters can be made geographically available. A description of how the SMUs are linked to the STUs and the percentage occurrence of each STU in each corresponding SMU is given within the SGBDB. All SMUs were assigned a dominant STU based on the greatest percentage of coverage within the SMU (see Figure 5.5).

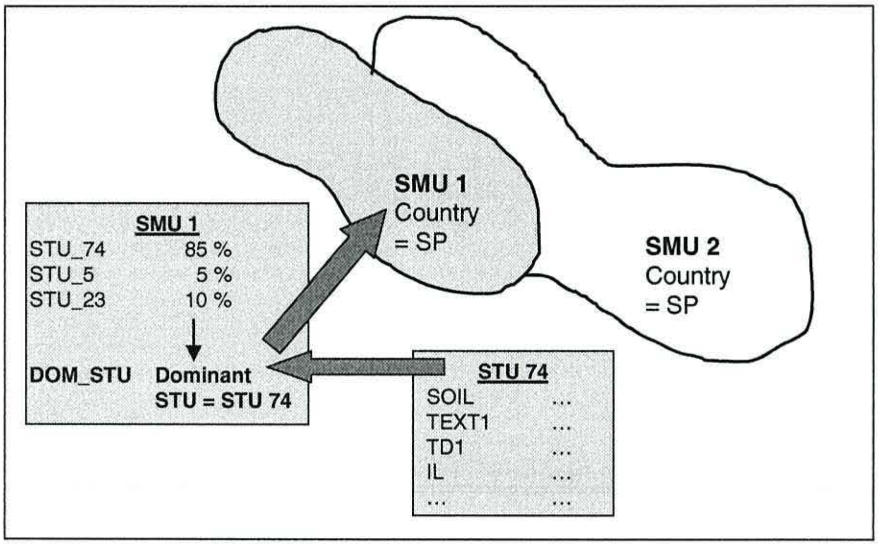


Figure 5.5. STU and SMU relationship.

SPADE contains soil profile information that was compiled through the collaboration of national experts within the EU. These soil profiles are estimated data that are not geo-referenced, and are an estimation based on expert knowledge of typical soil types, physical and chemical parameters. The frequency distribution of SOC values on agricultural land estimated within the SPADE data is shown in figure 5.6. From this it can be seen that the dominant SOC estimated values occur between 0.01 and 0.02 kg C kg^{-1}. The SPADE database is not spatially continuous and therefore, for this study the PTR database that contains spatially continuous data was used.

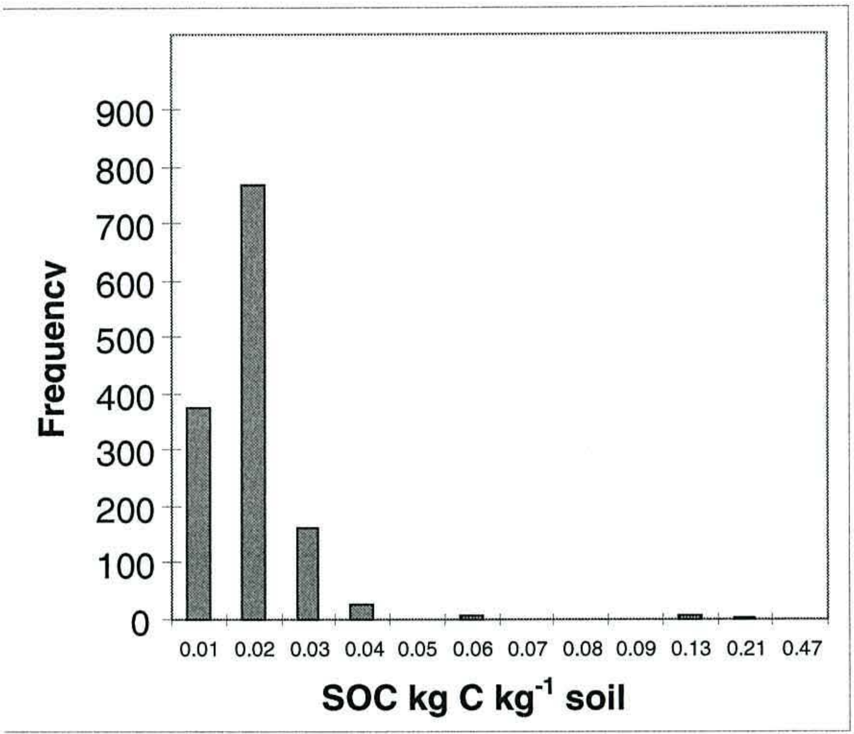


Figure 5.6. Frequency distribution of estimated soil organic carbon (SOC) from agricultural profiles within the SPADE v.1.0 database.

The major limitation of the PTR database for this study was that the data were only available as class data (see Table 5.5). The ranges of values in the classes provide a large uncertainty in the soil parameter values. This is of particular importance as the sensitivity analysis results (see chapter 4) indicate that the medium PTR class range of SOC (2.1% to 6%) (Figure 5.7) would produce a range of N_2O emissions from 1 kg N ha^{-1} yr^{-1} to 5 kg N ha^{-1} yr^{-1}.

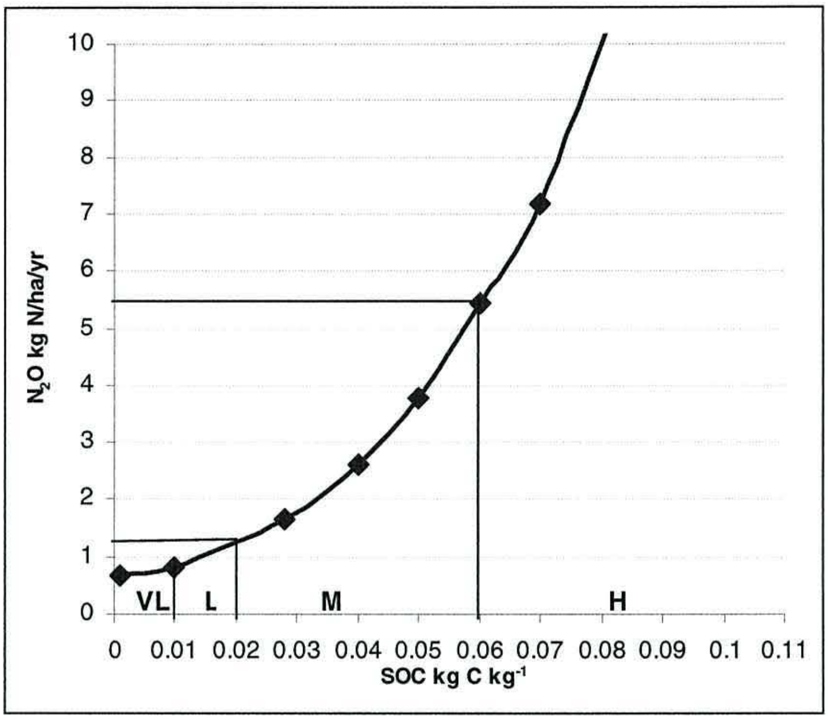


Figure 5.7. PTR soil organic carbon (SOC) classes and the DNDC predicted range in N_2O emissions. VL (very low), L (low), M (medium), H (high) SOC.

Table 5.5. PTR database class values used for this study.

PTR Class	Class Values
Soil Organic Carbon	
(H)igh	> 6.0%
(M)edium	2.1-6.0%
(L)ow	1.1-2.0%
(V)ery (L)ow	< 1.0%
Soil texture	
1- Coarse	(clay < 18 % and sand > 65 %)
2 - Medium	(18% < clay < 35% and sand > 15%, or clay < 18% and 15% < sand < 65%)
3 - Medium fine	(clay < 35 % and sand < 15 %)
4 - Fine	(35 % < clay < 60 %)
5 - Very fine	(clay > 60 %)
9 - No texture (histosols,)	
Topsoil Base Saturation	
(L)ow	<50%
(M)edium	50-75%
(H)igh	75%
Topsoil packing density	
(L)ow	< 1.4 g/cm3
(Medium)	1.4 – 1.75 g/cm3
(High)	No Data

The soil parameters required for the DNDC GIS database No.3 of 'soil properties' are shown in Table 5.6.

Table 5.6. Soil information required by the DNDC GIS database structure and example data.

Soil Properties		
1	Unit ID	*45055*
2	SOC (min, max)	*0.01*
4	Clay (min, max)	*0.2*
6	pH (min, max)	*6*
8	BD (min, max)	*1.4*

The initial content of total soil organic carbon data (SOC) in kg C kg^{-1} of soil including litter residue, microbes, humads and passive humus in the topsoil layer (0-5 cm) were derived from the PTR top-soil (0-30 cm) organic carbon (OC) value (see Figure 5.8). Figure 5.8 shows high organic soils in Northern European countries (e.g. Finland, Belgium and Scotland). However, high SOC values are also found in alpine zones of northern Italy and western France. Clay fractions of soil by weight data were derived from the PTR texture data (see Figure 5.9). Soil Bulk Density (BD) in g cm^{-3} in the topsoil layer (0-5 cm) data were derived from the PTR database packing density (PD) data based on R.A. Jones (*pers comm.* 2003) (see figure 5.10) where:

Bulk Density = PD - (CC × 0.009)

where:

PD = Packing density

CC = Clay content.

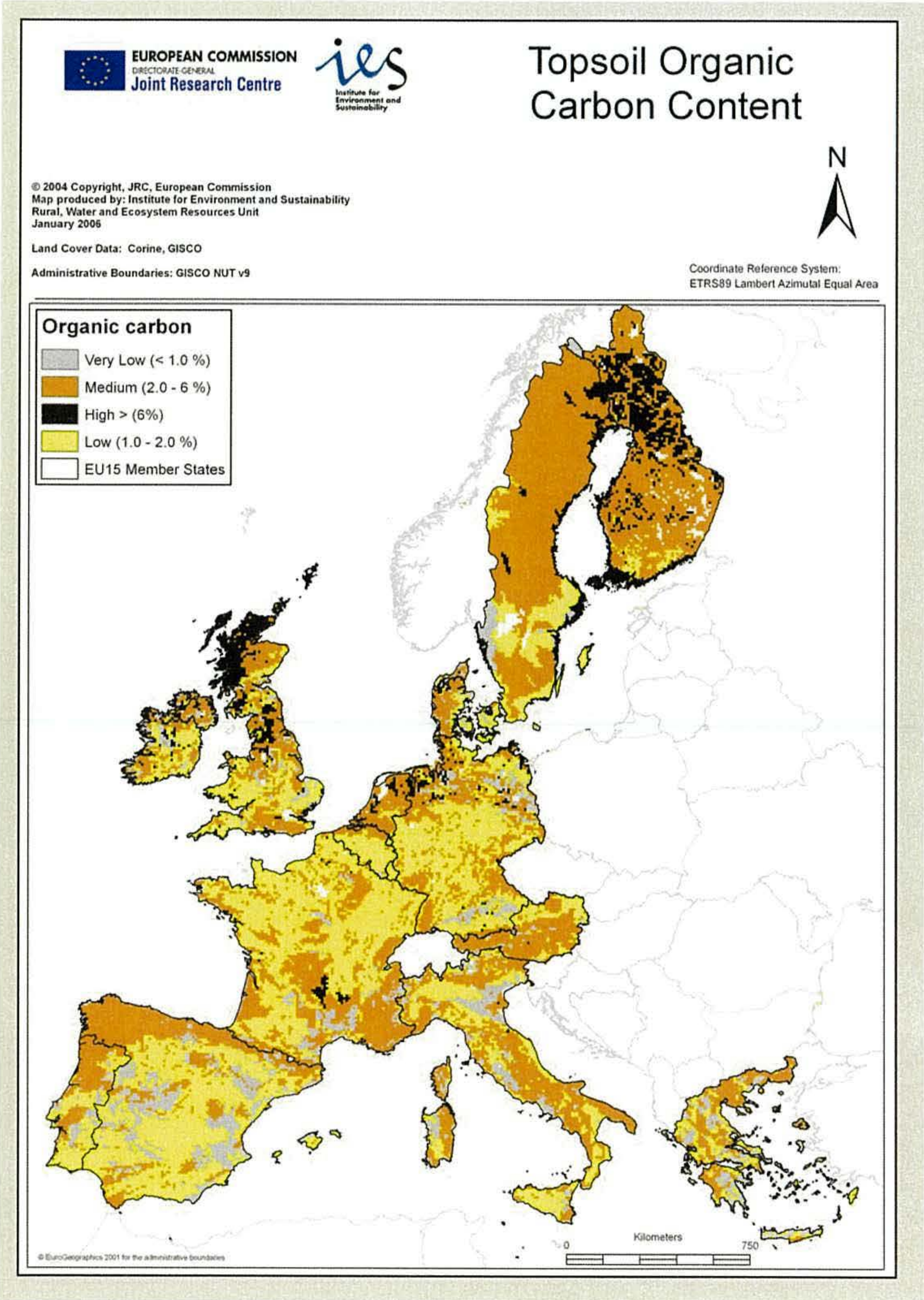


Figure 5.8. Topsoil Organic Carbon (topsoil 0-30cm) for the EU15 used in the DNDC predictions of N_2O emissions.

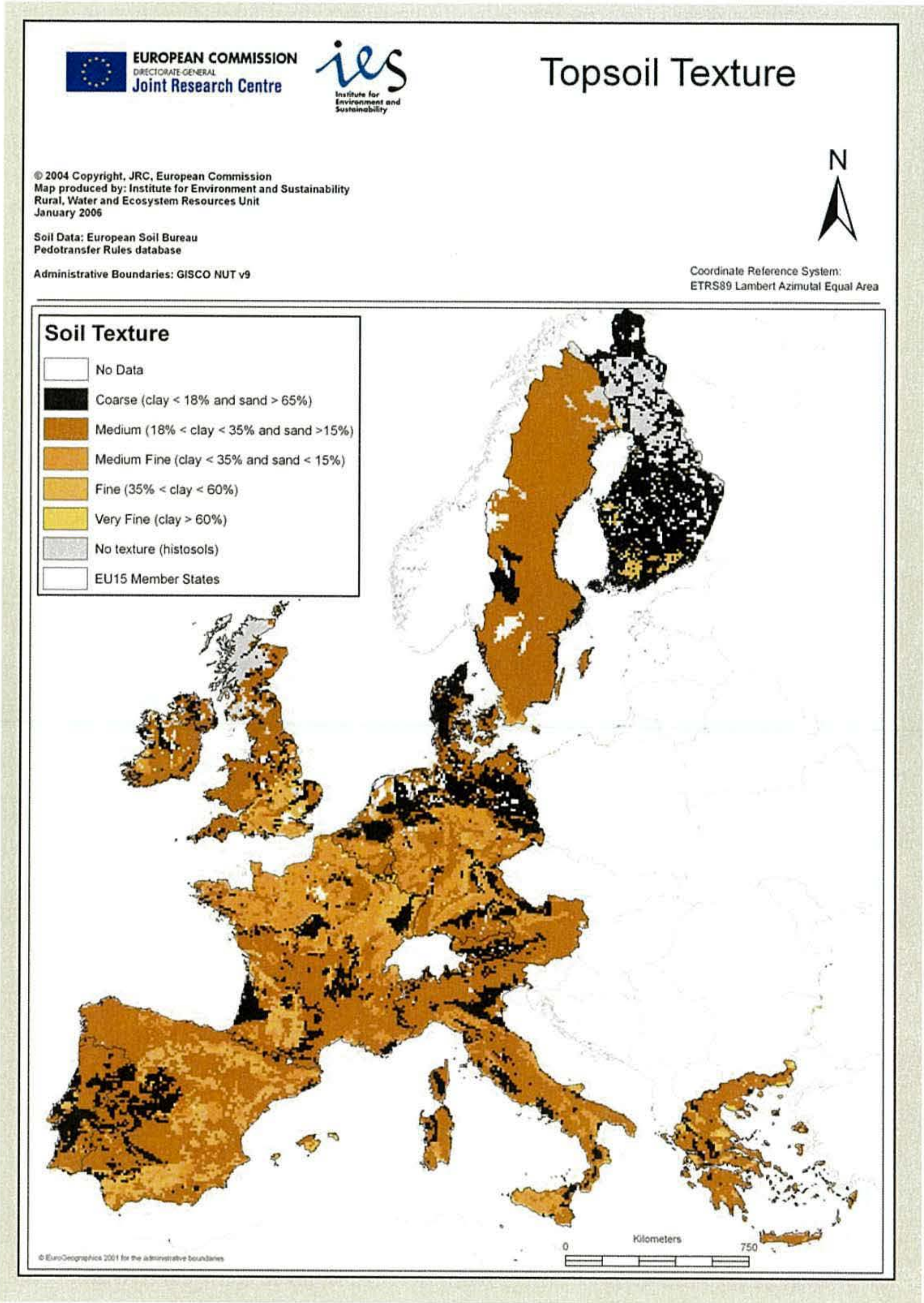


Figure 5.9. Topsoil texture for the EU15 used in the DNDC predictions of N_2O emissions.

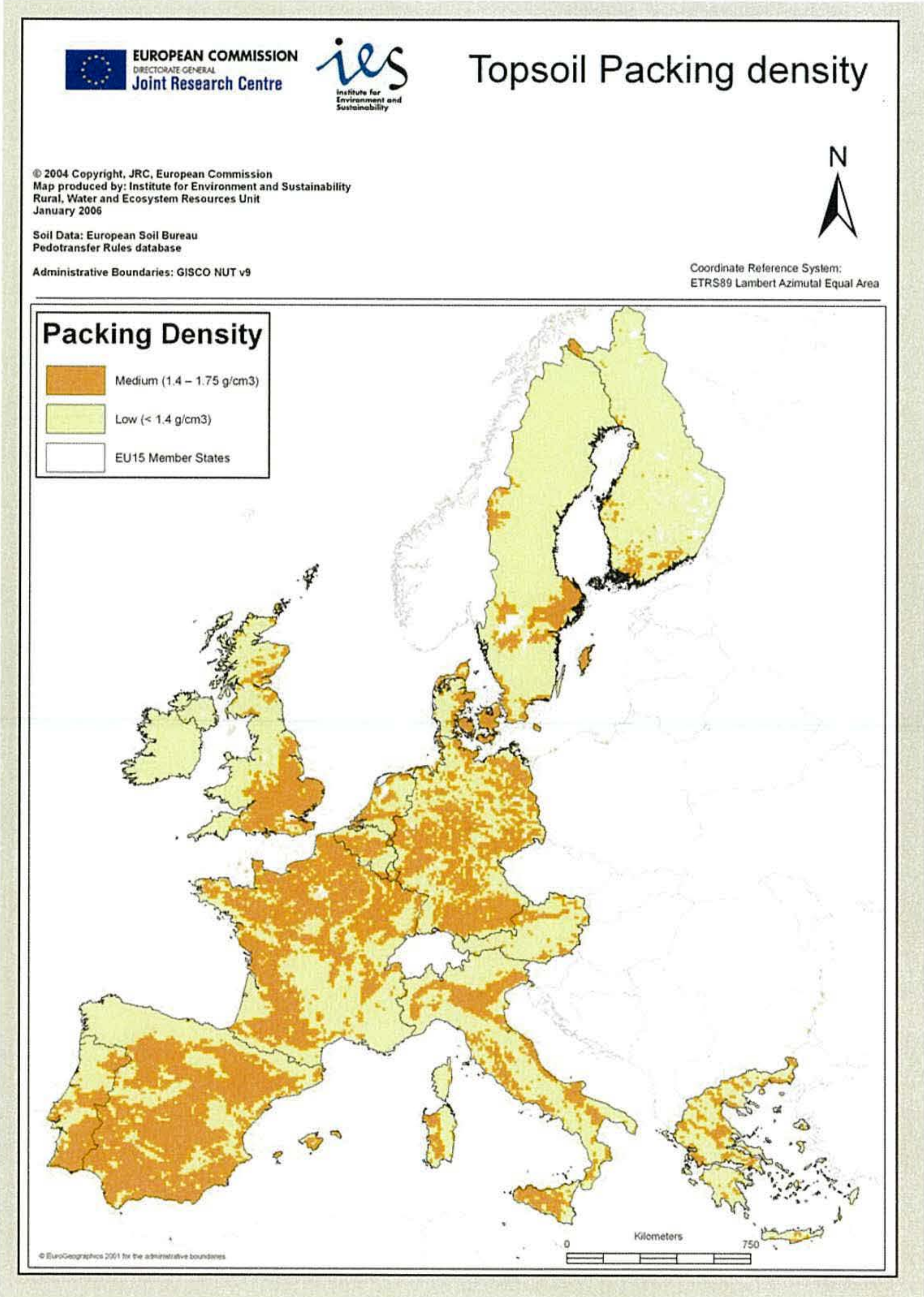


Figure 5.10. Topsoil packing density used to derive bulk density for use in the DNDC predictions of N_2O emissions.

Base saturation data, representing the fraction of CEC occupied by base cations, was used to derive soil pH. The relationship between pH and base saturation was investigated by Ciolkosz (2001).

A linear relationship (Figure 5.11) between base saturation (see Figure 5.12) and soil pH was estimated based on expert knowledge from the ESB's (R. Jones, *pers comm.* 2003). Inherent errors in the base saturation data produced unrealistic pH values in certain countries i.e. in Scandinavian countries.

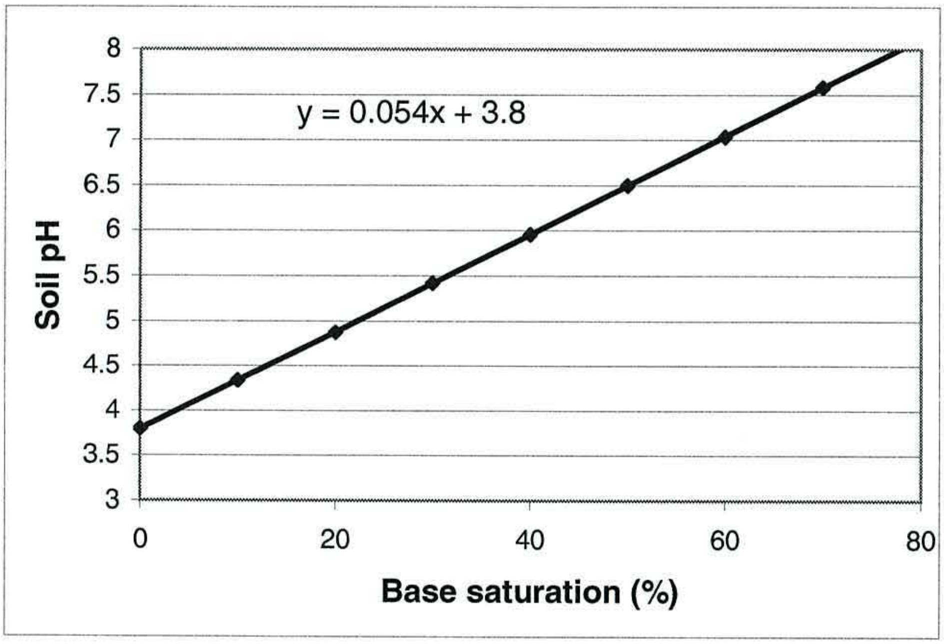


Figure 5.11. Linear relationship between soil pH and base saturation.

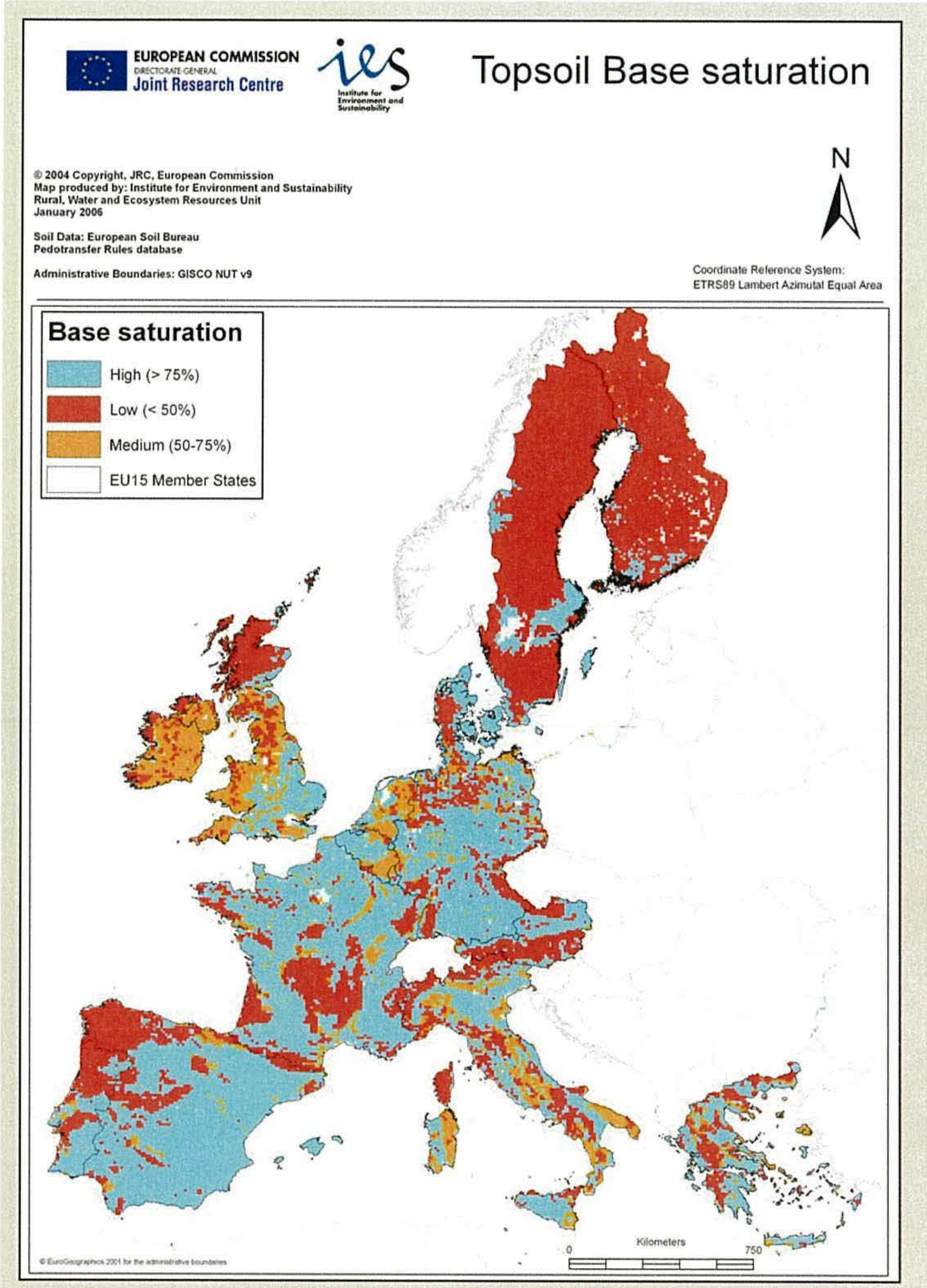


Figure 5.12. Topsoil base saturation used to derive soil pH for the EU15 for use in the DNDC predictions of European scale N_2O emissions.

The maximum and minimum soil values for each soil parameter within each NUTS level 3 unit were calculated within Arc View. To reduce the uncertainty in the spatial distribution of the soil data an agricultural mask, using CORINE agricultural classes (described in section 5.4), was used to extract soil data that corresponded solely to agricultural land use.

Li *et al.* (1992a) found that SOC is the dominant variable in soils influencing N_2O production and that by using the minimum and maximum SOC values to estimate N_2O emissions within each geographic unit, the variability in emissions due to soil heterogeneity could be modelled. For all the soil input parameters the DNDC model uses the median values. To convert the PTR class data to numerical values required by DNDC a series of lookup tables were created based on the expert knowledge of R.A. Jones (*pers comm.* 2003).

For Italy, a 1:250,000 (1:250 k) soil-database that contained measured SOC data was available within the ESBD (see Figure 5.13). An agricultural mask was also applied to the dataset to extract the SOC values in the same procedure used to process the European data. The SOC database for Italy displays lower values that are derived from the PTR database. The highest value of SOC for all agricultural soils in Italy derived from the 1:250 k database was 0.029 kg C kg^{-1} (2.9%) whereas the PTR displays a dominance of medium class values ranging from 2.1% to 6%.

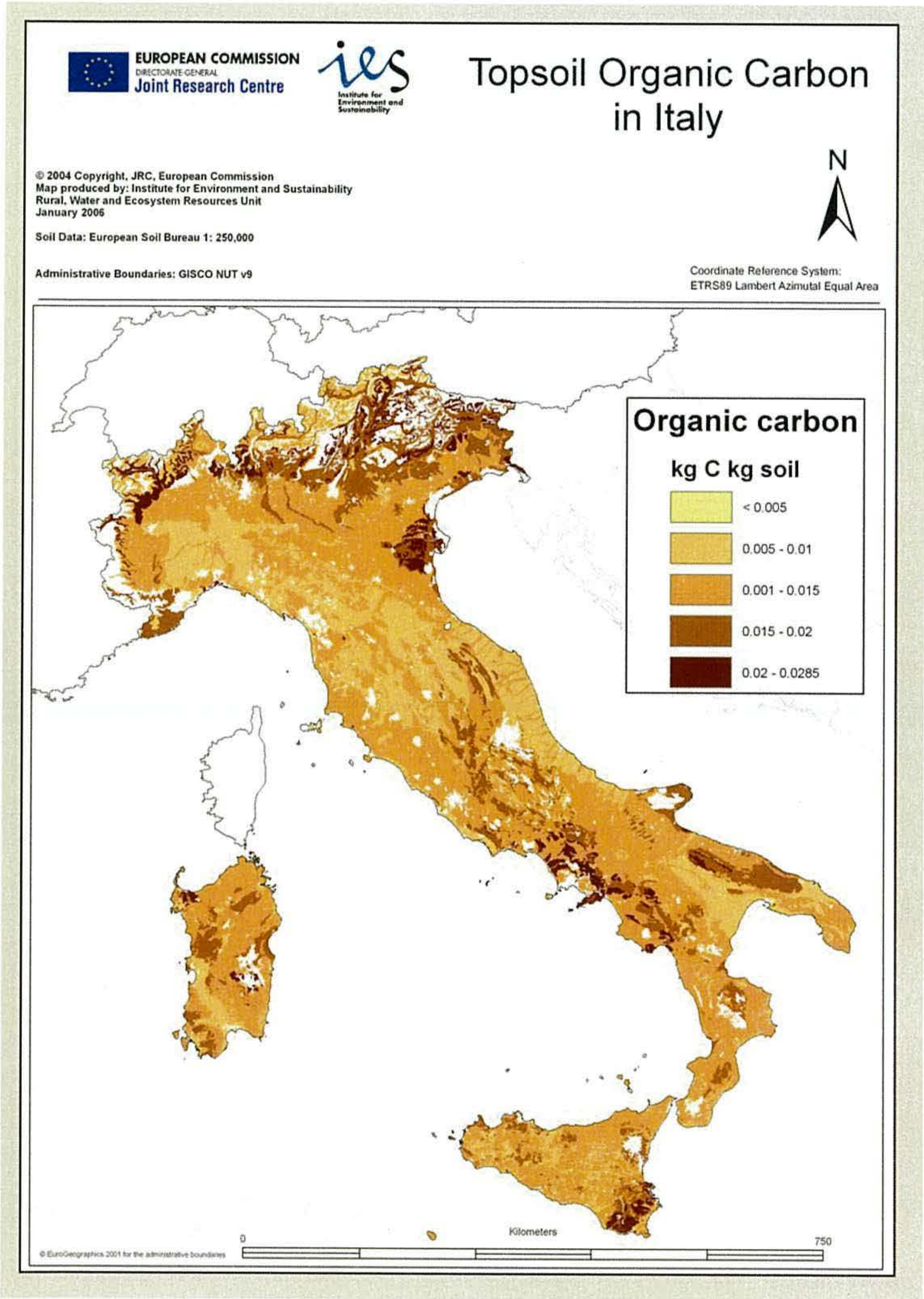


Figure 5.13. Soil organic carbon (SOC) data for the agricultural soils of Italy for use in the DNDC predictions of national scale N_2O emissions

5.6 Arable crop statistical data and processing

This section describes the sources for crop data and the methodology used to spatially disaggregate the data to NUTS level 3.

5.6.1 Arable data for Europe

The DNDC model was run for the following crops: Maize, Winter Wheat, Soybean, Leguminous-hay, Non-leguminous-hay, Spring Wheat, Winter Barley, Spring Barley, Oats, Durum Wheat, Pasture, Other cereals, Rye, Vegetables, Dried Vegetables, Potato, Sugar beet, Paddy rice, Fodder Roots, Silage Maize, Rapeseed, Tobacco, Sunflower and other industrial crops.

European crop data was matched as close as possible to the DNDC classes. For some crops this involved aggregation of the original crop data (e.g. pasture and leguminous hay.

For this study the crop data were derived from theme 5 (Agriculture and Fisheries) of the Eurostat - New Cronos statistical database. Within the data collection called Structure of agricultural holdings (Eurofarm), crop data are available from the table called Structure of agricultural holdings by region, main indicators 1990 to 1997 (Ef main). The New Cronos classification plan, used to classify the crop data, follows the preceding structure:

- New Cronos database
    - Theme 5: Agriculture, forestry and fisheries.
        - Eurofarm: Structure of agricultural holdings
            - Ef main: Structure of agricultural holdings by region.

The Ef main table contains Farm Structure Survey (FSS) data for 5 periods (1990-2000), covering 129 NUTS regions from 15 EU Member States and 155 items including, items relevant to this study, of crop area (ha) and livestock numbers.

FSS data for 1997 were extracted from the Ef main database, as this was the latest year with a complete dataset. The arable crop dataset for 2000 was not complete at the time of this study. The FSS data for 129 EU NUTS regions were joined to the NUTS coverage, and any data not within the extent of the digital soil map excluded, leaving a coverage with 126 NUTS. The NUTS excluded were the Azores, Madeira, and the Canaries.

Figure 5.15 shows the crop area for each of the FSS crop classes and total crop area (124.9 M ha) for the 126 NUTS selected within the EU15. Grassland is by far the dominant class. The dominant arable crops in the EU15 are common wheat and barley. One of the biggest uncertainties in the data is the class of industrial crops as no description is provided of what types of industrial crops are reported in each region. The spatial extent of the 126 NUTS (see figure 5.14) containing the New Cronos 1997 crop data for the area selected in this study, illustrates the various NUTS levels at which the data are available. The NUTS regions are not homogeneous in area. The difference in areas of the NUTS is important, as this can affect the extent to which the data are aggregated by New Cronos and the level to which the data must be disaggregated by for this study.

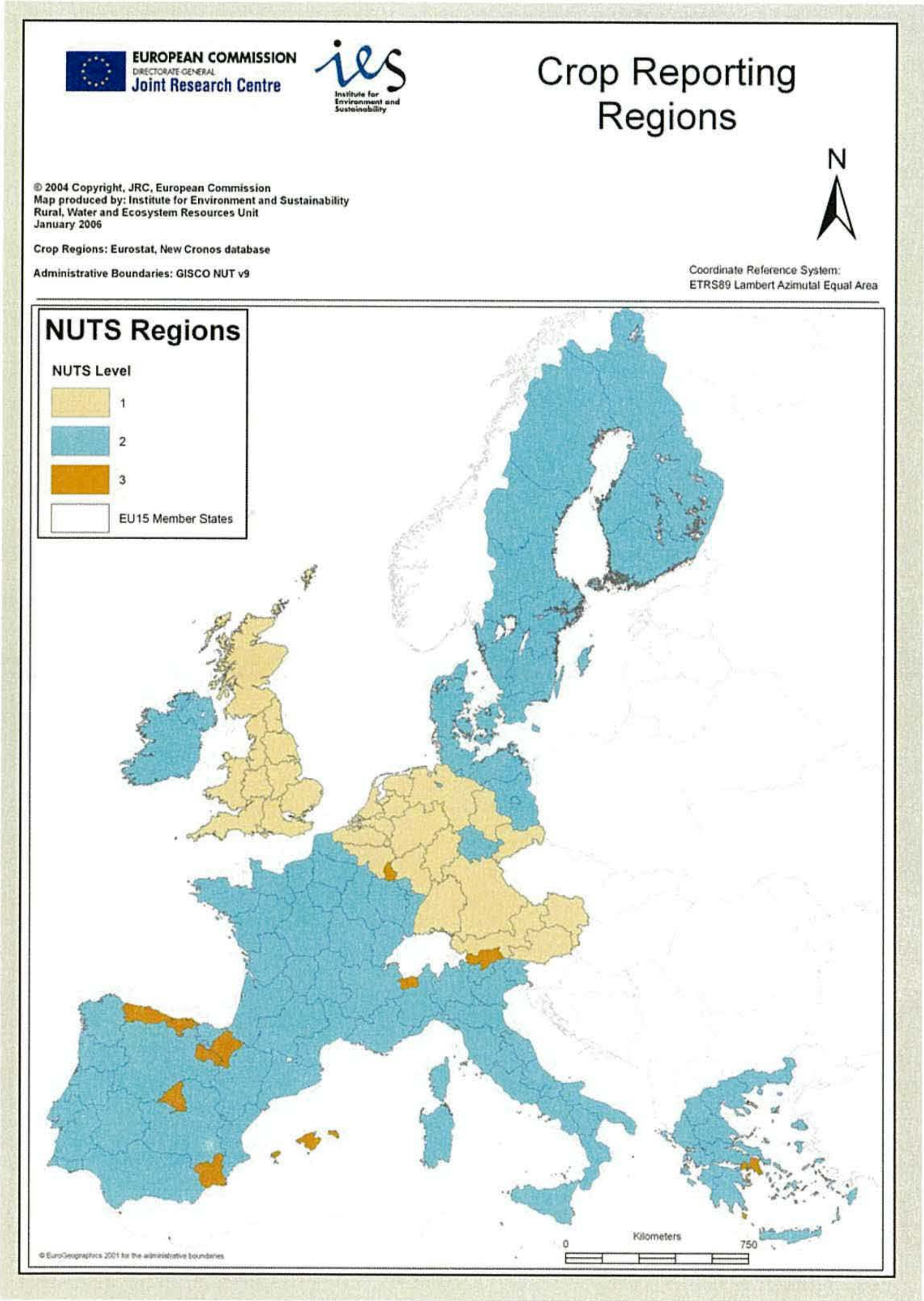


Figure 5.14. New Cronos crop reporting regions within the EU15 for use in the DNDC predictions of European scale N_2O emissions.

