UNITED
NATIONS

Framework Convention
on Climate Change

Distr.
GENERAL

FCCC/SBSTA/2004/INF.4
28 May 2004

ENGLISH ONLY

SUBSIDIARY BODY FOR SCIENTIFIC AND TECHNOLOGICAL ADVICE
Twentieth session
Bonn, 16–25 June 2004

Item 3 (d) of the provisional agenda
Methodological issues
Issues relating to greenhouse gas inventories

Estimation of emissions from agriculture

Note by the secretariat[*]

Summary

Agricultural soils are an important source of greenhouse gas emissions (primarily nitrous oxide (N_2O)) for a number of Parties included in Annex I to the Convention. The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (1996 IPCC Guidelines), as elaborated by the *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC good practice guidance), contain methodologies that are being used by many Parties to estimate N_2O emissions from agricultural soils. These methodologies range from tier 1 methods using default emission factors to complex tier 2 methods using country-specific emission factors. Although the 1996 IPCC Guidelines and the IPCC good practice guidance have proved to be useful tools for the estimation of N_2O emissions from agricultural soils, some areas for further improvement have been identified. This document contains suggestions that could be considered by the IPCC in its work on the development of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and by Parties in the preparation of national greenhouse gas inventories.

---

[*] This note was prepared by the secretariat on the basis of input provided by Mr. Andre van Amstel.

CONTENTS

Annexes

I. Introduction

A. Mandate

1. The Subsidiary Body for Scientific and Technological Advice (SBSTA), at its seventeenth session, invited the Intergovernmental Panel on Climate Change (IPCC) to revise the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (1996 IPCC Guidelines) taking into consideration the relevant work under the Convention and the Kyoto Protocol, and to aim to complete the work by early 2006.[1] In response, the IPCC initiated this work in 2003 and agreed on the terms of reference, table of contents and work programme for the development of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (2006 IPCC Guidelines).

2. The SBSTA, at its nineteenth session, considered the initial information on methodological issues relating to the preparation of national greenhouse gas (GHG) inventories by Parties, contained in document FCCC/SBSTA/2003/INF.10, and decided to forward it to the IPCC for consideration. It also requested the secretariat to continue to cooperate with the IPCC and to provide more detailed information based on the latest available GHG inventory submissions by Parties and the results of the technical review of GHG inventories. Such information could serve as input to the planned IPCC meetings that will take place during the development of the 2006 IPCC Guidelines.[2]

B. Scope of the note

3. This note addresses methodological issues relating to the estimation of nitrous oxide (N_2O) emissions from agricultural soils.[3] It provides an overview of the relevant IPCC methodologies, a brief description of the methodological information that was submitted by Parties included in Annex I to the Convention (Annex I Parties) in their 2003 GHG inventory submissions, and brief information on other methods and models that have been developed by the scientific community to estimate N_2O emissions from agricultural soils.

C. Possible action by the Subsidiary Body for Scientific and Technological Advice

4. The SBSTA is invited to consider the information in this note and forward it to the IPCC for its consideration. Parties may wish to consider the information in this note when preparing their national GHG inventories.

II. Background

5. Nitrous oxide is an important GHG with a high global warming potential – 310 times that of carbon dioxide (CO_2) according to the IPCC (2001a) – which is produced naturally in soils and aquatic systems through the microbial processes of nitrification and denitrification (Firestone and Davidson, 1989). Anthropogenic activities, such as use of organic and artificial fertilizer, have an impact on the nitrogen cycle and lead to an increase of N_2O emissions (as well as other emissions, such as ammonia (NH_3) and oxides of nitrogen (NO_X)) from soils and livestock systems (Vitousek et al., 1997).

6. Nitrification is the two-step oxidation of ammonium (NH_4^+) through nitrite (NO_2^-) to nitrate (NO_3^-), in which N_2O is released as a by-product, but the exact mechanism of N_2O formation is not fully understood (e.g. Williams et al., 1992). Nitrification is the main process of N_2O production in oxic soils (Groffman, 1991).

---

[1] FCCC/SBSTA/2002/13, paragraph 14 (f).

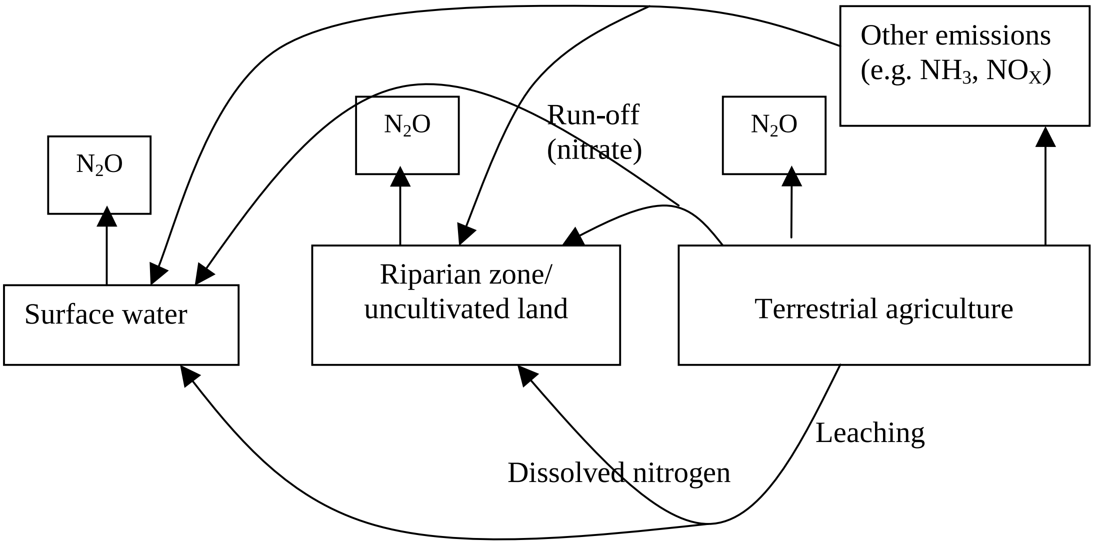
[2] FCCC/SBSTA/2003/15, paragraphs 17 (a) and (c).

[3] Methodological information on other sectors is provided in document FCCC/SBSTA/2004/INF.2 which deals with fugitive emissions from fuels and document FCCC/SBSTA/2004/INF.3 which deals with road transport.

7. Denitrification is the anaerobic process by which nitrogenous oxides, principally nitrite and nitrate, are reduced to N_2O and nitrogen (Tiedje, 1988). Under very low oxygen concentrations (in the range of 0–3 µmol/dm^3) all nitrate is reduced to nitrogen. However, at slightly higher oxygen concentrations (3–8 µmol/dm^3), the reduction of N_2O into nitrogen is reduced, leading to increased production and subsequent release of N_2O (Codispoti and Christensen, 1985). Hence, tiny differences in the local oxygen concentration can determine whether denitrification results in N_2O production or consumption.

