Calculation of nitrous oxide emission from agriculture in the Netherlands

Update of emission factors and leaching fraction

Alterra report 2151
ISSN 1566-7197

G.L. Velthof and J. Mosquera

Calculation of nitrous oxide emission from agriculture in the Netherlands

Commissioned by Agentschap NL, ROBP090110 and ROBP100139

Calculation of nitrous oxide emission from agriculture in the Netherlands

Update of emission factors and leaching fraction

G.L. Velthof[1] and J. Mosquera[2]

[1]Alterra, Wageningen UR
[2]Wageningen UR Livestock Research

Alterra report 2151
Alterra, part of Wageningen UR
Wageningen, 2011

Abstract

Velthof, G.L. and J. Mosquera. 2011. *Calculation of nitrous oxide emission from agriculture in the Netherlands. Update of emission factors and leaching fraction.* Wageningen, Alterra,. Alterrareport 2151. 66 blz.; 4 figs.; 17 tables.; .104 refs.

The Netherlands uses a partly country specific protocol for reporting of nitrous oxide (N2O) emissions to United Nations Framework Convention on Climate Change (UNFCCC). A study was conducted to update the N2O emission factors for nitrogen (N) fertilizer and animal manures applied to soils, based on results of Dutch experiments, and to derive a country specific methodology to calculate nitrate leaching using a leaching fraction (FracLEACH). The average emission factor for calcium ammonium nitrate (CAN) on mineral soils is similar for grassland (average ± standard error: 0.8 ± 0.1% of the N applied; n=26) and arable land (0.7 ± 0.3%; n=14). The emission factors for manure applied with low ammonia emission application techniques are on average higher for arable land (1.3 ± 0.3%; n=21) than for grassland (0.3 ± 0.1%; n=7). The emission factors for surface-applied manure are smaller, i.e. for arable land 0.6 ± 0.2% (n=6) and for grassland 0.1 ± 0.02% (n=5). The emission factor for CAN applied to peat soil is on average 3.0 ± 0.6% (n=4). The emission factors for livestock manure applied to peat soils were estimated using results from an incubation study; 1% for low ammonia emission application technique and 0.5% for surface-applied manure. It is recommended to use different emission factors for livestock manure applied to grassland and arable land and to update the emission factors for peat soil in the Dutch protocol. It is also recommended to use the STONE model to calculate N leaching from agriculture in the Netherlands. The FracLEACH (based on IPCC 1996) was calculated for three periods: 0.14 for 1987-1991, 0.13 for the period 1992-1997, and 0.12 for the period 1998-2008. The average FracLEACH in the Netherlands is lower than the default of IPPC (0.3), because of the large area of soils with a high denitrification capacity (and low leaching).

Keywords: agriculture, emission factor, fertilizer, manure, nitrous oxide, leaching, FracLEACH, STONE

ISSN 1566-7197

P.O. Box 47; 6700 AA Wageningen; The Netherlands, info.alterra@wur.nl

Alterra report 2151
Wageningen, April 2011

Contents

Summary

Agricultural soils are the main source of nitrous oxide (N_2O) emissions in the Netherlands, and accounted for 56% of national N_2O emissions in 2006. The N_2O emissions from agricultural soils consist of direct emissions through application of animal manures and fertilizers to soils, and indirect emissions from nitrogen leaching and run-off from emissions of ammonia and nitrogen oxides (NH_3 and NO_x). The Intergovernmental Panel on Climate Change (IPCC) has provided a general framework for the calculation of the emission of greenhouse gases (including N_2O) at the national level. These guidelines have been applied to the case of the Netherlands resulting in a number of partly country specific monitoring protocols. The Netherlands uses these protocols for reporting of greenhouse gas emissions to United Nations Framework Convention on Climate Change (UNFCCC).

In 1990, the reference year for Kyoto, all manures[1] were surface-applied to the soil of both grassland and arable land. Because of the Netherlands' policy to reduce NH_3 emissions, only low NH_3 emission manure application techniques are allowed since the early 1990's. In a field experiment in the Netherlands, it was found that on both grassland and maize land, (shallow) injection of manure increased the emission factor of N_2O in comparison to broadcast application. Moreover, the results showed differences in N_2O emission factors for grassland and arable land and it was suggested to use separate emission factors for grassland and arable land. Agentschap NL asked Alterra and Wageningen UR Livestock Research to conduct a study (project ROBP090110) in order to:

- update the data-base with N_2O emission factors for N fertilizer and manures, obtained in field experiments carried out in the Netherlands;
- carry out a literature study on emission factors from fertilizers and manures in countries with similar agricultural conditions as the Netherlands, with focus on the effect of manure application technique and land use on N_2O emission;
- estimate the N_2O emission factor for manure applied to peat soil, using data of the incubation experiment of Velthof et al. (2010a; 2010b) and field experiments on sand, clay, and peat soils of Velthof et al. (1996);
- derive average N_2O emission factors for calcium ammonium nitrate (CAN) and animal manures in the Netherlands, including an indication of the uncertainty of these emission factors.

In addition to the direct emissions of N_2O obtained in the Netherlands from managed soils that occur through a direct pathway (i.e., emission directly from the soils to which N is applied), emissions of N_2O also take place

---

[1] In this report the term manure is used as general term for the manures of cattle and pigs. In the Netherlands, slurries are by far the dominant manure type for cattle and pigs. Definitions:
- Manure. A general term to denote any organic material that supplies organic matter to soils together with plant nutrients, usually in lower concentrations compared to inorganic fertilizers.
- Slurry. Feaces and urine produced by housed livestock, usually mixed with some bedding material and some water during management to give a liquid manure with a dry matter content ranging from about 1 - 10%. Liquid manure denotes any manure from housed livestock that flows under gravity and can be pumped.

Source: Recycling Agricultural, Municipal and Industrial Residues in Agriculture Network (RAMIRAN) www.ramiran.net/DOC/Glossary2003.pdf through two indirect pathways, i.e. ammonia emission and nitrate leaching. In the IPCC methodology a leaching fraction (FracLEACH) is used to estimate the nitrate leaching and runoff. The leaching is multiplied with an emission factor for indirect N_2O emission from leaching (EF5). Agentschap NL also asked Alterra to assess if it is possible to derive a country specific leaching fraction (FracLEACH) for the Netherlands and to evaluate the N_2O emission factor for leaching (EF5) (project ROBP100139).

The data-base with N_2O emission factors was updated. The data-base contains in total 153 emission factors and includes emission factors for mineral N fertilizers, livestock manures, urine excreted during grazing and crop residues. The average emission factor is 1.3% of N applied; the standard error is 0.2%. In some of the experiments N_2O emissions were measured for only a short period (several weeks). If the short experiments are removed from the data-base (i.e. only experiments which last at least a full growing season of about six months are included), the average N_2O emission factor obtained from experiments in the Netherlands is 1.2 ± 0.1 % (n = 130).

The average emission factor for CAN on mineral soils is similar and not statistically significant for grassland and arable land (Table S1). The differences in CAN-derived emissions between arable land and grassland found in the experiment of Velthof et al. (2010) and Velthof and Mosquera (2011) are not shown in the total data-base with all emission factors obtained in the Netherlands. It is recommended not to change the emission factor of CAN, i.e. 1% for mineral soils, although the average N_2O emission factor for CAN in the Netherlands is slightly smaller (0.8%; Table S1).

The N_2O emission factors for manure applied to mineral soils with low NH_3 emission techniques is on average higher for arable land (1.3 ± 0.3%) than for grassland (0.3 ± 0.1%; Table S1). This difference is statistically significant at $\alpha = 0.1$. The emission factor for surface-applied manure is higher for arable land (0.6 ± 0.2%) than for grassland (0.1 ± 0.02%), which is statistically significant at $\alpha = 0.05$. For grassland, the N_2O emission factor for manures applied with low NH_3 emission techniques (0.3 ± 0.1%) were statistically significant higher ($\alpha = 0.05$) than that for surface-applied manure (0.1 ± 0.02%). For arable land, the difference in N_2O emission factor for manures applied with low ammonia emission techniques (1.3 ± 0.3%) and for surface-applied manure (0.6 ± 0.2%) was not statistically significant ($\alpha = 0.1$). However, the comparative field experiments carried out during a three-years period by Velthof and Mosquera (2011) showed that application of manure with low ammonia emission techniques resulted on average in statistically significant ($\alpha = 0.05$) higher N_2O emission than surface-application of manure, for both grassland and arable land.