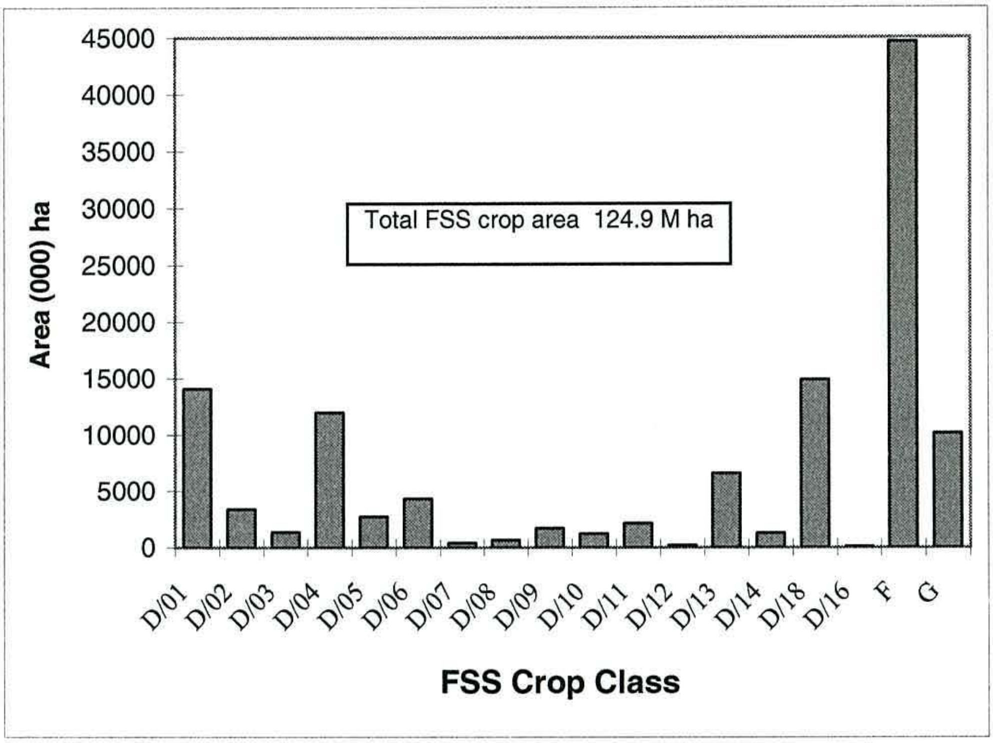


Figure 5.15. European crop total areas taken from FSS crop data for 1997.

The FSS codes used in figure 5.15 and the FSS crop classes they relate to are shown in Table 5.7.

Table 5.7. FSS codes and crop classes.

FSS code	FSS Crop Class
D/01	Common wheat
D/02	Durum wheat
D/03	Rye (including meslin)
D/04	Barley
D/05	Oats (including summer meslin)
D/06	Grain maize
D/07	Rice
D/08	Other cereals
D/09	Pulses for harvest as grain
D/10	Potatoes
D/11	Sugar beet
D/12	Fodder roots and tubers
D/13	Industrial crops
D/14	Fresh vegetables
D/18	Forage plants
D/16	Flowers
F	Permanent pasture/grassland
G	Permanent crops

5.6.2 Spatial disaggregation of European crop data

To calculate the crop area within the modelling unit (NUTS level 3) the FSS crop data for 1997 (described in section 1.6.1) were spatially disaggregated to the smaller NUTS 3 level in the procedure described in this section using a similar procedure to that described by Gallego *et al.* (2001).

The first step in the spatial disaggregation process was the calculation of the area of agricultural land in both the NUTS polygons containing FSS crop data (shown in Figure 5.14) and the NUTS level 3 polygons (Figure 5.2). The area of agricultural classes derived from the CORINE land cover database (GISCO 2000 coverage Lceugr100) were calculated by an Arc view function known as area analysis. No CORINE land cover data were available for Sweden. The CORINE agricultural land cover classes were also used to create an agricultural mask, which was used to extract the soil parameters from the ESDB database (described in section 5.5).

The CORINE land cover database contains 44 land cover classes that were derived from visual interpretation of Landsat and SPOT satellite images. The Landsat satellite was developed by NASA to acquire remotely sensed images of the Earth's land surface and surrounding coastal regions and the data is managed by U.S. Geological Survey (USGS). The SPOT satellite Earth observation system was designed by the French Space Agency and the data managed by Spot Image (SPOT IMAGE, 2004).

Area analysis of the CORINE land cover classes (see Figure 5.16) shows the dominance of non-irrigated arable land and pastures within Europe. The total area of agricultural land cover based on the CORINE classes of 139 M ha exceeds the crop data area (land use) reported by New Cronos of 124.9 M ha. This can be related to changes in land use since CORINE was created or differences in classification of land cover/land use types. The CORINE land cover codes and classes that correspond to the codes in figure 5.16 are shown in Table 5.8.

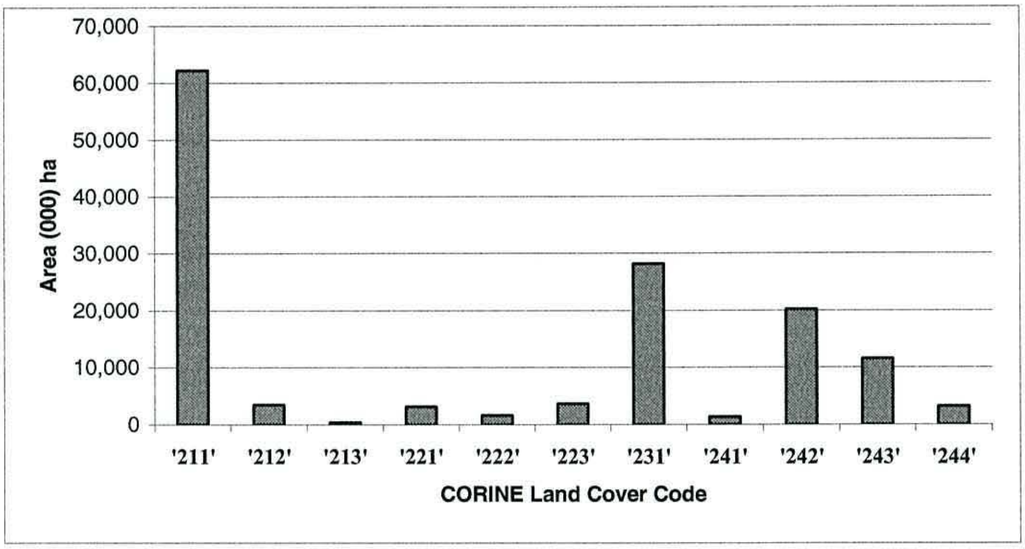


Figure 5.16. Area analyses of CORINE land cover agricultural classes.

Total area of CORINE land cover agricultural classes for the EU (excluding Sweden) is 139 M ha. See Table 5.8 for a list of CORINE LC codes.

Table 5.8. CORINE agricultural land cover classes.

Code	CORINE landcover class
211	Non-irrigated arable land
212	Permanently irrigated land
213	Rice fields
221	Vineyards
222	Fruit trees and berry plantations
223	Olive groves
231	Pastures
241	Annual crops associated with permanent crops
242	Complex cultivation patterns
243	Land principally occupied by agriculture
244	Agro-forestry areas

The CORINE arable land cover classes (211, 212 and 213) are described in the CORINE handbook as non-permanent lands under a rotation system used for annually harvested plants and fallow lands. These three classes can contain flooded crops such as rice fields and other inundated croplands (CORINE, 2000). With the exception of flooded paddy rice fields the CORINE land cover map does not identify where actual crops are grown. CORINE land cover classes 221, 222 and 223 refer to permanent land cover of fruit trees, olives and vineyards, which are outside the scope of this study.

Pastures (class 231) are described as lands that are permanently used (at least 5 years) for fodder production and include natural or sown herbaceous species, unimproved or lightly improved meadows and grazed or mechanically harvested meadows. Heterogeneous agricultural areas (classes 241, 242, 243 and 244) are described as areas of annual crops associated with permanent crops on the same parcel, annual crops cultivated under forest trees, areas of annual crops, meadows and/or permanent crops which are juxtaposed, landscapes in which crops and pastures are intimately mixed with natural vegetation or natural areas. From the descriptions it can be seen that identifying actual land use from satellite derived land cover data is often associated with high levels of error and uncertainty. Moreover, the CORINE land cover only provides a 'snap-shot' of the land cover situation when the images were taken (in this case 1986) so spatially distributing crop data from later years (*i.e.* 1997) could produce many uncertainties. Newer datasets are becoming available such as the Pan-European Land Cover Monitoring (PELCOM) 1 km land use database (Mucher *et al.* 1998) and a global vegetation map (Bartholome *et al.* 2002). The spatial distribution of the CORINE agricultural land cover classes on a 100 m × 100 m grid (see figure 5.17) illustrates how agricultural land cover dominates the European land area, with the exception of Finland that is dominated by forest.

Not all of the land cover within the CORINE agricultural grids is considered useable for agriculture, due to the generalisation of the original land cover images (Crouzet, 2001). Therefore, percentage of useable area land of the CORINE land cover classes and the relationship to FSS land use (crop) data were calculated using the data shown in Table 5.9.

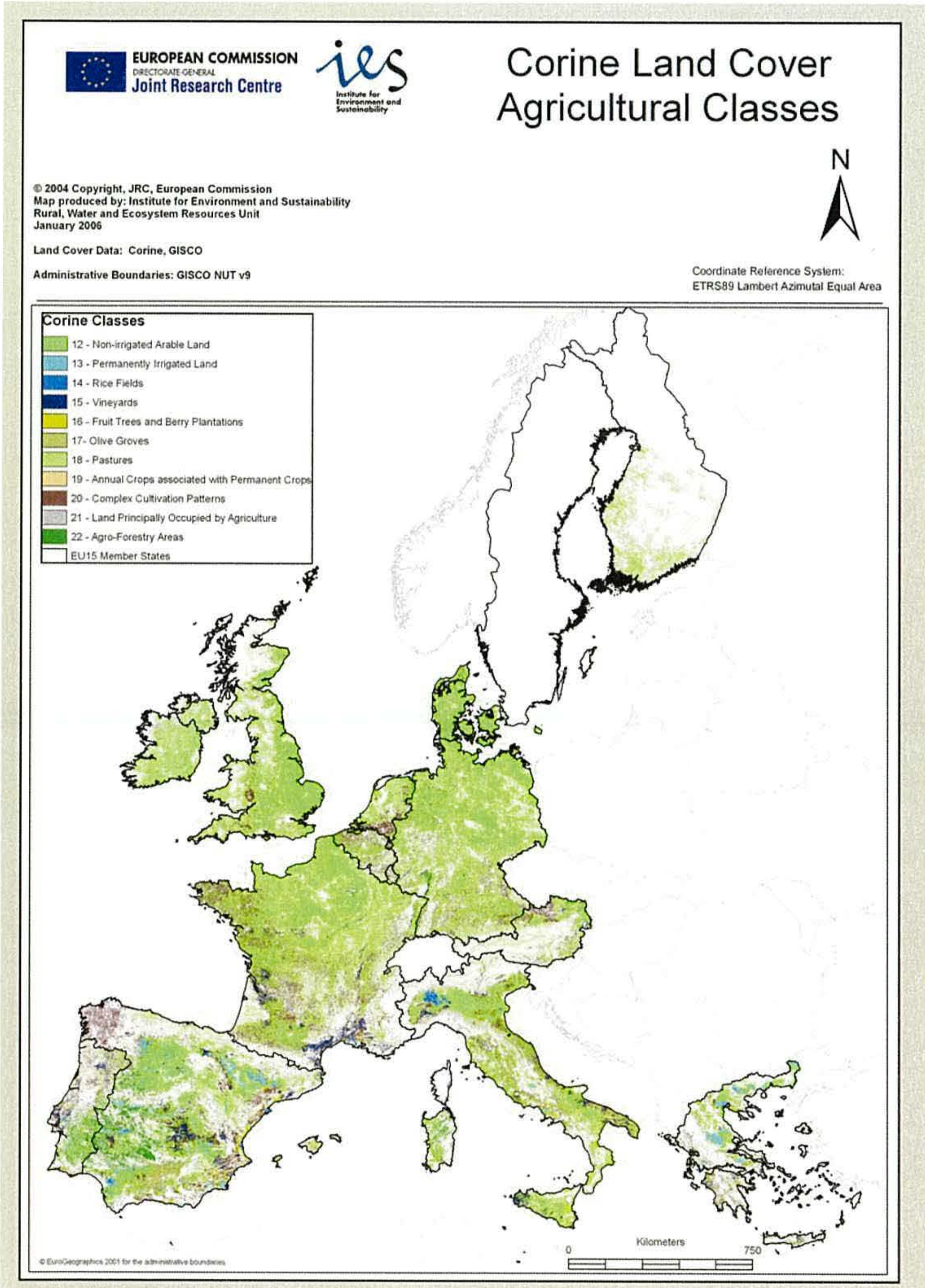


Figure 5.17. CORINE agricultural land cover classes (100 m × 100m grids) for the EU15 and used for the DNDC predictions of European scale N_2O emissions.

Dominant land cover is non-irrigated arable land. No CORINE data is available for Sweden in the GISCO database.

Table 5.9. Relationship between FSS crop classes and the utilisation rate of the various land areas of occupation of the land by CORINE Land cover code (EEA, 2000).

FSS code	Relation to Fss Crop Class	CORINE landcover code & useable area %						
		211	**212**	**213**	**231**	**241**	**242**	**243**
D/01	Common wheat	95					80	60
D/02	Durum wheat	95					60	60
D/03	Rye (including meslin)	95					60	60
D/04	Barley	95					60	60
D/05	Oats (including summer meslin)	95					60	60
D/06	Grain maize							
D/07	Rice			95				
D/08	Other cereals	95				80	60	60
D/09	Pulses for harvest as grain	95				80	60	60
D/10	Potatoes	95					60	60
D/11	Sugar beet	95					60	60
D/12	Fodder roots and tubers	95					60	60
D/13	Industrial crops	95					60	60
D/14	Fresh vegetables	95					60	60
D/18	Forage plants	95					60	60
D/16	Flowers	95					60	60
F	Permanent pasture/grassland				95			

The areal weighting procedure used to disaggregate the New Cronos data to the NUTS level 3 is described by the formula:

- **DissCrop** = FSScrop × ((CaLc_NUTS3 × CLcUa)/(CaLc_NUTSNC × CLcUa))

where:

- **DissCrop** = Disaggregated crop area (ha)
- **FSScrop** = FSS crop area (ha)
- **CaLc_NUTS3** = Total CORINE agricultural land cover area (ha) within each NUT 3
- **CaLc_NUTSNC** = Total CORINE agricultural land cover area (ha) within each New Cronos NUT
- **CLcUa** = CORINE Land cover useable area (%) (See Table 5.9)

The spatial distributions of New Cronos 1997 data are shown in Figure 5.18 and the spatially disaggregated data shown in figure 5.19.

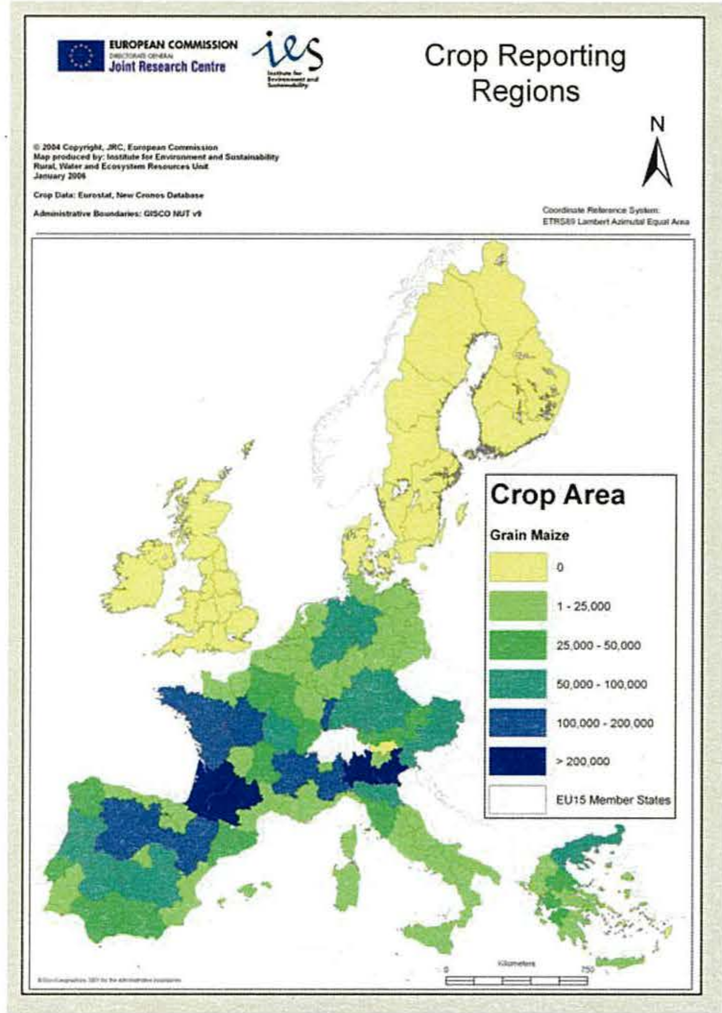


Figure 5.18. New Cronos Grain maize area for 1997.

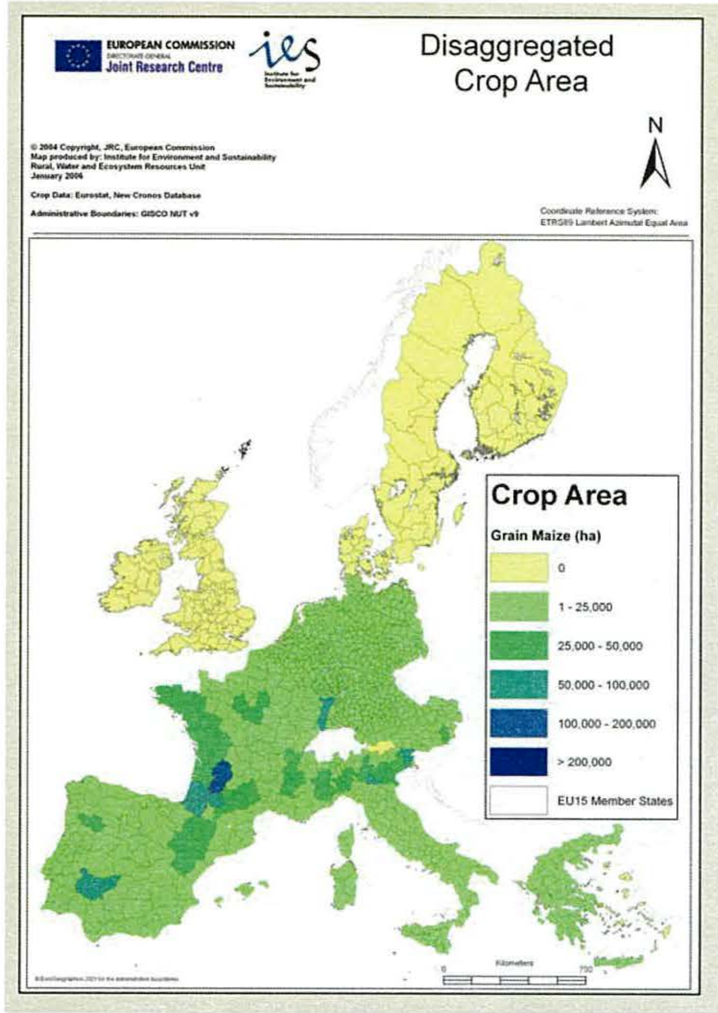


Figure 5.19. Spatially disaggregated Grain maize area.

The FSS crop data aggregates industrial crops, common wheat, barley and forage crops (see Table 5.9). To gain a wider estimation of N_2O emissions from as many crops as possible and to utilise the more extensive crop database within the DNDC crop characteristic library, these crop data (industrial crops, common wheat, barley and forage) were partitioned into sub-classes (see Table 5.10). Moreover, these partitioned crops have different fertiliser application rates and farm management practices that would affect the N_2O emission rate.

This process was undertaken using national crop yield information data taken from theme 5 of the New Cronos Agricultural Information System called 'agris'. The 'agris' database contains national statistics for 32 years, 25 geopolitical entities (EU15+ new Member States[7]), 47 elements of the agris nomenclature (*i.e.* area, yield, livestock numbers) and 489 items of the agricultural domains (*i.e.* crop or livestock type) (European Commission, 2003). The data is not comprehensive for all crops for all years, and there is a paucity of data for the member states. The disaggregated crop data for all the modelled crops in Europe are shown in appendix 3. A comparison between the original New Cronos data and disaggregated data by crop is shown in Figure 5.20.

Table 5.10. FSS crops partitioned to match DNDC classes

FSS-classes	**Partitioned crops (DNDC classes)**
Wheat	Winter wheat and spring wheat
Barley	Winter barley and spring barley
Industrial crops	Rape, soya, sunflower, other industrial crops
Forage plants	Silage maize, leguminous hay and non leguminous hay

[7] Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia and Slovenia.

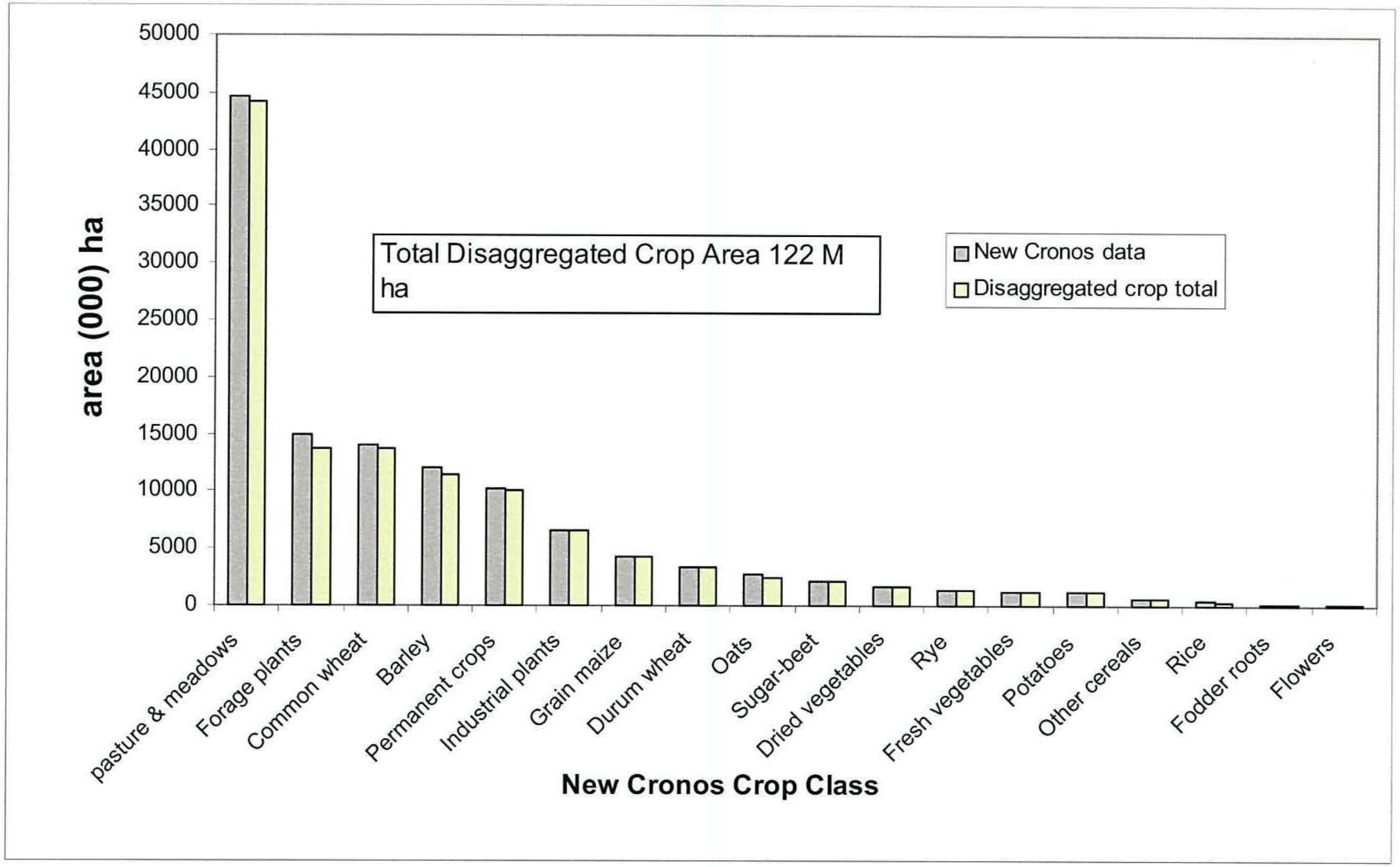


Figure 5.20. Reported crop area totals and disaggregated crop area totals for the EU15.

5.6.3 Arable data for Italy

Crop data for Italy were available at the NUTS level 3 derived from the Italian statistical agency (ISTAT, 2003) that holds agricultural data for the years 1996-2001. This ISTAT data contains 48 main arable crop classes and 14 pasture classes with a total agricultural area of 11,050,000 ha. Some of these crop classes were aggregated to produce a dataset containing 20 crop classes that matched the DNDC crop classes. The total crop area differs from crop data reported in New Cronos and agricultural land cover derived from the Corine land cover data. The New Cronos is derived from the ISTAT data. The small loss of area is probably accounted for by the aggregation of particular crops. The difference in CORINE land cover area and reported crop total reflects the differences in identification and classification of land cover types in the Corine land cover. In particular there are large uncertainties in the Corine classification of pasture and it is unknown what part is arable or natural grassland.

A comparison between the ISTAT crop data reported at NUTS level 3 and the New Cronos crop data spatially disaggregated to NUTS level 3 is shown in figure 5.21. Comparison with the disaggregated data shows that on the national scale crop totals are in very close agreement. However, the significant difference in crop area totals for pasture further highlights both the uncertainties in using the CORINE land cover coverage to disaggregate land use data and the differences in identification and classification of pasture.

The crop classes for Italy taken from the ISTAT data for 1997 show the dominance of pastureland. The second most common crop type is durum wheat. No fallow (set-aside) area is reported by ISTAT; therefore, it was excluded from this modelling exercise. The IPCC only report N_2O emissions for fertilised agricultural soils and do not include fallow land.

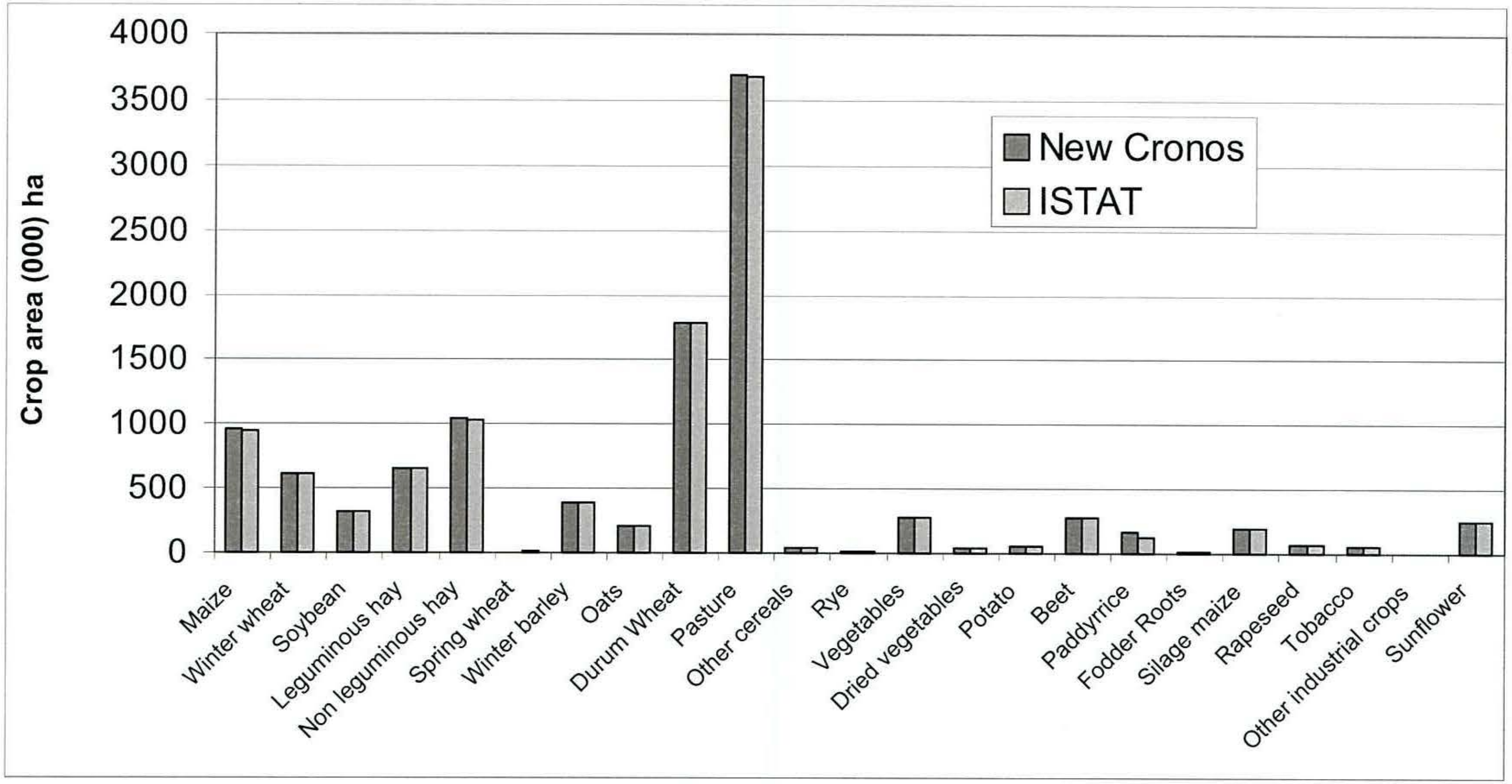


Figure 5.21. Modelled crop classes derived from ISTAT crop data and disaggregated New Cronos (NC) crop data.

5.7 Farming management

This section describes the farm management data requirements for the DNDC GIS database, shown in Table 5.11. In addition, the data requirements for the individual farm management data files for each crop at the national level are described.

Table 5.11. Farm management information and example data requirements for the DNDC GIS database.

Farming Management		
1	Unit ID	1001
2	Cropland (ha)	258298
3	Sown area (ha)	296506
4	Fertiliser tonnes	17229
5	Fertiliser (kg ha^{-1} yr^{-1})	66.7
6	Irrigation	0.4
	Fertiliser partitioning	
7	NO_3-	0.05
8	NH_4HCO_3	0.21
9	Urea	0.38
10	NH_3	0
11	NH_4NO_3	0.21
12	$(NH_4)_2SO_4$	0.06
13	$(NH_4)_2HPO_4$	0.09

In the farm management file, cropland areas are differentiated from sown area data to account for double cropping systems.

5.7.1 Farm file structure

The farm file database structure of DNDC enables crop management data to be applied for each individual crop type within a chosen region. For this study, the region was defined as each EU Member State as the fertiliser data was available only at the national scale. The farm file structure contains the following information for each modelled crop:

- Optimum yield (kg)
- Planting timing (month/day)
- Harvest timing (month/day)
- Fertilisation timing (month/day)
- Fertilisation rate (kg N ha^{-1})
- Percent residue left

Farm management files were created for each EU member state for each of the crops/crop classes shown in the yield Table 5.12.

5.7.2 Optimum yield

Optimum yield (kg ha^{-1}) data at optimum conditions (N, water, temp.) were derived from the New Cronos 'agris' database, described in section 5.6.2, is shown in Table 5.12. For regions with crops reported but no yield data, yield values were taken from the neighbouring member state considered to possess similar climatic conditions. The DNDC crop characteristic library contains default values for the C content of indvidual crops.

Table 5.12. Crop yield information (kg ha^{-1}) for each of the EU Member States. Data from New Cronos for 1997. 'n' indicates not applicable.

Crop	AT	BE	DK	FI	FR	DE	GR	IE	IT	LU	NL	PT	SE	ES	UK
Maize	9,780	10,823	9,066	9,000	9,066	8,658	10,401	9,000	9,627	5,000	12,518	4,911	9,151	4,911	9,000
Winter wheat	7,338	7,991	7,295	3,986	6,826	7,338	2,560	8,026	4,270	5,947	7,800	1,200	n	6,083	7,800
Soybean	2,202	n	2,764	2,622	2,764	n	2,000	2,622	3,802	n	2,764	3,802	2,198	3,802	2,764
Leguminous hay	9,105	n	2,406	2,474	2,406	n	10,000	5,073	2,675	4,971	14,399	2,675	2,296	2,675	5,073
Non leguminous hay	20,470	n	35,932	28,201	20,470	n	20,470	28,201	20,470	n	28,201	20,470	n	20,470	28,201
Spring wheat	5,582	6,040	5,250	3,665	4,724	5,582	5,408	6,791	5,408	4,689	7,000	5,242	n	5,242	5,439
Winter barley	5,610	7,700	5,949	5,194	6,131	6,498	2,416	6,990	2,416	5,843	6,303	878	2,070	4,863	6,267
Spring barley	4,472	5,579	5,221	3,438	5,759	4,882	4,821	5,381	4,821	5,034	6,400	4,302	2,445	4,302	4,940
Oats	4,268	5,670	5,167	3,368	4,265	5,119	1,849	6,397	2,058	5,263	5,600	579	1,302	4,045	5,782
Durum wheat	4,088	n	3,282	3,245	3,282	5,052	2,362	6,000	2,256	n	5,052	1,103	1,782	1,103	6,000
Pasture	5,207	0	4,049	4,093	4,049	5,207	673	4,093	673	6,490	5,207	673	n	4,093	4,093
Other cereals	6,667	n	6,667	5,726	6,667	n	5,749	5,726	5,749	n	6,667	5,749	4,763	5,749	5,726
Cotton	1,300	1,097	1,816	576	1,816	1,300	1,300	1,300	1,300	1,300	1,074	1,300	1,411	1,220	1,395
Rye	3,585	4,550	5,393	2,075	4,360	5,430	2,025	5,699	849	5,324	5,600	695	1,483	4,718	5,699
Vegetables	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400
Dried vegetables	3,130	4,341	4,042	n	4,972	n	1,656	4,027	1,679	3,237	4,003	n	680	3,395	3,733
Potato	28,833	46,600	39,615	22,714	38,661	38,406	19,146	25,885	22,428	26,960	44,317	12,848	21,682	33,725	42,922
Beet	58,406	68,330	48,797	38,969	74,315	51,163	59,704	51,044	46,502	50,000	57,914	42,678	54,126	43,985	56,638
Paddy rice	n	n	n	n	5,892	n	10,000	n	6,195	n	n	5,761	n	n	n
Silage maize	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Fodder roots	28,201	28,201	35,932	28,201	28,201	28,201	28,201	28,201	28,201	28,201	28,201	28,201	28,201	28,201	28,201
Rape	2,351	3,811	2,825	1,933	3,544	3,136	865	2,728	865	3,496	3,401	2,086	1,478	2,086	3,245
Tobacco	2,514	3,380	2,694	2,685	2,694	2,514	2,216	2,662	2,708	n	2,514	2,314	2,778	2,662	2,662
Other industrial crops	1,816	1,097	1,816	576	1,816	1,301	1,301	1,301	1,301	n	1,074	1,220	1,411	1,220	1,395
Sunflower	2,200	1,710	2,282	1,000	2,282	2,467	1,353	1,710	2,122	n	2,467	406	1,279	1,710	1,710

5.7.3 Crop management timing

Crop management timing data for tillage, planting and harvesting were derived from the JRC MARS Unit's rapid areas assessment data that contains crop management task data for 53 sites with the EU collected over a period of two growing seasons (1995-1996). A national average for each Member State of tillage, fertilisation, crop planting and harvesting timing dates was calculated from the MARS database. Theissen polygons were created in Arc view to spatially allocate the crop sites to the NUTS level 3 modelling units (see Figure 5.22). Where no fertilisation timing data were available, fertilisers were applied five days before planting following the methodology used by Li *et al.* (2000). Tillage practices were characterised as conventional tillage, where the soil was tilled to a depth of 15-25 cm.