8. Some agricultural activities, such as fertilizer use, add nitrogen to soils, increasing the amount of nitrogen available for nitrification and denitrification, and ultimately the amount of N_2O emitted. The emissions of N_2O that result from anthropogenic nitrogen inputs occur through both a direct pathway (directly from the soils to which the nitrogen is added) and through two indirect pathways (through volatilization as NH_3 and NO_X and subsequent redeposition, and through leaching and run-off of nitrate). An overview of the pathways of nitrogen and the related nitrous oxide emissions is given in figure 1.

Figure 1: Pathways of nitrogen and related nitrous oxide emissions



III. Methodologies according to the 1996 IPCC Guidelines and the IPCC good practice guidance

9. The methodology recommended in the 1996 IPCC Guidelines and the IPCC good practice guidance takes into account all nitrogen fluxes of the agricultural nitrogen cycle (IPCC, 1997; 2001b). Three sources of N_2O are distinguished in the IPCC methodology:

(a) Direct emissions from agricultural soils

(b) Direct emissions from animal production (including emissions from housing that are reported under Manure Management (section 4.2 of the 1996 IPCC Guidelines) – not discussed in this note)

(c) Emissions indirectly induced by agricultural activities.

10. Anthropogenic input of nitrogen to agricultural systems comes from, for example, synthetic fertilizer, animal wastes, and increased biological nitrogen-fixation from crops, as well as nitrogen derived from cultivation of mineral and organic soils through enhanced organic matter mineralization.

Nitrous oxide may be produced and emitted directly in agricultural fields, animal confinements or pastoral systems or may move from agricultural systems into ground and surface waters through surface run-off, nitrogen leaching, and consumption by humans and subsequent introduction into sewage systems which transport the nitrogen ultimately into surface water. Ammonia and NO_X emissions are also emitted from agricultural systems and may be transported off-site and serve to fertilize other systems which leads to enhanced production of N_2O.

11. The IPCC methodology gives default values for the parameters that are needed to estimate emissions from agricultural systems in temperate and tropical climates. The methodology does not take into account different crops, soils and climatic conditions, which are known to regulate N_2O production, because insufficient data are available to provide appropriate emission factors that reflect differences in crops, soils and climates. The method also uses a linear extrapolation between N_2O emissions and fertilizer nitrogen application, and in the indirect emissions section does not account for the lag time between nitrogen input and the resulting ultimate production of N_2O.

A. Direct nitrous oxide emissions from soils

12. Most studies on N_2O emissions from agricultural soils investigate the difference in N_2O production between fertilized and unfertilized fields. Emissions from unfertilized fields are considered background emissions, but actual background emissions from agricultural soils may be higher than historical natural emissions as a result of enhanced mineralization of soil organic matter. This is particularly observed in organic soils in cold, temperate and warm climates worldwide. Background emissions may also be lower than historical emissions due to depletion of soil organic matter (IPCC, 1997).

13. According to the IPCC methodology, the following sources of N_2O can be distinguished:[4]

(a) Synthetic fertilizers

(b) Animal excreta used as fertilizer

(c) Biological nitrogen fixation

(d) Crop residue and sewage sludge application

(e) Cultivation of soils with a high organic matter content.

B. Indirect nitrous oxide emissions from nitrogen used in agriculture

14. Pathways for synthetic fertilizer and manure input that give rise to indirect emissions considered in the 1996 IPCC Guidelines are volatilization and subsequent atmospheric deposition of NH_3 and NO_X (originating from the application of fertilizers), nitrogen leaching and run-off and human consumption of crops followed by municipal sewage treatment. Emissions from the formation of N_2O in the atmosphere from NH_3 or from food processing are not considered in the guidelines. Emissions of N_2O from human consumption of crops followed by municipal sewage treatment are accounted for under the Waste sector.

IV. Information reported by Annex I Parties

A. Methods and emission factors used by Annex I Parties

15. An overview of the methods and emission factors used by Annex I Parties to estimate N_2O emissions from agricultural soils is given in table 1. This information was extracted from the official 2003 GHG inventory submissions.

---

[4] Sewage sludge application is not considered in this note because either the emissions are negligible or there are not sufficient data to estimate emissions and removals.

Table 1: Overview of methods and emission factors used in the emission inventory to estimate nitrous oxide emissions from agricultural soils in 2001

Party	Methods	Emission factors
Australia	CS	CS
Austria	T1	D
Belarus	D	D
Belgium	CS	CS
Bulgaria	D	D
Canada	T1	D
Czech Republic	D	D
Denmark	CS, M	CS, M
Estonia	D	D
Finland	D	D/CS
France	T2	T2
Germany	CS	CS
Greece	T1	D
Hungary	D	CS
Iceland	D	D
Ireland	D	CS, D
Italy	D	D, CS
Japan	CS	CS
Latvia	T1	D
Luxembourg	C	C
Netherlands	CS/T1b	CS
New Zealand	D	CS, D
Norway	D	D, CS
Poland	T2	CS
Portugal	D	D
Romania	D	D
Slovakia	C, CS	C, D, CS
Spain	CS, D	CS, D
Sweden	D, C	CS
Switzerland	CS	CS
United Kingdom of Great Britain and Northern Ireland	T1a, T1b	D
United States of America	T1a, T1b	D

C = CORINAIR; D = default; CS = country specific; T1 = tier 1, T1a = tier 1a; T1b = tier 1b; T2 = tier 2; M = model

16. Most Annex I Parties estimate N_2O emissions from nitrogen use in agriculture and indirect emissions due to deposition and to leaching and run-off on the basis of the 1996 IPCC Guidelines tier 1 methodology, but a few use country-specific values for emission factors or other parameters that are needed for the estimation of emissions. In particular, some Annex I Parties use country-specific values for the amount of nitrogen that is produced from animals (nitrogen excretion) and lost from soils through leaching and run-off. Denmark was the only Annex I Party to report using a model to estimate N_2O emissions.

B. Alternative calculations to estimate nitrous oxide emissions

17. An alternative calculation was carried out using default emission factors (instead of the country-specific ones) and country activity data for the year 2001. The IPCC default emission factors for different categories within direct and indirect N_2O emissions are associated with relatively large uncertainty ranges. These ranges were taken into account to calculate low, medium and high estimates, as shown in table 2 where the total N_2O emissions from agricultural soils, resulting from this alternative

calculation, are presented. The results of a fourth calculation, based on the medium calculation and the replacement of the N_2O estimates from crop residues using national activity data with estimates based on activity data from the Food and Agriculture Organization of the United Nations (FAO) are also presented in table 2.