The literature study showed higher N_2O emission factors for mineral fertilizer applied to soils (1.9% of the mineral fertilizer N applied to both grassland and arable land) than found in the Netherlands. There was no clear effect of N fertilizer type. There are only a limited number of studies in literature in which the effect of manure application technique on N_2O emission has been quantified. In most studies, manure application with low NH_3 emission technique increases N_2O emission.

The emission factor for CAN applied to peat soil is for the Netherlands on average 3.0 ± 0.6%, which is higher than the N_2O emission factor of 2% used in the current protocol. The emission factors for livestock manure applied to peat soils were calculated using the results from an incubation study. The estimated emission factor for manures applied to peat soils with a low ammonia emission application technique is 1% and that for surface-applied manures 0.5% (see Table S1).

We recommend the following changes in emission factors to be used for quantification of N_2O emission from fertilized soils (Table S2):

- Use different emission factors for livestock manure applied to grassland (0.1% for surface-applied manure and 0.3% for manure applied with low ammonia emission) and arable land (0.6% for surface-applied manure and 1.3% for manure applied with low ammonia emission).

- Use for peat soils an emission factor of 3% for CAN, 1% for manure applied with a low ammonia emission technique, and 0.5% for surface-applied manure.
- Use the current N2O emission factor for CAN applied to mineral soils, i.e. 1%.

Tabel S1
Average N_2O emission factors (in % of N applied) and standard errors for CAN and livestock manure in the Netherlands, based on the data set with emission factors obtained from experiments in the Netherlands. The emission factors for manure applied to peat soil were calculated from results from an incubation study.

Soil type	Source	Applicationtechnique	Land use		
			Arable land	Grassland	All
Mineral soils	CAN		0.7 ± 0.3 (n=14)	0.8 ± 0.1 (n=26)	0.8 ± 0.1 (n=40)
	Livestock manure	Low emission	1.3 ±0.3 (n=21)	0.3 ± 0.1 (n=7)	1.1 ± 0.2 (n=28)
		Surface	0.6 ± 0.2 (n=6)	0.1 ±0.02 (n=5)	0.4 ± 0.2 (n=11)
Peat soil	CAN			3.0 ± 0.6 (n=4)	
	Livestock manure	Low emission		1*	
		Surface		0.5*	

*estimated from an incubation study

In the Dutch manure policy two models are used to estimate nitrate leaching, i.e. the WOG-model, a model developed to underpin N application standards in the Netherlands, and the STONE-model, a model used to evaluate environmental consequences of manure policy. The submodel ANIMO is used to calculate the nitrate leaching in STONE. Both the WOG-model and STONE-model can be used to calculate a country specific FracLEACH for the Netherlands.

It was concluded that STONE is more suitable for calculation of an average FracLEACH in the Netherlands than the WOG-model, because i) it is developed for national scale (includes detailed maps of soil types, land use and groundwater levels), ii) it contains a fertilizer and manure distribution model, which is also used by the Pollutant Release & Transfer Register for the calculation of regional ammonia emissions, and iii) it includes both a calculation module for leaching and for surface runoff (overland flow). The leaching fractions of the WOG model are only based on leaching to groundwater, not on surface runoff.

An analyzis of STONE results showed that FracLEACH may change in time. Therefore, it is recommended to calculate FracLEACH for three periods:

- 1987 - 1991: to be used as the average for the year 1990 (the reference year);
- 1992 - 1997: the period with relative high N inputs to soils and in which farmers were obliged to apply manure with a low ammonia emission technique (this was not yet obliged in 1990);
- 1998 - 2008: the period in which the N inputs to soils strongly decreased in the Netherlands, and low ammonia emission application techniques were obliged.

Table S2

Emission factors for direct N_2O-N emission from agricultural soils (% of N input) according to current protocol and the recommended changes in emission factors .

N source	Current protocol[1]		Recommended changes[1]	
	Mineral soil	Organic soil	Mineral soil	Organic soil
Fertilizer application				
ammonium fertilizer (no nitrate)	0.5	1.0		
other types of fertilizer	1.0	2.0		3.0
Animal manure application grassland				
above-ground (surface spreading)	1.0	2.0	0.1	0.5
low-ammonia emission application	2.0	2.0	0.3	1.0
Animal manure application arable land				
above-ground (surface spreading)	1.0	2.0	0.6	
low-ammonia emission application	2.0	2.0	1.3	
Meadow manure livestock				
faeces	1.0	1.0		
urine	2.0	2.0		
Nitrogen fixation	1.0			
Crop residues	1.0			
Cultivation of histosols		2.0		
Sewage sludge	1.0			

[1] Emission factors current protocol are based on nett N input, i.e. the N input corrected for ammonia emissions after application. The recommendations are based of total N input (without correction for ammonia emission)

The leaching fractions are calculated using the leaching derived from the STONE model and the total N inputs according the Pollutant Release and Transfer Register). The FracLEACH (based on IPCC-1996 methodology) was calculated for the three periods: 0.14 for 1987-1991, 0.13 for the period 1992-1997, and 0.12 for the period 1998 - 2008.

There are no results from the Netherlands (both measurements and modeling) to derive specific N_2O emission factors for the indirect N_2O emission from leached nitrate in the Netherlands (EF5). For the first budget period of the Kyoto protocol (2008-2012), the Netherlands is obliged to use the IPCC-1996 method. However, it is recommended to use the IPCC-2006 emission factors for indirect N_2O emission derived from leached nitrate in the following budget period, as the most recent scientific insights are used for underpinning the IPCC-2006 emission factor.

1 Introduction

Agricultural soils are the main source of nitrous oxide (N_2O) emissions in the Netherlands, and accounted for 56% of national N_2O emissions in 2006. The agricultural N_2O emissions consist of direct emissions through application of animal manures and fertilizers to soils, and indirect emissions from nitrogen leaching, run-off and ammonia (NH_3) emission.

The Intergovernmental Panel on Climate Change (IPCC) has provided a general framework for the calculation of the emission of greenhouse gases (including N_2O) at the national level. These guidelines have been applied to the case of the Netherlands resulting in a number of partly country specific monitoring protocols, which are published by the Ministry of Housing, Spatial Planning and the Environment (VROM) and yearly updated, if needed (www.greenhousegases.nl). The Netherlands uses these protocols for reporting of greenhouse gas emissions to United Nations Framework Convention on Climate Change (UNFCCC).

The monitoring protocols used in the Netherlands to calculate the emission of N_2O differentiate between two manure[2] application techniques: broadcast application and application with low NH_3 emission techniques (see Table 1).

The N_2O emission factors used in the Netherlands for broadcast application (1% of applied N) are lower than for low NH_3 emission manure application techniques (2% of applied N). In 1990, the reference year for Kyoto, all manure was broadcast to the soil of both grassland and arable land. Because of the Netherlands' policy to reduce NH_3 emissions, only low NH_3 emission manure application techniques are allowed since the early 1990's.

---

[2] In this report the term manure is used as general term for the manures of cattle and pigs. In the Netherlands, slurries are by far the dominant manure type for cattle and pigs. Definitions:

- Manure. A general term to denote any organic material that supplies organic matter to soils together with plant nutrients, usually in lower concentrations compared to inorganic fertilizers.
- Manure. Feaces and urine produced by housed livestock, usually mixed with some bedding material and some water during management to give a liquid manure with a dry matter content ranging from about 1 - 10%. Liquid manure denotes any manure from housed livestock that flows under gravity and can be pumped.