The MARS unit also possesses a phenological crop calendar for 11 major crops linked to the MARS 50 km × 50 km meteorological grid (Willekens *et al.* 1998). However, the 50 km crop calendar database was not suitable for this study as many of the data required by the DNDC model (*e.g.* tillage and harvesting) were absent from the database.

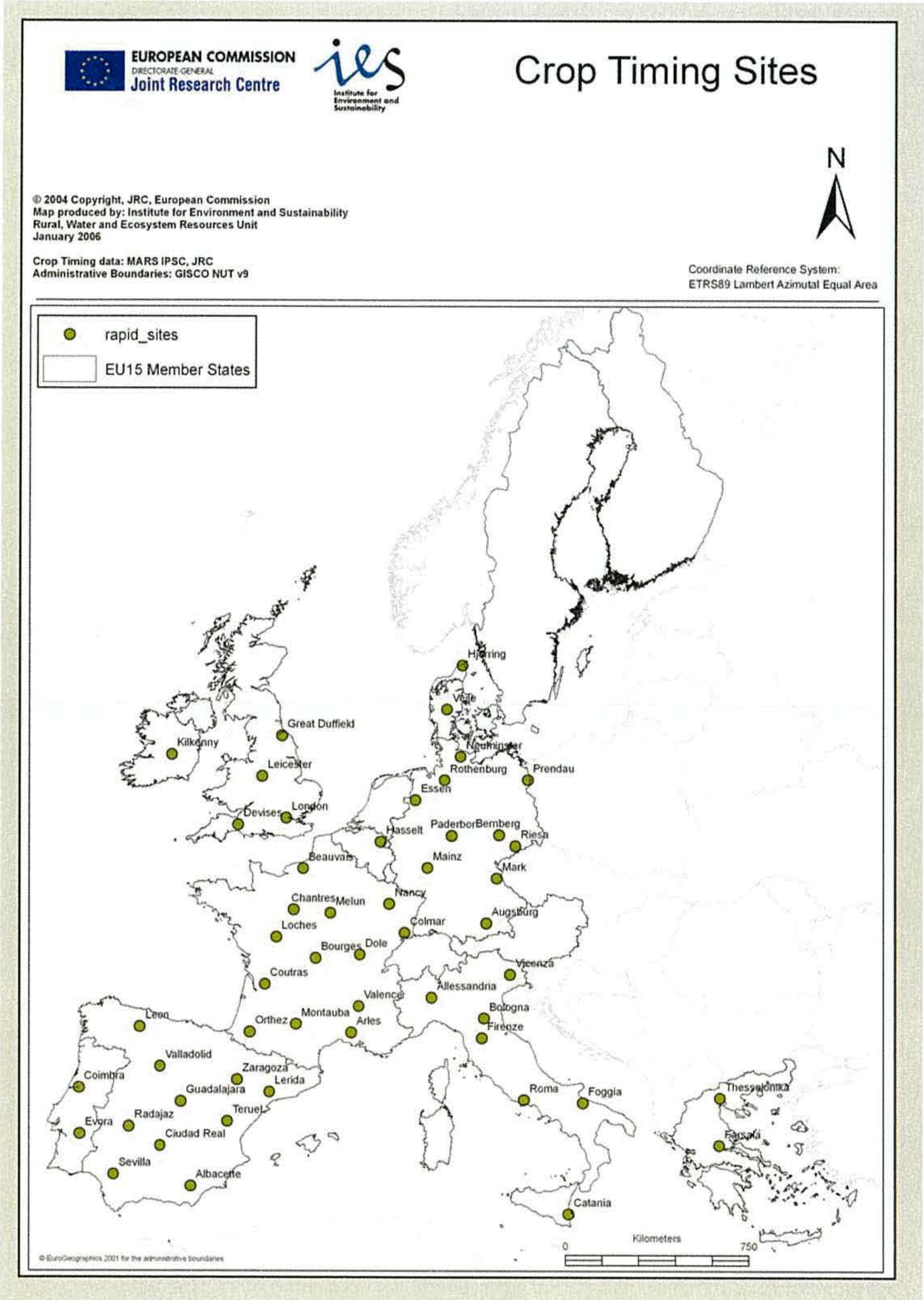


Figure 5.22. JRC's MARS unit crop calendar sample sites.

5.7.4 Fertiliser application rates

The mineral N fertiliser application rates (kg N ha yr^{-1}) for each crop were derived from a fertiliser use report for 1996 to 1997 produced jointly by the Food and Agriculture Organization of the United Nations (FAO), the International Fertilizer Development Centre (IFDC) and the International Fertilizer Industry Association (IFA) (IFA/FAO/IFDC, 1999). The uncertainties in the fertiliser data are:

1. A very limited number of governmental agencies collect fertiliser data and in many cases, data are restricted to a few major crops.
2. Not all countries report data for the same year.
3. Multi-cropping is practised in many countries, making it difficult to quantify the amount used on each crop. Moreover, some countries made estimates for a group of crops (*e.g.* cereals) rather individual crops such as wheat and maize.
4. Double cropping is practiced in some of the countries. In many cases, most or all of the fertilizer is applied to one crop, but the fertilizer benefits both the crops.

The uncertainties expressed by (IFA) (IFA/FAO/IFDC, 1999) refer to the worldwide collection of data. No specific comments were made on European data collection. Fertiliser application rates differ significantly between the EU Member States as can be seen in the example for wheat shown in figure 5.23 with the highest rate occurring in the UK (190 kg N ha^{-1} yr^{-1}) and the lowest in Portugal and Finland

(80 kg N ha^{-1} yr^{-1}). The fertiliser application rates for all crops are shown in appendix 4.

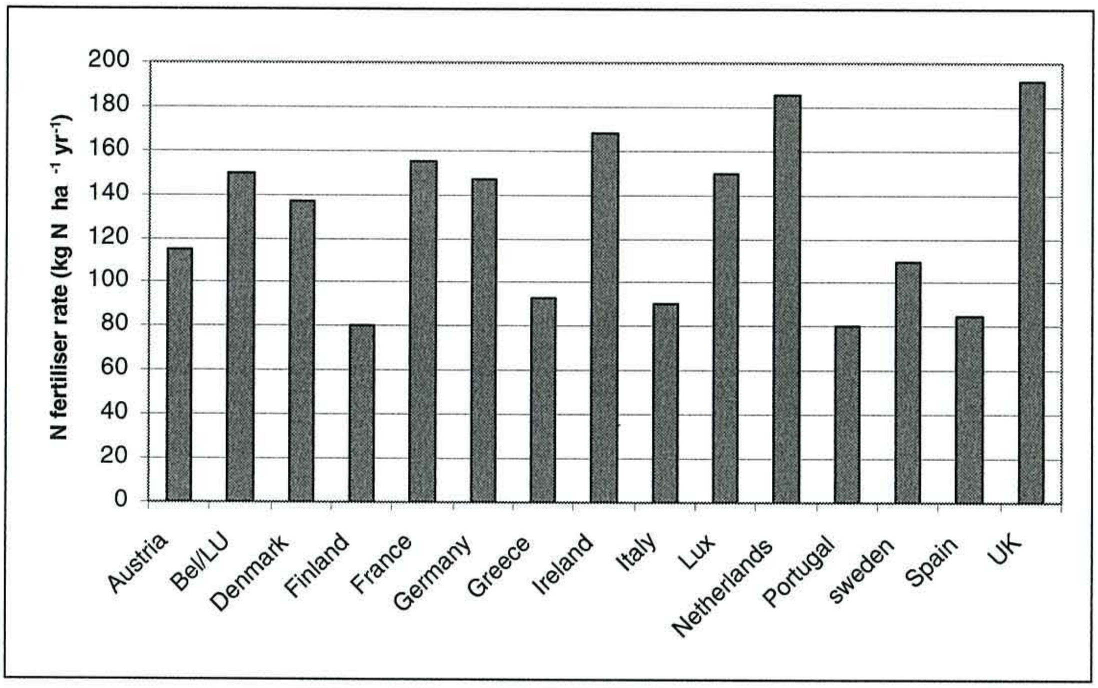


Figure 5.23. Wheat fertilisation rates (kg N ha^{-1} yr^{-1}) in EU member states

5.7.5 Fertiliser partitioning

The farm management database in DNDC allows the partitioning of mineral N fertiliser into various types. The partitioning data were derived from FAO data and applied to mineral N fertiliser data described in section 5.7.4. Figure 5.24 shows the EU percentages of fertiliser types consumed, according to the (FAO, 2003) for the following fertiliser types required by the DNDC model:

- Nitrates (NO_3^-)
- Ammonium bicarbonate (NH_4HCO_3)
- Urea (Urea)
- Anhydrous ammonia (NH_3)

- Ammonium nitrate (NH_4NO_3)
- Ammonium sulphate ($(NH_4)_2SO_4$)
- Di-ammonium phosphate ($(NH_4)_2HPO_4$)

As was shown in the sensitivity analysis, the type of mineral fertiliser applied has a significant effect on N_2O emissions. This data generally is only available at the national scale, which precludes the accurate simulation of fertiliser patterns.

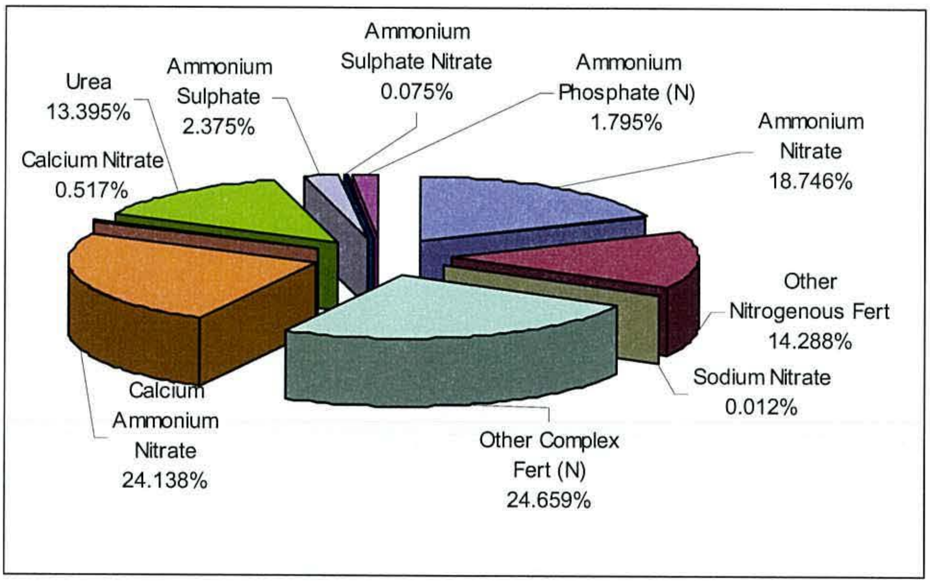


Figure 5.24. Fertiliser types as percentage use in EU (FAO 1997)

5.7.6 Crop residue incorporation

The percentage crop residue requirement for DNDC is defined by Li (2002) as the fraction of aboveground crop residue (leaves and stems) left as stubble or litter in the field. In the absence of suitable crop residue data a default figure of 20% for crop residue incorporation was used. The IPCC produce a table of recommended crop residue incorporation data for use in producing inventory estimations, for a limited number of crops, but the data is not country specific. This is an area of data provision that requires more investigation.

5.7.7 Irrigation index

The irrigation index specifies a fraction (0-1) of water deficit, whenever water stress occurs, which will be supplied through irrigation. In the absence of such data on a European scale the presence or not of water-management regime was derived from the ESDB.

5.8 Manure

The default version of DNDC 7.7 (Li, 2002) uses livestock population data to calculate the N input to soil due to manure. No account for the distribution of manure from one region to another was taken by the model and test runs for Italy using livestock population data, derived from New Cronos FSS data for 1997, showed excessive N inputs from organic manure in many regions. Therefore, for this study a decision was made to use organic manure N application rate data derived from the New Cronos database (theme 8 (Environment and Energy)). This database contains nitrogen balance data including:

- Removal by harvest of grazing
- Organic manure applied to agricultural land
- Mineral fertilisers applied to agricultural land
- Wet and dry deposition from the atmosphere
- Surplus of nitrogen
- Fixation by leguminous crops

The organic manure data available within the New Cronos database are available for the same NUTS areas as the FSS crop data described in section 5.6.1.

5.9 Model application

The GIS database and relational data required to run the DNDC model for Italy and other EU member states was constructed based on the data described in this chapter (Sweden could not be included due to lack of CORINE land cover data).

6 Results and discussion

This first section of this chapter describes the modelled estimates of N_2O emissions for Italy. Comparisons are shown between total N_2O emission estimates for Italy using various combinations of the soil organic carbon content (1:250 k and 1:1 M scales) and arable crop data [Italian regional data (ISTAT NUTS level 3) data and New Cronos (NUTS level 2) disaggregated data]. The second section describes the calculation of N_2O emission factors from modelled scenarios and comparison with IPCC default emission factors. The IPCC defines an emission factor as the average emission rate of a given pollutant for a given source, relative to units of activity. An N_2O emission inventory for Italy of both direct and indirect emissions from agricultural soils and comparison between estimates using the IPCC methodology are displayed in a spreadsheet similar to that used by the IPPC methodology. The third section describes validation of the modelled results by comparison with measured N_2O estimates. The fourth section illustrates estimations of N_2O emissions at a pan European level.

Total emission estimates using the DNDC model and emissions calculated using the IPCC methodology are expressed in units of tonnes (t) N_2O-N yr^{-1} where N_2O-N indicates the weight of N_2O emissions as N. Regional emission rates are expressed in kg N_2O-N ha^{-1} yr^{-1}. The IPCC reports emission inventories solely as units of Gg N_2O, which is calculated by multiplying N_2O-N by 44/28 [the molecular weight of N_2O (44) and N_2 (28)]. 1 Gg is equivalent to 10^3 tonnes.

6.1 Estimation of N_2O emissions in Italy

The estimated emissions from differing soil organic carbon content and arable crop data combination scenarios for Italy for 1997 are described in this section. To create a 'baseline scenario' the DNDC model was run, in regional mode using the data derived from the European harmonised database compiled for this study (as described in Chapter 5). In the first scenario SOC was derived from the 1:250 k measured values for Italy and arable crop data for 1997 extracted from the Italian regional data (ISTAT NUTS level 3). The second scenario used SOC derived from the 1:1 M SOC PTR estimated data and the ISTAT crop data whilst the third scenario used the 1:1 M SOC PTR and European scale arable crop data extracted from New Cronos (NUTS level 2) disaggregated to NUTS level 3. The DNDC model produces just one value for total N_2O emissions from agricultural soils (*i.e.* from all sources of emissions: mineral fertiliser, manure, crop residue, N deposition) in comparison to the IPCC methodology that estimates the emissions from each source.

6.1.1 Comparison of SOC and crop data

The lowest mean modelled total of N_2O emissions from agricultural soils for the whole of Italy for 1997 was 44,700 t N_2O–N yr^{-1} (see Table 6.1). Even this lowest estimate for direct N_2O emissions by far exceeds the 20,500 t N_2O–N yr^{-1} reported for 1997 using the IPCC methodology by CRPA (1999). However, as will be shown in section 6.2, the calculation of background emissions using the IPCC methodology differ considerably to those estimated by the DNDC model.

Table 6.1. Total estimated N_2O emissions for Italy for 1997 from three scenarios using different combinations of soil organic carbon content (SOC) and crop input data within the DNDC model.

Scenario	**SOC data source**	**Crop data source**	**Mean N_2O emissions ($t\ N_2O\text{-}N\ yr^{-1}$)**
1	1:250 k	ISTAT (NUTS 3)	44,700
2	1:1M (PTR class)	ISTAT (NUTS 3)	76,300
3	1:1M (PTR class)	New Cronos (Disaggregated)	99,500

The other two scenarios (see Table 6.1) gave N_2O emission estimates of 76,300 t N_2O-N yr^{-1} for scenario 2 and 99,500 t N_2O-N yr^{-1} for scenario 3. The latter scenario is nearly 5 times the estimate made by the CRPA (20,500 t N_2O–N yr^{-1}) for 1997. The high estimation from scenario 3 is very significant, as the soil and crop data used in scenario 3 are the only data available to make a pan-European estimation of N_2O emissions (described in section 6.4).

The difference in N_2O emission estimates between scenario 1 (44,700 t N_2O–N yr^{-1}) and scenario 2 (76,300 t N_2O-N), where only the scale of SOC data was changed, implies that the N_2O emission totals at the national scale were highly sensitive to the coarseness of the SOC input data. The sensitivity of the DNDC model to SOC content has already been shown in this thesis and also reported by Brown *et al.* (2002), Grant *et al.* (2003) and Li and Aber (2000). However, the results presented here indicate that the uncertainty within the input data and the coarseness of the data can also result in significant uncertainty in the estimation of N_2O at the regional scale. The mean SOC data derived from the 1:250 k database for Italy displayed in Figure 6.1 is comparatively lower for the majority of regions in Italy, than the SOC data derived from the 1:1 M PTR database shown in Figure 6.2.

This indicates an over-estimation of SOC in the latter. Some of these uncertainties may derive from the generalisation process used in producing the 1:1 SGDB, an inherent characteristic in all geographic data (Joao, 1998) and over-estimation of SOC within the pedo-transfer rules. To reduce the uncertainty in N_2O emission estimates the SOC data needs to be based on measurements with actual values and not on classes of SOC (i.e. high, medium or low). As shown in Figure 5.7, the medium class of SOC produces a large range of N_2O emissions and the upper limit of the high class is unknown, although this can be estimated using measured data (see Figure 5.6). The IPCC methodology does not take into account the total area of SOC, but only that of histosols. In the emission inventory for 1997 for Italy only 9000 ha of histosols were reported accounting for just 113 t N_2O-N yr^{-1} out of the direct emission total of 20,500 t N_2O–N yr^{-1} (i.e. approximately 0.5% of total emissions) (CRPA, 1999).

The difference in N_2O emissions between scenario 2 (76,300 t N_2O-N), and scenario 3 (99,500 t N_2O-N), where the spatial scale of crop data was changed, indicates that changes in the spatial distribution due to the disaggregation procedure can affect regional N_2O emission estimates. At the national scale the crop area totals of the two crop scenarios are comparable 11,061,000 ha for ISTAT and 11,118,00 ha for New Cronos (see Figure 5.19 chapter 5), and thus similar national total mineral N fertilisation inputs were modelled. From this result it can be inferred that N_2O emissions were affected not only by the total mineral N fertiliser amounts applied (*e.g.* the IPCC approach) but also by the climatic and soil conditions under which the crops were grown.

To illustrate that N_2O emissions were affected by the localised soil and climate conditions, the regional estimates were further analysed. Regional changes in N_2O emissions due to changes in SOC and arable crop distribution were analysed for a single representative crop in Italy. Durum wheat is the dominant arable crop in Italy (see Figure 5.9 in chapter 5) and is grown throughout most of Italy with the exception of the alpine zone in the north of Italy (see Figure 6.3). However, the results of the spatial disaggregation (using aerial weighting based on the Corine land cover map of the New Cronos data) show durum wheat in several regions of the alpine zones of north Italy (see Figure 6.4) Although the disaggregated crop area are low in these alpine zones, N_2O emissions will be produced in zones not recorded before. Moreover, these alpine zones are characterised with high SOC contents that may produce high estimations of N_2O. The changes in the spatial distribution of the durum wheat crop illustrate the errors and uncertainties produced by the process of disaggregating the New Cronos crop data (NUTS level 2) to the smaller NUTS level 3. Where possible, N_2O emission estimates should be made using crop data reported at the smallest scale available.

N_2O emissions from durum wheat estimated using the ISTAT crop data and 1:250 k SOC display a relatively even distribution (see Figure 6.5) with the highest emission estimates being concentrated in the southern region of Foggia (NUTS level 3 code IT911; see Figure 6.8). In contrast, N_2O emissions from durum wheat estimated using the ISTAT crop data and the 1:1M PTR SOC data (Figure 6.6) show high estimates in several regions surrounding Foggia (in particular NUTS level 3 regions IT912 and IT921; see Figure 6.8). These high emission estimates occur in the region of Puglia (NUTS level 2 code: IT9) that is characterised by a large concentration of arable crops, dominated by durum wheat, permanent irrigation and relatively fertile soils.

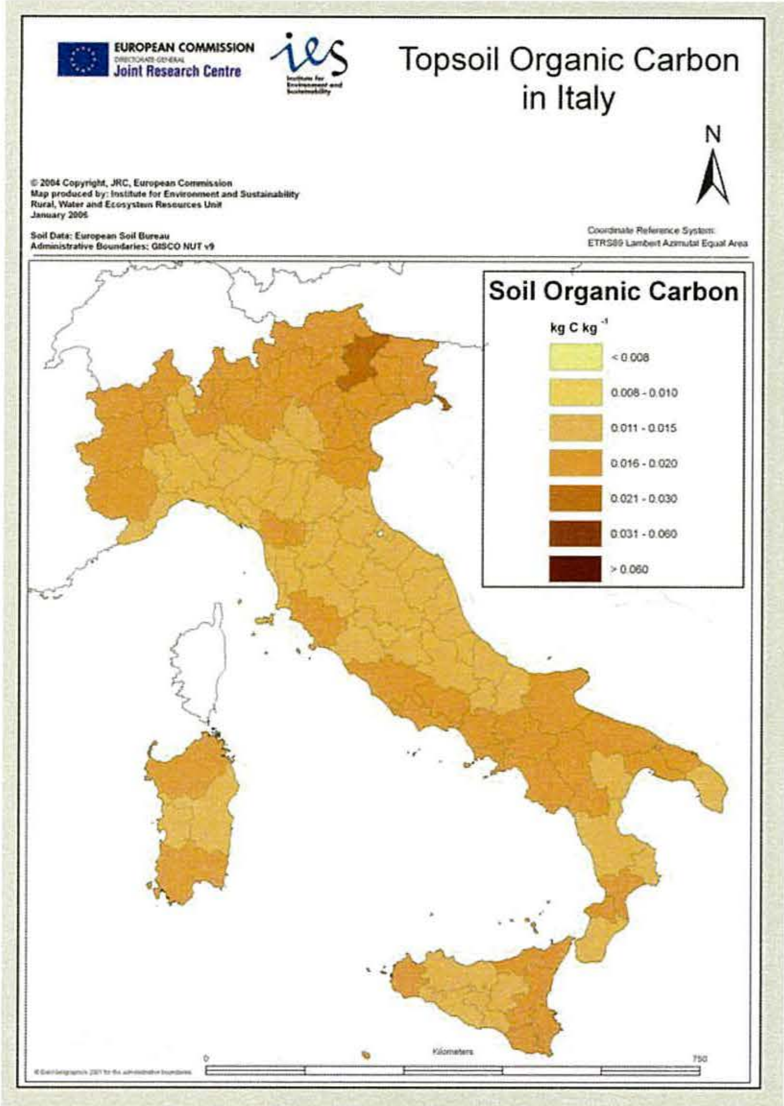


Figure 6.1. Mean soil organic carbon (SOC) content derived from the 1:250 k SOC data that was subsequently used to model N_2O fluxes in Italy.

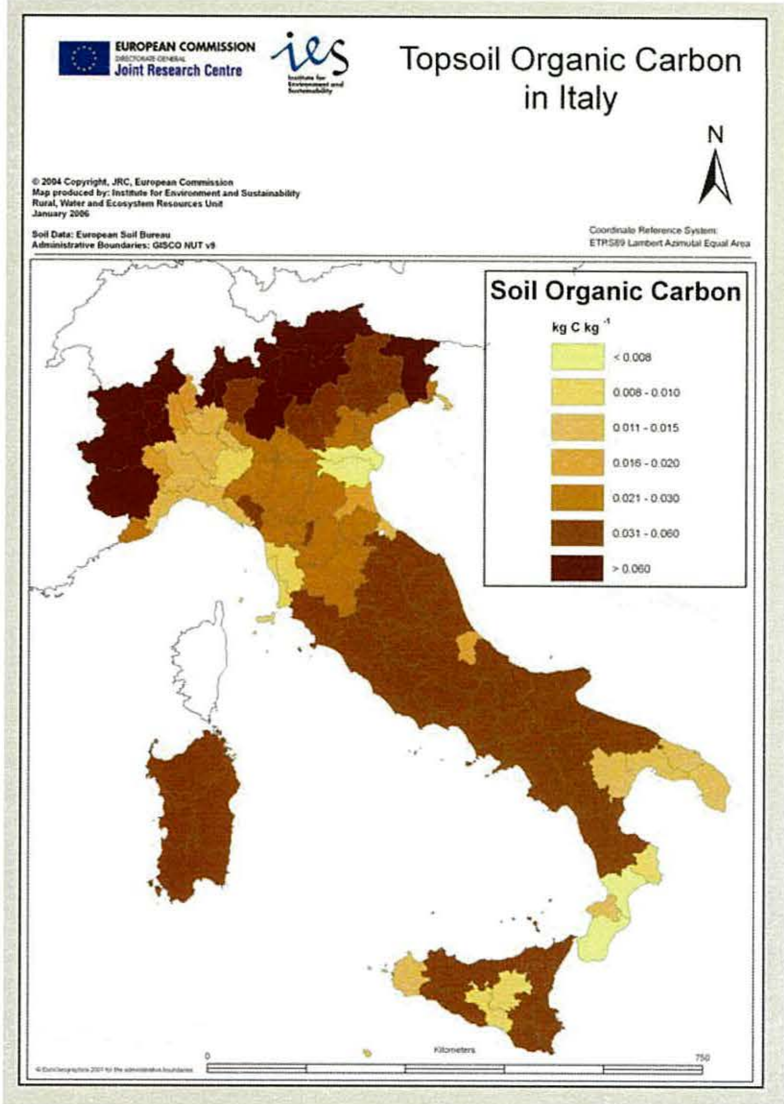


Figure 6.2. Mean soil organic carbon (SOC) derived from 1:1 M PTR SOC data that was subsequently used to model N_2O fluxes in Italy.

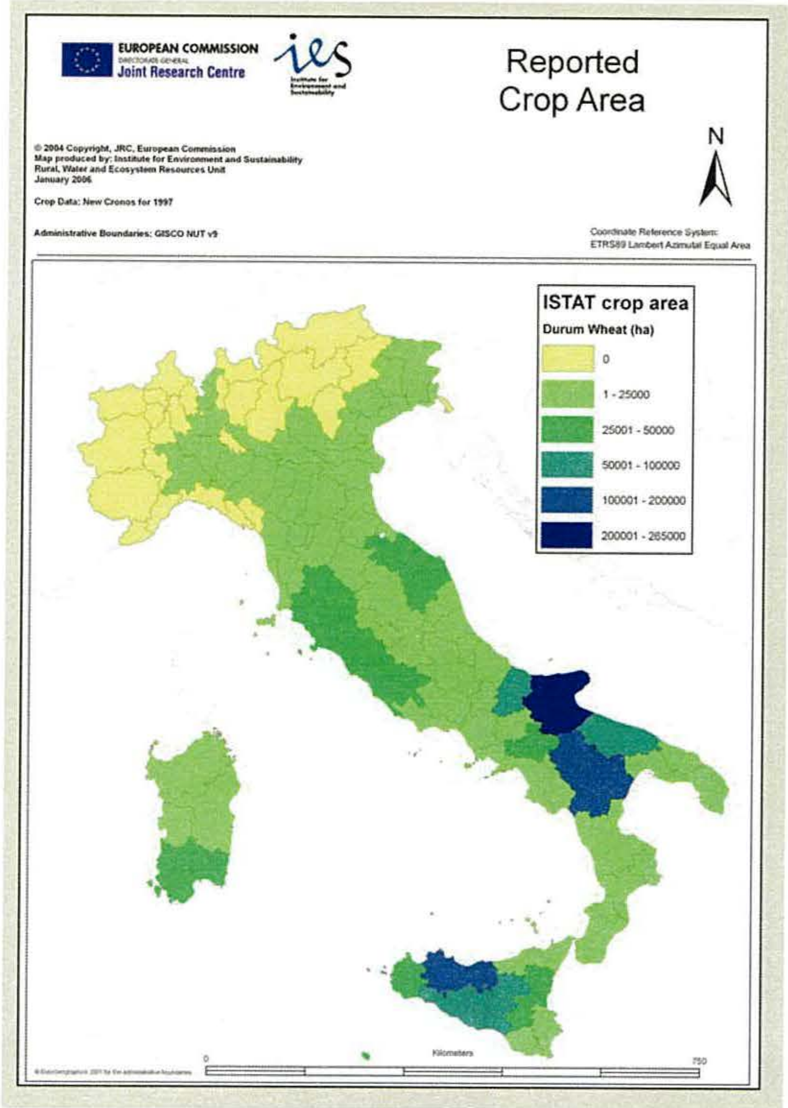


Figure 6.3. ISTAT NUTS level 3 reported crop area for durum wheat (ha) in Italy.

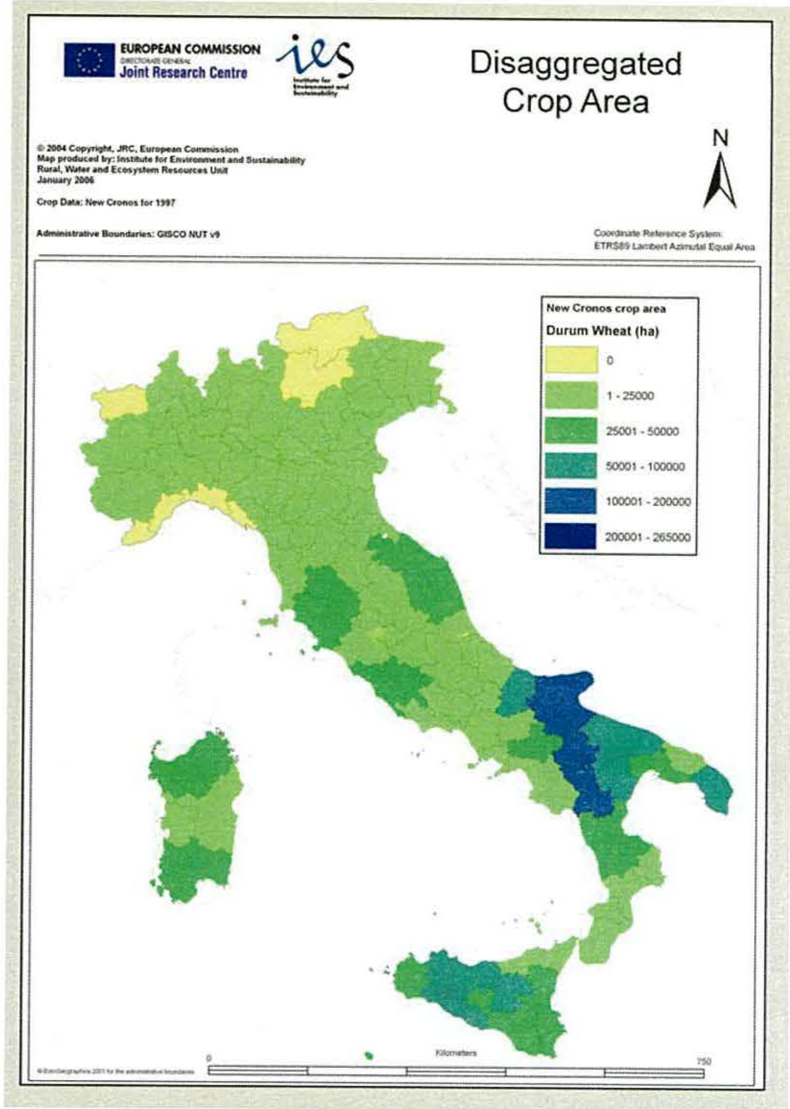


Figure 6.4. New Cronos disaggregated crop area for durum wheat (ha) in Italy.

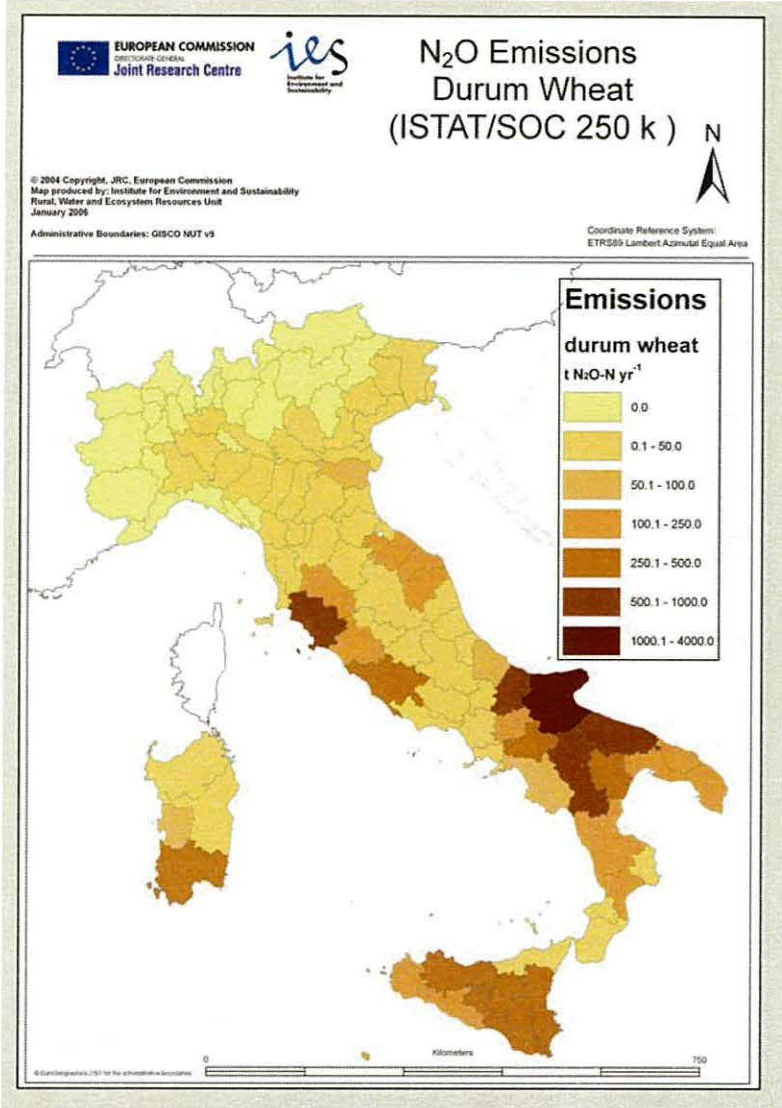


Figure 6.5. DNDC model predicted N_2O emissions in Italy from durum wheat cropping activities estimated using ISTAT crop data and the 1:250 k scale SOC map.

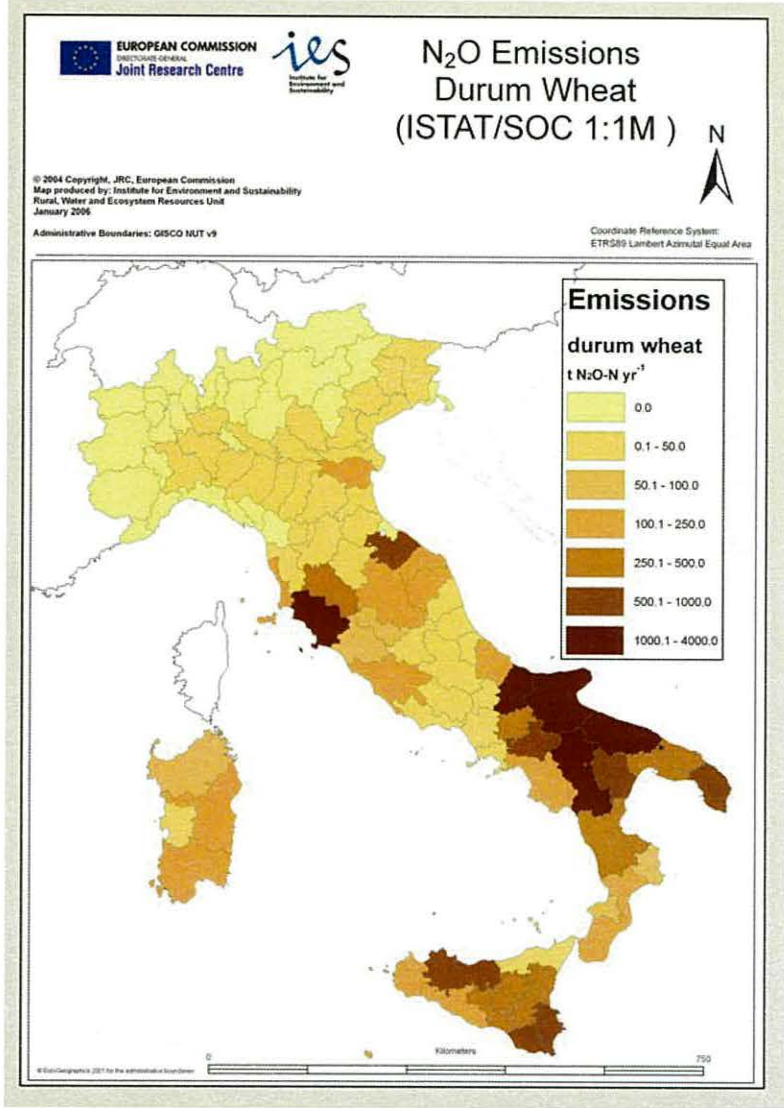


Figure 6.6. DNDC model predicted N_2O emissions from in Italy durum wheat cropping activities estimated using ISTAT crop data and the 1:1 M scale PTR SOC map.