Table 2: Nitrous oxide emissions in 2001 from agricultural soils using default emission factors and country activity data

Party	Low estimate	Medium estimate	High estimate	Medium estimate and FAO data	Submitted data
Australia	21.70	91.49	144.26	115.60	62.21
Austria	1.49	9.13	32.23	8.86	11.42
Belarus	0.00	0.00	0.00	0.00	16.99
Belgium	0.00	0.00	0.00	0.45	16.82
Bulgaria	0.98	6.84	33.12	6.84	9.00
Canada	20.33	107.63	352.54	95.85	116.10
Czech Republic	2.55	15.50	61.82	14.06	16.84
Denmark	4.46	25.54	88.74	19.91	25.54
Estonia	4.19	21.10	39.46	0.82	1.04
Finland	5.00	10.75	27.91	10.30	12.05
France	243.88	1 245.18	2 569.43	281.01	175.96
Germany	36.04	129.06	448.60	126.14	128.52
Greece	32.50	159.64	283.95	19.14	19.46
Hungary	103.63	521.27	972.28	14.98	17.11
Iceland	0.02	0.12	0.22	0.12	0.20
Ireland	20.81	103.76	222.04	23.87	26.12
Italy	106.05	540.04	1 104.18	155.27	78.02
Japan	4.81	31.35	138.03	34.71	65.07
Latvia	0.73	2.67	9.51	2.42	3.09
Netherlands	3.31	20.47	27.41	21.39	23.12
New Zealand	17.86	80.26	240.20	63.46	39.19
Norway	3.12	7.50	21.87	7.53	9.25
Poland	22.73	49.27	75.22	47.41	52.82
Portugal	22.04	111.47	222.40	16.80	18.97
Romania	1.30	8.47	33.36	8.47	20.00
Slovakia	0.44	2.74	14.81	2.74	8.00
Spain	10.37	56.14	234.45	57.12	62.76
Sweden	50.09	239.29	445.99	17.24	8.00
Switzerland	40.57	203.30	385.12	26.45	8.28
United Kingdom	110.64	561.42	1 174.46	92.30	87.70
United States	177.23	948.19	3 016.18	901.07	1 008.98
Total	**1 068.87**	**5 309.59**	**12 419.79**	**2 192.33**	**2 158.63**

18. The medium estimate of the total amount of N_2O is more than twice the amount actually reported by Annex I Parties. This difference is primarily due to the emissions from crop residues. When the FAO activity data are used for crop residues, the total amount of N_2O emissions is much closer to the data submitted by Annex I Parties (for a breakdown of these emissions according to the IPCC subsectors see table 3). Although FAO data are considered to be the best available international statistics for agriculture, when comparing national activity data with FAO activity data some large differences were found, especially in the area of crop production. The reasons for these differences are not entirely clear and need further investigation.

Table 3: Nitrous oxide emissions from agricultural soils using default emission factors (medium estimate) and country activity data for IPCC subsectors in 2001

	IPCC subsectors										
Party	**Synthetic fertilizer**	**Organic fertilizer**	**Nitrogen-fixing crops**	**Crop residues**	**IPCC crop residues**[a]	**Histosols**	**Pasture range and paddock**	**Atmospheric deposition**	**Nitrogen leaching and run-off**	**Improved pasture**	**Total**[a]
Australia	20	4			1		68			23	**116**
Austria	2	2					1		3		**9**
Bulgaria	3							1	3		**7**
Canada	31	17	11	16	4		9	6	16		**96**
Czech Republic	4	3		2			1	1	5		**14**
Denmark	5	5	1	6			1	1	7		**20**
Estonia				20							**1**
Finland	3	1		1		4	1		1		**10**
France	46	28	124	967	3		19	10	51		**281**
Germany	36	24		4	1	17	9	8	32		**126**
Greece	6	1		142	1		11				**19**
Hungary	5	1	2	507				1	5		**15**
Ireland	8	1		80			9	2	3		**24**
Italy	14	8	97	389	4		7	4	20		**155**
Japan	10	7			3			2	12		**35**
Latvia	1								1		**2**
Netherlands	6	6			1		3			5	**21**
New Zealand	4	1	2	17			46	5	5		**63**
Norway	2	1				2	1		1		**8**
Poland	16	10	2	3	2	16	2				**47**
Portugal	3	2	1	95	1		5	1	4		**17**
Romania	5								3		**8**
Slovakia	1								1		**3**
Spain	20	6	1	2	3		11	6	12		**57**
Sweden	4	1	2	224		3	2	1	2	2	**17**
Switzerland	1	1	21	177			1	1	2		**26**
United Kingdom	22	8	16	471	1		15	5	23	1	**92**
United States	191	47	228	95	47	8	129	40	211		**901**
Total	**467**	**186**	**509**	**3 218**	**75**	**52**	**352**	**96**	**426**	**31**	**2 193**

[a] The “IPCC crop residues” column is an alternative calculation using FAO activity data; this column is used to estimate the total amount of N_2O emissions, instead of the column “Crop residues”.

V. Other methods and models to estimate nitrous oxide emissions

A. Models to estimate biogenic emissions of nitrous oxide

19. Various models are available to simulate the processes governing the natural and agricultural nitrogen cycle. Some of them also explicitly estimate emissions of GHGs, such as N_2O. Models of N_2O production are complex, because they must be able to model soil chemistry, microbiology, physics, and the soil microclimate – factors that all have a large influence on nitrogen transformation and diffusion of gases (Denmead, 1997). Most of the models described here focus on agricultural activities and not on the total nitrogen cycle. Thus, they do not take into account non-agricultural components such as uncultivated land and riparian zones, the subsoil, and the fresh-water system. Most process-based

models are not developed primarily to quantify indirect N_2O emissions, but sometimes it is possible to expand or adapt the models in such a way that they do include the estimation of indirect emissions due to leaching and run-off.

20. Eleven models are described below in terms of their suitability for quantifying direct and indirect N_2O emissions at the national level. These models have either been presented at national or international workshops and conferences or been published in scientific journals. Some of them are described in detail on the Internet. The models are presented in alphabetical order without any indication of preference.

1. CANDY

21. CANDY (CArbon–Nitrogen–DYnamics) is a process-based model developed by the German Centre for Environmental Research Leipzig-Halle (UFZ). It can be used to calculate nitrate leaching in arable and horticultural ecosystems in a cool temperate climate. The model inputs are daily weather data, plant development characteristics, soil texture data and information on agricultural management. Carbon and nitrogen dynamics are described for agricultural soils. The model is based on homogeneous soil layers of 10 cm thickness described by a set of state variables (e.g. coarseness). The model can make calculations at plot, field and catchment scale, but not at national scale (Franco et al., 1995). However, it is possible to extrapolate the model outputs for nitrate leaching and gaseous nitrogen losses to the national scale. The model is available on request at UFZ. CANDY has a user-interface that is connected to a databank that allows handling of the input data, start of the day step simulation, and forecasting of soil nitrate supply and organic matter content.

2. CASA

22. The Carnegie-Ames-Stanford Approach (CASA) biosphere model was developed in the United States by the National Aeronautics and Space Administration (NASA) Ames Research Center (Potter et al., 1993). CASA is an ecosystem model that integrates global satellite, climate, vegetation and soil data sets to examine nitrogen trace gas fluxes (including N_2O). The model uses remote sensing data to calculate net primary production. The CASA model is extended with an application for direct nitrogen emissions (Potter et al., 1996; 1997). CASA is limited to the terrestrial system, and does not model indirect emissions of N_2O. Moreover, simulations of complicated agricultural management systems with different types of fertilizers are not possible. The model has been applied at the global level and at the regional level in the United States and the Brazilian Amazon region.