Source: Recycling Agricultural, Municipal and Industrial Residues in Agriculture Network (RAMIRAN) www.ramiran.net/DOC/Glossary2003.pdf

Table 1

Emission factors for direct N_2O emission from agricultural soils in the Netherlands (% of nett N input), i.e. the N input corrected for ammonia emissions after application (Van der Hoek et al., 2007).

N source	Mineral soil	Organic soil
Fertilizer application		
ammonium fertilizer (no nitrate)	0.5	1.0
other types of fertilizer	1.0	2.0
Animal manure application		
above-ground (surface spreading)	1.0	2.0
low-ammonia emission application	2.0	2.0
Meadow manure livestock		
faeces	1.0	1.0
urine	2.0	2.0
Nitrogen fixation	1.0	
Crop residues	1.0	
Cultivation of histosols		2.0
Sewage sludge	1.0	

The effect of manure application technique on N_2O emission was quantified in field experiments (2007-2009) and incubation experiments of Velthof et al. (2010; the results of the field experiments are published in Velthof and Mosquera, 2011). The aim of these experiments was to derive N_2O emission factors for shallow injected cattle manure (on grassland), injected cattle and pig slurries (on maize land) and broadcast slurries. Shallow injection is the most used NH_3 abatement application method in the Netherlands for grassland and injection for maize land. In the experiments, a treatment with calcium ammonium nitrate (CAN) was included, because it is the most used mineral N fertilizer in the Netherlands. In line with the IPCC Guidelines, emission factors were derived after correction for N_2O emission from unfertilized plots. On both grassland and maize land, (shallow) injection of manure increased the emission factor of N_2O in comparison to broadcast application (Table 2). The average emission factor for grassland (based on both grassland sites and all years) was 1.7% of the N applied for CAN, 0.4% for shallow injected cattle manure, and 0.1% for broadcast cattle manure (Table 2). The average emission factor for CAN applied to maize land was 0.1% of the N applied. The average emission factor of cattle manure injected to maize land was 0.9% and that of broadcast cattle manure was 0.4%. The average emission factor of injected pig manure was 3.6% and that of broadcast pig manure 0.9%. The high emission factor of injected pig manure was mainly due to the high emission factor in the wet year 2007 (7.0% of the applied N).

The field experiments were carried out on sandy and clay soils and can be used to derive N_2O emission factors for mineral soils. However, about 15 percent of the grasslands in the Netherlands are located on peat soils. An incubation study was conducted to quantify the N_2O emission from cattle manure applied to peat, sand, and clay soils (Velthof et al., 2010b). The calculated N_2O emission factors in the incubation study were higher than generally found in field experiments. However, the ratio in emission factors between fertilized peat soil and fertilized mineral soil in this incubation study and results of other field studies can be used to estimate N_2O emission factors for manure applied to peat soil under field conditions.

Table 2 '

Average N_2O emission factors obtained in the field experiments of Velthof and Mosquera (2011) on mineral soils and the emission factors according to the current protocol (see Table 1).

Land use	Fertilizer and manure application technique	Emission factor experiments, %	Emission factor current protocol[1], %
Grassland	CAN	1.7	1 (0.97)
	Cattle manure; shallow injection	0.4	2 (1.7)
	Cattle manure; broadcast	0.1	1 (0.8)
Arable land	CAN	0.1	1 (0.97)
	Cattle manure; injection	0.9	2 (1.7)
	Cattle manure; broadcast	0.4	1 (0.8)
	Pig manure; injection	3.6	2 (1.7)
	Pig manure, broadcast	0.9	1 (0.8)

[1] The figures in between brackets are the emission factors based on total N input, i.e. not corrected for ammonia emission. The emission factors of Velthof and Mosquera (2011) are based on uncorrected N inputs

Velthof and Mosquera (2011) concluded on basis of their results (Table 2) that on both grassland and maize land, (shallow) injection of manure increased the emission factor of N_2O in comparison to broadcast application. Moreover, the results showed significant differences in N_2O emission factors for grassland and arable land. It was therefore suggested to use separate emission factor for grassland and arable land.

Agentschap NL asked Alterra and Wageningen UR Livestock Research to conduct a study (project ROBP090110) in order to:

- update the data-base with N_2O emission factors obtained in field experiments carried out in the Netherlands with the results of Velthof and Mosquera (2011) and other recent studies;
- carry out a literature study on emission factors from fertilizers and manures in countries with similar agricultural conditions as the Netherlands, with focus on the effect of manure application technique and difference in N_2O emission between grassland and arable land;
- estimate the N_2O emission factor for manure applied to peat soil, using data of the incubation experiment of Velthof et al. (2010) and field experiments on sand, clay, and peat soils of Velthof et al. (1996);
- to derive average emission factors for calcium ammonium nitrate (CAN) and animal manures in the Netherlands, including an indication of the uncertainty of these emission factors.

In addition to the direct emissions of N_2O from managed soils that occur through a direct pathway (i.e., directly from the soils to which N is applied), emissions of N_2O also take place through two indirect pathways, i.e. ammonia emission and nitrate leaching. In the IPCC methodology a leaching fraction (FracLEACH) is used to estimate the nitrate leaching via leaching and runoff. The leaching is multiplied with an emission factor for indirect N_2O emission from leaching (EF5). There is a lot of knowledge about nitrate leaching in the Netherlands and several leaching models are available. Clearly, there is scope for improvement by deriving a country-specific leaching fraction for the Netherlands. Agentschap NL also asked Alterra to assess if it is possible to derive a country specific leaching fraction (FracLEACH) for the Netherlands and to evaluation the N_2O emission factor for leaching (EF5) (project ROBP100139). It was decided to combine both studies in one report. Chapter 2 deals with the update of the emission factors for fertilizers and manures and Chapter 3 with the indirect N_2O emission.

2 Direct nitrous oxide emission from fertilizers and manures

2.1 Nitrous oxide emission factors derived from field experiments

2.1.1 Method

The data base with N_2O emission factors derived from field experiments in the Netherlands in the period 1993 - 2003 (Kuikman et al., 2006) was updated. Several studies that were used by Kuikman et al. (2006) have been published now in the scientific literature (e.g Van Groenigen et al., 2004, 2005; Schils et al., 2008; Velthof et al., 2010a). The emission factors in the published papers are included in the data-base and replace the emission factors from the reports used by Kuikman et al. (2006). Emission factors derived in recent experiments were added to the data-base, including those of Velthof and Mosquera (2011).

Emission factors were only included when they were obtained in field experiments with replicates and a unfertilized controlled. The emission factor was calculated as:

N_2O-N emission factor (in %) =
[(N_2O-N emission from fertilized soil) – (N_2O-N emission from unfertilized soil)]/(N applied) * 100

where N_2O-N is the emission from fertilized plot, N_2O-N is the emission from unfertilized plot, and N applied is the N applied as fertilizer of manure, all expressed in kg N per ha.

This method to calculate emission factors is in line with the method proposed by IPCC.

For monitoring studies that lasted more than one year, the emission factors for each separate year are included in the data base.

2.1.2 Results and discussion

The total data-base with emission factors is presented in Appendix 1 and the method and results of the statistical analyzes are presented in Appendix 2.

Table 3 shows for each N source the number of N_2O emission factors, and the mean, standard error, minimum, and maximum emission factor. The N sources include mineral N fertilizers, livestock manures, urine excreted during grazing, and crop residues. In total there are 153 values with emission factors, resulting in an average emission factor of 1.3% of N applied; the standard error is 0.2%.

In some of the experiments N_2O emission was only measured during a short period (i.e. several weeks). If the short experiments are left out of the data base (i.e. only experiments which lasted at least a full growing season of about six months are included), the average emission factor is 1.2 ± 0.1 % (n = 130). This agrees with the average emission factor of 1.1% derived by Kuikman et al. (2006) from 86 series of one year measurements (period 1993 - 2003).