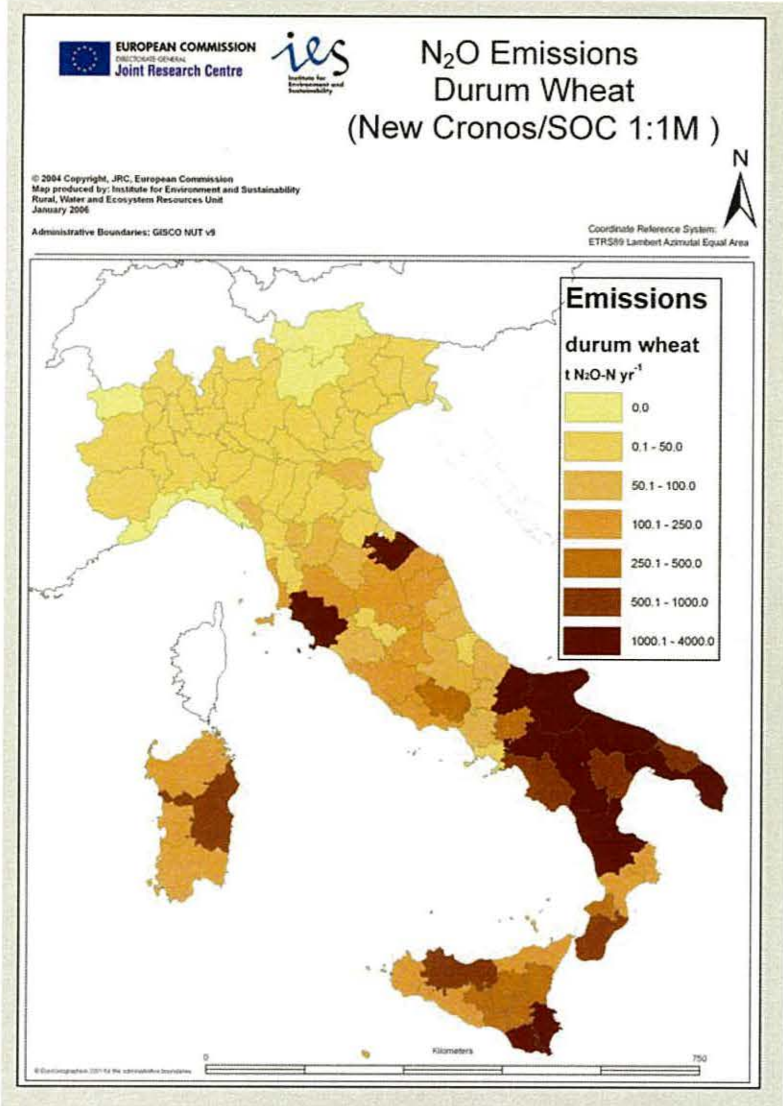


Figure 6.7. DNDC model predicted N_2O emissions from durum wheat cropping activities estimated using the New Cronos crop dataset and the 1:1M scale PTR SOC map.

Figure 6.8. Map showing the NUTS level 3 regions for Italy.

The results clearly show that changing the spatial distribution of crops has a significant affect on the estimated N_2O emissions. This is further supported by the example in Table 6.2 where the total cropping area of durum wheat disaggregated from the New Cronos dataset in Vibo (IT934) was 4.2 times greater than that reported by ISTAT but N_2O emissions increased by a factor of 7.7. The results are a further indication that other factors are involved in the increase in N_2O emissions, such as climate and soil type.

Table 6.2. The effect of changes to crop area on N_2O emissions from the Puglia region of Italy as predicted with the DNDC model.

		SOC content	Crop area		Crop area change	N_2O emission scenarios		Relative change in emissions
		(kg C kg^{-1} soil)	(ha)			(t N_2O-N yr^{-1})		
NUTS code	**Region Name**	1:1 M PTR	ISTAT (a)	New Cronos (b)	ISTAT to New Cronos	Scenario (1) ISTAT and 1:1 M PTR	Scenario (2) New Cronos and 1:1 M PTR	Scenario 1 to 2
IT934	VIBO	0.0115	2,202	9,236	*4.2*	56.5	434.0	7.7
IT915	LECCE	0.013	19,240	81,711	*4.2*	530.1	3,296.5	6.2
IT935	REGGIO	0.007	2,409	11,344	*4.7*	108.0	516.5	4.8
IT931	COSENZA	0.044	17,050	37,735	*2.2*	396.9	1,746.8	4.4
IT932	CROTONE	0.008	12,000	22,222	*1.9*	53.2	158.6	3.0
IT913	TARANTO	0.0095	22,529	37,731	*1.7*	451.7	1,236.6	2.7
IT914	BRINDISI	0.01	9,835	14,678	*1.5*	254.5	580.3	2.3
IT921	POTENZA	0.0565	114,000	127,064	*1.1*	2,270.3	3,913.2	1.7
IT912	BARI	0.044	82,000	94,772	*1.2*	1,696.8	2,469.8	1.5
IT933	CATANZARO	0.007	15,500	13,173	*0.8*	157.3	186.1	1.2
IT922	MATERA	0.014	107,500	94,776	*0.9*	530.7	570.5	1.1
IT911	FOGGIA	0.0455	265,000	182,168	*0.7*	3,679.6	2,342.5	0.6
IT9	**Totals**		**669,265**	**726,610**	***1.1***	**10,185.6**	**17,451.4**	**1.7**

Although the total ISTAT and disaggregated crop area vary by only a factor of 1.1 at the NUTS level 2 (IT9; see Table 6 .2) the spatial disaggregation procedure resulted in considerable differences in the distribution of these crops. This further highlights the uncertainty in relating land use types (e.g. arable crops) to CORINE agricultural land cover types.

In order to gain an understanding of the effect of management and localised conditions on N_2O emissions, it is common practice to report emission rates (either per region or per crop), thus eliminating the uncertainty in crop distribution data. However, an understanding of where individual crops are likely to be grown is still required. An alternative method for the calculation of emission rates by individual crops can be based on a single hectare approach where each crop would be modelled as a single hectare, thus producing a matrix of emission values that can be applied to a crop statistical database. This methodology would enable simple crop change scenarios to be undertaken without the need to re-run the mechanistic model. However, it must be noted that any scenarios to replicate future conditions would need to take into account spatial changes in crop areas, along with management issues, such as fertiliser rates, and climate.

To summarise, the results of the modelling exercise for Italy have shown that the calculation of national total N_2O emissions estimates were highly dependent on an accurate understanding of the spatial locations of crops and thus other factors such as climatic and soil conditions. These factors have been shown to significantly affect predicted N_2O emissions. It is essential that to undertake predictions of N_2O emissions under future scenario changes in crop distribution (i.e. replacing certain cereal crops with industrial crops) a good understanding of the spatial location of crop changes are known and not just changes to total crop areas. The results have also shown that large-scale datasets (e.g. pan-European soil data) include inherent inconsistencies due to generalisation and estimations that can significantly affect predicted rates of N_2O emissions.

6.1.2 *Crop-wise distribution of N_2O emissions in Italy*

All N_2O emissions estimates in this section use the ISTAT NUTS 3 level arable crop data combined with minimum and maximum SOC values derived from the 1:250 k measured dataset hereafter called the IT baseline scenario. In addition, a second scenario using the 'real' mean SOC values calculated using Arc view was undertaken.

The spatial distributions of the mean N_2O emission estimate rates (kg N_2O-N ha-1 yr-1) for Italy in 1997, from all of the arable crops combined are shown in Figure 6.9. The percentage contributions of each area to the national total emission estimate are shown in Figure 6.10. Mean emission rates by crop are shown in Figure 6.11.

Regional emission rates exceed 10 kg N ha^{-1} yr^{-1} in Vercelli, Ragusa, Vibo, Brindisi, Grosseto, Ferrara, Novara and Pavia. Brindisi is an area dominated by durum wheat with a high mineral N fertilisation rate (90 kg N ha^{-1} yr^{-1}). Vercelli, Novara and Pavia are areas in the north of Italy dominated by large areas of rice fields (73,202 ha, 37,585 ha and 84,488 ha respectively) with relatively high mineral N fertilisation rates (100 kg N ha^{-1} yr^{-1}).

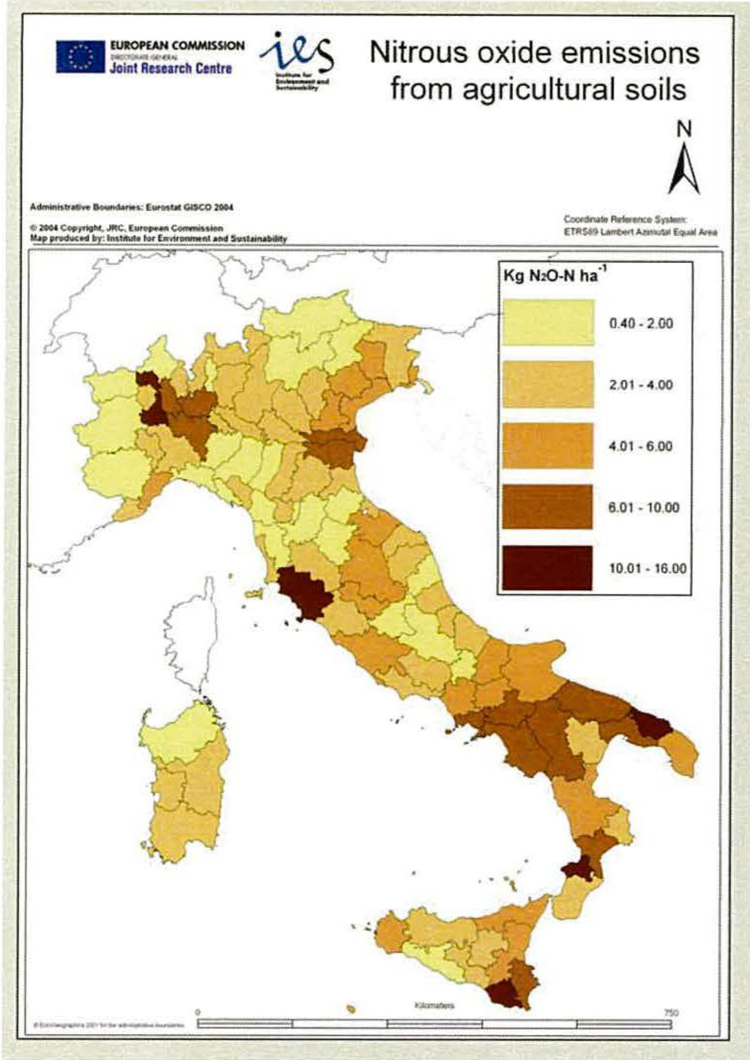


Figure 6. 9. Regional mean N_2O emission rates for Italy in 1997 predicted with the DNDC model using ISTAT NUTS 3 level crop data and the IT baseline SOC data.

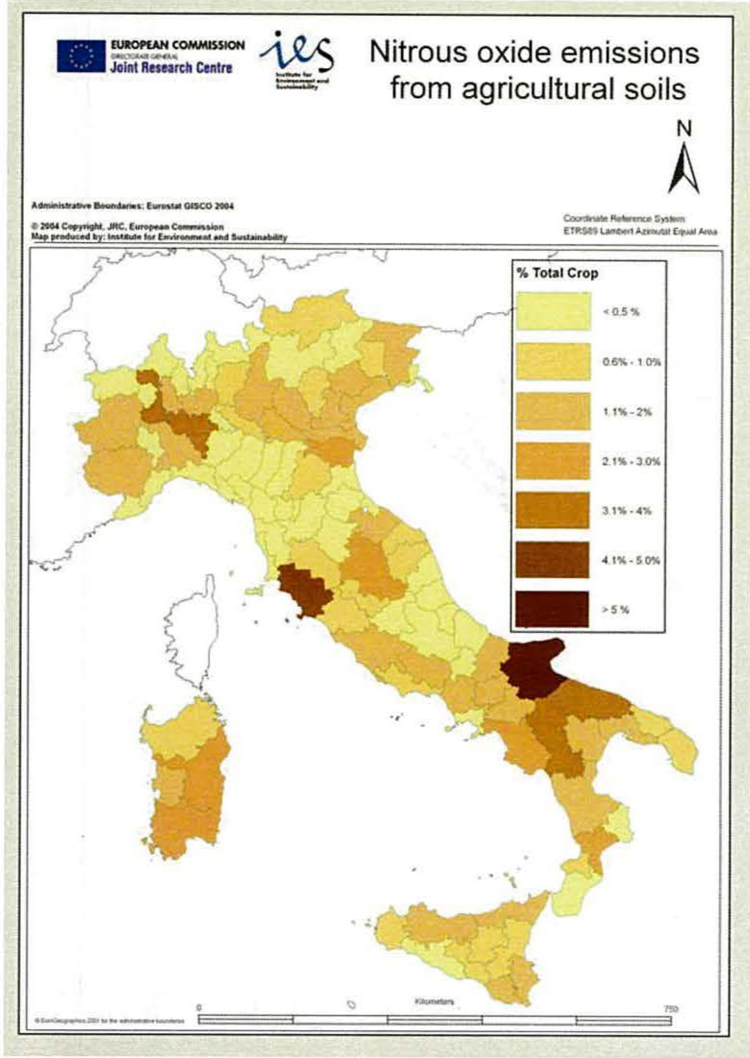


Figure 6.10. Relative contribution of regional N_2O emission rates for Italy in 1997 derived from Figure 6.9.

Table 6.3 shows the total for crop areas for Italy and the total N inputs from mineral fertiliser, manure and crop residue.

Table 6.3. Total crop areas and N input from fertiliser, manure and crop residue in Italy.

Crop Class	ISTAT crop area	Total N fertiliser	Total N manure	Crop Residue N
	(000) ha	(000) t N yr^{-1}	(000) t N yr^{-1}	(000) t Nyr^{-1}
Maize	1,034.9	186.3	80.4	25.2
Winter wheat	703.2	63.3	35.9	8.5
Soybean	299.6	13.5	24.6	2.9
Leguminous hay	416.2	0.4	13.8	16.9
Non leguminous hay	999.2	6.5	53.5	50.5
Winter barley	336.3	28.6	15.3	5.6
Oats	138.9	13.9	4.3	2.1
Durum wheat	1664.6	149.8	41.9	51.6
Pasture	4,274.7	64.1	197.5	106.7
Other cereals	41.3	4.1	2.2	0.6
Vegetables	344.4	37.9	14.3	2.4
Dried vegetables	65.0	1.9	2.0	0.2
Potato	95.6	9.6	3.8	1.5
Beet	287.9	25.9	17.2	4.9
Paddy rice	240.2	24.0	19.7	3.2
Fodder Roots	27.2	2.7	1.2	0.5
Silage maize	293.7	17.6	24.8	13.5
Rapeseed	68.4	5.5	2.8	0.7
Sunflower	238.9	10.8	7.7	1.4

Table 6.4 shows the fertilisation rate of the modelled crops and N_2O emissions (kg N_2O-N ha^{-1} yr^{-1}).

Table 6.4. Crop fertilisation rates and emission rates (kg N ha^{-1} yr^{-1}).

Crop	Fertilisation rate (kg N ha)	Mean N_2O Emission (kg N_2O-N ha^{-1})	Max N_2O Emission (kg N_2O-N ha^{-1})	Min N_2O Emission (kg N_2O-N ha^{-1})
Maize	180.0	5.5	16.1	1.18
Winter wheat	90.0	6.2	15.4	1.31
Soybean	45.0	6.9	15.0	1.69
Legume hay	1.0	4.9	19.4	0.34
Non legume hay	6.5	3.2	11.4	0.31
Winter Barley	85.0	6.2	16.9	1.44
Oats	100.0	6.4	17.2	1.11
Durum Wheat	90.0	7.0	19.0	1.60
Pasture	15.0	1.1	4.1	0.18
Other cereals	100.0	4.4	11.6	1.09
Vegetables	110.0	5.2	14.8	1.15
dried vegetables	30.0	5.1	13.2	1.10
Potato	100.0	3.4	13.5	0.36
Beet	90.0	2.7	8.9	0.62
Paddy rice	100.0	12.0	25.3	4.53
Fodder Roots	100.0	3.6	12.3	0.41
Silage maize	60.0	1.3	4.3	0.22
Rapeseed	80.0	7.5	16.4	1.90
Sunflower	45.0	4.9	13.6	1.09

Total N_2O emission estimates from the modelled crops are shown in Figure 6.11. The largest contribution to total emissions comes from durum wheat reflecting the dominant crop area (Table 6.3) and high mineral fertilisation rate of 90 kg N ha^{-1} yr^{-1}. The lowest contribution comes from pasture with a low fertilisation rate of 15 kg N ha^{-1} yr^{-1}. However, there is a large range between the minimum and maximum emission estimates, resulting from the large area of the modelled geographic unit (*e.g.* NUTS level 3). This range of SOC values may be reduced if a smaller geographic unit was used.

The N_2O results using the 'real' mean SOC data produces a significant skew towards the estimations produced by the absolute minimum SOC input data, as shown by the error bars in Figure 6.11. This indicates that the mean SOC is lower than the median value used in the DNDC simulations. The modelling exercise assumed that crop fertilisation is the same for crops and all types of soil, whereas in practice the mineral N fertiliser application rate can be reduced for certain crops on soils with high SOC (MAFF, 2000).

Improving the understanding of the soil/crop/fertilisation relationship coupled with running the model on a smaller grid size (*e.g.* 10 km) would reduce the range in the SOC values and the uncertainty of N_2O emissions related to the SOC data.

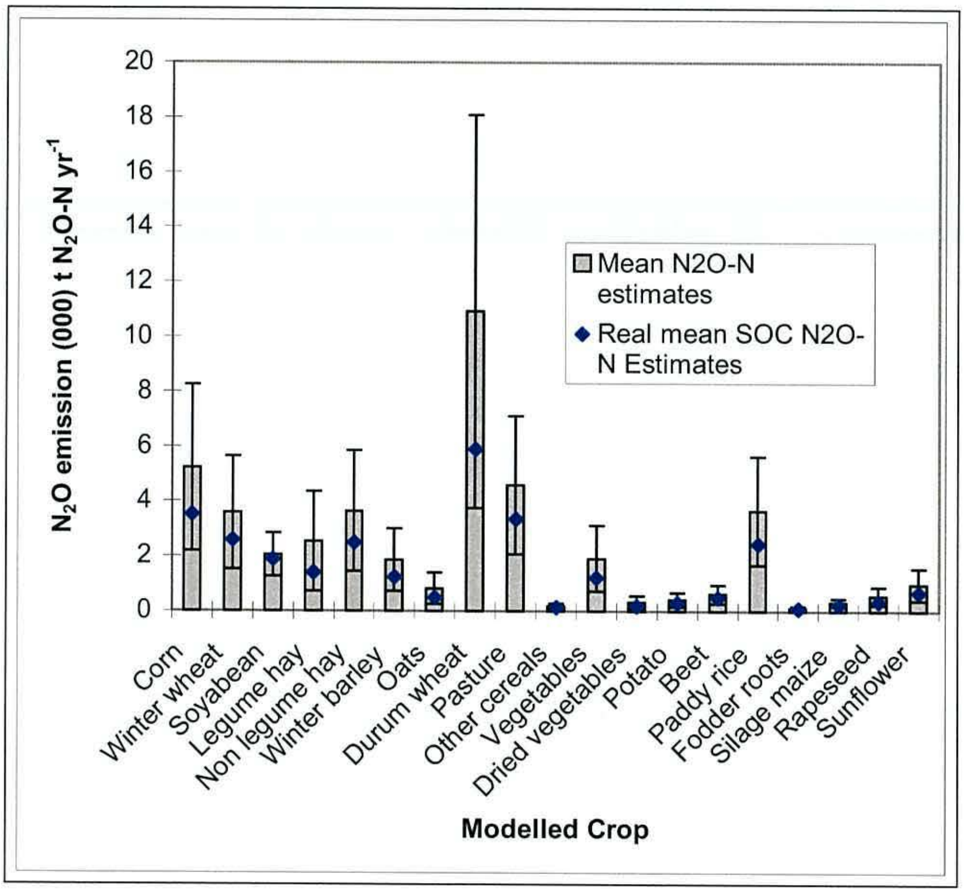


Figure 6.11. Mean total estimated emissions (000) t N_2O-N yr^{-1} from modelled crops in Italy.

The error bars indicate the range of estimates produced by the minimum and maximum SOC values of each NUTS level 3. The diamonds represent N_2O-N emissions estimates using the 'real' mean SOC.

The average crop N_2O emission rates (kg N_2O-N ha^{-1} yr^{-1}) for Italy show significant differences between the crop types (see Table 6.4) that cannot be directly attributed to the fertilisation rates. For instance, the emission rates for maize and winter wheat are 5.5 and 6.2 kg N_2O-N ha^{-1} yr^{-1} respectively while the fertilisation rates for these two crops are 180 and 90 kg N ha^{-1} yr^{-1} respectively. The emission factors derived from these estimates for maize and winter wheat were **0.031** and **0.069** respectively. From this result it can be inferred that the crop type significantly affects N_2O emission rate. However, this could be attributed to the climate and soil conditions under which the crops are grown. The highest emission rate comes from leguminous hay, mainly due to the low fertilisation rate (1 kg N ha^{-1} yr^{-1}) and that legumes also fix atmospheric N_2, which also enters the soil.

6.2 Direct emissions from agricultural soils in Italy

The results discussed in this section were based on the IT baseline scenario derived from Italian SOC data (scale: 1:250 k) and regional crop data (ISTAT NUTS level 3) described in Section 6.1. The rest of the data were derived from the European database. The data were used to run the DNDC model in a series of scenarios estimating N_2O emissions from the sources accounted for in the IPCC methodology (see Section 3.2). In addition, IPCC factors were applied to the same source data to make a comparison between the modelled and statistical methodologies.

The IPCC methodology for producing national inventories relates N_2O emissions to the national total amounts of N input to soils from various sources [i.e. the emission factor for N_2O related to N fertiliser input (EF1) is 0.0125 (kg N_2O kg^{-1} N input] (see Appendix 1). In contrast, the DNDC model estimates are a total emission estimate from all sources including 'background' sources not directly related to farm management. However these background sources can still be influenced by historical land use (this is described in more detail later in the thesis). To make a comparison with the IPCC emission factors, multiple scenarios of zero mineral fertiliser, organic manure, N deposition and crop residue were undertaken. The results from each scenario were subtracted from the IT baseline emission results following a similar methodology used by Brown *et al.* (2002) and Li *et al.* (2001) to give estimations of N_2O emissions from each source identified by the IPCC. The DNDC model joins all the sources of N together providing a single estimate of N_2O emissions, as occurs in reality when measurements are taken directly in the field.

Emissions not accounted for by the individual N inputs can be attributed to background sources (*i.e.* N mineralisation). However, it should be noted that the historical land use could also effect background emissions (Mogge *et al.*, 1999). The emission fractions used in the IPCC methodology to calculate N content in the various input sources are shown in Table 6.6.

Table 6.6. IPCC emission fractions used to calculate N content in sources of N_2O.

Fraction	Description	Value
$Frac_{BURN}$	Fraction of crop residue burned	**0.10**
$Frac_{GASF}$	Fraction of synthetic fertilizer N applied to soils that volatilizes as NH_3 and NOx	**0.10**
$Frac_{GASM}$	Fraction of livestock N excretion that volatilizes as NH_3 and NOx	**0.20**
$Frac_{LEACH}$	Fraction of N input to soils that is lost through leaching and runoff	**0.30**
$Frac_{NCRBF}$	Fraction of N in non-N-fixing crop	**0.30**
$Frac_{NCRO}$	Fraction of N in N-fixing crop	**0.015**
$Frac_{R}$	Fraction or crop residue removed from the field as crop	**0.45**

6.2.1 *Emissions of N_2O due to mineral N fertiliser*

The comparative methodologies used to estimate N_2O emissions due to application of mineral N fertiliser are shown in Table 6.7. The DNDC model produced a mean total N_2O emission estimate for Italy due to the application of mineral N fertiliser of **4,700** t N_2O-N yr^{-1}. In contrast, the IPCC methodology produced a higher emission estimate of **7,490** t N_2O-N yr^{-1}.

Table 6.7. Methodologies used to estimate N_2O emissions in Italy due to mineral N fertilisation using either the DNDC model or IPCC methodology.

Modelled methodology:
$N_2O\text{-}N(f) = N_2O(b) - N_2O(zf)$
where:
N_2O-N(f) = N_2O-N emission due to N fertilisation
N_2O-N(b) = N2O-N emission IT baseline scenario
N_2O-N(zf) = N_2O-N emission zero fertiliser scenario.
IPCC methodology:
$N_2O\text{-}N = [\text{Total N fert} - FRAC_{GASF}] \times 0.0125$
where:
$FRAC_{GASF} = 0.1$

Both methodologies used the total mineral N fertiliser applied to soils in Italy for 1997 of **666,380** t N yr^{-1}. However, the DNDC model produced a NH_3 and NO_x emission estimate of **5,400** t N yr^{-1}, equal to a volatilisation fraction of **0.008**. Whilst, the IPCC methodology produced an NH_3 and NO_x emission estimate of **66,638** t N yr^{-1} using the higher volatilisation fraction ($FRAC_{gasf}$) of 0.1. This lower volatilisation rate in the modelled estimate would result in more mineral N fertiliser being available for N_2O emission than in the IPCC approach. However, the DNDC modelled estimate was significantly lower than that calculated using the IPCC method. This result would indicate that the emission factor in which the N_2O emission estimate is related to mineral N fertiliser input is lower in the DNDC modelled approach. The default IPCC emission factor (EF1) used to calculate total N_2O emissions due to mineral N fertiliser application is 0.0125 (kg N_2O-N kg^{-1} N input). A mean emission factor of **0.0086** (kg N_2O-N kg^{-1} N input) was derived from the linear regression (see Figure 6.12) of the DNDC modelled N_2O emission estimates plotted against mineral N fertiliser application for each of the 103 regions in Italy (minus volatilised NH_3 and NO_x).

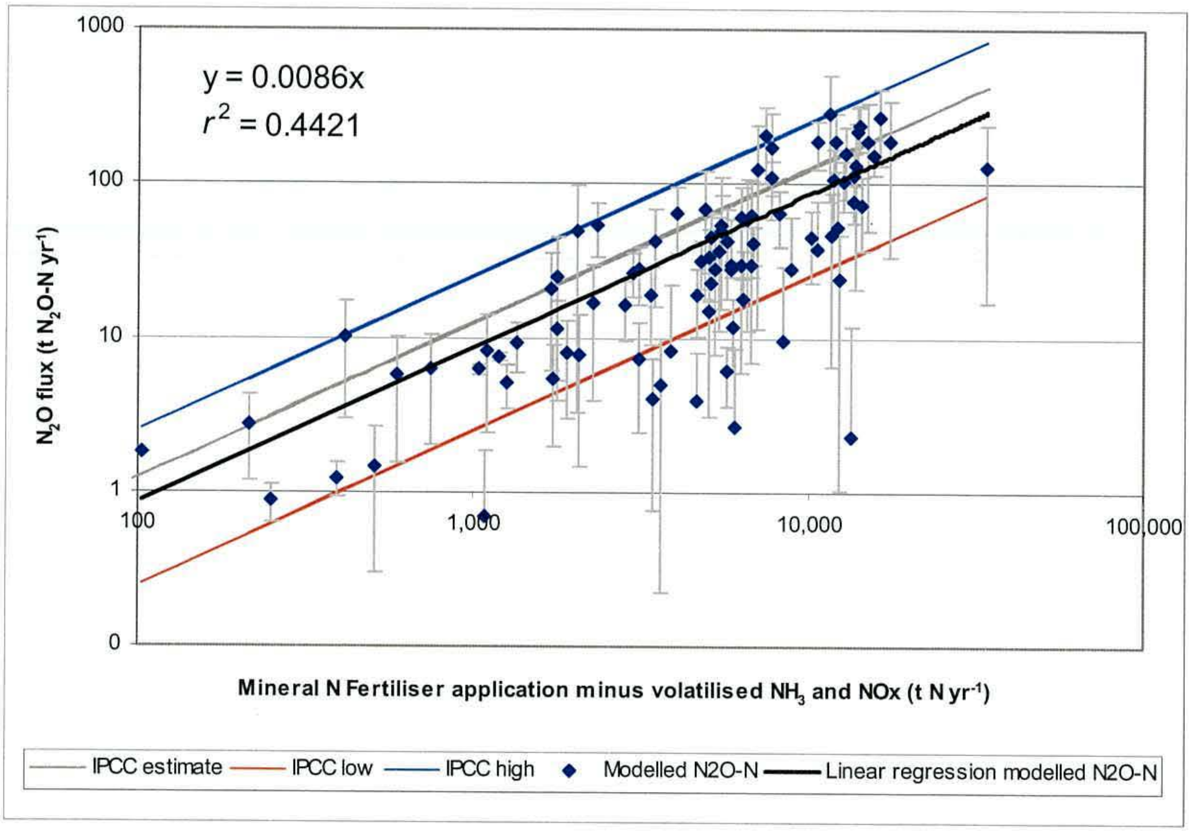


Figure 6.12. N_2O-N emissions (t N_2O-N yr^{-1}) accountable to N fertiliser application plotted against mineral N fertiliser application minus volatilised NH_3 and NO_x (t N yr^{-1}).

Each point represents a region within Italy. Modelled N_2O-N emission estimates are indicated by the diamonds with error bars to account for the range of SOC within each NUTS region. IPCC estimations are shown using the default emission factor EF1 0.0125 ± 0.01, with the range indicated by IPCC high and IPCC low.

The low r^2 value of **0.44** of the estimated emission trend is an indication of the non-linear relationship between N_2O emissions and mineral N, as were the findings of Kaiser *et al.* (1998). The non-linear relationship indicates that other factors such as temperature and soil type are also major drivers of N_2O emissions (Smith *et al.* 2003).

To identify the other factors that may have affected N_2O emissions, a statistical test was performed using the "least squares" method to calculate a straight line between emissions and input data of total annual rainfall, N uptake, N fixation by leguminous crops, SOC, atmospheric N deposition ($NH_4^+ + NH_3$) and N fertiliser. The results of the statistical test showed that SOC, N input due to fixation and N uptake were significant factors in N_2O-N emissions producing an r^2 value of **0.67**. The statistical test results could be used to create a simple regression equation using the significant factors to estimate emissions of N_2O-N due to N fertiliser. Such a simplified regression equation would be an improvement on the IPCC methodology that just relates emissions to N input.

An emission factor relating N_2O emissions to mineral N application was calculated for each NUTS region. Figure 6.13 shows that the majority (**59%**) of the DNDC modelled emission factors were between 0.01 and 0.0125 (the IPPC default emission factor), while **78** % of the modelled factors were between the IPCC ranges of 0.0125 ± 0.01 (see Figure 6.13). The estimated fractions that fall outside the IPCC range can be of use in identifying sites where further investigation is required, either through more detailed (smaller scale) scale modelling or actual measurement campaigns.

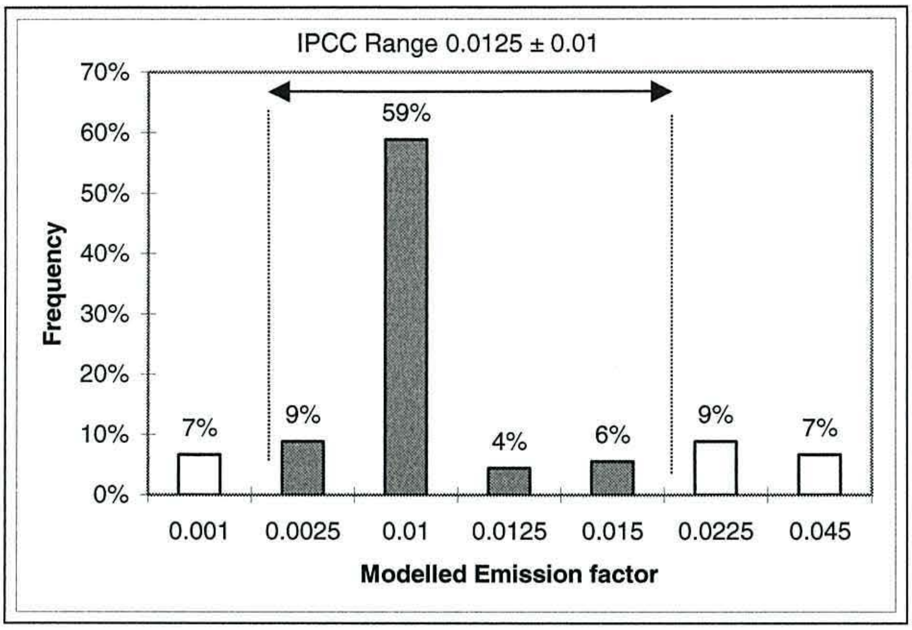


Figure 6.13. Frequency analysis of mean DNDC modelled emission factors (kg N_2O-N kg^{-1} N input) for 103 regions within Italy.

Using the DAISY model, Leip (2000) estimated N_2O emission factors to range from 0.0021 to 0.0041 in Bovolenta and 0.010 to 0.012 for a site in Barboni (both in the Po valley, in the north of Italy). Studies in Cadriano, Italy carried out in 1996 by the Ministerio dell'Ambiente, (1998), reported emission factors between 0.004 and 0.020 within the range of the IPCC methodology

The DNDC modelled N_2O emissions did not always decrease when mineral fertiliser was not applied, contrary to other findings (Dobbie *et al.* 2003). In **5**% of the mean emission estimates produced by the DNDC model, no decrease or an increase in N_2O emissions were recorded. Over the whole of Italy, this increase amounted to **280** t N_2O-N yr^{-1} (**0.6** % of the mean N_2O-N emission total for Italy). The largest increases in N_2O-N emissions (**84** t N_2O-N yr^{-1}) were estimated on pastureland in the Bolzano region in the alpine zone of north Italy. An area dominated by pasture with a climate of high rainfall.

To investigate why the DNDC model recorded increases in N_2O emissions from pasture with no fertiliser applied, a series of simulations using the DNDC field scale model were undertaken. Scenarios of mineral N fertilisation application rates of 15 kg N ha^{-1} yr^{-1} and no mineral N fertiliser application were undertaken for pasture in the Bolzano region. The remaining input data for the field scale runs were derived from the regional GIS database created by this study for Italy.

The results showed that the total amount of NO_3^- leached from the top soil was reduced from **17.6** kg N ha^{-1} yr^{-1} to **2.5** kg N ha^{-1} yr^{-1} when mineral N fertilizer was removed, which is consistent with the reduction of fertiliser inputs. However, N_2O emissions increased from the fertilised scenario to the non-fertilised scenario from **1.25** to **1.53** kg N_2O-N ha^{-1} yr^{-1} respectively. If the plant growth is depressed by N deficiency, the plant demand for water will decrease (C. Li, *pers. comm.* 2003). This could in turn alter the soil moisture regime and hence elevate N_2O production (Ball *et al.* 1999). A slight increase in soil moisture from the fertilised scenario to the non-fertilised scenario was recorded for the later part of the year but this does not explain the increase in peak emissions.

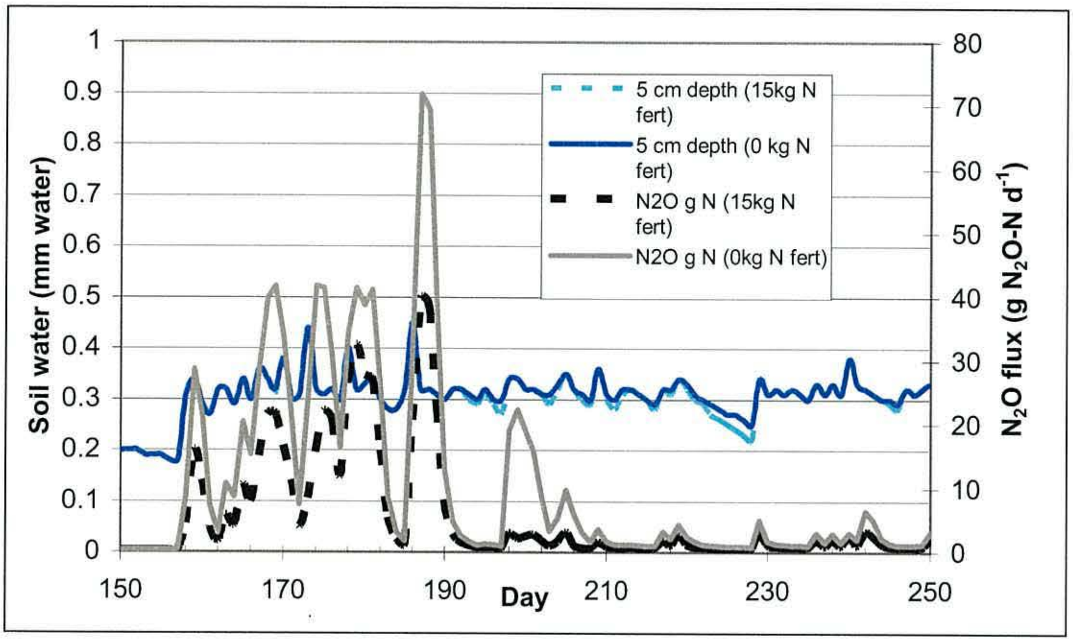


Figure 6.14. DNDC modelled N_2O and soil moisture content (at 5 cm depth) estimations for Bolzano, Italy.