3. DAISY

23. The Department of Agricultural Sciences of The Royal Veterinary and Agricultural University in Frederiksberg, Denmark, developed DAISY – a mathematical simulation model for the soil–plant system – to enable simulation of water dynamics and nitrogen dynamics in crop production for various agricultural management practices and strategies. The simulation of nitrogen dynamics can be performed in variable time-steps, and nitrogen losses and nitrate leaching are calculated (Hansen, 2002; Hansen et al., 1990). A simple parameter set with weather data and detailed descriptions of the soil profile are the basic inputs for the model. The hydraulic properties, the soil and crop management strategies and the drainage and irrigation properties complete the set of input parameters. DAISY is applicable for calculations in arable ecosystems in a cool temperate climate where snow cover and frost occur, but does not give a value for the fraction of nitrogen leaching ($FRAC_{LEACH}$) from the agricultural system, and does not model indirect N_2O emissions. Simulated annual balances of inorganic nitrogen show vast differences in the amount of nitrate leaching, ranging from 13 to 50 per cent of the total nitrogen applied to a field (Hansen et al., 1990). The software for the model is freely available on the Internet, including a manual (Abrahamsen, 1999) and a ‘start up’ tutorial (Abrahamsen, 2003). Some modelling experience is necessary for using the DAISY model. It is not known whether DAISY has been applied in countries other than Denmark.

4. DAYCENTURY/CENTURY-NGAS

24. DAYCENTURY/CENTURY-NGAS is an American/German ecosystem model developed by researchers of Colorado State University, the United States Department of Agriculture, and the German Max Planck Institute (Del Grosso et al., 2002). It simulates the terrestrial nitrogen, carbon, phosphorus and sulphur cycles on a daily basis, and can be used in different climatic regions. The model uses remote sensing data to calculate net primary production. It includes a number of submodels, one of which simulates fluxes of trace gases, including N_2O (Parton et al., 1996). The model does not cover leaching losses or indirect N_2O emissions. It has been successfully applied at the country level in the United States, but can also be applied at plot, regional and global scales.

5. DNDC

25. The denitrification–decomposition (DNDC) model was developed in the United States by the Institute for the Study of Earth, Oceans and Space at the University of New Hampshire to predict trace gas emissions from arable ecosystems (Li, 2000) in cool, temperate and tropical systems. The model has two submodels: one to simulate soil properties such as temperature, moisture and pH, and another to simulate nitrification and denitrification to estimate the emissions of nitrogen compounds such as NO, nitrogen and N_2O. It also predicts CO_2 emissions from decomposition. The DNDC model does not explicitly account for indirect N_2O emissions, but calculates nitrogen leaching from the agricultural system. The model simulates emissions in time steps of hours and days on the local, regional as well as on the national scales (DNDC, 2002). DNDC has been applied in different countries. In the United Kingdom is has been adapted to cover indirect emissions. For China it has been adapted to take account of information from all different provinces.

6. ECOSYS

26. ECOSYS, developed in Canada by the University of Alberta, is a comprehensive mathematical model for natural and managed ecosystems (Grant, 2001). The spatial scale of the model varies from micro-site to field scale in minute and hour integration time steps. The model output provides estimates of gases in solution (including N_2O) surface fluxes, nitrate uptake from each soil layer and soluble nitrogen concentrations. In the biochemical output of the model, concentrations of nitrogen and N_2O are presented for the gaseous and aqueous phases of each soil layer. Biological nitrate and N_2O reduction are also calculated. The model can be used for simulations in arable ecosystems in cool temperate (boreal) climates as well as in warm temperate subtropical climates. It is not known whether ECOSYS has been applied in countries other than Canada.

7. INITIATOR/NITROGENIUS

27. INITIATOR is a model developed to simulate the agricultural nitrogen cycle in the Netherlands (De Vries et al., 2003). Boundary conditions for INITIATOR are hydrological data that are calculated separately. The model output is geographically explicit and given on grid cells of 250 x 250 m to cover the whole of the Netherlands. The Netherlands is divided in about 6,000 map units, the spatial scale of which varies from a few to several thousand hectares. The model accounts for all major nitrogen fluxes, and can be used to quantify direct and indirect emissions of N_2O. INITIATOR takes into account interactions between the terrestrial system and the aquatic system. It is simple, but based on more detailed process-based models available for the Netherlands. The calculated N_2O emissions from aquatic systems are different from those estimated using the 1996 IPCC Guidelines, but it is difficult to validate the results because of lack of experimental data, in particular for indirect emissions (De Vries et al., 2003). The model was designed explicitly for calculating the agricultural nitrogen balance for the Netherlands.

8. N-MODEL

28. The N-MODEL was developed by Kroeze and Seitzinger (1998), but in contrast to the other models described here it was developed primarily to quantify N_2O emissions from aquatic systems. The model simulates emissions from rivers, estuaries and continental shelves as a function of human activities on the land. Following the 1996 IPCC Guidelines, the model also estimates terrestrial emissions of N_2O due to agricultural activities. The model also calculates the impact of fertilizer use, sewage and atmospheric deposition of nitrogen loading to aquatic systems and associated N_2O formation. The output of the agricultural based models mentioned in this section can serve as the input for the N-MODEL. For the terrestrial system, the background N_2O emission for non-agricultural soils is set to 0.5 kg N_2O-N per hectare. For synthetic fertilizer as well as for manure application 1.25 per cent of the nitrogen inputs is estimated as indirect N_2O emission. For aquatic systems the indirect N_2O emissions for both rivers and estuaries/shelves are 0.3–3 per cent of the nitrification and denitrification rates. The N-MODEL is a global model, and has been applied to 177 watersheds worldwide. Output is mainly on a grid of 1^o longitude by 1^o latitude. The model has not been developed for application to the national level. However, it has been successfully applied at the European level. Small adaptations to the model could make it suitable for national fresh-water systems.

9. OVERSEER

29. The OVERSEER model, developed by the Ministry of Agriculture and Forestry of New Zealand, is a decision-support system that assists farmers in New Zealand in nutrient management practices (MAF, 2003). It calculates the nutrient balance of grazing systems from stocking rates, production, supplementary feed, fertilizer inputs, rainfall, etc. OVERSEER is an empirical, annual time step model (Ledgard et al., 1999) which provides average estimates for the nutrients nitrogen, phosphorus, potassium and sulphur. OVERSEER can be used for scenario studies in assessing the environmental impact and sustainability of agricultural management. The nutrient budget at farm level is calculated and GHG emissions associated with the nitrogen cycle and fertilizer use are reported. OVERSEER can play a role in agriculture policy by assessing the environmental impact and sustainability of agricultural management. OVERSEER has been validated extensively using field data from different dairy farms in New Zealand (Ledgard et al., 1999). The model is freely available on the Internet (http://www.agresearch.co.nz/overseerweb/). The input is at farm level, but regional and national studies are also possible.