The average emission factor of the experiments longer than six months (Table 3) was higher for peat soils (4.5 ± 0.9%) than for clay soils (1.3 ± 0.2 %) and sand soil (0.7 ± 0.1%). The average emission factor was somewhat higher for grassland (1.4 ± 0.2%) than for arable land (1.0 ± 0.2%).

Table 3

N_2O-N emission factors for N sources derived from field experiments in the Netherlands (mean, standard error[*], minimum and maximum). Emission factors are presented for the total data set and for data set with experiments which lasted at least a whole growing season (> six months).

	Total data set					Experiments > 6 months				
	n	N_2O emission factor, % of N				n	N_2O emission factor, % of N			
		mean	st error	min	max		mean	st error	min	max
N source										
Ammonium sulphate	6	0.3	0.1	0.1	1.0	3	0.2	0.1	0.1	0.3
Ammonium sulphate + DCD	2	0.1	0.0	0.1	0.1					
Calcium Ammonium Nitrate (CAN)	52	1.3	0.2	-0.2	8.3	44	1.0	0.2	-0.2	4.5
CAN + cattle slurry	19	0.6	0.2	0.1	3.1	19	0.6	0.2	0.1	3.1
CAN + grazing	8	3.0	0.8	0.8	6.8	8	3.0	0.8	0.8	6.8
Cattle slurry	35	0.5	0.1	-0.6	2.0	31	0.6	0.1	-0.6	2.0
Calcium Nitrate	3	5.8	3.4	0.1	12.0					
Pig slurry	8	2.0	0.8	0.1	7.0	8	2.0	0.8	0.1	7.0
Sugar beet leaves	2	0.2	0.1	0.1	0.3	2	0.2	0.1	0.1	0.3
Urea	3	0.3	0.2	0.1	0.7					
Urine patch	7	1.6	0.2	0.9	2.1	7	1.6	0.2	0.9	2.1
Urine/dung	8	4.2	1.3	1.0	11.4	8	4.2	1.3	1.0	11.4
Total	153	1.3	0.2	-0.6	12.0	130	1.2	0.1	-0.6	11.4
Soil										
Clay	39	1.1	0.2	-0.6	4.6	35	1.3	0.2	-0.6	4.6
Peat	12	4.5	0.9	1.5	11.4	12	4.5	0.9	1.5	11.4
Sand	102	1.0	0.2	-0.2	12.0	83	0.7	0.1	-0.2	7.0
Total	153	1.3	0.2	-0.6	12.0	130	1.2	0.1	-0.6	11.4
Land use										
Arable land	49	1.0	0.2	-0.6	7.0	49	1.0	0.2	-0.6	7.0
Grassland	104	1.5	0.2	0.0	12.0	81	1.4	0.2	0.0	11.4
Total	153	1.3	0.2	-0.6	12.0	130	1.2	0.1	-0.6	11.4
N application rate, kg N per ha		264	175	50	880		293	173	50	880

[*] *a measure of the uncertainty in the emission factors*

The update of the emission factors was made because the results of Velthof and Mosquera (2011) showed large differences in emission factors between CAN and livestock manures and between grassland and arable land (See Table 2). Table 4 shows the average emission factors for CAN and livestock manures obtained in field experiments in the Netherlands. In this table cattle manures and pig manures are combined. There is evidence that N_2O emission from pig manures is higher than from cattle manures (Table 3 and Velthof et al., 2003; 2010b), which is attributed to the higher contents of ammonium and easily degradable organic N and C in pig manures than in cattle manures. However, the number of measurements of N_2O emission from pig manure is small and derived from only one location. Therefore, the results of pig and cattle manures were combined in the analyzis.

The emission factors for CAN applied to clay soil are higher than for CAN applied to sand soils, especially for arable land. Those for livestock manure were (somewhat) smaller for clay soils than sandy soils (Table 4). Statistical analyzis showed (see Appendix 2) that there was no statistically significant difference in the average N_2O emission factors for sandy and clay soils. Statistical analyzes of subsets of the data, showed that the emission factor for CAN was statistically significant higher for arable land on clay soil (average emission factor 1.7%) than for arable land on sand soil (average emission factor 0.2%). The statistical analyzes showed that there was no statistically significant difference between clay and sand soils for CAN applied to grassland, manure applied with a low ammonia emission technique to grassland and arable land, and manure surface-applied to grassland and arable land (Appendix 2). It must be noted that most of the results of CAN applied to arable crops on clay soils were obtained from one location with high N_2O emissions and those for sand from one location with dry sandy soils and low emission (Van Groenigen et al., 2004; Velthof et al., 2010b). Because most of the differences in emission factors between sand and clay soils were not significant, the results for clay and sandy soils were combined (mineral soils) in the further analyzis (see Table 5). Differentiation amongst sandy and clay soils may be considered when more emission factors for different soil types are available.

The emission factors for CAN applied to grassland on peat soil were significantly (see Appendix 2) higher than those for CAN applied to grassland on mineral soils. The average emission factor for CAN on peat soil is 3.0 ± 0.6% (n =4). This is higher than the emission factor of 2% used in the protocol of the Netherlands (Table 1).

Table 4
Average and standard errors of N_2O emission factors for CAN and livestock manure (low ammonia emission application technique and broadcast surface application) for arable and grassland in the Netherlands (experiments > six months), split in factors for sand, clay, and peat soils.

Soil	N source	Manure application technique	Land use								
			Arable land			Grassland			All		
			Average	se	n	Average	se	n	Average	se	n
Clay	CAN		1.7	± 0.6	5	1.1	± 0.3	9	1.3	± 0.3	14
	Livestock manure	Low emission	1.1	± 0.3	7	0.3	± 0.1	2	0.9	± 0.3	9
		Surface				0.1	± 0.1	2	0.1	± 0.1	2
	Average		1.3	± 0.3	12	0.8	± 0.2	13	1.1	± 0.2	25
Sand	CAN		0.2	± 0.1	9	0.7	± 0.2	17	0.5	± 0.1	26
	Livestock manure	Low emission	1.5	± 0.5	14	0.3	± 0.1	5	1.2	± 0.4	19
		Surface	0.6	± 0.2	6	0.1	± 0.0	3	0.5	± 0.2	9
	Average		0.9	± 0.2	29	0.5	± 0.1	25	0.7	± 0.1	54
Average mineral soils			1.0	± 0.2	41	0.6	± 0.1	38	0.8	± 0.1	79
Peat	CAN					3.0	± 0.6	4	3.0	± 0.6	4

Table 5 shows that the average emission factor for CAN on mineral soils is similar and not statistically significant for grassland and arable land (Appendix 2). The differences in CAN-derived emissions between arable land and grassland found in the experiment of Velthof et al. (2010; see Table 2) are not shown in the total data-base with all emission factors obtained in the Netherlands. It is recommended not to change the emission factor of CAN in the protocol, i.e. 1% for mineral soils, although the average N_2O emission factor for CAN in the Netherlands is slightly smaller (0.8%).

The N_2O emission factors for manure applied with low ammonia emission techniques is on average higher for arable land (1.3 ± 0.3%) than for grassland (0.3 ± 0.1%). This difference is statistically significant at $\alpha = 0.1$ (Appendix 2). The emission factor for surface-applied manure is higher for arable land (0.6 ± 0.2%) than for grassland (0.1 ± 0.02%), which is statistically significant at $\alpha = 0.05$ (Appendix 2). For grassland, the N_2O emission factor for manures applied with low ammonia emission techniques (0.3 ± 0.1%) were statistically significant higher ($\alpha = 0.05$) than that for surface-applied manure (0.1 ± 0.02%). For arable land, the difference in N_2O emission factor for manures applied with low ammonia emission techniques (1.3 ± 0.3%) and for surface-applied manure (0.6 ± 0.2%) was not statistically significant ($\alpha = 0.1$). The field experiments of Velthof and Mosquera (2011) showed that application of manure with low ammonia emission techniques resulted on average in statistically significant ($\alpha = 0.05$) higher N_2O emission than surface application of manure, for both grassland and arable land.