The simulations represent two field scale runs for Bolzano either with mineral fertiliser additions of 15 kg N ha^{-1} or zero N fertiliser scenarios.

The increase in emissions under the 'no fertiliser scenario' for pasture sites highlights the uncertainties in the model and its ability to model real processes in soils under extreme conditions. Further investigation through measurements of emissions and soil processes (soil moisture, temperature) are therefore required to validate the DNDC modelled estimates. The results also highlight the uncertainties in the definition of what constitutes fertilised pasture or forage and how much is actually fertilised and at what rate. Definitions of pastureland vary significantly between datasets. These results also bring into question uncertainties in the methodology of using the difference between using zero fertiliser and fertilised scenarios to calculate emissions due to mineral N fertiliser. A more detailed approach that uses finer divisions between the maximum and zero fertilised rate may produce better results.

6.2.2 *Emissions due to animal wastes (organic manure) applied to soils*

The methodologies used to estimate N_2O emissions due to application of organic manure are described in Table 6.8. The DNDC model produced a mean N_2O emission estimate of **5,420** t N_2O-N yr^{-1} for Italy whilst the IPCC methodology produced an estimate of **4,370** t N_2O-N yr^{-1}.

Table 6.8. DNDC and IPCC methodologies used to estimate N_2O-N emissions arising from manure application in Italy.

Modelled methodology:
N_2O-N(m) = N_2O(b) – N_2O(zm)
where:
N_2O-N(m) = N_2O-N emission due to manure application
N_2O-N(b) = N_2O-N emission IT baseline scenario
N_2O-N(zm) – N_2O-N emission zero fertiliser scenario.
IPCC methodology:
N_2O-N = [Total manure N - ($FRAC_{gasm}$)] x 0.00125
where:
FRACgasm = 0.38

Within Italy, modelled N_2O emissions due to manure N were higher than emissions due to mineral N fertiliser, concurrent with the findings of Velthof *et al.* (2003). However, Velthof *et al.* (2003) found that N_2O emissions from manure were highly dependent on the type of manure applied, particularly to the contents of inorganic N and easily mineralisable N, such as liquid pig manure. The version of the DNDC model used in this study could not differentiate between the types of manure applied.

Total manure applied in Italy for 1997 was **563,238** t N yr^{-1}. The default IPPC fraction ($FRAC_{gasm}$ = 0.38) was used to estimate NH_3 and NO_x volatilised from total manure, producing a total emission of **214,030** t N yr^{-1}. In contrast the modelled emission estimate of NH_3 and NO_x volatilised from total manure was **39,000** t N yr^{-1}. A plot of the DNDC modelled emission estimates of N_2O due to manure against the portion of manure after volatilisation shows an emission trend (by linear regression) of **0.0099** (kg N_2O-N kg^{-1} N input) with a high r^2 value of **0.675** (see Figure 6.15). This value is close to the IPCC emission factor of 0.0125. The very narrow range (closeness to the trend line) between the minimum and maximum estimates indicates that N_2O emissions due to N manure are far less affected by the large range of SOC input data than emissions due to mineral N fertiliser.

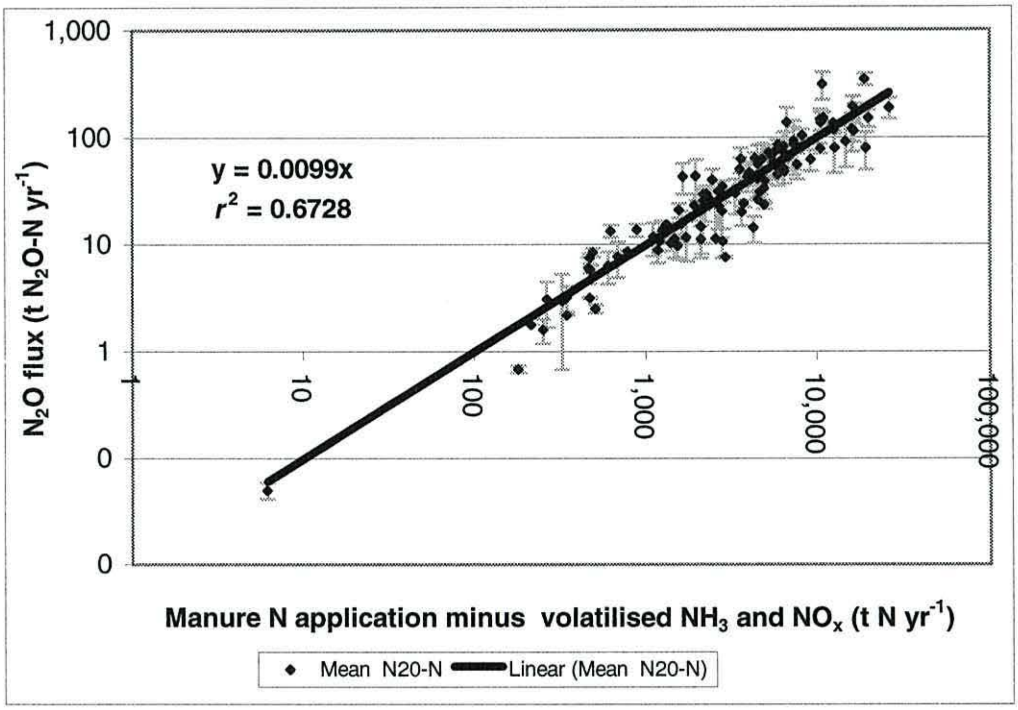


Figure 6.15. Mean N_2O-N emissions (t N yr^{-1}) plotted against manure N application (t N yr^{-1}) for Italy as predicted with the DNDC model.

Error bars indicate the range of values due to high and low SOC. Each point represents a geographic region within Italy.

The soil processes, and thereby N_2O emissions, are affected in a very different way by organic manure application than by mineral N fertiliser addition. The organic carbon content of the manure must firstly undergo decomposition before it can release inorganic N into the soil. This therefore regulates to some extent the subsequent rates of nitrification and denitrification processes operating in the soil, which determine the amount of N_2O produced. The DNDC decomposition/mineralisation sub model uses a decomposition rate for organic manure that is determined by the C/N ratio of the manure and the soil conditions (temperature, moisture, Eh, and N availability etc.). If the organic manure possesses a low C/N ratio, there will be a delay in N_2O emissions of several days or weeks after the application of manure. However, if the organic manure has a high C/N ratio, the decomposition of the manure may consume more soil free N that would result in a reduction of N_2O emissions (C. Li. *pers. comm.* 2004).

6.2.3 Emissions due to nitrogen fixing crops

The N_2 fixing properties of crops in the DNDC model are controlled by an N_2 fixation factor in the crop characteristic library. The default index is one, whereas soybean for instance has an N fixation index of two. Changing the N fixation indices to zero in the DNDC crop library gave unsatisfactory results that could not be used to determine the emissions due to N fixing crops. Therefore, the estimated N_2O emissions from the N fixing crops of soybean and pulses were taken from the IT baseline scenario (described in section 6.1.2), giving a total estimation of **2,380** t N_2O-N yr^{-1} for Italy. In contrast, the IPCC methodology, where N_2O emissions from N_2-fixing crops are related to the N fraction content ($FRAC_{NCRO} = 0.03$) of the total harvested biomass of N fixing crops (see Table 6.9), gave an estimation of **622** t N_2O-N yr^{-1}.

Table 6.9. DNDC and IPCC methodologies used to estimate N_2O-N due to N_2 fixing crops in Italy.

Modelled methodology:
N_2O-N = N_2O-N emission from N fixing crops in IT baseline scenario
IPCC methodology:
N_2O-N = 2 x harvested crop biomass of soybean and pulses x ($FRAC_{ncro}$) x 0.0125
where:
$FRAC_{ncro}$ = 0.030

A plot of the modelled N_2O-N emission estimates (see Figure 6.16) due to N_2 fixing crops against N content of the total biomass (**3,745** t N yr^{-1}) gives a very high r^2 value of **0.9** that indicates a good relationship between modelled N_2O-N emissions and the total N content of total N fixing crop biomass. However, the emission factor of **0.064** is significantly higher than the IPCC factor of **0.0125**. The IPCC good practice guidelines recognises that the factor of two used to multiply the harvested biomass is much too low for pulses and soybeans, and additionally leguminous fodder crops such as alfalfa should be taken into account (Smith *et al.* 2000b).

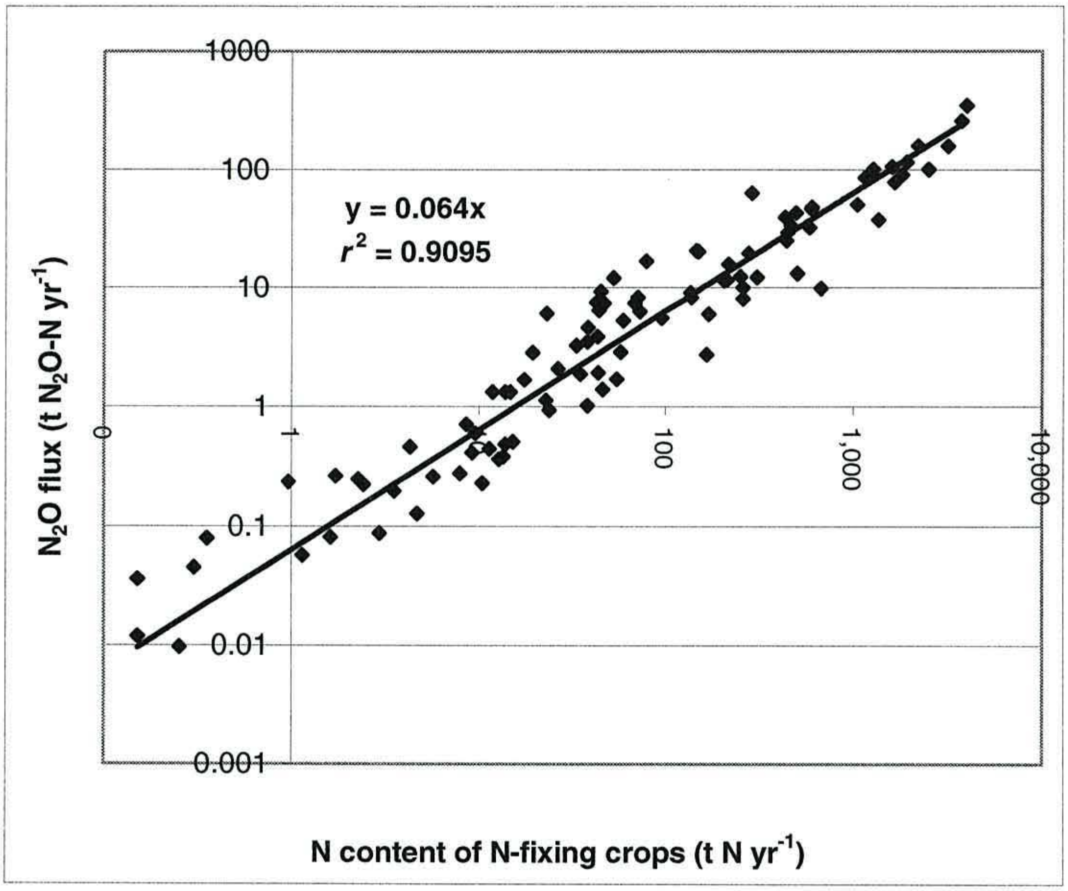


Figure 6.16. N_2O-N emission estimates from N fixing crops (Soybean and Pulses) against total N content of these crops for Italy as predicted with the DNDC model.

Each point represents a geographical region within Italy.

6.2.4 Emissions due to incorporation of crop residue

The methodologies used to estimate N_2O emissions due to incorporation of crop residues are shown in Table 6.10. The IPCC methodology relates N_2O due to incorporation of crop residue into the soils using a default fraction (FRACr = 0.45) of crop residue removed from the field. In reality the percentage of crop residue incorporated varies greatly between crops and regions. However, due to the lack of crop residue data for Italy, the DNDC model was run using the model's default crop residue incorporation fraction of 0.2. The model initiates a year run by incorporating

0.2 of the previous years crop into the soil, which in this study was the same as the modelled crop as the previous crop rotation was unknown.

Table 6.10. DNDC model and IPCC methodologies used to estimate N_2O-N emissions arising from crop residue incorporation into the soil.

Modelled methodology:
N_2O-N(cr) = mean N_2O(b) - N2O(zcr)
where:
N_2O-N(b) = N_2O-N emission baseline scenario
N_2O-N(zcr) = N_2O-N zero crop residue scenario
IPCC methodology:
N_2O-N = 2 x harvested crop x N content (1.5%) minus harvested parts (45%) minus fraction of crop residue burnt (10%) minus fraction used a biofuels x 0.0125

The DNDC modelled N_2O-N emissions due to crop residue was estimated to be **2,490** t N for Italy compared to the IPCC estimate of **8,500** t N as shown in the Table 6.8. Even accounting for the difference in fractions of crop residue incorporated, the DNDC model under-estimates N_2O emissions due to crop residue incorporation in comparison to the IPCC methodology.

Log plots (see Figure 6.17) of DNDC modelled N_2O-N emissions against N fraction of the total crop residue incorporated produced an emission trend of 0.014 compared to the IPCC default factor of 0.0125 (kg N_2O-N kg yr^{-1}). However, the r^2 value of 0.49 indicates a poor relationship between N_2O-N emissions and the total N fraction of crop residue incorporated. This agrees with the findings of Velthof *et al.* (2002) that although incorporation of crop residues can be a potentially important source of N_2O, they are poorly quantified.

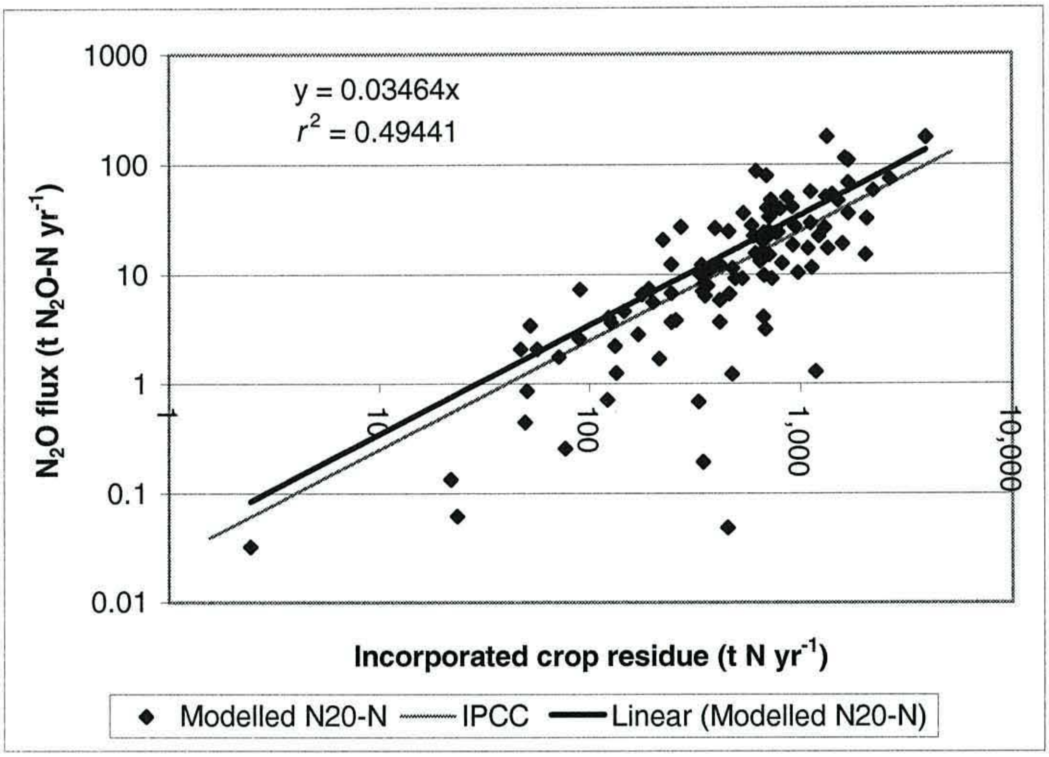


Figure 6.17. DNDC predicted N_2O-N emissions (t N yr^{-1}) plotted against incorporated crop residue N (t N yr^{-1}).

Each point represents a geographical region within Italy. The trend line shown in black is derived from the DNDC model data while the IPCC methodology estimate is shown in blue.

6.3 Indirect emissions from agricultural soils in Italy

Indirect emissions are classified by the IPCC as emissions due to the fraction of manure and fertiliser volatilised as NH_3 and NO_x (EF4) and emissions due to nitrogen leached to groundwater, rivers or estuaries (EF5). Although, DNDC is primarily designed to model direct N_2O emissions, the model does estimate values of N leached from agricultural soil. However, the DNDC model does not give an estimate of N_2O emissions due to the amount of N leached. The DNDC modelled fraction of N leached was compared with the IPPC methodology.

6.3.1 Emissions due to N leached

The total amount of nitrate leached from the topsoil (30 cm) was estimated by the DNDC model as **484,000** t N yr^{-1} from an initial total N input of **1,228,000** t N (mineral N fertiliser and organic manure). Linear regression of the N leaching estimates against total N fertilizer and manure gives a trend leaching factor of **0.32** as shown in Figure 6.18. The low r^2 value of **0.32** is an indication of the non-linear relationship between N leached and total application of mineral N fertiliser and manure N fertiliser. The IPCC methodology uses a default-leaching fraction ($Frac_{leach}$) value of **0.3**. The frequency distribution of the N leached results, shown in Figure 6.19, clearly illustrates that the predicted fraction as a proportion of the N input varies considerably from the 0.3 IPCC factor. From this result, it can be inferred that the rate of N leaching is affected by localized conditions (i.e. soil type or climate) and not solely by the amount of N applied to soils.

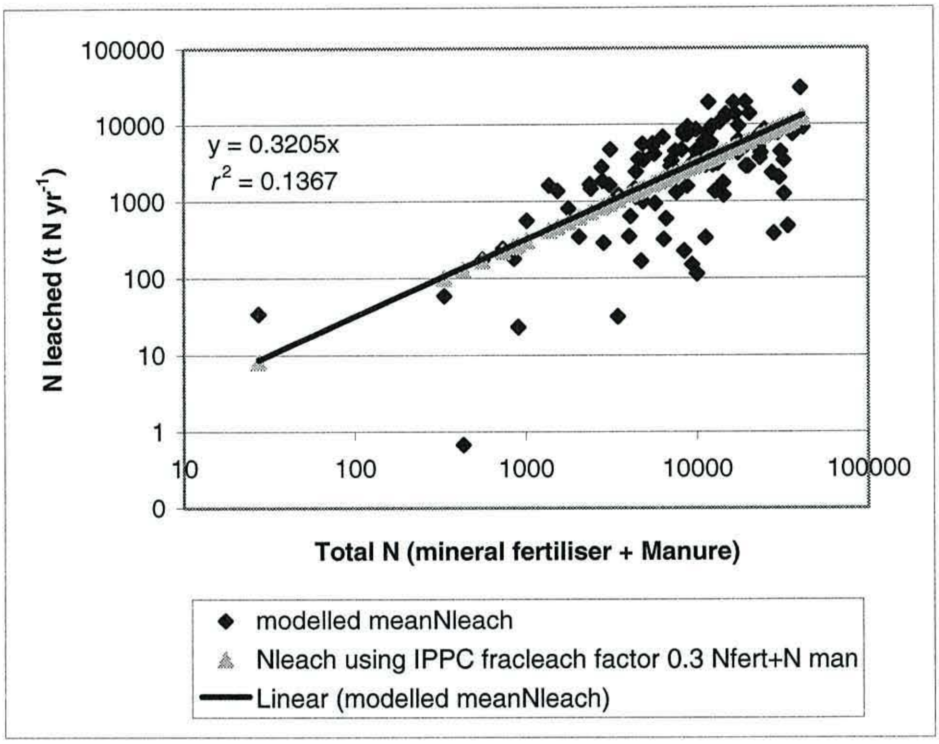


Figure 6.18. Fraction of manure and fertiliser leached as a proportion of the total N input as predicted with the DNDC model. Each point represents a region within Italy.

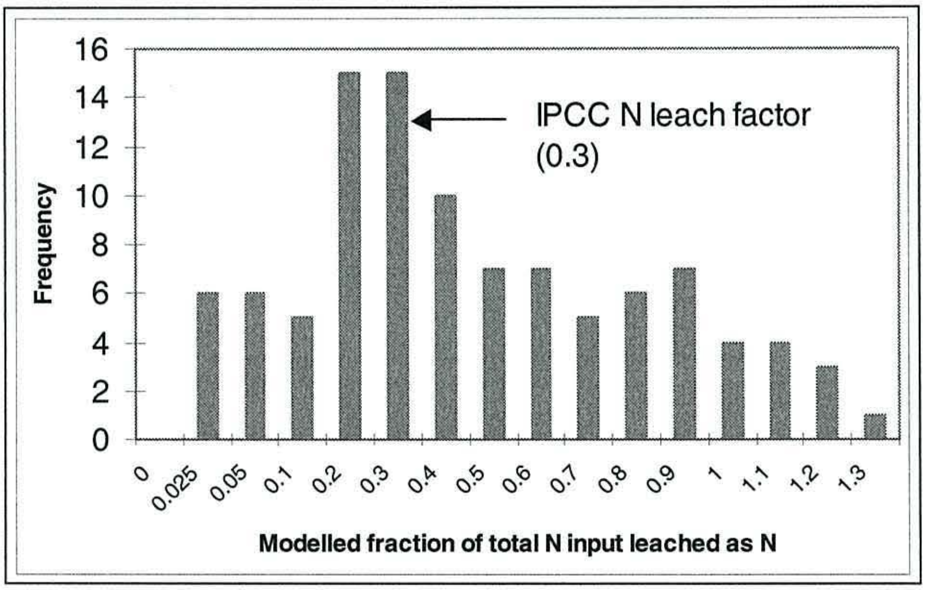


Figure 6.19. Frequency distribution of modelled N leach factors as predicted with the DNDC model. The default IPCC value is also shown.

6.3.2 *Emissions due to atmospheric deposition*

The IPCC methodology bases its estimate of N_2O emissions due to atmospheric deposition of N, on the fraction of mineral N fertiliser and organic manure volatilised as NH_3 and NO_x and re-deposited on nearby soil using the methodology shown in Table 6.11.

Table 6.11. Methodologies used to estimate N_2O-N due to atmospheric deposition.

Modelled methodology:
N_2O-N(ndep) = mean N_2O(b) - N_2O(zndep)
where:
N_2O-N(b) = N_2O-N emission baseline scenario
N_2O-N(zndep) = N_2O-N zero N deposition
Modelled estimation of NH_3 and NO_x volatilised from manure and N fert
FracGASF = NH_4(b)+NO_x (b) - (NH_4(zf)+NO_x(zf)
FracGASM = NH_4(b)+NO_x (b) - (NH_4(zm)+NO_x(zm)
IPCC methodology:
N_2O-N = [(Nfert x fraction volatilised) + (manure x fraction volatalised) x 0.01

In contrast, the DNDC model takes into account atmospheric wet deposition of NH_4^+ and NO_3^- in ppm linked to the rainfall input (see Section 5.4). The DNDC modelled estimate of N_2O-N due to atmospheric N deposition of NH_4^+ and NO_3^- was **1,200** t N_2O-N yr^{-1}. In contrast, the IPPC methodology gave an estimate of atmospheric deposition related emissions of **2,800** t N_2O-N yr^{-1}. The modelled estimate of wet deposition N plotted against atmospheric deposition of NH_4^+ and NO_3^- is shown in Figure 6.20. The extremely low r^2 value indicates a poor relationship between atmospheric N deposition and N_2O emissions.

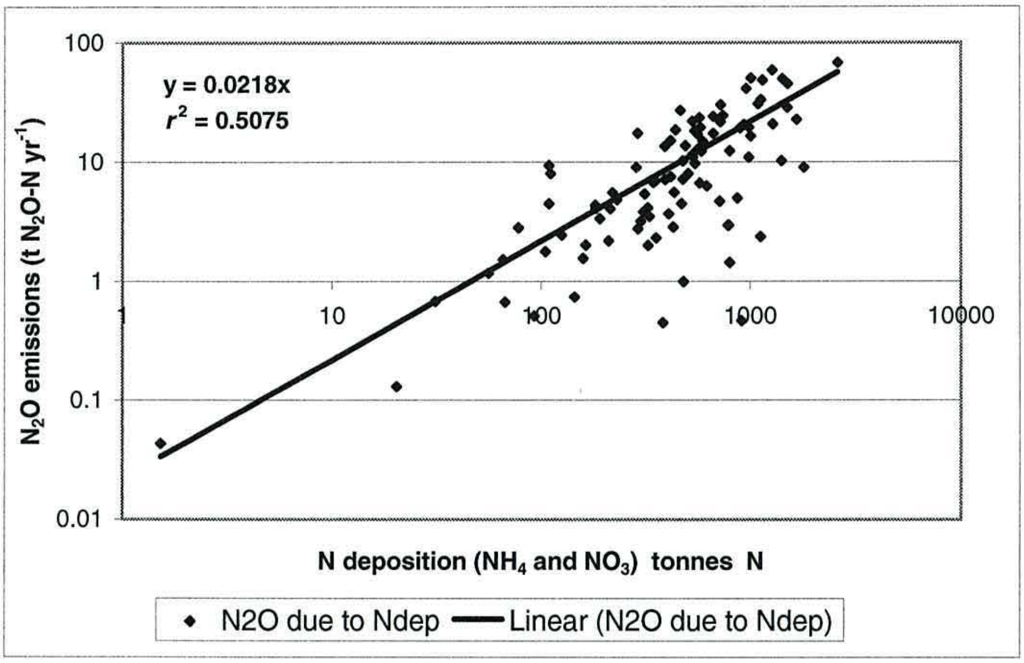


Figure 6.20. Estimated emission of N_2O-N due to wet N deposition of NH_4 and NO_3 as predicted with the DNDC model.

Each point represents a region within Italy

6.3.3 Inventory report of N_2O emissions from agricultural soils

Using the results described in sections 6.2 and 6.3, a spreadsheet was created in the style of the IPCC inventory report for article 4 emissions (see Figure 6.21). All results are displayed in the molecular weight of Gg N_2O (N_2O-N x 44/28). The IPCC emission estimates have been calculated using the same input values as the modelled estimates. The spreadsheet clearly shows the differences between the two methodologies, with the most significant difference occurring between the estimates of background emissions. Animal production is not taken into account by this study, as this estimate is purely a statistical estimate based on livestock population data.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Description N input to soils (kg N.yr)	Modelled Value	IMPLIED EMISSION FACTORS Unit		IPCC (Gg N_2O)	Model (Gg N_2O)
Direct Soil Emissions					**22.431**	**23.575**
Synthetic Fertilizers	Use of synthetic fertilizers - (vol frac) (kg N/yr)	**666,384,408**	(kg N2O-N/kg N)	0.0125	**11.781**	7.504
Animal Wastes Applied to Soils	Nitrogen input from manure applied to soils -(volfrac) (kg N/yr)	**563,238**	(kg N2O-N/kg N)	0.0125	**6.859**	8.522
N-fixing Crops	Dry pulses and soybeans, fodder roots and leguminous hay produced (kg dry biomass/yr)	**1,245,094,138**	(kg N2O-N/kg dry biomass)	0.0125	**0.978**	3.7
Crop Residue	Dry production of other crops (kg dry biomass/yr)	**8,274,387,700**	(kg N2O-N/kg dry biomass)	0.0125	2.700	3.802
Cultivation of Histosols	Area of cultivated organic soils (ha) CRF-ITA2001	*9000*	(kg N2O-N/ha)	8.0	0.113	n/d
Other modelled sources						
Nitrogen Deposition	Modelled (NH4 + NH3) dep	**58,258,076**	(kg N2O-N/ha)			1.921
Background	Modelled N_2O not accounted for					48.065
	Total crop area	11,570,102	(Kg N2O-N ha)	1	**11.570**	
Animal production	N excretion on pasture range and paddock (kg N/yr)	*224,539,606*	(kg N2O-N/ha)	0.020	7.057	*n/d*
Indirect Emissions					**14.394**	**19.213**
Atmospheric Deposition	Volatized N (NH_3 and NOx) from fertilizers and animal wastes (kg N/yr)	**44,465,556**	(kg N2O-N/kg N)	0.01	***3.363***	0.70
		214,030,486				
Nitrogen Leaching and Run-off	N from fertilizers and animal wastes that is lost through leaching and run off (kg N/yr)	**471,279,228**	(kg N2O-N/kg N)	0.025	***11.031***	18.51
	IPCC methodology (0.3)	*280,785,842*		Total	**48.396**	**90.853**

Figure 6.21. Comparison of IPCC emissions with modelled emissions in the IPCC format. Results are shown in Gg N_2O.

6.4 Background emissions

In Section 6.2 the DNDC model was used to estimate N_2O emissions from direct sources in accordance with the IPCC methodology. The DNDC modelled baseline estimate used to calculate emission estimates from direct sources also includes N_2O from background sources that can be attributed to mineralisation of SOC. The DNDC model was developed to simulate N_2O fluxes produced by nitrification and denitrification as well as by decomposition. The decomposition sub-model of DNDC provides the initial status of available NO_3^- and soluble carbon pools required for the initialisation of the denitrification process (Li *et al.* 1992)

Background emissions of **28,500** t N_2O-N yr^{-1} were calculated by removing the DNDC modelled N_2O emissons attributed to direct sources from the total of N_2O emissions in the baseline scenario estimate (see Table 6.12). The DNDC modelled estimate of background emissions exceeds that attributed to direct sources. Van Beek *et al.* (2004) found N_2O losses originating deeper than 20 cm below the soil surface of a peatland were not wholly related to the total N input of mineral fertiliser but to an almost equal amount of N attributed to the mineralisation of peat. Flessa *et al.* (1998) observed higher N_2O emissions from an unfertilised meadow on peatland, where cultivation practices enhanced mineralisation. However, Flessa *et al.* (2002a) also observed that in some sites with no N input background emissions were significantly lower than emissions from fertilised soils. Brown *et al.* (2002) ran the DNDC model for the UK and estimated background N_2O emissions of 33,800 t N_2O-N yr^{-1} against a total estimate of 50,900 t N_2O-N yr^{-1} from agricultural practices.

Brown *et al.* (2002) inferred that the background component was partly the result of hitorical landuse, and that if background emissions were included in the IPCC inventory, the total N_2O emission for the UK would increase to 78,300 t N_2O-N yr^{-1}.

Background N_2O emissions cannot be considered completely natural or independent of anthropogenic influence. Emissions of N_2O from the soils can be affected by the historical land-use of the site. Long-term land use such as N application or cultivation may have enhanced the SOC available for mineralisation and subsequently N_2O emissions (Mogge *et al.* 1999).

Table. 6.12. N_2O emission estimates from direct and background sources for Italy calculated using the DNDC model.

Emission Source	Emission estimate (t N_2O–N yr^{-1})
Mineral N fertiliser	4,700
Organic N manure	5,420
N fixation by crops	2,380
Incorporation of Crop residue	2,490
Atmospheric deposition	1,200
Total direct sources	16,190
Total Modelled Emission Estimate (baseline scenario)	44,700
Background (N_2O not accounted for in baseline scenario)	28,510

6.5 European results

European estimates were undertaken using the pan-European database including the disaggregated New Cronos crop data and the 1:1 M PTR soil database as described in chapter 5.

The DNDC modelled N_2O emission estimates from 1050 regions in Europe for all crops ranged from 0.28 to 39.61 kg N_2O-N ha^{-1} yr^{-1} (see Table 6.13). The range in N_2O emission measurements reported by IFA/FAO (2001) was 0.01 to 56.4 kg N_2O-N ha^{-1} yr^{-1}). The mean DNDC modelled N_2O emission estimate was 7.55 kg N_2O-N ha^{-1} yr^{-1} whilst the median was 4.16 kg N_2O-N ha^{-1} yr^{-1}.

Table 6.13. DNDC modelled N_2O emission statistics.

Mean	7.55
Standard Error	0.23
Median	4.16
Standard Deviation	7.57
Range	39.33
Minimum	0.28
Maximum	39.61

The frequency distribution of modelled N_2O emission estimates is shown in Figure 6.22. These results indicate that the majority of emissions are low but there are a few high emissions that increase the mean emission estimate to 7.55 kg N_2O-N ha^{-1} yr^{-1}. Using the IPCC methodology based on N input alone Boeckx and Van Cleemput (2001) estimated a range of N_2O emissions per ha agricultural land for European countries between 1.7 and 14.2 kg N_2O-N ha^{-1} yr^{-1}.

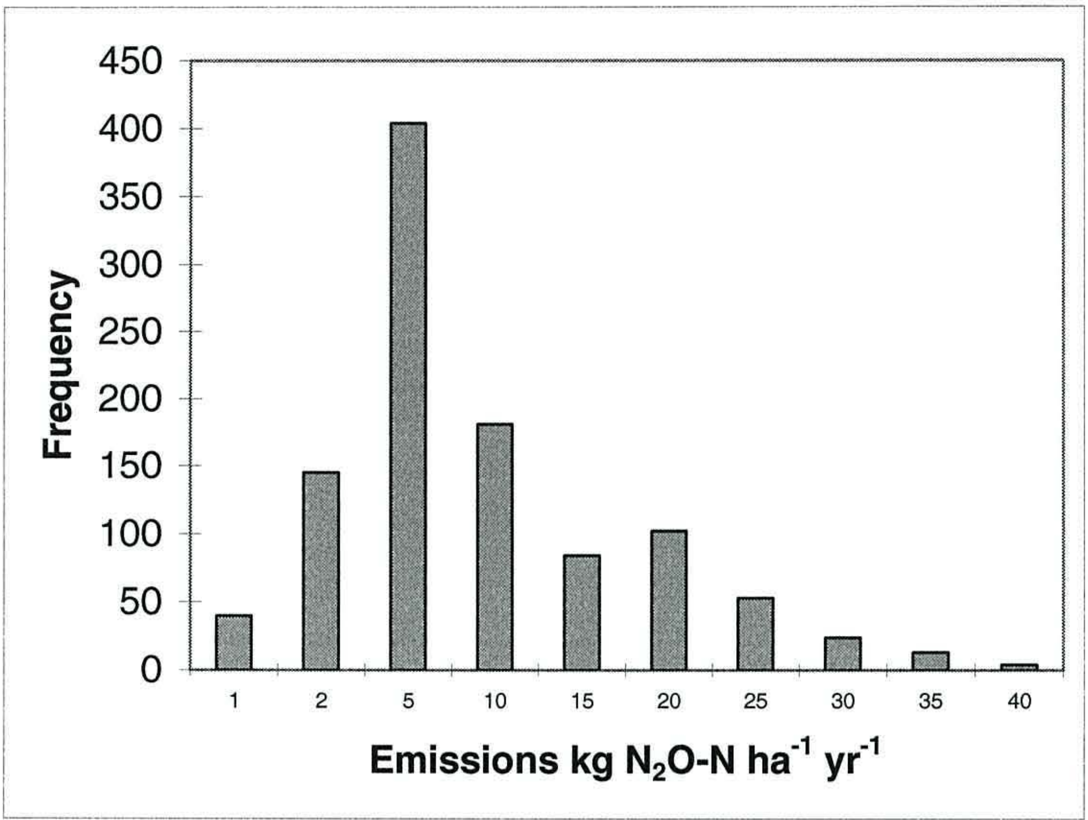


Figure 6.22. Frequency distribution of DNDC modelled N_2O emissions for 1050 regions across Europe.

Four percent of the modelled N_2O emissions results (44 out of 1050 NUTS 3 regions) were over 20 kg N_2O-N ha^{-1} yr^{-1}, with all the high emissions occurring on soils with a high mean SOC value (see Figure 6.23). The IFA/FAO (2001) dataset recorded high N_2O-N emission greater than 20 kg N_2O-N ha^{-1} yr^{-1} also on organic soils These results compare favourably with the findings of Van Beek *et al.* (2004), Bareth *et al.* (1999), Flessa *et al.* (1998) and Mogge *et al.* (1999).