10. STONE

30. The STONE model was developed in the Netherlands and consists of three submodels – CLEAN, OPS/SRM and ANIMO. Boundary conditions for STONE are hydrological data that are calculated separately. The model was developed for evaluating the impact of changes in the agricultural system due to policy measures and focuses on nitrogen and phosphorus emissions from the agricultural sector to ground- and surface water in the Netherlands. It can generate spatial patterns of nitrogen and phosphorus leaching to the surface waters and the (upper) groundwater for subregions or for the Netherlands as a whole. Scenario analysis can be undertaken taking into consideration the impact of environmental policy measures on the reduction of nutrient emissions. The model has been thoroughly tested and validated for estimations of indirect N_2O emissions in the Netherlands. This model shows good performance in grassland and arable ecosystems in a cool temperate climate. The amount of nitrate leaching is calculated at different spatial scales and integration times. The model can be used for calculations at the national level. The model output can be input for other models calculating the N_2O forming processes after leaching and run-off of nitrogen components of the agricultural system (Beusen et al., 1999; Rijtema et al., 1995). The STONE model was recently successfully analysed and tested by De Willigen et al. (2003) and used to calculate nutrient emissions from agriculture in the Netherlands (Wolf et al., 2003). An extensive data set for the Netherlands is available for STONE calculations.

11. SUNDIAL

31. The SimUlation of Nitrogen Dynamics In Arable Land (SUNDIAL) model was developed in the United Kingdom in 1995 by Rothamsted Research (Smith et al., 1995) (www.rothamsted.bbsrc.ac.uk/aen/sundial/sundial.htm). The model interprets the effects of crop management, soil type and different weather patterns on nitrate leaching and is being used for simulating nitrogen dynamics in arable land. Nitrogen losses by crop uptake and nitrate leaching and in gaseous form (volatilization) are considered. The amount of nitrogen leaching is calculated and nitrate is assumed to be infinitely soluble in water and to move downwards at the same rate as the water in which it is dissolved. Nitrification and denitrification are assumed to occur only in the top 25 cm layer of the soil profile. Main weekly values are used as input and the results of the model calculations are presented on a weekly basis. It is not known if SUNDIAL has been applied for any country other than the United Kingdom.

B. Evaluation of the models

32. Ten models (all except N-MODEL, which was developed specifically to estimate emissions from aquatic systems) were evaluated using the criteria described in the table 4; the evaluations are shown in table 5. The purpose of this evaluation is not to determine which model is better or worse, but to provide GHG inventory experts with an understanding of the limitations and/or relative advantages of the models in terms of their application.

33. In addition to the evaluation presented in table 5, the following general observations can be made:

(a) All models simulate nitrification and denitrification for the agricultural cycle and almost all of them are able to calculate the amount of total nitrogen, nitrate, ammonium and mineral nitrogen formed during these processes;

(b) Simple temporal resolutions are usually sufficient for the purpose of inventories, but models with variable time steps can provide the user with results varying from hourly calculations to output on a daily, weekly or monthly basis;

(c) Models that use remotely sensed images for estimating global GHG emissions may not be easily adapted to specific calculations for indirect emissions from agricultural systems;

(d) Some of the models are specially designed to estimate nitrogen emissions from the agricultural sector to ground- and surface waters or quantify direct and indirect emissions of N_2O, whereas other models are designed as a decision support system to enable better nutrient management at farm level (e.g., DAISY, OVERSEER);

(e) Adaptation of the input parameters or modification of an existing model to a country-specific model is sometimes possible. For example, the United Kingdom successfully applied the DNDC model on adapted agricultural input data. With some modifications to DNDC or some of the other models it might be possible to estimate indirect N_2O emissions;

(f) None of the models calculates the fraction of fertilizer and manure nitrogen lost through leaching and run-off in the (non-)agricultural system.

Table 4: Explanation of the scores assigned to the criteria used for evaluation

Criteria	Explanation	Score
Availability	No free access/availability	1
	Available under conditions/on request	2
	Free access/Internet download	3
Transparency	No clear modelling explanation, not easily understood	1
	Processes are clearly modelled and easily understood	2
Documentation	No clear explanation of the meaning of processes in the model available	1
	Little and incomplete model explanation/not all processes are described	2
	Detailed users manual or step-by-step explanation of processes	3
Reliability	The model is not consistent	1
	The model is of moderate quality/or older model without update	2
	The model is consistent	3
Process based	Not process based	1
	Partly process based	2
	Fully process based	3
Input data set/ data requirements	Large and detailed input parameters needed. Information is difficult to obtain	1
	Medium parameter set for input with rather detailed information	2
	Small and basic parameter input. Simple dataset for meteorological and soil physical parameters	3
Temporal resolution/ variable time steps	Small resolution: only yearly input/output	1
	Medium resolution: with weekly/monthly/yearly input/output	2
	Large resolution with hourly/daily input/output and optional monthly/yearly results	3
Spatial resolution	The data are presented on field scale or farm level	1
	The data are presented on regional/national level	2
	The data are presented on various scales	3
Feasibility of scenario studies	Scenario studies are not possible	1
	Scenario studies are possible	2
Flexibility	The model is static: no changes possible	1
	Change of conditions and (dis)aggregation of sources possible	2
	The model can be easily adapted to new conditions and aggregation/disaggregation of sources is possible	3
Terrestrial/aquatic interactions	The model does not consider terrestrial/aquatic interactions	1
	The model does consider terrestrial/aquatic interactions	2

Table 5: Evaluation scores for 10 models

	Criteria										
Model	Availability	Transparency	Documentation	Reliability	Process based	Input data set/data requirements	Temporal resolution/ variable time steps	Spatial resolution	Feasibility of scenario studies	Flexibility	Terrestrial/aquatic interactions
CANDY	2	2	1	3	3	3	3	3	2	3	1
CASA	2	1	1	2	1	3	2	2	1	1	1
DAISY	3	2	3	3	3	2	1	2	2	3	1
DAYCENTURY/CENTURY-NGAS	3	2	3	3	3	1	3	2	2	3	1
DNDC	2	2	2	3	3	2	3	3	2	3	1
ECOSYS	1	1	2	2	3	3	3	3	2	3	1
INITIATOR/NITROGENIUS	2	2	3	3	3	3	1	2	2	3	2
OVERSEER	3	2	3	3	3	3	1	1	2	3	2
STONE	2	2	3	3	3	1	1	2	2	3	1
SUNDIAL	2	1	2	3	3	1	2	1	2	3	1

34. Frolking et al. (1998) compared CASA, DAYCENTURY/CENTURY-NGAS and DNDC models with respect to their performance in terrestrial systems. The models were run with minimal site-specific tuning, except for the hydraulic parameterization for the CASA and DNDC models. Adjustment of the soil texture class was necessary to achieve a better fit with the measured soil water contents. Nitrous oxide emissions were simulated with the models and compared with year-round field measurements from five sites in three countries (Germany, United Kingdom (Scotland) and United States (Colorado State)).