On basis of the analyzis of the data set of emission factors in the Netherlands, it is recommended to use specific emission factors for manures applied to grassland and for manures applied to arable land on mineral soils. For CAN it is recommended to use an emission factor of 1% for all mineral soil types and types of land use. For peat soil, it is recommended to use an emission factor of 3%.

Table 5
Average and standard errors of N_2O emission factors for CAN and livestock manure (low ammonia emission application technique and broadcast surface application) for arable and grassland in the Netherlands, split in factors for mineral soils and peat soils.

Soil type	Source	Application technique	Land use		
			Arable land	Grassland	All
Mineral soils	CAN		0.7 ± 0.3 (n=14)	0.8 ± 0.1 (n=26)	0.8 ± 0.1 (n=40)
	Livestock manure	Low emission	1.3 ±0.3 (n=21)	0.3 ± 0.1 (n=7)	1.1 ± 0.2 (n=28)
		Surface	0.6 ± 0.2 (n=6)	0.1 ±0.02 (n=5)	0.4 ± 0.2 (n=11)
Peat soil	CAN			3.0 ± 0.6 (n=4)	

2.2 Literature study on emission factors for fertilizers and manure

A literature study was carried out to summarize results of studies performed outside the Netherlands. The study focuses on experiments in which emission factors of CAN and livestock manure were derived, including effects of application technique.

Table 6 presents a summary of the results of the literature study. The average emission factor for manures on grassland was 0.8 ± 0.4% and that of arable land 0.6 ± 0.1%.

The literature study showed that emission factors for CAN obtained for the Netherlands (0.8%) are similar to those obtained in other countries (0.7%). The average emission factors for slurries obtained in the Netherlands (0.6% for cattle and 2.0% for pig manure; Table 2) are also somewhat higher than obtained in other countries (0.3 for cattle and 0.8% for pig manure).

Table 6

Summary of the results of N_2O-N emission factors (in % of N) derived from literature, excluding studies from the Netherlands[1.]

Fertilizer	Grassland			Arable land		
	average	se.	n	average	se.	n
Manures	**0.8**	**0.4**	**19**	**0.6**	**0.1**	**24**
Cattle manure	0.3	0.1	13	0.4	0.1	14
Pig manure	0.3	0.1	4	0.8	0.2	7
Unknown	1.9		1	---		0
Mix of manures	7.5		1	0.7	0.1	3
Mineral fertilizers	**1.9**	**0.3**	**81**	**1.9**	**0.4**	**59**
Ammonium fertilizers	0.3	0.1	12	2.2	1.7	2
Ammoniun nitrate	2.3	0.3	42	2.1	0.4	48
Calcium ammonium nitrate	0.7	0.2	7	0.7	0.3	7
Calcium, sodium of potassium nitrate	2.3	0.9	20	1.4	0.9	2
Manure + mineral fertilizers	**5.4**	**3.0**	**3**	**1**	**0.7**	**8**

[1] References:

Abbasi and Adams (2000); Ambus et al. (2001); Anger et al. (2003); Arah et al. (1991); Ball et al. (2000); Burford et al. (1981); Chadwick et al. (2000); Christensen (1983), Clayton et al. (1994); Clayton et al. (1997); Clemens et al. (1997); Colbourn and Harper (1987); Colbourn et al. (1984); Conrad et al. (1983); Dobbie and Smith (2003a); Dobbie et al. (1999); Eggington and Smith (1986); Ellis et al. (1998); Glatzel and Stahr (2001); Goossens et al. (2001); Hénault et al. (1998a); Jambert et al. (1997); Jørgensen et al. (1997); Kaiser et al. (1996); Kaiser et al. (1998b); Kamp et al. (1998); McTaggart et al. (1997); Misselbrook et al. (1998); Mogge et al. (1999); Petersen (1999); Rodhe et al. (2006); Ryden (1981); Seiler and Conrad (1981); Skiba et al. (1992); Skiba et al. (1998); Slemr et al. (1984); Smith et al. (1998a, b); Van Cleemput et al. (1994); Webster and Dowdell (1982); Weslien et al. (1998); Wulf et al. (2002); Yamulki and Jarvis (2002); Yamulki et al.(1995)

Table 7 shows results of studies in which N_2O emission factors of different fertilizers and manures were derived in the same experiment. Table 7 shows that, on average, the emission factors of different N fertilizer types may be similar, but that under specific conditions there are large differences in emission factors between fertilizers. For example, the studies of Egginton and Smith (1986) clearly show much higher N_2O emissions from nitrate fertilizer applied to grassland than from cattle manure. This is in agreement with the experiments of Velthof and Mosquera (2011). These differences in N_2O emission between N fertilizer types can be used to set up mitigation strategies.

Table 7

Results of studies in which different fertilizers and manure were applied in the same experiment, excluding studies from the Netherlands.

Land use	Reference	N type	Application rate, kg N/ha	N_2O-N emission factor, % of N		n
				average	se.	
Grassland	Christensen (1983)	Manure + Ammonium nitrate	492	1.9		1
		Ammonium nitrate	100-200	1.5	0.3	2
	Ellis et al. (1998)	Cattle manure	45	0.1		1
		Ammonium nitrate	60	0.1		1
	Egginton and Smith (1986)	Cattle manure	298-1230	0.3	0.2	2
		Nitrate	100-400	3.6	3.3	2
	Egginton and Smith (1986)	Cattle manure	700	0.5		1
		Nitrate	700	1.9		1
	Clayton et al. (1997)	Manure + Ammonium nitrate	360	2.2		1
		Ammonium	360	0.3	0.1	2
		Ammonium nitrate	360	0.8	0.4	2
		Nitrate	360	0.8	0.4	2
	Conrad et al. (1983)	Ammonium	100	0.2	0.1	8
		Nitrate	100	0.0	0.0	5
	Seiler and Conrad (1981)	Ammonium	100	0.5	0.2	2
		Nitrate	100	0.3	0.2	2
Arable land	Clemens et al. (1997)	Cattle manure	56	0.7	0.1	3
		Calcium ammonium nitrate	56	0.3	0.2	4
	Petersen (1999)	Cattle and pig manure	152	0.6		1
		Calcium ammonium nitrate	100	0.6		1
	Henault et al. (1998a)	Ammonium	170	0.6		1
		Ammonium nitrate	170	0.9	0.3	2
		Nitrate	170	0.4		1

The results of the Netherlands (Table 5) show that application of manure with a technique that decrease ammonia emission (such as injection and shallow injection) increases N_2O emission. There are only a limited number of studies in literature in which the effect of manure application technique on N_2O emission has been quantified (Table 8). In most studies, manure application with low NH_3 emission technique increases N_2O emission.

Table 8
Summary of emission factors derived in studies in which effect of manure application technique on N_2O emission has been assessed, outside the Netherlands.

	Reference	Manure type	Application rate, kg N/ha	Application technique	Number	Emission factor, % of N	
						average	se
Grassland	Ellis et al. (1998)	Cattle manure	45	Surface spreading	1	0.1	
				Incorporation	1	0.2	
	Rohde et al. (2006)	Cattle manure	67.5	Narrow injection	1	0.3	
				Deep injection	1	1.1	
	Wulf et al. (2002)	Cattle manure	129	Surface spreading	1	0.1	
				Narrow injection	1	0.1	
				Deep injection	1	0.3	
Arable land	Clemens et al. (1997)	Cattle manure	56	Surface spreading	3	0.7	0.1
				Narrow injection	4	0.6	0.1
				Deep injection	4	0.4	0.2
	Petersen (1999)	Cattle + pig manure	152	Surface spreading	1	0.6	
				Incorporation	2	0.8	0.1
	Wulf et al. (2002)	Cattle manure	129	Surface spreading	1	0.1	
				Narrow injection	1	0.1	
				Deep injection	1	0.2	
	Weslien et al. (1998)	Pig manure	162	Surface spreading	1	0.3	
				Incorporation	3	0.4	0.1
	Weslien et al. (1998)	Pig manure	100	Surface spreading	1	1.2	0.0
				Incorporation	2	1.3	0.1

2.3 Emission factors for direct N_2O emission from peat soil

About fifteen percent of the grasslands in the Netherlands are located on peat soils. Velthof et al. (2010) carried out an incubation study to quantify the N_2O emission from cattle manure applied to peat, sand, and clay soils. Two application techniques were tested: surface application and shallow injection. Also the N_2O emission from CAN as reference fertilizer was quantified.