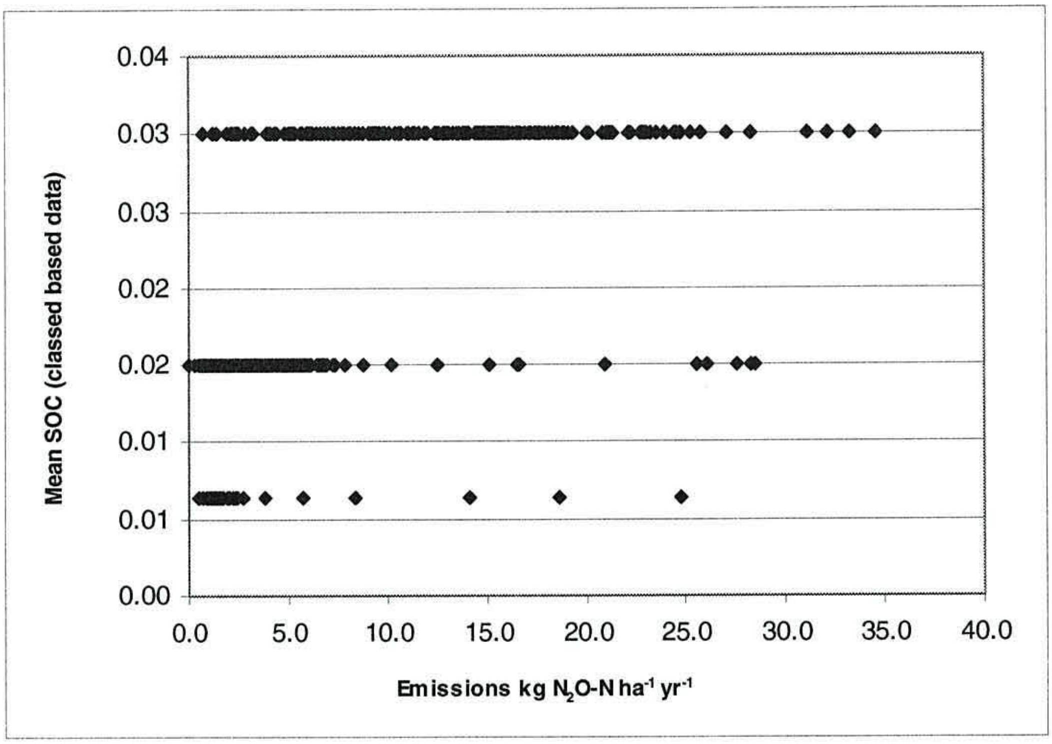


Figure 6.23. Correlation between modelled N_2O emissions (kg N_2O-N ha^{-1} yr^{-1}) and mean SOC derived from class based PTR data.

The DNDC modelled N_2O emission estimates (kg N_2O-N ha^{-1} yr^{-1}) per NUTS level 3 for Europe from all crops are displayed in Figure 6.24a. A more spatially representative distribution is also shown Figure 6.24b using a CORINE agricultural land cover mask. Masking off non-agricultural land cover shows how sparse agriculture actually is in the north of Finland and Scotland, UK. Whilst these regions possess soil conditions that may be conducive to high N_2O emissions the low intensity of agriculture reduce the relative total contribution to European emissions.

The high DNDC modelled emissions for Italy follow a similar spatial pattern of the N_2O emission estimates based on the Italian national scale data, as described in section 6.1. DNDC modelled N_2O emissions are high in the south of Italy in an area characterised by intensive, permanently irrigated agricultural land, under relatively hot conditions that are conducive to high rates of denitrification.

Estimated N_2O-emission rates (kg N ha^{-1} yr^{-1}) for some of the major crops in Europe estimated at the NUTS level 3 are shown in figures 6.25 to 6.30. All of these figures use the same scale to enable direct comparison and show emission results at the NUTS 3 level and not in the land cover scale.

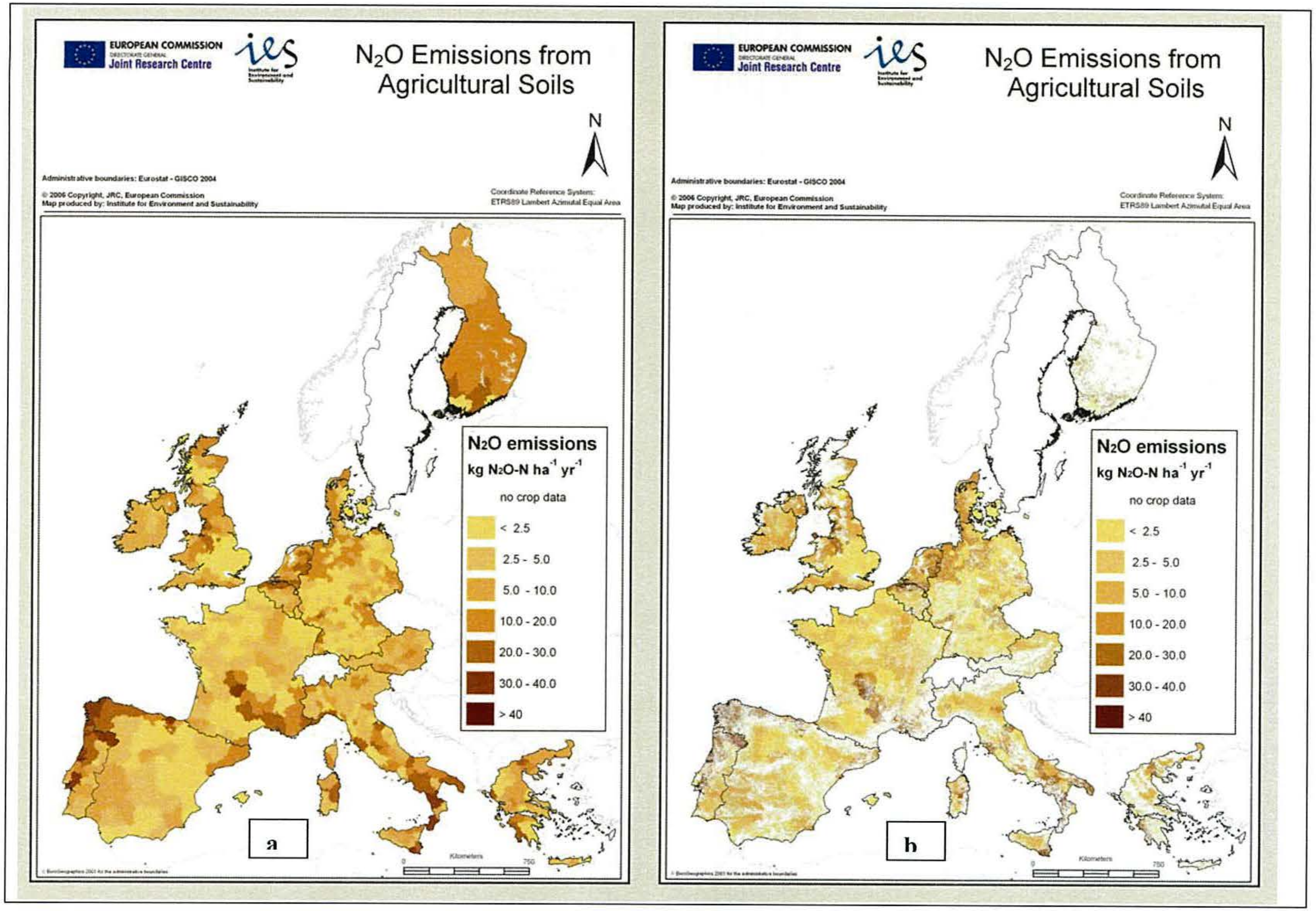


Figure 6.24. DNDC model predicted N_2O emissions for 1050 regions in Europe derived from the average N_2O emissions from all crops by cell (a) and with a non-agricultural land cover mask applied (b).

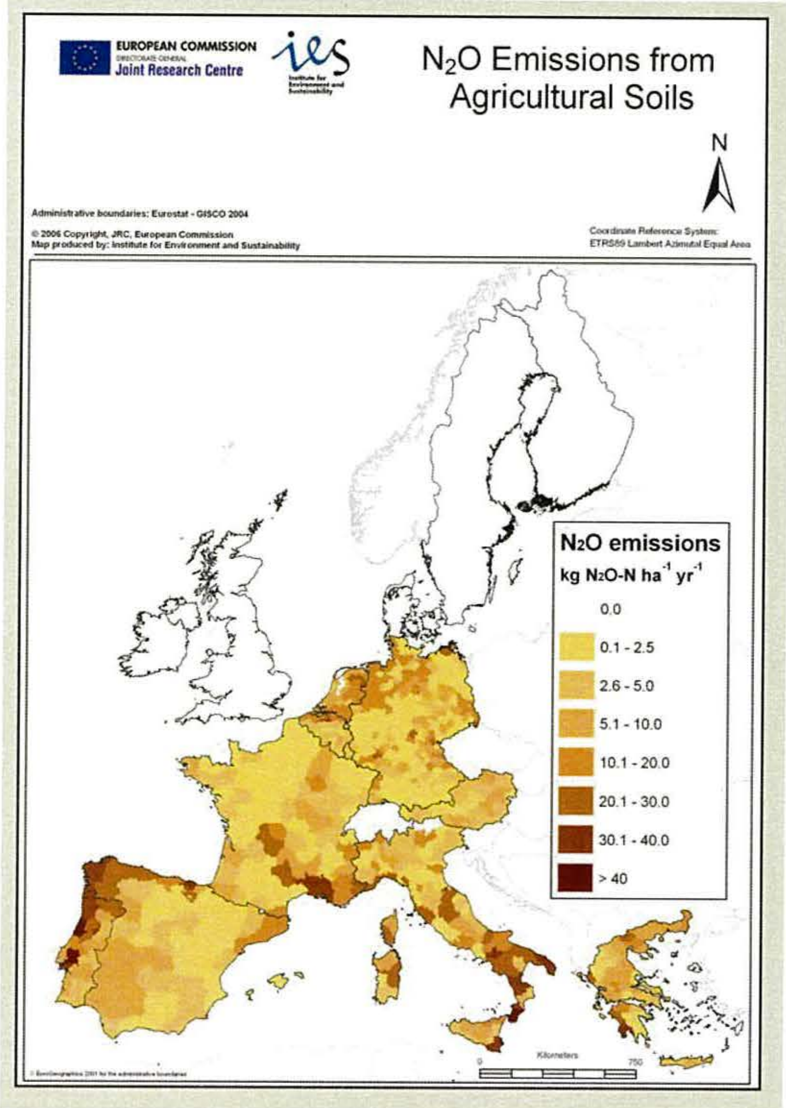


Figure 6.25. DNDC model predicted N_2O emissions from maize.

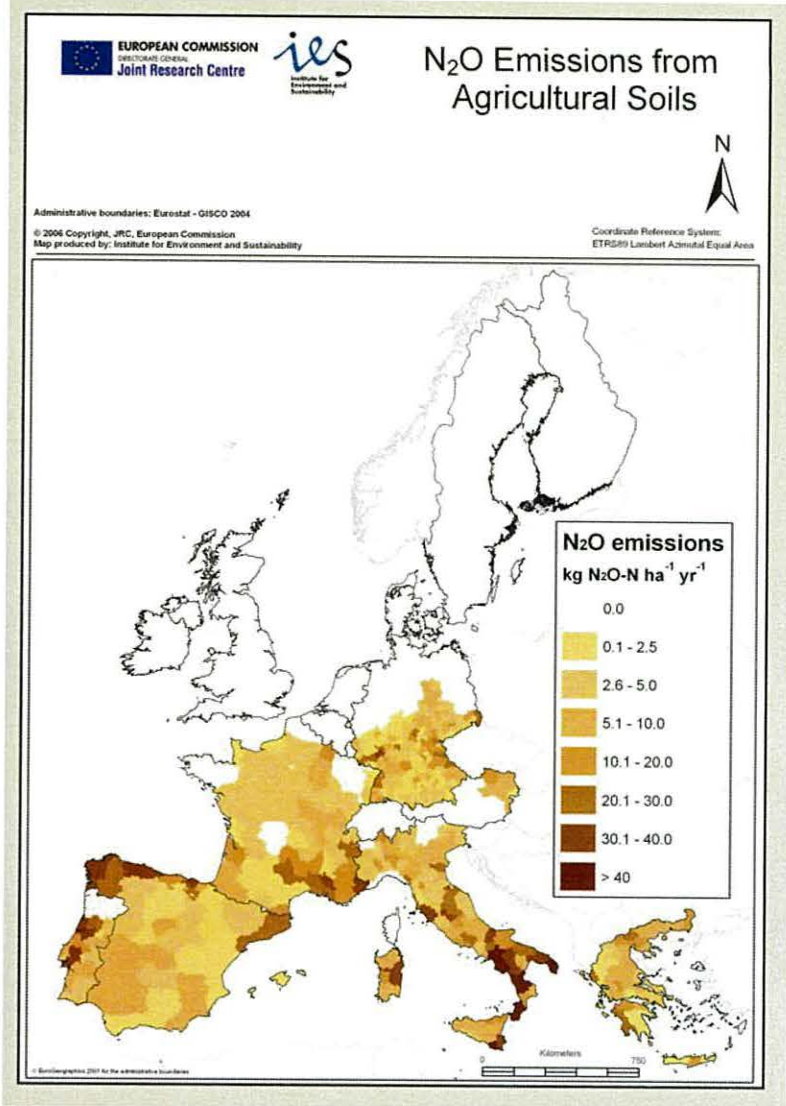


Figure 6.26. DNDC model predicted N_2O emissions from Durum wheat.

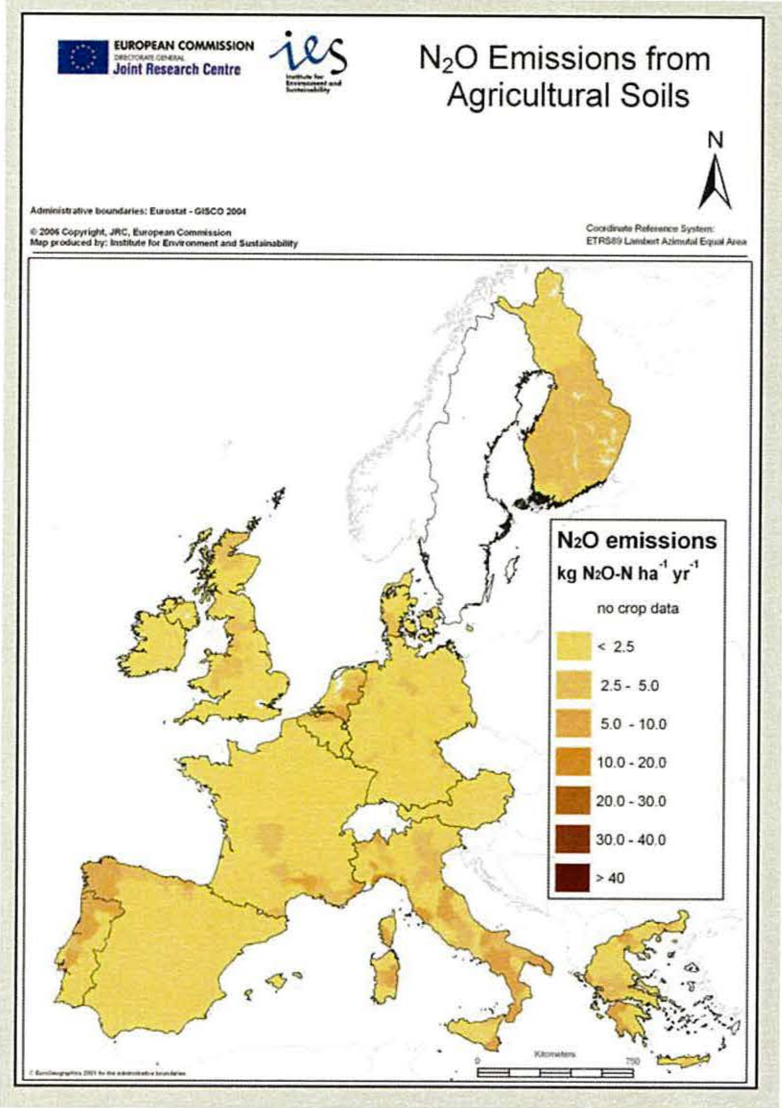


Figure 6.27. DNDC model predicted N_2O emissions from pasture.

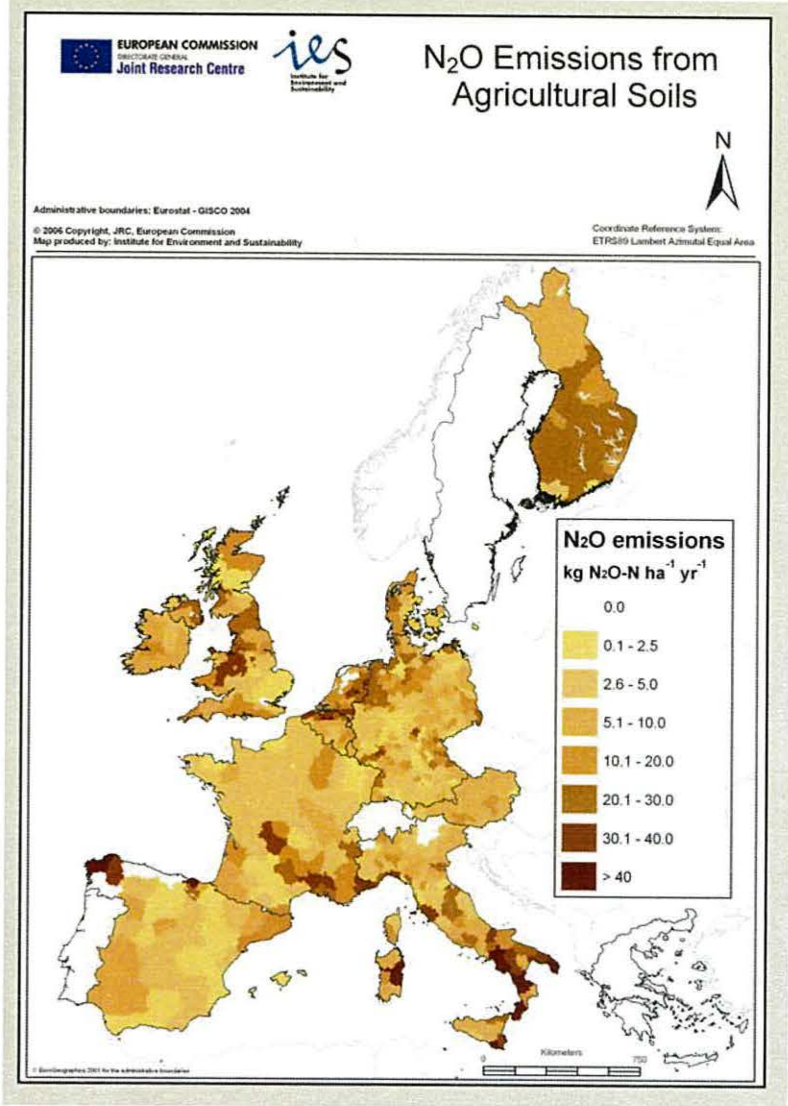


Figure 6.28. DNDC model predicted N_2O emissions from rapeseed.

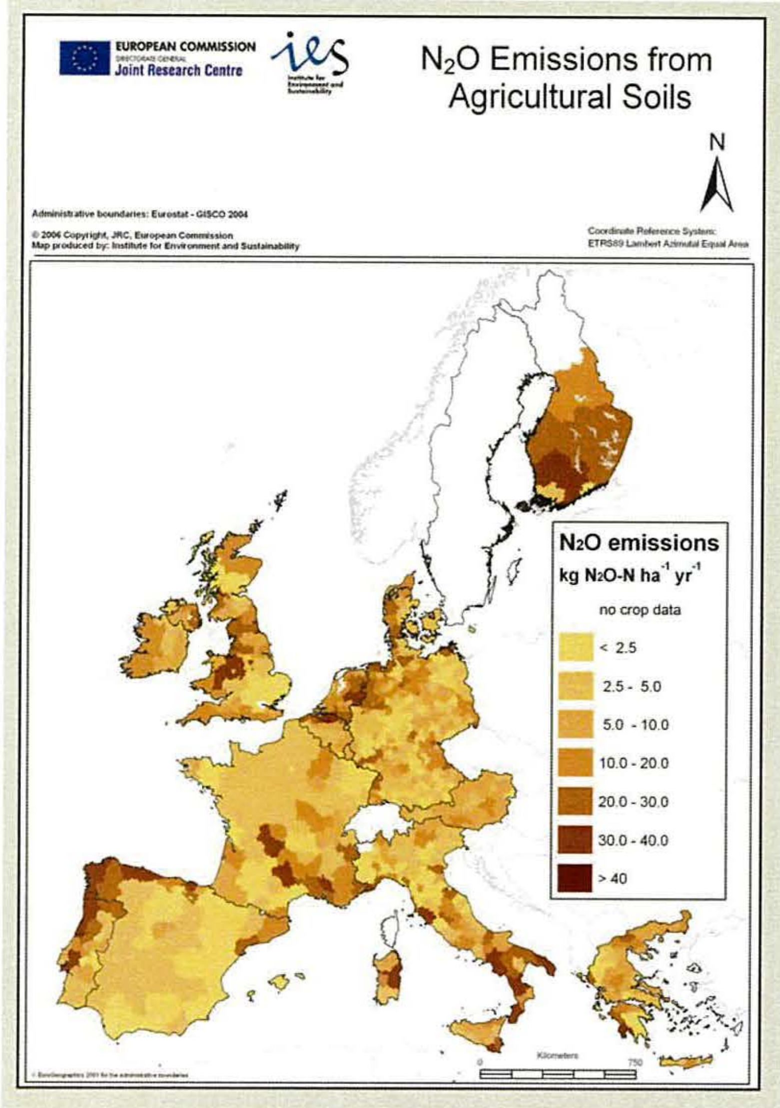


Figure 6.29. DNDC model predicted N_2O emissions from winter wheat.

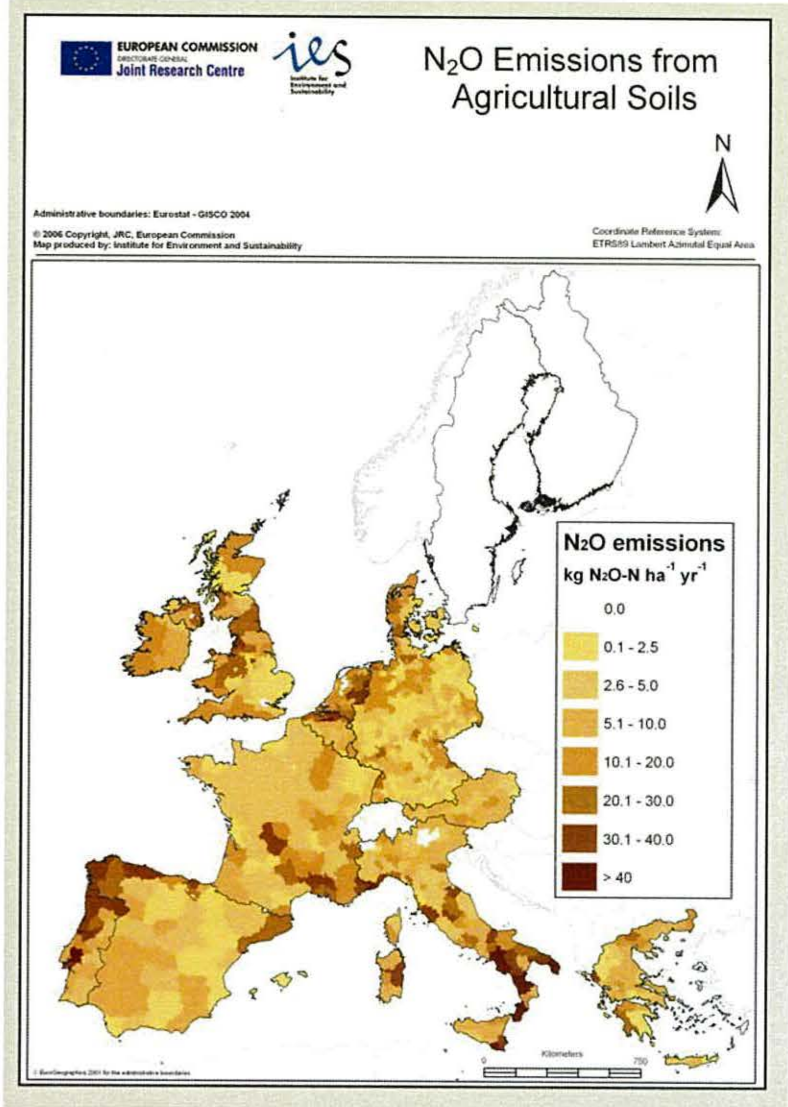


Figure 6.30. DNDC model predicted N_2O emissions from winter barley.

The DNDC modelled N_2O emission estimates from all the crops modelled in each European Union Member State are shown in Table 6.14. This table clearly shows that highest N_2O-N emissions rates occur from rice in Spain, France, Greece, Italy and Portugal with a range of 29.5 to 55.7 kg N_2O-N ha^{-1} yr^{-1}. N_2O emissions from rice fields are strongly related to water management, particularly periods of drainage (Li *et al.* 2004). This study did not have sufficient data on water management of rice field to make a valid estimation of N_2O from rice fields. N_2O-N emissions estimates for pasture were by far the lowest estimates across Europe (see table 6.12) and can be related to the low N fertilisation application rate for pasture derived from the Eurostat data.

Total DNDC modelled N_2O emission are shown in Table 6.15 which indicates that cereal crops cereals make the largest contribution to total N_2O emissions in Europe. The total DNDC modelled N_2O emission rates are strongly related to the agricultural area shown in Table 6.16. Total mineral N fertiliser input is shown in Table 6.17.

Table 6.14. DNDC model N_2O-N emission rates in kg N ha^{-1} yr^{-1} for crops modelled in Europe. "n" indicates no crop modelled.

Crop	AT	BE	DE	DK	ES	FI	FR	GR	IE	IT	LU	NL	PT	UK
Maize	3.9	8.2	5.3	n	8.3	n	5.7	7.8	n	10.0	4.8	10.1	21.7	n
Winter wheat	6.5	12.8	7.3	8.3	7.7	21.5	7.1	8.6	8.3	10.6	8.5	16.7	19.8	12.6
Soybean	5.8	n	n	n	4.7	n	6.7	11.3	n	8.9	7.6	n	n	n
Leguminous hay	6.7	n	6.8	6.6	n	n	n	8.2	n	11.7	10.8	n	n	n
Non leguminous hay	3.0	8.4	5.1	3.8	n	13.5	5.2	9.1	6.0	8.2	7.3	9.0	22.7	7.3
Spring wheat	n	10.7	6.1	6.8	n	15.5	6.1	n	6.1	10.4	8.7	13.6	n	n
Winter barley	6.0	13.0	6.5	8.3	9.5	n	7.7	7.3	8.8	13.7	14.1	17.5	20.9	12.1
Spring Barley	5.6	10.1	6.0	6.2	7.3	15.4	5.5	n	6.0	n	0.0	12.1	n	8.9
Oats	8.5	13.5	5.9	6.4	9.0	15.4	7.2	7.3	8.6	11.1	17.1	15.8	18.7	11.8
Durum wheat	7.3	n	7.1	n	9.3	n	6.7	7.6	n	13.2	18.5	n	16.0	n
Pasture	0.8	2.4	1.1	1.4	1.4	3.1	1.1	2.5	1.5	3.3	3.2	3.2	3.9	1.6
Other cereals	4.9	10.1	n	n	7.3	15.6	5.8	7.2	6.4	12.0	8.5	16.1	19.5	9.5
Cotton	5.6	10.7	n	n	6.9	13.0	5.9	8.2	n	n	0.0	13.4	n	9.4
Rye	9.2	13.1	7.9	7.3	9.4	20.1	7.4	9.4	n	13.7	13.9	15.8	20.6	10.1
Vegetables	5.6	10.2	7.1	7.0	7.4	14.7	5.7	6.4	5.9	10.2	11.9	12.8	18.5	9.1
Dried vegetables	6.1	11.6	7.3	7.0	7.8	14.0	6.2	9.3	5.8	10.3	14.1	13.7	18.6	10.0
Potato	2.1	6.1	3.4	3.7	5.7	12.8	3.6	6.8	4.5	5.8	7.1	7.8	16.0	5.2
Beet	4.8	5.5	3.4	2.8	3.3	11.6	1.9	4.9	4.2	4.0	3.1	6.5	n	4.2
Paddy rice	n	n	n	n	32.4	n	55.7	29.5	n	29.4	31.7	n	53.7	n
Fodder roots	1.7	6.3	6.0	5.6	7.6	n	3.1	7.9	5.2	8.6	7.3	6.6	18.0	8.6
Silage maize	1.5	2.8	1.8	1.4	2.5	n	n	2.6	n	2.6	2.3	3.7	6.5	1.8
Rapeseed	8.0	13.5	8.6	7.8	8.4	19.9	7.3	n	7.5	13.8	12.2	18.1	n	12.9
Tobacco	6.5	11.0	n	7.7	5.2	n	6.0	8.7	n	8.4	7.5	n	16.9	n
Other industrial crops	5.9	10.4	6.5	6.8	4.6	13.7	n	n	n	8.7	7.7	13.9	10.7	9.0
Sunflower	5.0	5.6	n	7.3	6.6	14.6	5.6	9.4	n	9.3	7.7	15.8	19.9	7.3

Table 6.15. DNDC modelled N_2O emissions (000) t N_2O-N yr^{-1} from all modelled crops in Europe using 1:1m PTR soil data.

Crop	AT	BE	DE	DK	ES	FI	FR	GR	IE	IT	LU	NL	PT	UK	EU
Maize	825	271	2,123	0	3,319	0	6,701	2,273	0	4,894	2	168	3,606	0	24,182
Winter wheat	1,454	1,984	20,312	7,399	4,934	442	21,941	1,891	535	5,547	83	2,217	1,624	15,165	85,527
Soy bean	85	0	0	0	11	0	401	0	0	2,479	0	0	0	0	2,975
Leguminous hay	438	0	380	472	0	0	0	95	0	7,223	0	0	0	0	8,608
Non leguminous hay	178	1,038	7,765	511	0	10,213	20,441	733	4,001	7,738	99	888	6,177	9,611	69,392
Spring wheat	0	52	296	145	0	1,538	110	0	138	57	3	187	0	0	2,525
Winter barley	438	390	3,677	5,078	5,368	0	6,876	709	336	5,657	67	55	226	7,106	35,984
Spring barley	947	48	10,487	2,271	6,097	9,190	1,903	0	842	0	41	584	0	3,228	35,637
Oats	406	61	4,617	362	2,386	6,053	869	554	160	3,589	18	40	601	889	20,605
Durum wheat	97	0	60	0	3,055	0	2,893	4,825	0	32,920	0	0	129	0	43,978
Pasture	1,524	1,102	5,627	512	9,354	76	9,939	1,140	5,110	12,174	87	3,483	2,308	14,908	67,344
Other cereals	172	103	0	0	208	32	2,057	78	37	411	22	53	204	72	3,448
cotton	44	59	0	0	335	28	451	1,839	0	0	0	25	0	222	3,004
Rye	529	27	6,988	843	858	490	258	102	0	140	4	100	1,495	42	11,877
Vegetables	65	408	706	93	971	253	1,117	416	19	3,305	0	987	725	642	9,708
Dried vegetables	334	28	1,133	880	948	178	2,676	134	16	673	3	52	457	894	8,407
Potato	48	394	1,405	198	736	479	328	150	88	354	3	1,743	951	564	7,442
Beet	173	407	2,050	274	304	366	868	245	138	896	0	886	0	234	6,841
Paddy rice	0	0	0	0	3,663	0	485	49	0	7,624	0	0	3,187	0	15,007
Fodder roots	2	75	139	281	106	0	87	2	61	59	1	9	139	349	1,309
Silage maize	127	521	511	370	2,224	0	0	102	0	439	17	1,135	409	210	6,065
Rapeseed	390	32	8,976	906	255	1,290	5,175	0	32	920	20	4	0	3,579	21,578
Tobacco	1	2	0	3	51	0	38	337	0	395	0	0	14	0	842
Other industrial crops	20	133	254	104	97	18	0	0	0	37	1	41	1	297	1,003
Sunflower	179	0	0	39	2,043	4	3,494	2,384	0	1,946	0	3	315	2	10,409
Total Emissions	8,476	7,136	77,507	20,743	47,322	30,649	89,105	18,059	11,513	99,478	472	12,658	22,567	58,015	503,701

Table 6.16. Crop Area (000) ha.

Crop	AT	BE	DK	DE	ES	FI	FR	GR	IE	IT	LU	NL	PT	UK	EU
Corn	189.7	23.6	0.0	367.4	507.3	0.0	1,834.3	206.3	0.0	1,019.5	0.5	12.7	164.7	0.0	4,326.0
Winter wheat	246.2	203.0	668.3	2,659.9	1,538.3	20.8	4,856.4	220.5	66.2	653.3	9.3	125.0	209.3	2,033.3	13,509.8
Soybean	14.1	0.0	0.0	0.0	3.3	0.0	80.2	0.0	0.0	328.2	0.0	0.0	0.0	0.0	425.9
Leguminous hay	63.5	0.0	54.2	55.3	0.0	0.0	0.0	9.6	0.0	671.5	0.0	0.0	0.0	0.0	854.1
Non leguminous hay	63.5	120.3	100.6	1,510.4	0.0	682.5	4,688.5	65.2	661.8	1,055.2	16.2	77.6	300.5	1,383.3	10,725.8
Spring wheat	0.0	6.5	16.5	47.5	0.0	102.7	29.4	0.0	22.4	6.6	0.4	12.5	0.0	0.0	244.5
Winter barley	81.8	43.3	462.1	555.5	1,241.7	0.0	1,174.9	90.5	39.3	401.6	6.5	2.6	25.3	838.5	4,963.7
Spring barley	181.3	7.0	276.9	1,717.1	2,546.5	583.8	508.2	0.0	141.9	0.0	6.1	39.3	0.0	518.1	6,526.1
Oats	47.2	6.2	43.1	793.1	541.4	382.9	132.1	46.5	18.7	210.5	2.8	2.0	82.4	99.9	2,408.7
Durum wheat	12.4	0.0	0.0	9.4	738.8	0.0	281.5	528.9	0.0	1,780.5	0.0	0.0	22.8	0.0	3,374.3
Pasture	1,938.8	511.2	315.0	5,158.2	8,554.9	24.3	8,674.6	393.7	3,293.2	3,859.7	65.0	1,000.4	891.9	9,466.4	44,147.0
Other cereals	34.7	9.8	0.0	0.0	38.7	2.1	356.4	6.0	6.0	48.3	3.2	2.9	38.6	10.1	556.8
cotton	8.5	8.2	0.0	0.0	137.6	2.2	110.6	200.7	0.0	0.0	0.0	2.0	0.0	42.4	512.3
Rye	60.3	1.7	88.3	853.6	155.6	24.6	41.4	16.9	0.0	10.0	0.5	5.0	64.3	9.3	1,331.5
Vegetables	12.0	34.0	10.6	92.8	248.7	17.3	266.4	51.0	3.2	278.6	0.0	71.9	45.8	131.5	1,263.8
Dried vegetables	55.0	3.8	95.3	184.9	379.1	12.8	655.9	15.3	2.7	47.8	0.4	4.2	25.4	177.0	1,659.7
Potato	24.6	57.5	39.3	301.6	75.6	35.1	156.4	17.1	19.3	49.6	0.8	179.9	50.4	165.5	1,172.8
Beet	50.0	95.8	69.5	501.9	169.4	35.7	476.3	44.3	31.7	285.2	0.0	114.1	0.0	195.9	2,069.8
Paddy_rice	0.0	0.0	0.0	0.0	85.3	0.0	7.4	1.2	0.0	240.2	0.0	0.0	46.7	0.0	380.8
Fodder Roots	1.2	9.9	37.4	22.2	8.9	0.0	39.1	0.3	11.9	8.0	0.2	1.2	7.3	48.8	196.3
Silage maize	84.7	180.5	232.1	276.3	775.5	0.0	0.0	32.1	0.0	191.9	9.9	232.8	70.5	120.3	2,206.5
Rapeseed	51.0	3.5	90.5	1,040.3	57.9	65.4	965.2	0.0	4.5	75.3	2.2	0.2	0.0	468.2	2,824.3
Tobacco	0.1	0.3	0.3	0.0	14.4	0.0	9.2	36.9	0.0	52.5	0.0	0.0	2.1	0.0	115.7
Other industrial crops	3.6	18.9	11.9	40.4	34.6	1.4	0.0	0.0	0.0	4.9	0.2	3.2	0.1	57.4	176.6
Sunflower	35.6	0.0	4.3	0.0	969.7	0.3	890.2	239.1	0.0	252.5	0.0	0.2	54.9	0.4	2,447.3
Total Crop area	3,259.9	1,344.9	2,616.1	16,187.6	18,823.3	1,993.9	26,234.9	2,222.0	4,322.8	11,531.3	124.3	1,889.8	2,102.9	15,766.4	108,420.0

Table 6.17. Total Mineral N fertiliser input (000) t N yr^{-1}.