35. Frolking et al. (1998) concluded that to a large extent the models simulate similar processes for the general cycling of nitrogen through the agro-ecosystems, but use in some cases different algorithms for these processes. From a comparison of the modelled nitrogen gas fluxes with the measured nitrogen trace gas fluxes it was concluded that the calculated N_2O emissions were within a factor of about 2 of the observed annual fluxes. Moreover, when models produce similar N_2O fluxes, they differ greatly in their estimates for other trace gases (NH_3, NO and N_2).

36. None of the models in this comparison has satisfactory algorithms for winter denitrification, but algorithms for freeze–thaw effects on the N_2O:N_2 ratios of nitrogen gas production during denitrification (Melin and Nommik, 1983) are being developed for the CASA and DAYCENTURY/CENTURY-NGAS models.

37. DNDC overestimated the annual N_2O flux by a factor 5 to 15 compared to the observed data, caused by frost-induced denitrification in winter and simulation of denitrification-induced N_2O emissions following summer rains. The duration of denitrification in DNDC (as in other models) is influenced by the water content of the soil, and the flow of water through the soil. The different results for estimated N_2O fluxes are due to the use of different mechanisms and parameterization of the movement of water through the soil. The results of the DNDC model were found to be sensitive to rainstorm events data, after which the model estimated occasional denitrification peaks. This resulted in large N_2O peaks and an increased total annual flux compared to the field measurements. Frolking et al. (1998) did not find a direct correlation between the soil moisture results and the simulated N_2O, NO and nitrogen fluxes, because many components of each model are influenced by the soil moisture content. They concluded that additional field data on N_2O emissions and other components of the nitrogen cycle are necessary to evaluate models.

38. Frolking et al. (1998) did not draw a conclusion on which model was best for calculating direct and indirect N_2O emissions from the agricultural sector. The strengths and weaknesses of the models can be clarified by comparing results using the same input data.

39. DNDC has been successfully applied at the country level in the United Kingdom and the United States, and at the European level (EU–15), by the Soil and Waste Unit of the Institute for Environment and Sustainability of the Joint Research Centre of the European Union. For more information on the results of some applications for the DNDC model see annex I to this document.

VI. Conclusions

40. The N_2O emissions reported by Annex I Parties appear to represent a reasonable assessment of actual N_2O emissions from agricultural soils although there is scope to improve the accuracy of these estimates and reduce the associated uncertainties. The results of an alternative calculation performed demonstrated that when using the IPCC default method with FAO activity data for crop residues the calculated total N_2O emissions are in good agreement with the submitted data. There are differences between the activity data for crop production used by some Annex I Parties for their GHG inventories and statistical information published by FAO. These differences need to be investigated further to determine their causes and decide on possible action from the Parties.

41. The 1996 IPCC Guidelines encourage Parties to use national methodologies if they better reflect their national circumstances. Mechanistic process-based models (considered a tier 3 method), could be

applied to estimate N_2O from agricultural soils provided that care is taken to ensure that indirect N_2O emissions are also estimated. However, the use of such models should be considered provided that the extra effort of collecting input data with geographic detail results in a reduction of uncertainties.

42. Some of the models described in this document could be used as an alternative to the IPCC tier 1 or tier 2 methods if the models can be adapted for use in different countries. In the past this has been done, for example to DNDC for a number of countries (China, United Kingdom and European countries), whereas in the near future (in 2004) Germany will make an attempt to use DNDC for calculating its national budgets of emissions from the agricultural sector. The following general observations can be made about the use of DNDC and the IPCC methodology:

(a) The DNDC model requires a large amount of input data at the sub-national level compared to simple national statistics for the IPCC methodology

(b) The DNDC model depends on good quality meteorological data such as temperature and moisture compared to no meteorological data in the IPCC methodology

(c) The DNDC model depends on good quality soil organic carbon content data compared to the simple approach without soil types or with only two types in the IPCC methodology

(d) The DNDC model uses many assumptions on the driving forces for the N_2O emissions per soil type. However, these assumptions may not be supported by measurements published in refereed publications.

43. To improve N_2O emissions for agricultural soils it is imperative that the nitrogen cycle is realistically modelled. The IPCC could undertake a model comparison study to determine whether various models do indeed provide realistic modelling for the nitrogen cycle. Such an evaluation would assist national inventory experts in selecting specific models and would increase confidence in the modelled results.

44. Uncertainties need special attention in the indirect N_2O emissions. Uncertainties in model calculations for indirect N_2O emissions from agricultural systems will be reduced if more experimental data become available. This experimental research needs to focus on the indirectly quantified nitrogen fluxes that are used as the balance in nitrogen budgets. The inaccuracies as well as the concentration range of the data from field experiments must be quantified more precisely so that additional experimental studies can reduce the uncertainties in the input data of the models. However, if at field sites only N_2O emissions are measured, the performance of a model for the other gaseous nitrogen losses cannot be evaluated. The discussed models will converge on reasonable N_2O flux results, but that does not necessarily mean that they would yield a reasonable partitioning of total nitrogen gas losses. For calculating the nitrogen inputs and outputs based on experimental field data, statistical upscaling tools are needed to take into account large spatial and temporal variability of nitrogen fluxes. A more detailed scientific study on the processes involved will help to understand the underlying processes, and facilitate further development of the process-based models for nitrogen budget studies of agricultural systems (Kroeze et al. 2003).

Annex I

Results of some applications of the DNDC model

A. United Kingdom

1. Brown and Jarvies (2001) have extended a United Kingdom version of the model (United Kingdom-DNDC) so that it also quantifies indirect N_2O emissions due to leaching and run-off. The new methodology in the United Kingdom was developed by a team from the Institute of Grassland and Environmental Research (IGER), the Soil Survey and Land Research Centre, the Silsoe Research Institute and the Institute of Arable Crop Research. This model simulates the microbially mediated processes of decomposition and denitrification by which N_2O is produced from nitrogenous compounds within the soil on a daily basis. Development of this model required alteration of its input databases to include United Kingdom data, and also the inclusion of nitrogen input from grazing animals and applied animal wastes. United Kingdom data on soils, climate, animal numbers, crop areas and agricultural practices were collated, establishing new databases for the model. The model was used to estimate N_2O emissions for each of 18 agricultural crops in each county in the United Kingdom for each of the three dominant soil types of the country. The model was also used to estimate background emissions, assuming the absence of animals and fertilizer input. Predicted emission values for each run were used to calculate emission factors, comparable to those used in the IPCC methodology. Emission factors were calculated for each crop in each county for each nitrogen source (fertilizer, farm yard manure, slurry and nitrogen deposited while grazing), giving a total of 4,104 emission factors. These were presented, together with the nitrogen input data for each source for each crop for each county, in a user-friendly, transparent spreadsheet (Brown and Jarvis, 2001).

2. In order to compare the predictions of the United Kingdom-DNDC model with measured data, the model was validated by comparison with 16 sets of field measurements from contrasting soil, crop and fertilizer types. Agreement between measured and simulated data was generally good. This validation exercise is important to give confidence in the emission estimates produced by United Kingdom-DNDC, and it highlighted the need for more and better data, particularly for more frequent measurements and assessments of a wider range of crops (Brown and Jarvis, 2001).