The total N_2O emission in the incubation study increased in the order control < surface applied cattle manure < shallow injected cattle manure < CAN, for all soil types. The total N_2O emission increased in the order clay soil < sandy soil < peat soil. The N_2O emission factor in the incubation study for shallow injected cattle manure ranged from 0.5% (sandy and clay soil) to 3.5% (peat soil). The N_2O emission factor for broadcast cattle manure was lower and ranged from -0.1% (sandy soil) to 1.7% (peat soil). The N_2O emission factor for CAN was 4.0% for the sandy soil, 1.4% for the clay soil, and 10.5% for the peat soil.

The results of the incubation studies cannot be directly used to derive N_2O emission factors, because the conditions do not represent field conditions and, because of this, the emission factors are relatively high. However, the relative differences in N_2O emissions between treatments and soils can be used in combination with results of field experiments (Velthof et al., 1996 and Velthof et al., 2010b) to estimate N_2O emission factors.

Table 9 shows emission factors for N_2O emission from grasslands in the field studies of Velthof et al. (1996) and Velthof and Mosquera (2011) and the incubation study of Velthof et al. (2010b). In Table 10 these emission factors are averaged for mineral soils and peat soils. Both the field and incubation studies show higher N_2O emission factors for peat soil. This is because the conditions for N_2O emission are more optimal in peat soils than in mineral soils. Peat soil have a higher denitrification capacity than mineral soil (because of the higher organic matter content). Moreover, under field conditions, peat soil are generally more wet than in mineral soils, because of the high groundwater level.

The emission factors for manure application to peat soils (indicated in bold in Table 11) are calculated assuming that the ratio in N_2O emission between CAN and manure found in the incubation study also applies for field conditions. Thus the N_2O emission factor for surface applied manure is calculated as 1.7 * 3.0 /10.5 = 0.5 % and that for narrow-band applied as 3.5 * 3.0/10.5 = 1.0%.

An alternative method of calculation results in similar emission factors. In this calculation, it is assumed that the ratio in emission factors between the incubation study and field study for mineral soils is also applicable for peat soils. This results in the following emission factors:

- For CAN: 10.5 * 1.9 / 2.7 = 7.4%
- For cattle-manure, surface-applied: 1.7 * 0.1 / 0.1 = 1.7%
- For cattle-manure, narrow-band applied: 3.5* 0.5/ 0.5 = 3.4%

The emission factor 7.4% for CAN is much higher than the 3.0 % found in the field study. This suggest that the conditions in the incubation study enhanced N_2O emission from peat soil more strongly than from mineral soil. The emission factor for CAN can be directly derived from the field experiments, i.e. 3.0%. If the emission factors for livestock are corrected for the difference in the calculated and measured emission factor for CAN, the following emission factors are obtained:

- CAN: 3.0 %
- Cattle-manure, surface-applied: 1.7/ 7.4 * 3.0 = 0.7%
- Cattle-manure, narrow-band applied: 3.4/7.4 * 3.0 = 1.3%

These calculated emission factors are similar to those calculated with the other method, i.e 0.5% for surface-applied manure and 1.0% for narrow-band applied manure.

For surface-applied manure it is suggested on basis of the calculation above to use an emission factor of 0.5% and for manure applied with a low ammonia emission application technique 1%. These emission factors do not include the N_2O emission due to enhanced N mineralization of cultivated peat soils A fixed country-specific emission factor of 4.7 kg N_2O-N per hectare is used for agricultural use of peat soils (see protocol on www.greenhousegases.nl).

There are no data of N_2O emission factors for arable land on peat soils, which is only a small area in the Netherlands.

Concluding, it is recommended to use for peat soils the following emission factors: 3% for CAN, 1% for manure applied with a low NH_3 emission technique, and 0.5% for surface-applied manure.

Table 9

Emission factors for N_2O emission from grasslands in the field studies of Velthof et al. (1996) and Velthof and Mosquera (2011) and the incubation study of Velthof et al. (2010b).

Soil type	Treatment	Velthof et al. (1996)	Velthof et al. (2010b)	Velthof and Mosquera (2011)
		Field study	Incubation study	Field study
Sandy soil	CAN	1.0	4.0	1.6
	Cattle manure; surface-applied		-0.1	0.1
	Cattle manure; narrow band applied		0.5	0.6
Clay soil	CAN	0.9	1.4	2.2
	Cattle manure; surface-applied		0.3	0.1
	Cattle manure; narrow band applied		0.5	0.3
Peat soil	CAN	2.0	10.5	
	Cattle manure; surface-applied		1.7	
	Cattle manure; narrow band applied		3.5	
Peat soil	CAN	4.0		
	Cattle manure; surface-applied			
	Cattle manure, narrow band applied			

Table 10

Average emission factors for N_2O emission from grasslands on mineral soils and peat soils in the field studies of Velthof et al. (1996) and Velthof and Mosquera (2011).

Soil type	Treatment	Velthof et al. (1996)	Velthof et al. (2010b)	Velthof and Mosquera (2011)
		Field study	Incubation study	Field study
Mineral soils	CAN	1.0	2.7	1.9
	Cattle manure; surface-applied		0.1	0.1
	Cattle manure; narrow band applied		0.5	0.5
Peat soils	CAN	3.0	10.5	
	Cattle manure; surface-applied		1.7	
	Cattle manure; narrow band applied		3.5	

Table 11
Average emission factors for N_2O emission from grasslands on mineral soils and peat soils in the field studies of Velthof et al. (1996) and Velthof and Mosquera (2011). The emission factors for manure application to peat soils (indicated in bold) are calculated assuming that the ratio in N_2O emission between CAN and manure found in the incubation study also applies for field conditions.

Soil type	Treatment	Velthof et al. (1996)	Velthof et al. I(2010b)	Velthof and Mosquera (2011)
		Field study	Incubation study	Field study
Mineral soils	CAN	1.0	2.7	1.9
	Cattle manure; surface-applied		0.1	0.1
	Cattle manure; narrow band applied		0.5	0.5
Peat soils	CAN	3.0	10.5	
	Cattle manure; surface-applied	0.5	1.7	
	Cattle manure; narrow band applied	1.0	3.5	

2.4 Recommendations

Table 12 shows the average emission factors for CAN and livestock manure in the Netherlands and their uncertainty, based on the analyzis of the data set with emission factors in the Netherlands (Chapter 2.1; including the statistical analyzes in Appendix 2) and the calculation of emission factors of peat soil from an incubation study (Chapter 2.3).

Table 12
Average N_2O emission factors (in % of N applied) and standard errors for CAN and livestock manure in the Netherlands, based on the analyzis of the data set with emission factors in the Netherlands. The emission factors for manure applied to peat soil were calculated from results from an incubation study.