Crop	AT	BE	DK	DE	ES	FI	FR	GR	IE	IT	LU	NL	PT	UK	EU
Corn	22.77	1.65	0.00	48.13	121.74	0.00	311.84	45.39	0.00	183.50	0.03	0.57	26.34	0.00	761.98
Winter wheat	28.32	30.45	98.25	364.41	130.76	1.66	752.74	20.50	11.13	58.79	1.39	23.12	16.74	390.40	1,928.66
Soybean	0.64	0.00	0.00	0.00	0.03	0.00	3.61	0.00	0.00	14.77	0.00	0.00	0.00	0.00	19.05
Leguminous hay	0.00	0.00	1.62	5.80	0.00	0.00	0.00	0.10	0.00	0.67	0.00	0.00	0.00	0.00	8.19
Non leguminous hay	3.18	4.21	15.29	276.40	0.00	103.74	562.62	11.74	79.42	6.86	0.57	2.72	24.04	110.67	1,201.45
Spring wheat	0.00	0.97	2.42	6.51	0.00	8.22	4.56	0.00	3.76	0.59	0.07	2.32	0.00	0.00	29.41
Winter barley	7.77	4.76	61.46	44.44	95.61	0.00	129.24	8.06	4.32	34.14	0.72	0.21	1.52	104.81	497.06
Springbarley	17.22	0.77	36.83	137.37	196.08	43.20	55.90	0.00	15.61	0.00	0.67	3.15	0.00	64.76	571.54
Oats	3.31	0.55	4.23	57.89	38.87	26.81	13.21	4.41	1.80	21.05	0.26	0.16	4.94	11.29	188.77
Durum wheat	1.43	0.00	0.00	1.29	62.80	0.00	43.63	49.19	0.00	160.25	0.00	0.00	1.83	0.00	320.40
Pasture	67.86	75.65	28.98	980.05	333.64	2.73	641.92	5.90	365.54	57.89	9.62	263.11	35.68	1,135.96	4,004.53
Other cereals	2.43	0.88	0.00	0.00	2.78	0.14	35.64	0.57	0.57	4.83	0.29	0.24	2.31	1.14	51.83
Cotton	0.38	0.41	0.00	0.00	1.24	0.11	4.98	10.03	0.00	0.00	0.00	0.10	0.00	2.88	20.14
Rye	4.22	0.15	8.66	62.31	11.17	1.72	4.14	1.61	0.00	1.00	0.05	0.40	3.86	1.05	100.34
Vegetables	1.32	3.74	1.70	13.17	58.70	1.38	21.31	9.68	0.19	30.65	0.00	9.35	5.95	17.50	174.64
Dried vegetables	0.11	0.08	2.38	4.62	4.93	0.32	16.40	0.77	0.01	1.43	0.01	0.08	0.13	0.53	31.79
Potato	2.71	8.63	4.72	37.70	11.11	2.46	23.47	3.94	2.33	4.96	0.13	30.58	5.04	27.80	165.57
Beet	4.25	11.49	8.62	55.21	30.50	4.29	61.92	6.20	5.80	25.66	0.00	11.98	0.00	21.54	247.47
Paddy rice	0.00	0.00	0.00	0.00	6.13	0.00	0.74	0.11	0.00	24.02	0.00	0.00	2.80	0.00	33.80
Fodder roots	0.06	0.35	5.69	4.05	0.29	0.00	4.69	0.05	1.42	0.05	0.01	0.04	0.59	3.90	21.19
Silage maize	8.90	15.34	16.71	21.55	62.04	0.00	0.00	3.21	0.00	11.51	0.84	9.31	5.64	6.86	161.91
Rapeseed	6.37	0.53	12.67	145.64	6.37	5.89	139.96	0.00	0.68	6.02	0.33	0.04	0.00	95.05	419.55
Tobacco	0.01	0.01	0.02	0.00	2.16	0.00	0.28	1.66	0.00	2.36	0.00	0.00	0.08	0.00	6.57
Other industrial crops	0.20	0.38	0.84	3.64	5.18	0.05	0.00	0.00	0.00	0.22	0.00	0.30	0.00	2.99	13.81
Sunflower	1.60	0.00	0.21	0.00	8.73	0.02	40.06	11.95	0.00	11.36	0.00	0.01	0.49	0.03	74.47
Total	**185.0**	**161.0**	**311.3**	**2,270.2**	**1,190.9**	**202.7**	**2,872.9**	**195.1**	**492.6**	**662.6**	**15.0**	**357.8**	**138.0**	**1,999.2**	**11,054.1**

6.6 Validation

It was shown in section 2 of this thesis that N_2O measurements at the European scale for different crop types, management and soils are sparse. Therefore a direct comparison of measured data with the DNDC mechanistic model that takes into account many different climatic and farm management conditions is difficult.

The input data used to run the DNDC model and modelled results for the NUTS level 3 region of Modena, Italy are shown Table 6.18. The IFA/FAO (2001) dataset based on the findings of Arcara *et al.* (1999) contains N_2O measurements measured weekly for 150 days from a site in Modena, Italy with a maize crop grown on a poorly drained soil under four different mineral N fertiliser regimes (see Table 6.19). The modelled SOC input data for the NUTS level 3 region of Modena (NUTS code IT404) has a range from 0.0085 to 0.0144 kg C kg^{-1} soil producing a range of N_2O emissions from 1.9 kg N_2O-N ha^{-1} $yr^{-1}$to 3.7 kg N_2O-N ha^{-1} yr^{-1}. In contrast the measured N_2O estimates range from 0.656 kg N_2O-N ha^{-1} $yr^{-1}$to 1.84 kg N_2O-N ha^{-1} yr^{-1}. The high estimates of the model are the total for 365 days, whereas the measured data was only collected for 150 days. Peaks of N_2O emission may have been missed during the measurement period and the daily regional climate data used to run the model is unlikely to reproduce the exact site conditions. The type of N fertiliser applied during the modelled estimates is only given at the national scale, and cannot therefore replicate the measured site conditions. In addition the model takes into account mineralisation of SOC of 78.3 kg N ha^{-1} yr^{-1} that can be a significant source of N_2O as observed by Mogge *et al.* (1999).

Table 6.18 DNDC modelled input data and N_2O emissions for a maize crop in Modena, Italy.

Modelled data	**Max**	**Min**	**Mean**
Soil texture	0.18	0.01	0.095
Soil organic carbon content	0.0144	0.0085	0.0115
Mineral N fertiliser	180	180	180
Manure N application	60	60	60
kg N_2O-N yr^{-1}	3.7	1.9	2.8

Table 6.19. Measured N_2O emissions from Maize cropped soils across Europe

Country	Texture	SOC (%)	Fertilizer type	N-rate	Kg N_2O-N ha^{-1} yr^{-1}
BE	Sandy loam	2.7	AN	150	2.25
DE	Sand	1.3	FYM	92.7	5.3
DE	Sand	1.2	Cattle slurry	332.7	2.1
DE	Organic	34.3		275	15.6
DE	Loam	1.6	CAN	65	1.77
DE	Loam	1.6	CAN	130	2.74
DE			CAN	65	1.341
DE			CAN	130	2.406
ES	Clay	1	AS	45.4	0.3603
ES	Clay	1.5	Pig slurry	133	0.4966
ES	Clay	2.1	Pig slurry	112	0.4255
FR	Sand	19	AA	280	11.0
IT	Silty clay	1.2		0	0.653
IT	Silty clay	1.2	U	225	1.295
IT	Silty clay	1.2	Pig slurry	225	1.275
IT	Silty clay	1.2	Pig slurry + U	450	1.844

Table 6.19 shows N_2O measurements from maize crops in various locations in Europe. The measurements range from 0.653 kg N_2O-N ha^{-1} yr^{-1}on a silty clay soil in Italy to 15.6 kg N_2O-N ha^{-1} yr^{-1} on an organic soil in Germany. Jambert *et al.* (1997) measured N_2O emissions of 11 kg N_2O-N ha^{-1} yr^{-1} from an irrigated maize crop.

The DNDC modelled results (see Table 6.20) for maize in Germany range from 0.38 to 24.87 kg N_2O-N ha^{-1} yr^{-1}. The DNDC modelled results from maize show a large range in emissions that can be attributed to the large variations in input data such as SOC and climate. A large range in N_2O emissions was also found by

Butterbach-Bahl *et al.* (2004) who estimated a range from 0.5 to 26 kg N_2O-N ha^{-1} yr^{-1} in Saxony, Germany using the DNDC model. Butterbach-Bahl *et al.* (2004) also found that variations in the SOC and soil texture data significantly affected the modelled N_2O emissions.

Table 6.20. DNDC Modelled emissions from Maize in a range of countries across Europe.

Country	Range	kg N_2O-N ha^{-1} yr^{-1}
Belgium	Min	0.69
	Max	30.29
Germany	Min	0.38
	Max	24.87
Italy	Min	0.74
	Max	40.34
Spain	Min	0.25
	Max	39.07

The DNDC modelled results for pasture show low N_2O estimates for pasture (0.8 to 3.3 kg N_2O-N ha^{-1} yr^{-1}). This is in contrast to Smith *et al.* (1998), Vermoesen *et al.* (1996) and Goosens *et al.* (2001) who all found that N_2O emissions were higher from grazed grassland than from cereal crops. However, Goosens et al (2001) measurements were taken on intensively managed grassland. The IFA/FAO (2001) data records a range of N_2O emissions from grassland of 0.08 to 19.8 kg N_2O-N ha^{-1} yr^{-1}, the latter occurring on organic soils. The version of the DNDC model used in this thesis did not take into account N input from grazing (e.g. urine and faceal inputs) while the manure application data derived from Eurostat data did not differentiate between crop types or land use. Therefore it can be inferred that the DNDC modelled runs for Europe have underestimated N_2O emissions from pasture due to an underestimation of N input.

Goosens *et al.* (2001) measured N_2O emissions from arable land in Belgium from 0.3 to 1.5 kg N_2O-N ha^{-1} yr^{-1}. The DNDC model N_2O estimates for Belgium ranged from 2.8 to 13.5 kg N_2O-N ha^{-1} yr^{-1}. In the Netherlands, Van Groenigen *et al.* (2004) observed N_2O emissions of 6.81 kg N_2O-N ha^{-1} yr^{-1} from silage maize with a high application of slurry. The DNDC modelled mean N_2O emissions from silage maize in the Netherlands was 3.7 kg N_2O-N ha^{-1} yr^{-1}. This indicates that the N input data for manure is underestimated for silage crops.

The DNDC model produced a mean estimate of N_2O from winter wheat of 7.3 kg N_2O-N ha^{-1} yr^{-1} (with a range of 0.6 to 30.3 kg N_2O-N ha^{-1} yr^{-1}). Flessa *et al.* (2002a) measured emissions from a wheat field in the range of 1.3 to 16.8 kg N_2O-N ha^{-1} yr^{-1} but also measured emissions of 4.2 to 56.4 kg N_2O-N ha^{-1} yr^{-1} on peaty soils in Germany. The measurement data shows that emissions are highest on soils with a high soil organic carbon content. The IFA/FAO (2001) data also records emissions of 56.4 kg N_2O-N ha^{-1} yr^{-1} from an organic soil in Germany.

Brown *et al.* (2002) used the DNDC model to produce a range of N_2O emissions from 0.07 to 7.41 kg N_2O-N ha^{-1} yr^{-1}. The modelled estimates for the UK produced in this thesis ranged from 1.6 to 12.9 kg N_2O-N ha^{-1} yr^{-1} (see Table 6.14). Brown *et al* (2002) estimated emissions from grassland, potatoes and sugar beet at 3.5, 3.7 and 4.1 kg N_2O-N ha^{-1} yr^{-1} respectively. In contrast the DNDC modelled emissions in this thesis for the same crops were 1.6, 5.2 and 4.2. It can be clearly seen that N_2O emissions from pasture in this thesis are significantly lower. The estimates produced by Brown *et al.* (2002) use more detailed data (i.e. soil and grazing data) not available at the European scale. To fully validate the DNDC model, more field scale runs using input parameters as close to the site conditions as possible must be undertaken. The European emission estimates produced in this thesis are average emission rates for NUTS 3 regions and cannot be directly compared to site measurements.

A comparison of the DNDC modelled N_2O emission results for Europe produced by this thesis with regression estimates based on measurements produced by Freibauer *et al.* (2004) is shown in Figure 6.31. The results indicate a significant difference between the DNDC modelled estimates and the regression estimates highlighting the need for the DNDC modelled results to be compared with actual measurement data. Unfortunately, this was outside of the scope of this thesis.

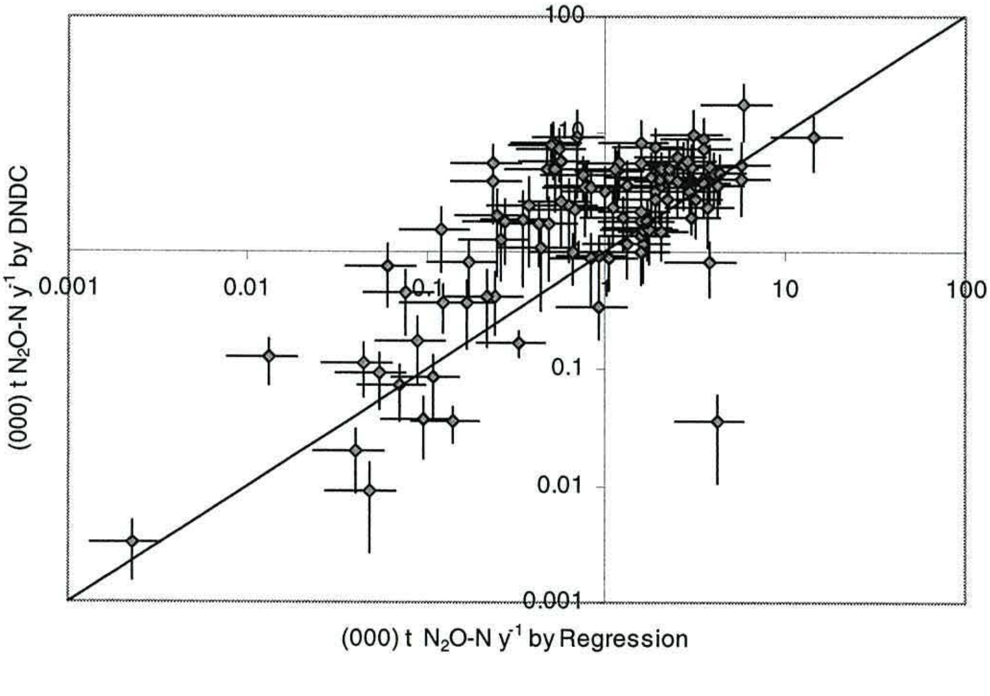


Figure 6.31. Comparison of modelled N_2O estimates with regression results between the DNDC model and those predicted by Freibauer *et al.* (2004).

To summarise, what is required from measured datasets if they are to be used to validate the results from mechanistic N_2O emission models are the spatial location (longitude and latitude), to enable correlation with data from geographic dataset (GIS coverages), combined with detailed measurements/descriptions of the soil parameters, daily climate data, and agricultural management. Many N_2O emissions measurements do not cover a complete year or are taken at irregular intervals, which can omit episodic N_2O fluxes, thereby not giving a true estimation. This is important if the mechanistic models that run on a daily time step are to be fully validated.

The modelled estimates produced in this thesis are difficult to validate against measured estimates as inaccuracies or deficiencies in data used to drive the model data do not allow site conditions to be accurately replicated. Moreover the DNDC model runs for 365 days taking into account all peak emissions due to meteorological events.

7 Conclusions

The main aims of this thesis were:

1. To create a pan-European database and to evaluate the suitability, availability and uncertainties of data relevant to modelling estimates of N_2O emissions.
2. To evaluate the role of a software tool, combining the pan-European database with a 'state of the art' bio-geochemical mechanistic model, for estimating N_2O emissions from fertilised agricultural soils on a regional scale.
3. To assess the suitability of such a modelling tool in producing direct and indirect N_2O emission estimates for Italy in comparison to the IPCC methodology.
4. To produce an estimate of N_2O emissions for Europe from fertilised agricultural soils.

Conclusions from the studies described in this thesis to achieve these aims are described in this chapter.

7.1 Regional N_2O estimates for Italy

The regional N_2O emission estimates for Italy exhibited a great dependency on the scale and accuracy of the soil organic carbon input data. This was illustrated by the total N_2O estimates for Italy where scenarios of SOC content derived from the 1:250,000 measured data and the 1:1,000,000 PTR estimated data were 44,700 t N_2O–N yr^{-1} and 76,300 t N_2O–N yr^{-1} respectively. These results draw attention to the uncertainty in the accuracy of the 1:1,000,000 PTR estimated SOC data, when compared to the 1:250,000 SOC measured data that can be considered the more accurate representation of SOC in soils in Italy. This uncertainty highlights the need for further Europe-wide field measurements of SOC.

The scale of the geographic modelling unit (NUTS 3 level) produced a large range in the N_2O emissions within some NUTS 3 region that was directly related to the large range in minimum and maximum SOC values within the regions. Although the range in SOC values should produce a range in N_2O estimates as described by Li *et al.* (1992) reducing the size of the modelling unit (*e.g.* 10 km grid) would reduce the uncertainty in N_2O emissions. A nested approach could be used where finer scale runs are undertaken for regions where a large range in the SOC values and land use are known (*e.g.* the region of Lombardia that extends from alpine pastures down to the rice plains of the Po valley). A clear understanding of the exact correlation between crop types and SOC values is required.

It was shown that daily meteorological data was essential for estimating N_2O emissions due to the daily-time step of the DNDC model and sensitivity of N_2O emissions to changes in temperature and precipitation. Finer scale regional N_2O

emission estimates would benefit from more refined daily meteorological data that incorporates factors such as altitude to account, for localised changes in climate due to adiabatic lapse rates. Moreover, N_2O measurements should be reported with daily meteorological data (e.g. TRAGNET) to enable validation and further development of mechanistic N_2O emission models.

Changes in the spatial distribution of the arable crop input data produced a considerable change in the DNDC modelled N_2O emission estimates. This was demonstrated by the different total N_2O estimates for Italy produced between two crop scenarios: one using the ISTAT NUTS level 3 (76,300 t N_2O–N yr^{-1}) and the other using the predominantly NUTS level 2 New Cronos data that was disaggregated crop to the finer scale of the NUTS level 3 modelling unit (99,500 t N_2O–N yr^{-1}). The spatial disaggregation procedure used in this study changed the spatial location and thereby climatic and soil condition crops under which the crops were grown, thus affecting the N_2O estimates.

The method of spatial disaggregation relied on the CORINE land cover dataset that is a remotely-sensed 'snapshot' of the landcover situation in 1990. The agricultural land cover classes within the CORINE dataset cannot be directly related to the 'land use' (i.e. the crop type). No CORINE data were available for Sweden. The ongoing development of CORINE 2000 should provide a more up-to-date account of land cover. Uncertainties in the crop distribution can be reduced by the provision of finer scale crop data at the European scale. To reduce uncertainties in crop distribution, potential N_2O emissions can be modelled using a single hectare approach for each crop type within each geographic modelling unit. This approach would produce a matrix of potential N_2O emission values for individual crops that can be then applied to regional crops statistics.

The largest contribution to total N_2O emissions was from Durum wheat, the dominant crop in Italy, with a relatively high fertiliser application rate compared to other crops. Differing crop uptake rates affected N_2O emission rates. Corn and winter wheat, used similar fertiliser application rates but displayed different rates of N_2O emissions. This assertion is further supported by the sensitivity analysis where the same fertiliser application rate was applied to each crop, with differing emission rates. The spatial distribution, thereby, the localised conditions under which the crops were grown and management practices that are applied to the crops (*i.e.* fertiliser application, tillage, planting and harvest timing) must also be taken into account.

7.2 Regional N_2O estimates for Europe

In total, 5,400 N_2O estimates were produced by this modelling exercise for 1050 NUTS level 3 regions across Europe, taking into account the full range of SOC values within each region as well as pH, texture and bulk density, meteorological data, atmospheric deposition, and crop management. These results demonstrate potential N_2O estimates from agricultural soils on a European scale for the first time. By showing individual crop-wise distributions of N_2O emissions the potential for denitrification under different crop-regimes can be estimated. This is important for both GHG policy and for the Nitrate Directive, where derogation can be given to areas with a high potential for denitrification.

When compared to the national datasets for Italy, the Pan-European datasets were shown to display higher SOC values and different crop distributions. These higher SOC values and crop changes both resulted in higher estimations of N_2O emissions. To undertake a comprehensive validation of the Europe-wide input data a comparison must be made with the national data (e.g. N fertiliser application or crop area) used by the EU Member States to compile the national inventories for each country. Given the uncertainty in the accuracy of the pan-European data soil and crop and uncertainty in the IPCC methodology, no direct comparison can be made between the total estimates for European countries.

7.3 Inventory analysis of N_2O estimates

The modelled N_2O estimates from direct and indirect sources showed significant differences to the estimates produced using the IPCC methodology. The DNDC modelled emissions due to mineral N fertiliser for the whole of Italy (0.008 of N input) were shown to be lower than the IPCC factor of 0.0125 but within the IPCC range. However, a very low correlation was shown between mineral N fertiliser application and N_2O emissions, as assumed by the IPCC indicating that other factors such as climate and soil type effect N_2O emissions. Statistical analysis showed that SOC, N fixation in soils and N uptake were the most significant factors driving N_2O emissions.

Uncertainties in the DNDC model were highlighted by increases in N_2O emissions from pastures in alpine zones of northern Italy (prone to high rainfall and therefore high levels of wet N deposition) when fertiliser was not applied. The increase in N_2O emissions was attributed to a reduction in N uptake by crops, when no fertiliser was applied, thereby, increasing soil moisture and optimising conditions for denitrification. The relatively small increase in emissions from pastures with no fertiliser application was magnified when multiplied by the total pasture area, stressing the need for an accurate understanding of land use types such as pasture and how much area is actually fertilised.

Estimated emissions of N_2O due to organic manure showed a good correlation with the IPCC factor, indicating that the emissions were less affected by the range of SOC values. However, there was a significant difference in the amount of organic fertiliser volatilised by the model compared to the IPCC default IPCC factor of (30%).

The DNDC model was unable to satisfactorily estimate N_2O emissions due to N-fixing crops showing a much higher emission rate than the IPCC approach. The IPCC recognises that the current statistical approach for estimating emissions due to N-fixing crops, underestimates N_2O emissions. The DNDC model was also unable to successfully model N_2O emissions due to incorporation of crop residue. The major uncertainty in the modelled estimate was due to the lack of available crop residue data on a regional scale.

The DNDC estimated background emissions significantly higher than the IPCC approach. The DNDC model was shown to be very sensitive to SOC in the sensitivity analysis. The high estimation of background emissions was related to the high SOC input data. The IPCC approach does not appear to satisfactorily account for emissions from high organic soils. Although the IPCC approach takes into account emissions from histosols, these do not account for all high organic soils.

The N leached estimate from agricultural soils showed that N leached values vary considerably compared to the default N leached value used by the IPCC. There were considerable differences between the modelled estimates of atmospheric N deposition and the IPCC methodology that made the two methods difficult to compare.

The major limitations in the use of DNDC for producing an inventory of N_2O emissions from agricultural soils are that the model was primarily developed for direct emissions and that a single N_2O emission estimate is produced from all N input sources. No differentiation is made between the different N sources identified in the IPCC methodology. To make the comparison of modelled N_2O emissions with the IPCC estimates it was necessary to run the model with zero values for each N source. This produced unrealistic scenarios, for instance, of crops being grown with zero fertiliser. In reality this scenario would not occur and in the modelled estimates reductions in N uptake, crop stress and increases in soil moisture could in theory mask the true emissions due to N fertilisation.

7.4 Pan-European database

This study compiled a pan-European database that contained harmonised regional data relevant to run a mechanistic model (DNDC) on a regional scale. The development and acquisition of suitable data is a continuous process. Therefore, this study used only the data that were available within the time period of the study

(2000-2003). There are many alternative datasets that could be used for future work. This study identified the major sources of readily available data and identified uncertainties in the original data sets and processed data. The database compiled in this study could be utilised not only in further investigations of agricultural N_2O emissions but also for wider investigations of nutrient flow from agricultural practices. A GIS proved an essential tool in the creation of the pan-European database, to process and store the data, derive spatial relationships between data, to analyse, summarise and extract the data in the format required to run the DNDC model. The GIS was essential in the interpolation of datasets where limited spatial data was available. In particular, the N deposition available within the EMEP database contained measured NH_4^+ and NO_3^- data recorded by just 43 stations located in nine of the EU member states. A GIS was used to interpolate the limited data across Europe using theissen polygons.

Farm management data at the European scale are extremely poor. The sensitivity analysis showed the significant effect of farm management (*i.e.* timing of fertilisation, tillage, planting and harvesting) has on N_2O emissions. The MARS crop calendar database contains limited crop timing data for just 53 sites across Europe and can be considered far from comprehensive given the importance of such data to the accuracy of emission estimates.

Europe-wide data on the fertiliser application rates for crops on differing soil types are extremely poor (e.g. crops on high organic soils, with high rates of available N are often fertilised less). This paucity in data produced some of the major uncertainties in this modelling exercise. Incorporation of crop residue data are also lacking for most of Europe.

7.5 DNDC model evaluation

From the sensitivity analysis and analysis of the outputs, the DNDC model can be observed that the model is extremely dependent on accurate SOC data. The DNDC is a very complex model to run at the regional scale, accounting for microbial growth pattern in the soil. Perhaps, a more suitable method for regional modelling should be developed using the DNDC modelled results and measured results to produce simple regression equations that take into account the main drivers of N_2O. These equations would be easier to apply to future scenarios and would be more detailed than the IPCC approach that operates solely on the national scale.

The sensitivity analysis also showed that N_2O emissions differ between fertiliser type. Anhydrous ammonia produces the highest N_2O emissions whereas other forms of fertiliser containing NO_3^- produce the lowest. Regional data on the type of fertiliser applied is extremely poor, which limits the ability of the model to accurately estimate emissions. However, the DNDC model is an improvement on the IPCC approach that does not take into account the type of mineral N fertiliser applied. Overall, the DNDC is an overall improvement of the IPCC methodology in that it takes into account climate and soil conditions. However, the data required to run such a model successfully at the European scale does not exist at present.

7.6 Policy support

The results of this thesis are of particular interest and importance to European and regional policy makers. In addition to the obvious contribution to EU climate change obligations under the Kyoto Agreement, through the UNFCC monitoring mechanism (UNFCCC, 2004), the results of this thesis can be applied to a range of other environmental policies.

Of key importance are inputs to the development of a thematic soil protection strategy for Europe. The strategy recognises a number of key the threats to soils, two of which are diffuse contamination from agro-chemicals and a decline in soil organic matter. The first aspect falls directly within the scope of this study. Assessing the impact of reform of the CAP, through a reduction in nitrogen fertiliser, has an impact on the Nitrate Directive, which seeks to protect ground water resources. The outputs of this study have already been used to determine nitrate derogation zones. In a similar vein, the application of sewage sludge is seen in many regions as a waste management practice which directly benefits agriculture by the addition of organic matter to the soil. Given the links between N_2O emissions and organic matter, highlighted by this thesis, the potential to assess the impact of this issue on GHG emissions is evident.

Linked to the reform of the CAP is a drive towards the integration of environmental concerns into agriculture with a review towards sustainable agriculture. Through contributions to IRENA project complementing agri-environmental indicators on GHG emissions and N balance, the results of this thesis address these issues. Finally, this study provided an analysis of N_2O emissions from biomass crops associated with EU support towards bio-fuels research (Edwards *et al.* 2003). The European results produced by this study have been cited by the UNFCCC in making a comparison of N_2O emission estimates for EU member states produced by the IPCC methodology and the mechanistic model DNDC (UNFCC, 2004).

7.7 Conclusion summary

This thesis has clearly demonstrated that a mechanistic model and a database containing national and pan-European data can produce regional estimates of direct N_2O emissions from fertilised agricultural soils at the NUTS level 3 across Europe. These estimates can be used to identify regional patterns in N_2O emissions, related to climate, agricultural practices and soil conditions and for evaluating the IPCC emission factors. A regional map of N_2O emissions was produced for the first time.

However, uncertainties in the regional estimates of N_2O emissions remain due to the large uncertainties in both the raw and processed data. In particular, the estimates were shown to be very sensitive to the scale at which the SOC was reported and the spatial distribution of crops. This thesis showed that there is a paucity of data at the regional scale on crop timing, crop residue, fertiliser type and the soil/land use/crop relationship. The available data required significant processing before use in the model. The thesis highlighted the difficulty in validating the results due to the lack of systematic monitoring of N_2O emissions.

8 Recommendations for future work

This thesis has highlighted a range of uncertainties regarding the estimation of N_2O emissions in Europe. Further work is therefore required to rectify these deficiencies including the following:

1. To accurately model N_2O emissions from agricultural soils, indirect emissions from groundwater, rivers and estuaries must also be taken into account. In order to achieve this goal a hydrological flow model is required. Most of the currently available hydrological models do not take N_2O emissions into account and used mainly to determine nutrient levels in water-bodies. However, most of the hydrological models can estimate nitrate levels in groundwater and rivers, which is a vital parameter in the calculation of indirect emissions due to N leached from agricultural soils. Integration of one of the many mechanistic models that estimate direct N_2O emissions with a hydrological model could provide a useful tool in estimating both direct and indirect N_2O emissions.
2. To make further comparisons between the IPCC and modelled estimates a clear and precise methodology needs to be implemented, whereby the same N input data are used in both methodologies. Modelled and measured results can be used to produce simple regression equations that take into account not only N inputs but climate and soil parameters, factors not currently used by the IPCC methodology.
3. To reduce the range estimations due to the large range in SOC values a smaller size of geographic modelling unit could be used (*i.e.* 10 km grid). However, the

uncertainties produced by the need to disaggregate crop data to the finer scale, availability of climate data and processing time should all be taken into account.

4. There is a need for the systematic monitoring of N_2O emissions, taking into various crop and soil types, particularly crops grown on organic soils.

Appendix 1. IPCC methodology

Direct and indirect N_2O emissions from agricultural soils

$$N_2O = N_2O_{DIRECT} + N_2O_{INDIRECT}$$

- N_2O = N_2O emission from agricultural soil (kg N/y);
- N_2O_{DIRECT} = direct N_2O emission from agricultural soils (kg N/y);
- $N_2O_{INDIRECT}$ = Indirect N_2O emissions from agricultural soils (kg N/y)

Direct emissions

$$N_2O_{DIRECT} = [(F_{SN} + F_{AW} + F_{BN} + F_{CR}) \times E_{F1}] + F_{OS} \times E_{F2}$$

- F_{SN} = the total synthetic fertiliser excluding emissions of NH_3 and NO_x
- F_{AW} = manure nitrogen used as fertiliser in country, corrected for NH_3 and NO_x emissions and excluding manure produced during grazing (kg N/yr)
- F_{BN} = N fixed by N-fixing crops in country (kg N/yr)
- F_{CR} = N in crop residues returned to soils in country (kg N/yr)
- E_{F1} = emission factor for direct soil emissions (kg N_2O-N/kg N input)
- F_{OS} = area of cultivated organic soils within country (ha of histosol in FAO data base)
- E_{F2}= emission factor for organic soil mineralisation due to cultivation ((kg N_2O-N ha^{-1} yr^{-1})

$$F_{SN} = N_{FERT} \times (1 - FRAC_{GASF})$$

- N_{FERT} = total use of synthetic fertilizer (kg N/yr)
- $FRAC_{GASF}$ = fraction of total synthetic fertilizer nitrogen that is emitted as $NO_x + NH_3$

$$F_{AW} = [\ (N_{(T)} \times Nex_{(T)} \times AWMS_{(T)}\ ] \times [\ (1- (FRAC_{FUEL} + FRAC_{GRAZ} + FRAC_{GASM})]$$

- $N_{(T)}$ = number of animals of type T in the country
- $Nex_{(T)}$ = N excreted by animals of type T in a country (Kg N/yr)
- $AWMS_{(T)}$ = fraction of Nex(T) that is managed in one of the different distinguished animal waste management systems in a country
- $FRAC_{FUEL}$ = fraction of livestock nitrogen excretion contained in excrements burned for fuel (kg N/kg N totally excreted);
- $FRAC_{GRAZ}$ = fraction of livestock nitrogen excreted and deposited onto soil during grazing (kg N/kg N excreted)
- $FRAC_{GASM}$ = fraction of livestock nitrogen excretion that volatises as NH_3 and NO_x.

F_{BN} = 2 x $Crop_{BF}$ x $Frac_{NCRBF}$

- $Crop_{BF}$ = seed yield of pulses + soybeans in a country (kg dry biomass/yr)
- $Frac_{NCRBF}$ - fraction of nitrogen in N-fixing crop

F_{CR} = 2 x [$crop_0$ x $Frac_{ncr0}$ + $Crop_{BF}$ x $Frac_{NCRBF}$] x (1-$Frac_R$) x ($Frac_{BURN}$)

- $Crop_0$ = production of all other (i.e. non-N fixing) crops in a country (kg dry biomass/yr)
- $Frac_{NCR0}$ = fraction of nitrogen in non-N fixing crop
- $Frac_R$ = fraction of crop residue that is removed from the field as crop
- $Frac_{BURN}$ = fraction of crop residue that is burned rather than left on field

Indirect emissions

$N_2O_{INDIRECT} = N_2O_{(G)} + N_2O_{(L)}$

- $N_2O_{(G)}$ = N_2O produced from atmospheric deposition of NO_x and NH_3 (kg/yr)
- $N_2O_{(L)}$ = N_2O produced from nitrogen leaching and runoff (kg N/yr)

$N_2O_{(G)}$ = {N_{FERT} x $Frac_{GASF}$ + Nex x $Frac_{GASM}$} x EF_4

- EF_4 = emission factor for atmospheric deposition (kg N_2O-N/kg N NH_3 and NO_x-N emitted)

$N_2O_{(L)}$ = [(N_{FERT} + Nex) x $Frac_{LEACH}$] x EF_5

- $Frac_{LEACH}$ = Fraction of nitrogen leaching, the default value is 0.3 (0.1-0.8) kg N/kg of protein.
- EF5 = emission factor for leaching and runoff (Kg N_2O-N/kg N leaching/runoff)

Appendix 2. Crop areas in Europe

New Cronos disaggregated crop totals for 1997 (000) ha.