3. Using the new model, the emission estimate from United Kingdom agriculture was 53 million kg N_2O–N for 1990. This comprised 31.5 million kg from soil (including applied nitrogen from fertilizer, farm yard manure, slurry and nitrogen excreted during grazing), 9 million kg from housed livestock and stored wastes and 12.7 million kg from indirect sources such as emissions from leached nitrogen and re-deposited ammonia. This estimate is lower than many previous estimates (including the IPCC approach with 63.5 million kg N_2O-N or 103.05 million kg N_2O for 1990). In addition to the emissions that United Kingdom-DNDC attributed to current agricultural practices, there were also large background emissions, which are not truly natural background emissions, but are influenced by the agricultural history of the land. Including this component brings the total emissions to 86 million kg N_2O–N. This component is not usually accounted for when emissions from agricultural land are estimated, which means that current IPCC methodologies may underestimate the actual emissions from agricultural land by about 40 per cent.

4. The United Kingdom-DNDC approach is much more flexible than the previous methodologies for estimating emissions, taking full account of United Kingdom-specific information on agricultural practices, as well as background data. The United Kingdom-DNDC model will be used to investigate the effect of abatement options and environmental properties on N_2O emissions (Brown and Jarvis, 2001).

B. EU-15

5. The EU-15 DNDC exercise was executed by Mulligan (2003). The DNDC results were compared with UNFCCC data for 2000 (see table 1).

Table 1: Comparison of UNFCCC and DNDC Joint Research Centre estimates for nitrous oxide emissions (in Gg) from agricultural soils, 2000

		Modelled DNDC		
Party	**UNFCCC 2000**	**High value**	**Low value**	**Mean value**
Austria	11.6	11.8	4.8	8.3
Belgium	16.9	11.1	4.5	7.8
Denmark	26.8	28.9	10.0	19.5
Finland	12.2	44.1	17.5	30.8
France	180.2	103.6	34.0	68.8
Germany	131.8	117.4	39.8	78.6
Greece	21.0	24.9	7.9	16.4
Ireland	27.0	16.3	7.3	23.6
Italy	77.1	128.4	44.9	86.7
Luxembourg	0.0	0.7	0.3	0.5
Netherlands	23.2	19.7	9.2	14.4
Portugal	19.0	34.3	13.5	23.9
Spain	66.4	72.4	25.9	49.2
Sweden	18.0			
United Kingdom	93.6	88.1	28.5	58.3
EU-15	**725.2**	**701.8**	**248.2**	**486.8**

6. With the exception of Finland, Italy and Portugal the mean DNDC results are lower than the official country submissions to the UNFCCC for 2000. However, it is unclear which version of the DNDC model was used for this work and whether indirect emissions were included in the modelled results.

7. The conclusions from this model exercise were that the results show a wide range of emission rates often exceeding the IPCC rate of 1.25 per cent of nitrogen applied. The totals are lower than the country results, which may be attributed to the DNDC results being related only to cropland emissions. Mulligan noted that the method is dependent on climate, rainfall and accuracy of the soil organic carbon data and that the results could be improved by more accurate crop and fertilization data.

C. China

8. Li et al. (2001) compared the process-based DNDC to the IPCC methodology for developing a national inventory of N_2O emissions in China. This China-DNDC was used to assess the N_2O emissions from arable lands in China, using input data and agricultural management data for the 2,500 counties in mainland China. The total cropland area for 1990 was 0.95 million km^2. Total nitrogen-fertilizer use in China in 1990 was 16.6 Tg nitrogen. The average fertilization rate was 175 kg nitrogen per ha cropland. China-DNDC estimated total N_2O emissions from arable land in China in 1990 at 0.31 Tg N_2O-N per year. Simulations with zero nitrogen-fertilizer input were also run; the difference between the zero-fertilizer and the baseline run is an estimate of fertilizer induced nitrous oxide emissions. The fertilizer induced emission was 0.13 Tg N_2O-N per year, about 0.8 per cent of total nitrogen-fertilizer use (lower than the mean but within the IPCC range of 1.25+1.0 per cent). These results were compared with estimates of county scale IPCC methodology emission estimates; the totals were similar but geographical patterns were quite different.

Annex II

References

Abrahamsen, P. 1999. *DAISY program reference manual*. Technical report 81, Dina KVL. Department of Agricultural Sciences, The Royal Veterinary and Agricultural University, Frederiksberg, Denmark.

Abrahamsen, P. 2003. *DAISY Tutorial.* Dina KVL. Department of Agricultural Sciences, The Royal Veterinary and Agricultural University, Frederiksberg, Denmark.

Beusen, A.H.W., H.L. Boogaard, P.A. Finke, R. Heida, B. Gehrels, P. Groenendijk, J.A. van Jaarsveld, O.M. Knol, G.B.J. Overbeek and E. Scheper. 1999. *STONE 1.2 Technische documentatie versie 1.0*, RIVM, Bilthoven, the Netherlands (in Dutch).

Brown, L. and S. Jarvis. 2001. Estimation of nitrous oxide emissions from UK agriculture. *Institute of Grassland and Environmental Research Innovations* 2001: 60–63.

Codispoti, L.A., and J.P. Christensen. 1985. Nitrification, denitrification and nitrous oxide cycling in the eastern tropical South Pacific Ocean. *Marine Chemistry*: 16:277–300.

DNDC. 2002. *Users guide for the DNDC model. DNDC 7.7*. Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, USA.

Del Grosso, S., D. Ojima, W. Parton, A. Mosier, G. Peterson and D. Schimel. 2002. Simulated effects of dryland cropping intensification on soil organic matter and greenhouse gas exchanges using the DAYCENT ecosystem model. *Environmental Pollution* 116 (2002): 75–83.

Denmead, C.C. 1997. Progress and challenges in measuring and modelling gaseous nitrogen emissions from grasslands: an overview. In: Jarvis S.C. and Pain B.F. (eds.) *Gaseous nitrogen emissions from grasslands* . CAB International, Wallingford, UK, pp. 423–438

De Vries, W., O. Kros, O. Oenema and J. de Klein. 2003 Uncertainties in the fate of nitrogen II: A quantitative assessment of the uncertainties in major nitrogen fluxes in the Netherlands. *Nutrient Cycling in Agroecosystems* 66: 71–102.

De Willigen, P., P. Cleij, H.P. Oosterom. C.G.J. Schotten. 2003. *Lot van het stikstofoverschot. Analyse van STONE-berekeningen die zijn uitgevoerd in het kader van Evaluatie Meststoffenwet 2002*. Alterra, Research Instituut voor de Groene Ruimte. Rapport 732 (in Dutch).

Firestone, M.K. and E.A. Davidson. 1989. Microbiological basis of NO and N_2O production and consumption in soil. In: Andreae, M.O. and D.S. Schimel (eds.), *Exchange of trace gases between terrestrial ecosystems and the atmosphere*. John Wiley and Sons Inc. New York, pp. 7–21.