Soil type	Source	Application technique	Land use		
			Arable land	Grassland	All
Mineral soils	CAN		0.7 ± 0.3 (n=14)	0.8 ± 0.1 (n=26)	0.8 ± 0.1 (n=40)
	Livestock manure	Low emission	1.3 ±0.3 (n=21)	0.3 ± 0.1 (n=7)	1.1 ± 0.2 (n=28)
		Surface	0.6 ± 0.2 (n=6)	0.1 ±0.02 (n=5)	0.4 ± 0.2 (n=11)
Peat soil	CAN			3.0 ± 0.6 (n=4)	
	Livestock manure	Low emission		1*	
		Surface		0.5*	

*estimated from an incubation study

The Netherlands uses a country specific methodology to report to UNFCCC the N_2O emissions from N fertilizer and manure applied to soils. Therefore, it is recommended to use the emission factors derived from experiments in the Netherlands as the basis for the emission factors in the protocol used to report N_2O emission. We recommend the following changes in emission factors (see Table 13):

- use different emission factors for livestock manure applied to grassland (0.1% for surface-applied manure and 0.3% for manure applied with low ammonia emission) and arable land (0.6% for surface-applied manure and 1.3% for manure applied with low ammonia emission);
- use for peat soils the following emission factors: 3% for CAN, 1% for manure applied with a low NH_3 emission technique, and 0.5% for surface-applied manure.

It is recommended not to change the emission factor of CAN in the protocol, i.e. 1% for mineral soils (Table 13), although the average N_2O emission factor for CAN in the Netherlands is slightly smaller (0.8%).

The results of the recommended N_2O emission factors for manures are based on (recent) long-term field experiments, carried out in the Netherlands (Appendix 1). These emission factors are thus much more representative than the currently used emission factors, which were based on the assumptions of Kroeze (1994), using literature from outside the Netherlands.

The results show large variations in emission factors (with variations coefficient up to more than 100%), which is due to combination of factors, including soil type, soil properties, weather conditions, manure composition, and crop type. It is well known that emissions of N_2O have a high spatial and temporal variability. The large data set with emission factors of Stehfest and Boumans (2006), used to derive the default IPCC emission factors, also shows a large variation in emission factors. Despite the large variation in N_2O emission factors, statistical analyzes showed that most of the differences are statistically significant (Appendix 2).

The standard error is a measure of uncertainty of data or precision. The standard errors of the recommended emission factors are (Table 12):

- livestock manure surface-applied to grassland: 0.10 ± 0.02%;
- livestock manure applied with low ammonia emission technique to grassland: 0.3 ± 0.1%;
- livestock manure surface-applied to arable land: 0.6 ± 0.2%;.
- livestock manure applied with low ammonia emission technique to arable land: 1.3 ± 0.3%;
- CAN applied to peat soils: 3.0 ± 0.6%.

The uncertainty of the emission factors for manure applied to peat soil under field conditions cannot be calculated, because these emission factors were estimated using results of an incubation study.

The recommended changes in emission factor may lead to specific factors for manures applied to grassland and arable land. The use of manure on grassland in stead of arable land will results in smaller N_2O emission and may be an option to mitigate N_2O emission.

Table 13

Emission factors for direct N_2O-N emission from agricultural soils (% of N input) according to current protocol and the recommended changes in emission factors.

N source	Current protocol[1]		Recommended changes[1]	
	Mineral soil	Organic soil	Mineral soil	Organic soil
Fertilizer application				
ammonium fertilizer (no nitrate)	0.5	1.0		
other types of fertilizer	1.0	2.0		3.0
Animal manure application grassland				
above-ground (surface spreading)	1.0	2.0	0.1	0.5
low-ammonia emission application	2.0	2.0	0.3	1.0
Animal manure application arable land				
above-ground (surface spreading)	1.0	2.0	0.6	
low-ammonia emission application	2.0	2.0	1.3	
Meadow manure livestock				
faeces	1.0	1.0		
urine	2.0	2.0		
Nitrogen fixation	1.0			
Crop residues	1.0			
Cultivation of histosols		2.0		
Sewage sludge	1.0			

[1] Emission factors current protocol are based on netto N input, i.e. the N input corrected for ammonia emissions after application. The recommendations are based of total N input (without correction for ammonia emission)

3 Indirect nitrous oxide emission from nitrate leaching

3.1 Introduction

In addition to the direct emissions of N_2O from managed soils that occur through a direct pathway (i.e., directly from the soils to which N is applied), emissions of N_2O also take place through two indirect pathways, i.e. ammonia and NO_X emission and nitrate leaching.

In the IPCC methodology a leaching fraction (FracLEACH) is used to estimate the nitrate leaching via leaching and runoff. The leaching is multiplied with an emission factor for indirect N_2O emission from leaching (EF5). IPCC has changed its methodology for calculation of FracLEACH in the guidelines of 2006[3] in comparision with the guidelines of 1996[4]. The underpinning of the calculation of indirect N_2O emission is better in the guidelines of 2006 than of 1996. However, during the first budget period, countries have to use the guidelines of 1996 and the Good Practice Guidance 2000[5], except when they can show that the method and emission factors according to guidelines of 2006 are more reliable than those of the guidelines of 1996. The Netherlands has to use the IPCC guidelines of 1996 for FracLEACH. In this paragraph the calculation of indirect N_2O emission in both guidelines is shortly described.

According to the IPCC-1996 methodology, leaching is calculated as:

NLEACH = [Nfert + Nex] x FracLEACH

Where
- Nfert is the synthetic nitrogen fertilizer consumption
- Nex is the livestock nitrogen excretion
- FracLEACH is the fraction of the sum of Nfert and Nex that is lost through leaching and runoff (kg N per kg of nitrogen applied)

The indirect N_2O emission is calculated as

$N_2O(L) = N_{LEACH} \times EF5$

Where
- N_{LEACH} is the N leaching in a country
- EF5 is the emission factor for leaching/runoff (kg N_2O-N per kg N leaching/runoff)

---

[3] www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf

[4] www.ipcc-nggip.iges.or.jp/public/gl/guidelin/ch4ref7.pdf

[5] www.ipcc-nggip.iges.or.jp/public/gp/english/

The sum of the emission of N_2O due to NLEACH in
1) groundwater and surface drainage (EF5-g),
2) rivers (EF5-r),
3) coastal marine areas (EF5-e)
is calculated to obtain the total N_2O emission factor (EF5) for NLEACH.

The combined emission factor [EF5] for N_2O due to NLEACH is 0.025 kg N_2O-N per kg NLEACH, calculated as EF5-g + EF5-r + EF5-e = 0.015 + 0.0075 + 0.0025 kg N_2O-N per kg NLEACH).

According to the IPCC-2006 methodology, the N_2O emissions from leaching and runoff in regions where leaching and runoff occurs are estimated using the following equation:

$$N_2O_{(L)}\text{-}N = (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) * FracLEACH * EF5$$

Where:
- $N_2O_{(L)}$-N = annual amount of N_2O-N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N_2O-N per year
- F_{SN} = annual amount of synthetic fertilizer N applied to soils in regions where leaching/runoff occurs, kg N per year
- F_{ON} = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils in regions where leaching/runoff occurs, kg N per year
- F_{PRP} = annual amount of urine and dung N deposited by grazing animals in regions where leaching/runoff occurs, kg N per year
- F_{CR} = amount of N in crop residues (above- and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually in regions where leaching/runoff occurs, kg N per year
- F_{SOM} = annual amount of N mineralised in mineral soils associated with loss of soil C from soil organic matter as a result of changes to land use or management in regions where leaching/runoff occurs, kg N per year
- FracLEACH = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N per kg of N additions
- EF5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O-N per kg N leached and runoff.

The IPPC default FracLEACH is 0.3 kg N per kg N additions or deposition by grazing animals for regions where the excess rainfall in the rainy season (i.e. the difference between rainfall and evaporation) exceeds the soil water holding capacity, or where irrigation (except drip irrigation) is employed.