Crop	AT	BE	DK	DE	ES	FI	FR	GR	IE	IT	LU	NL	PT	UK
Corn	189.7	23.6	0.0	367.4	507.3	0.0	1,834.3	206.3	0.0	1,019.5	0.5	12.7	164.7	0.0
Winter wheat	246.2	203.0	668.3	2,659.9	1,538.3	20.8	4,856.4	220.5	66.2	653.3	9.3	125.0	209.3	2,033.3
Soy bean	14.1	0.0	0.0	0.0	3.3	0.0	80.2	0.0	0.0	328.2	0.0	0.0	0.0	0.0
Leguminous hay	63.5	0.0	54.2	55.3	0.0	0.0	0.0	9.6	0.0	671.5	0.0	0.0	0.0	0.0
Non leguminous hay	63.5	120.3	100.6	1,510.4	0.0	682.5	4,688.5	65.2	661.8	1,055.2	16.2	77.6	300.5	1,383.3
Spring wheat	0.0	6.5	16.5	47.5	0.0	102.7	29.4	0.0	22.4	6.6	0.4	12.5	0.0	0.0
Winter barley	81.8	43.3	462.1	555.5	1,241.7	0.0	1,174.9	90.5	39.3	401.6	6.5	2.6	25.3	838.5
Spring barley	181.3	7.0	276.9	1,717.1	2,546.5	583.8	508.2	0.0	141.9	0.0	6.1	39.3	0.0	518.1
Oats	47.2	6.2	43.1	793.1	541.4	382.9	132.1	46.5	18.7	210.5	2.8	2.0	82.4	99.9
Durum wheat	12.4	0.0	0.0	9.4	738.8	0.0	281.5	528.9	0.0	1,780.5	0.0	0.0	22.8	0.0
Pasture	1,938.8	511.2	315.0	5,158.2	8,554.9	24.3	8,674.6	393.7	3,293.2	3,859.7	65.0	1,000.4	891.9	9,466.4
Other cereals	34.7	9.8	0.0	0.0	38.7	2.1	356.4	6.0	6.0	48.3	3.2	2.9	38.6	10.1
cotton	8.5	8.2	0.0	0.0	137.6	2.2	110.6	200.7	0.0	0.0	0.0	2.0	0.0	42.4
Rye	60.3	1.7	88.3	853.6	155.6	24.6	41.4	16.9	0.0	10.0	0.5	5.0	64.3	9.3
Vegetables	12.0	34.0	10.6	92.8	248.7	17.3	266.4	51.0	3.2	278.6	0.0	71.9	45.8	131.5
Dried vegetables	55.0	3.8	95.3	184.9	379.1	12.8	655.9	15.3	2.7	47.8	0.4	4.2	25.4	177.0
Potato	24.6	57.5	39.3	301.6	75.6	35.1	156.4	17.1	19.3	49.6	0.8	179.9	50.4	165.5
Beet	50.0	95.8	69.5	501.9	169.4	35.7	476.3	44.3	31.7	285.2	0.0	114.1	0.0	195.9
Paddy rice	0.0	0.0	0.0	0.0	85.3	0.0	7.4	1.2	0.0	240.2	0.0	0.0	46.7	0.0
Fodder roots	1.2	9.9	37.4	22.2	8.9	0.0	39.1	0.3	11.9	8.0	0.2	1.2	7.3	48.8
Silage maize	84.7	180.5	232.1	276.3	775.5	0.0	0.0	32.1	0.0	191.9	9.9	232.8	70.5	120.3
Rapeseed	51.0	3.5	90.5	1,040.3	57.9	65.4	965.2	0.0	4.5	75.3	2.2	0.2	0.0	468.2
Tobacco	0.1	0.3	0.3	0.0	14.4	0.0	9.2	36.9	0.0	52.5	0.0	0.0	2.1	0.0
Other ind	3.6	18.9	11.9	40.4	34.6	1.4	0.0	0.0	0.0	4.9	0.2	3.2	0.1	57.4
Sunflower	35.6	0.0	4.3	0.0	969.7	0.3	890.2	239.1	0.0	252.5	0.0	0.2	54.9	0.4
Total	3,259.9	1,344.9	2,616.1	16,187.6	18,823.3	1,993.9	26,234.9	2,222.0	4,322.8	11,531.3	124.3	1,889.8	2,102.9	15,766.4

Appendix 3. ISTAT crop classes for Italy

1	**Total cereali**
1.1	Frumento in complesso
1.11	Frumento tenero
1.12	Frumento duro
1.2	Orzo
1.3	Avena
1.4	Mais
1.5	Sorgo
1.6	Cereali minori
1.7	Mais in erba
1.8	Mais maturazione cerosa
2	**Legumi secchi**
2.1	Fava da granella
2.2	Fagiolo secco
2.3	Pisello in complesso
2.32	Pisello da granella
2.32	Pisello proteico
2.4	Cece
2.5	Lenticchia
3	**Piante da tubero**
3.1	Patata in complesso
3.11	Patata primaticcia
3.12	Patata comune
4	**Legumi freschi**
4.2	Fagiolo fresco
4.3	Fagiolini freschi
4.1	Fava fresca
5	**Radici e bulbi**
5.1	Carota
5.2	Cipolla
5.3	Rapa
5.4	Barbabietola da foraggio
6	**Fusti foglie e infioescenze**
6.1	Broccoletto di rapa
6.2	Cavoli
6.21	Cavolo cappuccio
6.22	Cavolo di bruxelles
6.23	Cavolo verza
6.24	Altri cavoli
6.3	Cavolfiore
6.4	Finocchio
6.5	Insalate(Lattuga-Indivia-Radicchio)
6.51	Indivia
6.52	Lattuga
6.53	Radicchio
6.6	Prezzemolo
7	**Frutti**
7.1	Melanzana
7.2	Peperone
7.3	Pomodoro
7.4	Popone o melone
7.5	Zucchine
8	**Colivazioni industriali**
8.1	Colza
8.2	Girasole
8.3	Barbabietola da zucchero
8.4	Soia
9	**FORAGGERE TEMPORANEE**
9.1	ERBAI
9.11	Erbai Monofiti: totale
9.111	Erbai Monofiti: Mais Ceroso
9.112	Erbai Monofiti: Orzo in Erba
9.113	Erbai Monofiti: Orzo Ceroso
9.114	Erbai Monofiti: Loietto
9.115	Erbai Monofiti: Altri
9.12	Erbai Polifiti: totale
9.121	Erbai Polifiti: Graminacee
9.122	Erbai Polifiti: Leguminose
9.123	Erbai Polifiti: Altri miscugli
9.2	**PRATI AVVICENDATI**
9.21	Prati avvicendati Monofiti: Totale
9.211	Prati avvicendati Monofiti: Erba Medica
9.212	Prati avvicendati Monofiti: Lupinella
9.213	Prati avvicendati Monofiti: Sulla
9.214	Prati avvicendati Monofiti: Altre Specie
9.22	Prati avvicendati Polifiti: Totale
10	**FORAGGERE PERMANENTI**
10.1	Prati
10.2	Pascoli
10.3	Altri pascoli
10.4	Pascoli poveri

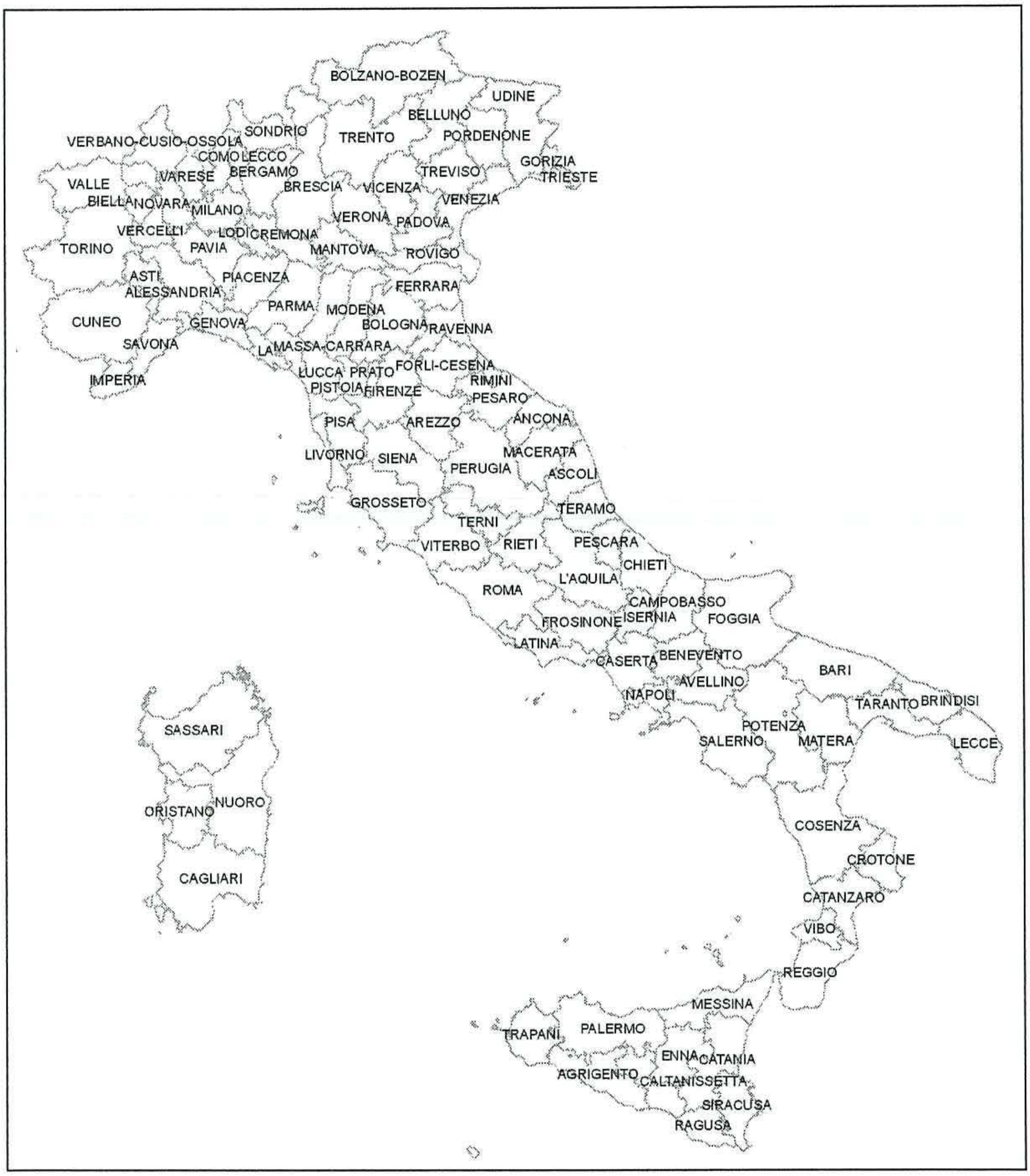
Appendix 4. Fertiliser application rates for Europe

Fertiliser application rates for Europe kg N ha^{-1} yr^{-1}.

Crop	Austria	Bel/LU	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Lux	Netherlands	Portugal	Sweden	Spain	UK
Wheat	115	150	137	80	155	147	93	168	90	150	185	80	110	85	192
Barley	95	110	80	74	110	133	89	110	85	110	80	60	78	77	125
Rye, oat, rice	70	90	73	70	100	98	95	96	100	90	80	60	68	71.8	113
Grain maize, incl. CCM	120	70	n	n	170	131	220	n	180	70	45	160	n	240	n
Potato	110	150	125	70	150	120	230	121	100	150	170	100	83	147	168
Sugar beet	85	120	110	120	130	124	140	183	90	120	105	150	100	180	110
Oilseed rape	125	150	140	90	145	140	n	150	80	150	180	100	110	110	203
Sunflower, soya, linseed	45	n	80	n	45	50	50	n	45	n	n	n	60	9	68
Pulses (peas, beans)	2	20	n	n	n	25	50	n	30	20	20	5	n	13	3
Vegetables	110	110	142	80	80	160	190	60	110	110	130	130	100	236	133
Fodder (legumes)	0	150	105	n	n	30	10	n	1	150	n	80	n	18	n
Fodder (others)	50	35	183	n	120	152	180	120	6.5	35	35	80	80	32	80
Silage maize	105	85	78	n	50	72	100	106	60	85	40	80	n	80	57
Others (incl. tobacco)	55	20	90	40	30	70	n	60	45	20	95	40	n	150	52
Perm. crops (fruit, vineyard)	36	50		40	35	35	59	n	70	50	60	48	n	54.2	50
Grassland fertilized	35	148	190	112	74	92	n	111	15	148	263	40	75	39	120
Set-aside, industrial crops	70	20	130	n	100	90	n	n	20	20	n	100	30	100	160
Fertilised forests	n	n	25	60	n	n	n	n	n	n	n	30	150	20	5

Appendix 5. Map of NUTS 3 level regions in Italy.

Map of Italy showing the NUTS 3 level regional names referred to in results section 6.1.



Glossary

Acronyms

BD	Bulk Density
BS	Base saturation
CEC	Cation Exchange capacity
CRPA	Centro Ricerche Produzione Animale
DEM	Digital Elevation Model
DG	Directorate General
EC	European Commission
EMEP	The Co-operative Programme for the Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe
ESB	European Soil Bureau
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FSS	Farm Structure Survey
GHG	Greenhouse Gas
GIS	Geographical Information System
GISCO	Geographic Information System for the European Commission
GWP	Global Warming Potential
HYPRES	Hydraulic Properties of European Soils
IEA	International Energy Agency
IFA	International Fertilizer Industry Association
IFDC	International Fertilizer Development Centre
IPCC	The Intergovernmental Panel on Climate Change
ISTAT	Italian Statistical Agency
JRC	Joint Research Centre
MARS	The Monitoring Agriculture and Regional Information Systems Unit
NUTS	The Nomenclature of Territorial Units for Statistics
OECD	Office of Economic Cooperation and Development
OM	Organic Matter
PD	Packing density
PTR	Pedotransfer Rules
SGBDB	Soil Geographical Database of Europe
SMU	Soil Mapping Unit
SOC	Soil Organic Carbon
SPADE	Soil Profile Analytical Database of Europe

STU	Soil Typological Unit
TRAGNET	U.S. Trace Gas Network
UNFCCC	United Nations Framework Convention on Climate Change
WFD	Water Framework Directive

Chemicals

NH_4HCO_3	Ammonium bicarbonate
NH_4NO_3	Ammonium nitrate
$(NH_4)_2SO_4$	Ammonium sulphate
NH_3	Anhydrous ammonia
CO_2	Carbon dioxide
$(NH_4)_2HPO_4$	Di-ammonium phosphate
HFC	Hydro fluorocarbon
CH_4	Methane
NO_3	Nitrate
N	Nitrogen
N_2O	Nitrous oxide
PFC	Per-fluorocarbons
SF6	Sulphur hexafluoride

UNITS

Gg	Gigagrams (tonnes x 10^3)
kg	kilograms (grams x 10^3)
T	Tonnes (kg x 10^3)
MT	Million (metric) tonnes
Pg	Petagrams(grams x $10^{15)}$
PPBV	Parts per billion by volume
Tg	Teragrams (grams x 10^{12})

References

Arah, J. R. M. and Smith, K. A. (1989) "Steady-state denitrification in aggregated soils: a mathematical model", Journal of Soil Science, vol. 40, pp 139-149.

Arcara, P.G., Gamba, C., Bidini, D. and. Marchetti, R. (1999) "The effect of urea and pig slurry fertilization on denitrification, direct nitrous oxide emission, volatile fatty acids, water-soluble carbon and anthrone-reactive carbon in maize-cropped soil from the Po plain (Modena, Italy)" Biological Fertility of Soils, vol. 29, pp 270–276

Augustin, J., Merbach, W. and Rogasik, J. (1998) "Factors influencing nitrous oxide and methane emissions from minertrophic fens in northeast Germany", Biological Fertility of Soils, vol. 28, pp 1-4.

Aulakh, M. S., Rennie, D. A. and Paul, E. A. (1984) "Gaseous Nitrogen losses from soils under zero-till as compared with conventional-till management systems", Journal of Environmental Quality, vol. 13, pp 130-136.

Ball, B. C., Scott, A. and Parker, J. P. (1999) "Field N_2O, CO_2 and CH_4 fluxes in relation to tillage compaction and soil quality in Scotland", Soil and Tillage Research, vol. 53, pp 29-39.

Bareth, G., Heincke, M. and Glatzel, S. (1999) "Estimation of Nitrous Oxide Emissions from agricultural Soils", Proceedings of Geoinformatics'99 Conference, Ann Arbor, pp 1-8.

Bareth, G., Heincke, M. and Glatzel, S. (2001) "Soil-land-use-system approach to estimate nitrous oxide emissions from agricultural Soils", Nutrient Cycling in Agroecosystems, vol. 60, pp 219-234

Bartholome, E., Belward, A. S., Achard, F., Bartalev, S., Carmona-Moreno, C., Eva, H., Fritz, S., Gregoire, J-M., Mayaux, P. and Stibig, H-J. (2002) Global Land Cover mapping for the year 2000. Project status November 2002, Technical report EUR20524, Series Office for Official Publications of the European Communities, Ispra.

Bates, J. (2001) "Economic evaluation of emission reductions of nitrous oxides and methane in agriculture in the EU. Bottom-up analysis. Feb 2001" in: Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change. Study for DG Environment. AEA Technology Report, Abingdon.

Boeckx, P. and Van Cleemput, O. (2001) "Estimates of N_2O and CH_4 fluxes from agricultural lands in various regions in Europe", Nutrient Cycling in Agroecosystems, vol. 60, pp 35-47.

Borjesson, G. and Svensson, B. H. (1997) "Nitrous oxide emissions from landfill cover soils in Sweden", Tellus vol. 49B, pp 357-363.

Bouwman, A.F. (1990) Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. In: Bouwman, A.F. (ed.), Soils and the greenhouse effect, Wiley and Sons, Chichester, pp. 61-127.

Bouwman, A. F. (1994) "Method to Estimate Direct Emission of Nitrous Oxide from Agricultural Soils", RIVM Report, 773004004. Bilthoven.

Bouwman, A.F. (1996) "Direct emission of nitrous oxide from agricultural soils", Nutrient Cycling in Agroecosystems, vol. 46, pp 53-70.

Bouwman, A. F. (1999) "Approaches to scaling of trace gas fluxes in ecosystems", Developments in Atmospheric Science, vol. 24, Elsevier Science, Amsterdam.

Bouwman, A.F., Boumans, L.J.M. and Batjes, N.H. (2002a) "Emissions of N_2O and NO from fertilized fields: Summary of available measurement data", Global Biogeochemical Cycles, vol. 16, 1058.

Bouwman, A. F., Boumans, L. J. M. and Batjes, N. H. (2002b), "Modeling global annual N_2O and NO emissions from fertilized fields", Global Biogeochemical Cycles, 16, 1080.

Brown, L., Syed, B., Jarvis, S. C., Sneath, R. W., Philips, V. R. and Goulding, K. W. T. (2002) "Development and application of a mechanistic model to estimate emission of nitrous oxide from UK agriculture", Atmospheric Environment, vol. 36, pp 917-928.

Butterbach-Bahl, K., Kesik, M., Miehle, P. and Li, C. (2004), "Quantifying the regional source strenth of N-trace gases across agricultural and forest ecosystems with process based models" Plant and Soil, vol. 260, pp 311-329.

Ciolkosz1, E.J. (2001) "The pH Base Saturation Relationships of Pennsylvania Subsoils", Agronomy Series Number 149, Department of Crop and Soils Sciences - The Pennsylvania State University, USA, November 2001, p12.

Chadwick, D., Misselbrook, T. and Pain, B. (1999) "Potential for reducing gaseous N emissions from high inputagriculture", Abstract in: 10th Nitrogen Workshop, 23-26 August 1999, Copenhagen.

Chao, C. C., Young, C. C., Wang, Y. P. and Chao, W. L. (2000) "Daily and seasonal nitrous oxide fluxes in soils from hardwood forest and different agroecosystems of Taiwan", Chemosphere: Global Change Science, vol. 2, pp 77-84.

Clayton, H., McTaggart, I. P., Parket, J., Swan, L. and. Smith, K. A. (1997) "Nitrous oxide emission from fertilised grassland: a two year study of the effect of N fertiliser form and environmental conditions", Biological and Fertility of Soils, vol. 25, pp 252-260.

Centro Ricerche Produzioni Animali (CRPA) (1999) A National Inventory of Ammonia and Greenhouse Gas Emissions from Agriculture in Italy, Centro Ricerche Produzioni Animali, Regio Emilia, Italy, 1 pp.

Cole, C.V., Duxbury, J., Freney, J., Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, N., Sauerbeck, D., and Zhao, Q. (1996) "Agricultural options for mitigation of greenhouse gas emissions". In: Climate Change 1995 - Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. R.T. Watson, M.C. Zinyowera, R.H. Moss, and D.J. Dokken (eds.), Cambridge University Press, Cambridge, pp. 745-771.

(CEC) Commission of the European Communities (2004) Report from the commission "catching up with the community's Kyoto target", Brussels, 20.12.2004 COM(2004) 818 final.

Crouzet, P. (2001) "Calculation of nutrient surpluses from agricultural sources - Statistics spatialisation by means of CORINE land cover - Application to the case of nitrogen", European Environment Agency, Technical report No. 51, Copenhagen, p 62.

Crutzen, P. J. (1981) "Atmospheric chemical processes of the oxides of nitrogen, including nitrous oxide" in: Denitifrification, Nitrification and Atmospheric Nitrous Oxide, C. C. Delwiche, Ed. John Wiley and Sons, New York, pp 17-44.

Dobbie, K.E. and Smith, K. (2003) "Impact of different forms of N fertiliser on N_2O emissions from intensive grassland", Nutrient Cycling in Agroecosystems", vol. 67, pp37-46.

(DOE) Department of the Environment (1987) "Handling Geographic Information: Report of the Committee of Enquiry Chaired by Lord Chorley", Her Majesties Stationary Office (HSMO), London.

(DETR) Department of the Environment, Transport and the Regions (1994) "The UK National Air QualityInformation Archive", [Available online from http://www.aeat.co.uk/netcen/airqual/reports/acidrain/nitdepb.html.]

Doluschitz, R., Bareth, G. and Hunder, S. (2002) "Integrating the Process-based Simulation model DNDC into GIS", In: Environmental Communication in the Information Society, Berger Druck, Horn, pp 649-654

Edwards, R., Griessmann, J. C., Larive, J. V. and Mahieu, V. (2003) "Well-to-wheels analysis of future automotive fuels and power trains in the European contex". Version 1b, December 2003. [Available online from http://ies.jrc.cec.eu.int.]

(EEA) European Environment Agency (2004) "Greenhouse gas emission trends and projections in Europe 2004", EEA report no. 5/2004. EEA, Copenhagen.

(EMEP) The Co-operative Programme for the Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (2001) EMEP measurement database [Available online from http://www.emep.int/]

Engel, T. H. and Priesack, E. (1993) "Expert-N a building block system of nitrogen models as a resource for advice, research, water management and policy". In:

Integrated soil and sediment research: A basis for proper protection, (Eds.: Eijsackers, H.J.P. and Hamers, T.) Kluwer Academic Publishers, Dordrecht, pp 503-507.

European Commission (2003) Farm Structure 1997 Survey. Theme 5 Agriculture and Fisheries. Series Office for Official Publications of the European Communities, Luxembourg.

(EUROSTAT) Statistical Office of the European Communities (2003) "The Geographic Information System of the European Commission (GISCO) reference database: Version: 07/2003", Brussels.

Flessa, H., Wild, U., Klemisch, M. and Pfadenhauer, J. (1998) "Nitrous oxide and methane fluxes from organic soils under agriculture", European Journal of Soil Science, vol. 49, pp 327-335.

Flessa, H., Ruser, R., Dorsch, P., Kamp, T., Jimenez, M.A., Munch, J.C. and Beese, F. (2002a) "Integrated evaluation of greenhouse gas emissions (CO_2, CH_4, N_2O) from two farming systems in southern Germany", Agriculture, Ecosystems and Environment, vol. 91, pp175-189.

Flessa, H., Ruser, R., Schilling, R., Loftfield, N., Munch, J.C., Kaiser, E.A. and Beese, F. (2002b) "N_2O and CH_4 fluxes in potato field:automated measurement, management effects and temporal variation", Geoderma, vol.105, pp 307-325.

The Food and Agriculture Organisation (FAO) (2003) FAO Statistics Division. Domain: Means of Production; Collection: Fertilizers [Available online from http://faostat.fao.org.]

Freibauer M. and Kaltschmitt M. (2000) "Biogenic emissions of greenhouse gases caused by arable and animal agriculture", In: Processes, inventories, mitigation. Stuttgart, Germany, Institute of Energy Economics and the Rational Use of Energy, p 144.

Freibauer A. and Kaltschmitt M. (2003): "Nitrous oxide emissions from agricultural mineral soils in Europe - controls and models", Biogeochemistry, vol. 63, pp 93-115.

Freibauer A., Mulligan D. T., and Smith P., (2004) "Importance of agricultural soils for the European greenhouse budget", International Conference on Greenhouse Gas Emissions from Agriculture - Mitigation Options and Strategies, Leipzig, Germany, 10-12 February 2004.

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

Gallego, J., C. Kayadjanian, and C. Vidal, (2001) "Geographical use of statistical data: Methodological overview", In: Towards agr-environmental indicators -

Integrating statistical and administrative data with land cover information. Topic report 6/2001. European Environment Agency, Copenhagen.

Goossens, A., De Visscher, A., Boeckx, P. and Van Cleemput, O. (2001) "Two-year field study on the emission of N_2O from coarse and middle-textured Belgian soils with different land use", Nutrient Cycling in Agroecosystems, vol. 60, pp 23-34.

Granli, T. and Bøckman, O. C. (1994) "Nitrous oxide from agriculture", Norwegian Journal of Agricultural Science Supplement, vol. 12, p 128.

Grant, B., Smith, W., Desjardins, R., Lemke, R and Li, C. (2003) "Estimated N_2O and CO_2 emissions as influenced by agricultural practices in Canada", Climatic Change, vol. 65, pp 315-332.

Groffman, P. M., Hardy, J. P., Nolan, S., Driscoll, C. T. and Fahey, T. J. (1999) "Snow depth, soil frost and nutrient loss in a northern hardwood forest", Hydrological Processes, vol. 13, pp 2275-2286.

Hartkamp, A. D., White, J. W., and Hoogenboom, G. (1999) "Interfacing geographic information systems with agronomic modeling: a review", Agronomy Journal, vol. 91, pp 761-772.

Henault, C., Devis, X..Page, S., Justes, E. Reau, R. and Germon, J.C. (1998) "Nitrous oxide emissions under different soil and land management conditions", Biology and Fertility of Soils, vol. 26, pp 199-207.

(IFA/FAO) International Fertilizer Industry Association / Food and Agriculture Organization of the United Nations (2001) "Global Estimates of Gaseous Emissions of NH_3, NO and N_2O from Agricultural Land", FAO, Rome, p105.

(IFA/IFDC/FAO) International Fertilizer Development Center (1999) "Fertilizer use by crop". 4th edition. FAO, Rome.

(IPCC) Intergovernmental Panel on Climate Change (1995) "Executive Summary" in: Climate Change 1994. The science of climate change, [J. T. Houghton, L. G. Meira Filho, J. Bruce, H. Lee, A. Callander, E. Haites, N. Harris, and K. Maskell, (eds)], Cambridge University Press, Cambridge, UK.

IPCC (1997) "Nitrous oxide and carbon dioxide in agriculture", In: OECD/IPCC/IEA phase II development of IPCC guidelines for natural greenhouse gas inventory methodology, Workshop Report. Geneva.

IPCC (2001a) "Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change" [Watson, R.T. and the Core Writing Team (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, pp 398.

IPCC (2001b) "Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change", [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X.

Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, pp 881.

(ISTAT) Instituto Nazionale di Statistica (2003) "Censimento Agricoltura" [Available online from www.istat.it.]

(IRRI) International Rice Research Institute (2004) "World Rice Statistics report - International Rice Research Institute", [Available online from http:/www.irri.org/science/ricestat/index.asp.]

Jambert, C., Serca, D. and Delmas, R. (1997) "Quantification of N losses as NH_3, NO and N_2O and N_2 from fertilised maize fields in south-western France", Nutrient Cycling in Agroecosystems, vol. 48, pp 91-104.

Joao, E. M., (1998) "Causes and consequence of map generalisation", Taylor and Francis, London.

Kaiser, E.A., Kohrs, K., Kucke, M., Schnug, E., Munch, J.C. and Heinemyer, O. (1998a) "Nitrous oxide release from arable soil: Importance of a perennial forage crop", Biology and Fertility of Soils, vol. 28, pp 36-43.

Kaiser, E.A., Kohrs, K., Kucke, M., Schnug, E., Heinemeyer, O. and Munch, J.C. (1998b) "Nitrous oxide release from arable soil: Importance of N-fertilisation, crops and temporal variation", Soil Biology and Biochemistry, vol. 30, pp 1553-1563.

Kammann, C., Grunhage, L., Muller, C., Jacobi, S. and Jager, H.J. (1998) "Seasonal variability and mitigation options for N_2O emissions from differently managed grasslands", Environmental Pollution, vol. 102, pp 179-186.

Kirkby, M.J., Jones, R.J.A., Irvine, B., Gobin, A, Govers, G., Cerdan, O., Van Rompaey, A.J.J., Le Bissonnais, Y., Daroussin, J., King, D., Montanarella, L., Grimm, M., Vieillefont, V., Puigdefabregas, J., Boer, M., Kosmas, C., Yassoglou, N., Tsara, M., Mantel, S., Van Lynden, G.J. and Huting, J. (2004) Pan-European Soil Erosion Risk Assessment: The PESERA Map, Version 1 October 2003. Explanation of Special Publication Ispra 2004 No.73 (S.P.I.04.73) European Soil Bureau Research Report No.16, EUR 21176, p 18.

Klemedtsson, L., Klemedtsson, A.K., Esala, M. and Kumala, A. (1999) "Inventory of N_2O emissions from farmed European peatlands: Proceedings of the workshop 'Biogenic emissions of GHG caused by arable land and animal agriculture'", Lokeburkg, Sweden.

Kroeze, C. and Seitzinger, S. P. (1998) "The impact of land use on N_2O emissions from watersheds draining into the North Eastern Atlantic Ocean and European seas", Environmental Pollution, vol. 102, pp 149-158.

Langeveld, C. A., Leffelaar, P. A and Goudriaan, J. (1997) "Modelling Nitrous Oxide Emissions at Various Scales", In: S.C. Jarvis and B. F. Pain, (eds). Gaseous Nitrogen Emissions from Grasslands, CAB International, Wallingford, UK, pp 331-337.

Leffelaar, P. A. (1988) "Dynamics of partial anaerobiosis, denitrification and water in a soil aggregate: Simulation", Soil Science, vol. 146, pp 427-444.

Li, C., Frolking, S. and 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, vol. 97, pp 9759-9776.

Li, C., Frolking, S. and Frolking, T. A. (1992) "A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model applications", Journal of Geophysical Research, vol. 97, pp 9777-9783.

Li, C., Frolking S., Crocker, G. J., Grace, P. R., Klir, J., Korchens, M., and Poulton, P. R. (1997) "Simulating trends in soil organic carbon in long-term experiments using the DNDC model", Geoderma, vol. 81, pp 45-60.

Li, C. (2000) "Modeling trace gas emissions from agricultural ecosystems", Nutrient Cycling in Agroecosystems, vol. 58, pp 259-276.

Li, C., (2002) "User's Guide for the DNDC Model version vDNDC7.7", Institute for the Study of Earth, Oceans and Space, University of New Hampshire, p 35. [Available online from http://www.dndc.sr.unh.edu/model]

Li, C. and Aber, A. (2000) "A process-orientated model of N_2O and NO emissions from forest soils: 1. Model development", Journal of Geophysical Research, vol. 105, pp 4369-4384.

Li, C., Mosier, A., Wassmann, R., Cai, Z., Zheng, X., Huang, Y., Tsuruta, H., Boonjawatt, J. and Lantin, R. (2004) "Modeling greenhouse gas emissions from rice-based production system: Sensitivity and upscaling", Global Biogeochemical Cycles, Vol. 18, pp 1-19.

(MAFF) Ministry of Agriculture, Fisheries and Food (2000), "Fertiliser Recommendations for Agricultural and Horticultural Crops (RB209 (Seventh edition)," MAFF Reference Book 209, The Stationery Office, London.

Merino, P., Estavillo, J.M., Besga, G., Pinto, M. and Gonzalez-Murua, C. (2001) "Nitrification and denitrification derived N_2O production from a grassland soil under application of DCD and Actilith F2", Nutrient Cycling in Agroecosystems, vol. 60, pp 9-14.

Ministerio dell'Ambiente, (1998) "Second National Communication under the Framework Convention on Climate Change", [Available online from http://www.miniambiente.it]

Montanarella, L. and Jones, R. J. A. (1999) "The European Soil Bureau. Soil resources of Europe", Office for Official Publications of the European Communities, Ispra, p 202.

Mogge, B., Kaiser, E.A. and Munch, J.C. (1999) "Nitrous oxide emissions and denitrification N-losses from agricultural soils in the Nornhoved Lake region:

Influence of organic fertilisers and land-use", Soil Biology and Biochemistry, vol. 31, pp 1245-1252.

Mosier, A., Schimel, D., Valentine, D., Bronson, K. and W. Parton. (1991) "Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands", Nature, vol. 350, pp 330-332.

Mosier, A.R., Duxbery, J.M, Frney, J.R., Heinemeyer, O. and Minami, K. (1996) "Nitrous oxide emissions from agricultural fields: Assessments, measurements and mitigation", Plant and Soil, vol. 181, pp 95-108.

Mosier, A, Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S. and van Cleemput, O. (1998) "Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle - OECD/IPCC/IEA phase II development of IPCC guidelines for national greenhouse gas inventory methodology", Nutrient Cycling in Agroecosystems, vol. 52, pp 225- 248.

Mucher, C.A., Steinnocher, K.T., Champeaux, J.L., Griguolo, S., Wester, K. and Loudjani, P. (1999) "Land Cover Characterization for Environmental Monitoring of pan-Europe", in: Nieuwenhuis G.J.A., Vaughan R.A., Molenaar M. (eds.), Operational Remote Sensing for Sustainable Development, A.A. Balkema, Rotterdam, pp.107-12.

Muller, C., Sherlock, R. R., Cameron, K. C., and Barringer, J. R. F. (1997) "Application of a mechanistic model to calculate nitrous oxide emissions at a national scale", in: Gaseous Nitrogen Emissions from Grasslands, CAB International, Wallingford, UK, pp 339-351.

Oenema, O., Velthof, G. and Kuikman, P. (2001) "Technical and policy aspects of strategies to decrease greenhouse gas emissions from agriculture", Nutrient Cycling in Agroecosystems, vol. 60, pp 301-315.

Parton, W. J., Schimel, D. S., Cole, C. V. and Ojima, C. V. (1994) "A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management." In: R.B. Bryant and R.W. Arnold (eds) Quantitive modelling of soil forming processes, SSSA Spec. Publ. 39. ASA, CSSA and SSA, Madison, WI, USA pp 147-167.

Paul, W. and Domsch, K. H., (1972) "Ein mathemathisches Modell für den Nitrifikationsprozeß im Boden ". Archives of Microbiology, vol. 87, 77-92.

Post, W. M., Emanuel, W. R. Zinke, P. J. and Stangenberger, A. G. (1982) "Soil carbon pools and world life zones", Nature, vol. 298, pp 156-159.

Potter, C. S., Matson, P. A., Vitousek, P. M, and Davidson, E. A. (1996) "Process modelling of controls on nitrogen trace gas emissions from soils worldwide", Journal of Geophysical Research, vol. 101, pp 1361-1377.

Rolston, D. E. and Marino, M. A. (1976) "Simultaneous transport of nitrate and gaseous denitrification products in soil", Soil Science Society of America Journal, vol. 40, pp 860-865.

Rounsevell, M. D. A., Evans, S. P., and Bullock, P. (1999) "Climate change and agricultural soils. Impacts and adaptation", Climatic Change, vol. 43, pp 683-704.

Rover, M, Heinemeyer, O. and Kaiser, E.A. (1998) "Microbial indiced nitrous oxide emissions from and arable soil during winter", Soil Biology and Biochemistry, vol. 30, pp 1859-1965.

Rover, M, Heinemeyer, O., Munch, J.C. and Kaiser, E.A. (1999) "Spatial heterogeneity within the plough layer: high variability of N_2O emission rates", Soil Biology and Biochemistry, vol. 31, pp 167-173.

Sahrawat, K. L. and Keeny, D. R. (1986) "Nitrous oxide emission from soils", Advances in Soil Science, vol. 4, pp 103-148.

Saltelli, A., Chan, K., and Scott, E. M. (2000) "Sensitivity Analysis", John Wiley and Sons, Chichester.

Schlesinger, W. H. (2000) "Carbon sequestration in soils: some cautions amidst optimism", Agriculture, Ecosystems and Environment, vol. 82, pp 121-127.

Smith, K.A. (1980) "A model of the extent of anaerobic zones in aggregated soils, and its potential application to estimates of denitrification", Journal of Soil Science, vol. 31, pp 263–277.

Smith, K. A., Thomson, P. E, Clayton, H., McTaggart, I. P., and Conen, F. (1998) "Effects of temperature, water content and nitrogen fertilisation on emissions of nitrous oxide by soils", Atmospheric Environment, vol. 32, pp 3301-3309.

Smith, K. A., Dobbie, K. E., Ball, B. C., Bakken, L. R., Sitaula, B. K., Hansen, S., Brumme, R., Borken, W. Christensen, S. and Prieme, A. (2000) "Oxidation of atmospheric methane in Northern European soils, comparison with other ecosystems, and uncertainties in the global terrestrial sink", Global Change Biology, vol. 6, pp 791-803.

Smith, P., Powlson, D. S., Glendining, M. J, and Smith, J. U. (1998) "Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming", Global Change Biology, vol. 4, pp 679-685.

Smith, P., Powlson, D. S., Smith, J. U., Falloon, P., and Coleman, K. (2000) "Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture", Global Change Biology, vol. 6, pp 525-539.

Smith, P., Goulding, K., Smith, K.A., Powlson, D.S., Smith, J.U., Faloon, P. and Coleman, K. (2001) "Enhancing the carbon sink in European agricultural soils: including trace gas fluxes in estimates of carbon mitigation potential", Nutrient Cycling in Agroecosystems, vol. 60, pp 237-252.

Smith, K.A., Ball, B.C., Conen, F., Dobbie, K.E., Massheder, J. and Rey, A. (2003) "Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes", European Journal of Soil Science, vol. 54, pp 779-791.

Spot Image (2004) "Spot Satellites: technical information" [Available online from http:/www.spot.com.]

Syring, K. M. and Benckiser, G. (1990) "Modelling denitrification losses from arable land", Mitteilungen der Deutschen Bodenkundlichen Gesellschaft, vol. 60, pp 404-406.

Tenreiro, J. E., (2000) Modelling N_2O fluxes at field and regional scale Contract No 14681-1998-12 F1ED ISP ES, University of Madrid, Spain, 46 pp.

(TRAGNET) United States Trace Gas Network (2000) "TRAGNET Database", [Available online from http://www.nrel.colostate.edu/projects/tragnet/]

Ojima, D., Mosier, A., Del Grosso, S. and Parton, W. (2000). "TRAGNET analysis and synthesis of trace gas fluxes", Global Biogeochemical Cycles, vol. 14, pp 995-997.

(UNFCCC) United Nations Framework Convention on Climate Change (2003) "Greenhouse Gas Inventory Database", [Available online from http://ghg.unfccc.int/.]

Van Beek, C.L., Hummelink, E.J.W., Velthof, G.L. and Oenema, O. (2004) "Denitrification in relation to groundwater level in a peat soil under grassland", Biology and Fertility of Soils, vol. 67, pp 233 - 244-xx.

Van Groenigan, J.W., Kasper, G.J., Velthof, G.L., Van den Pol-van Dasselaar, A. and Kuikman, P.J. (2004) "Nitrous oxide emissions from slurry maize fields under different fertiliser and slurry applications", Plant and Soil, vol. 263, pp 101-111.

Van Ranst, E. and Gellinck, B. (1998) "Inventory of Computer Models Using Soil Data - Evaluation of the usefulness of the European Soil Map and the EC Soil Analytical Database for computer models", EU report, Office for Official Publications of the European Communities, Luxembourg, p 111

Velthof, G.L., Kuikman, P.J. and Oenema, O. (2002) "Nitrous oxide emission from soils amended with crop residues", Nutrient Cycling in Agroecosystems, vol. 62, pp 249-261.

Vermoesen, A., Van Cleemput, O. and Hofman, G. (1996) "Long-term measurements of N_2O emissions", Energy Conservation Management, vol. 37, pp 1279-1284.

White, A., Cannell, M. G. R, and Friend, A. D. (2000) "The high-latitude terrestrial carbon sink: a model analysis", Global Change Biology, vol. 6, pp 227-245.

Willekens, A., Van Orshoven, J., and Feyen, J. (1998) "Estimation of the phenological calendar, Kc-curve and temperature sums for cereals, sugar beet, potato, sunflower and rapeseed across Pan Europe, Turkey and the Maghreb countries by means of transfer procedures", KUL, Leuven, p 46.