Franco, U., B. Oelschlagel and S. Schenk. 1995. Simulation of temperature, water and nitrogen dynamics using the model CANDY. CATENA Verlag. *Ecological Modelling*. 81: 213–222.

Frolking, S.E., A.R. Mosier, D.S. Ojima, C. Li, W.J. Parton, C.S. Potter, E. Priesack, R. Stenger, C. Haberbosch, P. Dorsch, H. Flessa and K.A. Smith. 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* 52: 77–105.

Grant, R.F. 2001. A review of the Canadian ecosystem model ecosys. In: Shaffer M. (ed.) *Modeling carbon and nitrogen dynamics for soil management*. CRC Press. Boca Raton, FL, pp.173–264.

Groffman, P.M. 1991. Ecology of nitrification and denitrification in soil evaluated at scales relevant to atmospheric chemistry. In: Rogers, J.E. and W.B. Whitman (eds.) *Microbial production and consumption of greenhouse gases: methane, nitrogen oxides and halomethanes*. American Society for Microbiology, Washington DC, pp. 202–217.

Hansen, S. 2002. *Daisy, a flexible soil-plant-atmosphere system model: equation section 1. Model Description.* Department of Agricultural Sciences, The Royal Veterinary and Agricultural University, Frederiksberg, Denmark. http://www.dina.kvl.dk/~daisy/

Hansen, S., H.E. Jensen, N.E. Nielsen and H. Svendsen 1990. *DAISY – soil plant atmosphere system model.* Technical Report A10, Miljøstyrelsen. Department of Agricultural Sciences, The Royal Veterinary and Agricultural University, Frederiksberg, Denmark. http://www.dina.kvl.dk/~daisy/

IPCC. 1997. *IPCC 1996 revised guidelines for greenhouse gas inventories*. Intergovernmental Panel on Climate Change (IPCC), Institute for Global Environmental Strategies, Tokyo, Japan.

IPCC. 2000. *Land use, land-use change, and forestry*. Cambridge, UK, Cambridge University Press.

IPCC. 2001a. *Climate change 2001: The scientific basis* (Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change). Cambridge, UK, Cambridge University Press.

IPCC. 2001b. *Good practice guidance and uncertainty management in national greenhouse gas inventories.* Intergovernmental Panel on Climate Change (IPCC), Institute for Global Environmental Strategies, Tokyo, Japan.

Kroeze, C. and S.P. Seitzinger. 1998: The impact of land use on N_2O emissions from watersheds draining into the northeastern Atlantic and European seas. *Environmental Pollution* 102: 149–151.

Kroeze, C., R., Aerts, N. van Breemen, D. van Dam, K. van der Hoek, P. Hofschreuder, M. Hoosbeek, J. de Klein, H. Kros, H. van Oene, O. Oenema, A. Tietema, R. van der Veeren and W. de Vries. 2003. Uncertainties in the fate of nitrogen I: An overview of sources of uncertainty illustrated with a Dutch case study. *Nutrient Cycling in Agroecosystems* 66: 43–69.

Ledgard, S.F., P.H. Williams, F.D. Broom, B.S. Thorrold, D.M.Wheeler, V.J. Willis, I.K. Boddy. 1999. Overseer – a nutrient budgeting model for pastoral farming, wheat, potatoes, apples and kiwifruit. In: L.D. Currie, M.J. Hedley, D.J. Horne and P. Loganathan (eds.) *Best soil management practices for production*. Occasional report No. 12. Fertilizer and Lime Research Centre, Massey University, Palmerston North, pp. 143–152.

Li, C. 2000. Modeling trace gas emissions from agricultural ecosystems. *Nutrient Cycling in Agroecosystems* 58: 259–276.

Li C., Y. Zhuang, M. Cao, P. Crill , Z. Dai, S. Frolking, B. Moore III, W. Salas, W. Song, X. Wang. 2001. Comparing a process-based agro-ecosystem model to the IPCC methodology for developing a national inventory of N_2O emissions from arable lands in China. *Nutrient Cycling in Agroecosystems* 60: 159–175.

MAF. 2003. *The OVERSEER nutrient budget model and estimates of N leaching*. Ministry of Agriculture and Forestry, New Zealand. http://www.maf.govt.nz/mafnet/rural-nz/

Melin, J. and H. Nommik. 1983. Denitrification measurements in intact soil cores. *Acta Agriculturæ Scandinavica* 33:145–151.

Mulligan, D.. 2003. *An estimation of nitrous oxide emissions from agricultural soils within the EU15 using a mechanistic model*. Presentation for the Copenhagen Workshop 27–28 February 2003 by the Joint Research Centre.

Parton, W.J., A.R. Mosier, D.S. Ojima, D.W. Valentine, D.S. Schimel K. Weier and A.E. Kulmala. 1996. Generalized model for N_2 and N_2O production from nitrification and denitrification. *Global Biogeochemical Cycles* 10(3): 401–412.

Potter, C.S., J.T. Randerson, C.B. Field, P.A. Matson, P.M. Vitousek, H.A. Mooney and S.A. Klooster. 1993. Terrestrial ecosystem production: A process model based on global satellite and surface data. *Global Biogeochemical Cycles* 7(4): 811–842.

Potter, C.S., P.A. Matson, P.M. Vitousek and E.A. Davidson. 1996. Process modelling of controls on nitrogen trace gas emissions from soils worldwide. *Journal of Geophysical Research* 101(D1): 1361–1378.

Potter, C.S., R.H. Riley and S.A. Klooster. 1997. Simulation modeling of nitrogen trace gas emissions along an age gradient of tropical forest soils. *Ecological Modelling* 97: 179–196.

Rijtema, P.E., P. Groenendijk. J.G. Kroes and C.W.J Roest, 1995. *Formulating of the nitrogen and phosphorus behaviour in agricultural soils, the ANIMO model*. Report 30 of the Winand Staring Centre, Wageningen. Netherlands.

Smith, J.U., N.J. Bradbury and T.M. Addiscott. 1995. SUNDIAL: simulation of nitrogen dynamics in arable land. A user-friendly, PC-based version of the Rothamsted Nitrogen Turnover model. *Agronomy Journal* 88: 38–43.

Tiedje, J.M. 1988. Ecology of denitrification and dissimilatory nitrate reduction to ammonia. In: Zehnder, J.B. (ed.) *Biology of anaerobic microorganisms*. Wiley and Sons, New York, pp. 179–244.

Vitousek, P.M., J. Aber, R.W. Howard, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger and G.D. Tilman. 1997. Human alterations of the global nitrogen cycle: causes and consequences. *Issues in Ecology* 1: 1–17, Ecological Society of America.

Williams, E.J., G.L. Hutchinson and F.C. Fehsenfeld. 1992. NO_X and N_2O emissions from soil. *Global Biogeochemical Cycles* 6(4): 351–388.

Wolf, J., A.W.H. Beusen, P. Groenendijk, T. Kroon, R. Rötter and H. van Zeijts. 2003. The integrated modeling system STONE for calculating nutrient emissions from agriculture in the Netherlands. *Environmental Modelling and Software* 18: 597–617.

- - - - -