There are three differences between IPCC 2006 and IPCC 1996:
- The overall value for the emission factor for leached N (EF5) has been changed from 0.025 to 0.0075 kg N_2O-N per kg N leached/in runoff water. This emission factor incorporates three components: EF5g, EF5r and EF5e, which are the emission factors for groundwater and surface drainage, rivers, and estuaries, respectively. IPCC 2006 suggested that the previously used emission factor for groundwater and surface drainage (EF5g ; 0.015) was too high and should be reduced to 0.0025 kg N_2O-N per kg leached N. The emission factor for rivers (EF5r) has also been reduced from 0.0075 kg N_2O-N per kg N to 0.0025 kg N_2O-N per kg N in the water. The value for estuaries (EF5e) remains at 0.0025 kg N_2O-N per kg N.
- The FracLEACH is in the IPCC 1996 Guidelines based on the total N excretion by livestock (Nex) and in the IPCC 2006 Guidelines it is based on livestock manure N applied on soils (F_{ON}). Thus, in the IPCC-1996 Guidelines substraction of N losses during housing and storage from total N excretion is not included.
- The IPCC-2006 methodology includes more sources of N input (crop residues, N mineralization) than IPCC-1996 in the calculation of FracLEACH.

The Netherlands uses the IPCC-1996 method for calculation of indirect N_2O emission (Source: www.greenhousegases.nl), i.e. the default factor for FracLEACH is 0.3, EF5 is 0.025 kg N_2O-N per kg NLEACH, and the total N excretion is included in the calculation without deducting of ammonia emission from housing, manure storage, grazing and use of manure.

There is a lot of knowledge about nitrate leaching in the Netherland and several leaching models are available. Clearly, there is scope to improve the quantification of indirect N_2O emission by deriving a country-specific FracLEACH fraction for the Netherlands. The aim of this study is to evaluate if country specific values for FracLEACH and EF5 can be derived for the Netherlands.

3.2 Estimation of FracLEAC and EF5 in other countries

In this paragraph, a description is given of FracLEACH and emission factors for indirect N_2O emission, used by some other countries. The descriptions of the different countries are based on the National Inventory Submissions 2010 of the countries to the UNFCCC (NIR2010 reports[6]). Notice that most of the countries use default values for FracLEACH (0.3) and the emission factors of the IPCC-1996 methodology (EF5=2.5% of leached N).

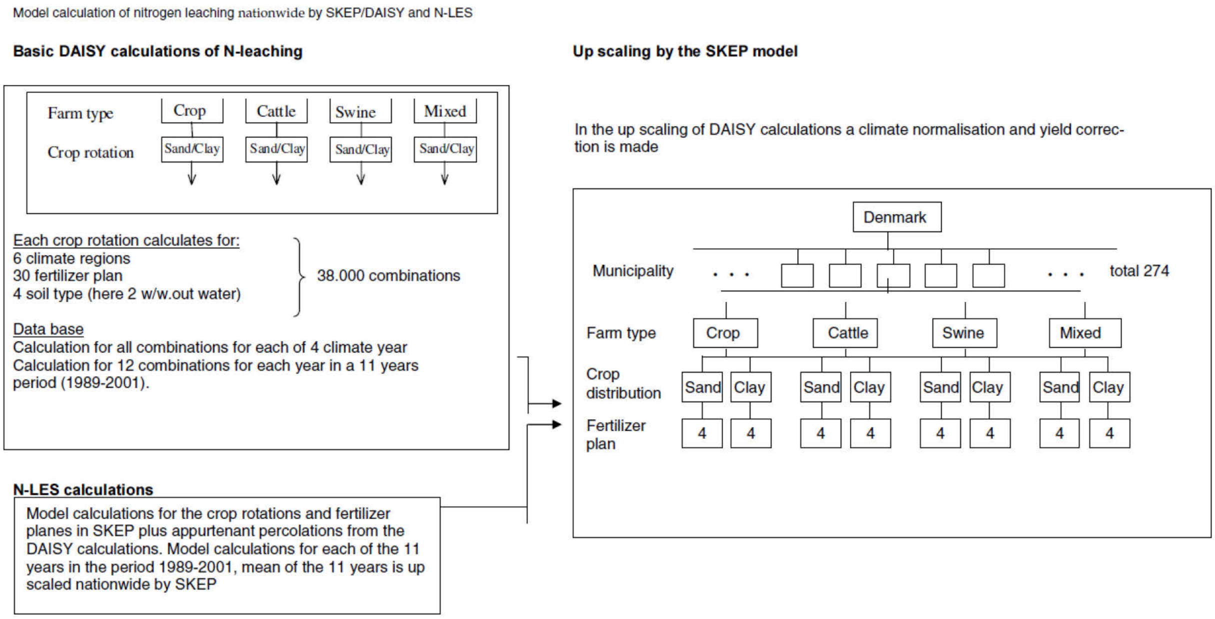
Flanders
In Flanders, the N leaching is based on the SENTWA model (System for the Evaluation of Nutrient Transport to Water), which is updated yearly (Pauwelyn and Depuydt, 1997). This model calculates empirically the discharge of nutrient streams caused by agriculture to the surface water (from animal manure, fertilizer and silage). The FracLEACH was 0.18 kg N per kg N and is region specific. The default IPCC 1996 EF5 factor is used (0.025 kg N-N_2O per kg N).

Denmark
The amount of N lost by leaching and run-off from 1986 to 2002 has been calculated by FAS. The calculation is based on two different model predictions, SKEP/Daisy and N-Les2, and for both models measurements from field studies are taken into account. SKEP/DAISY is a dynamical crop growth model taking into account the growth factors, where as N-Les2 is an empirical leaching model based on more than 1200 leaching studies performed in Denmark from the middle of the 1980 to 2002. The results of the two models differ only marginally. The average of the two model predictions is used in the emission inventory. Figure 6.5 of the Danish report shows leaching estimated in relation to the nitrogen applied to agricultural soils as livestock manure, synthetic fertilizer and sludge (Figure 1).

The model SKEP/DAISY is a dynamic model, N-LES is an empirical model and SKEP is an up scaling model. The SKEP/DAISY calculations were done for ten scenarios (the years 1984, 1989 and 1995-2002) and the N-LES calculations were done for an eleven year period (1990-2000). Both calculations were up scaled nation wide. The key parameters for the models were land use, nitrogen from synthetic fertilizer and manure, application practice for manure and ammonia emission at application of manure (SKEP/DAISY only). The calculations were normalized to an average climate. A schematic overview of the models is shown below.

---

[6] unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/5270.php)



Model calculation of nitrogen leaching nationwide by SKEP/DAISY and N-LES

Basic DAISY calculations of N-leaching

Up scaling by the SKEP model

Each crop rotation calculates for:
6 climate regions
30 fertilizer plan
4 soil type (here 2 w/w.out water)

Data base
Calculation for all combinations for each of 4 climate year
Calculation for 12 combinations for each year in a 11 years period (1989-2001).

N-LES calculations

Model calculations for the crop rotations and fertilizer planes in SKEP plus appurtenant percolations from the DAISY calculations. Model calculations for each of the 11 years in the period 1989-2001, mean of the 11 years is up scaled nationwide by SKEP

In the up scaling of DAISY calculations a climate normalisation and yield correction is made

The average proportion of nitrogen leaching and runoff has decreased from around 40 % in the middle of the nineties to around 34 % in 2008 (Figure 1). The decline is due to an improvement in the utilization of N in manure. The reduction in N applied is particularly due to the fall in the use of synthetic fertilizer, which has reduced by 45 % from 1990 to 2008. The proportion of N input to soils lost through leaching and runoff (FracLEACH) used in the Danish emission inventory is higher than the default value of the IPCC (0.30). The high values are due to the humid Danish climate, with the precipitation surplus during winter causing a downward movement of dissolved nitrogen in combination with a large share of well drained sandy soils[7]. FracLEACH has decreased from 1990 and onwards. At the beginning of 1990s, manure was often applied in autumn. Now the main part of manure application takes place in the spring and early summer, where there are nearly no downward movements of soil water. The decrease in FracLEACH over time is due to increasing environmental requirements and banning manure application after harvest. The data based on model estimates from FAS and NERI reflects the Danish conditions and is considered as a best estimate for FracLEACH in Denmark.

---

[7] //people.civil.aau.dk/~i5aa/b3-geo/PDF/Paper%20-%20Soil%20map%20of%20Denmark.pdf

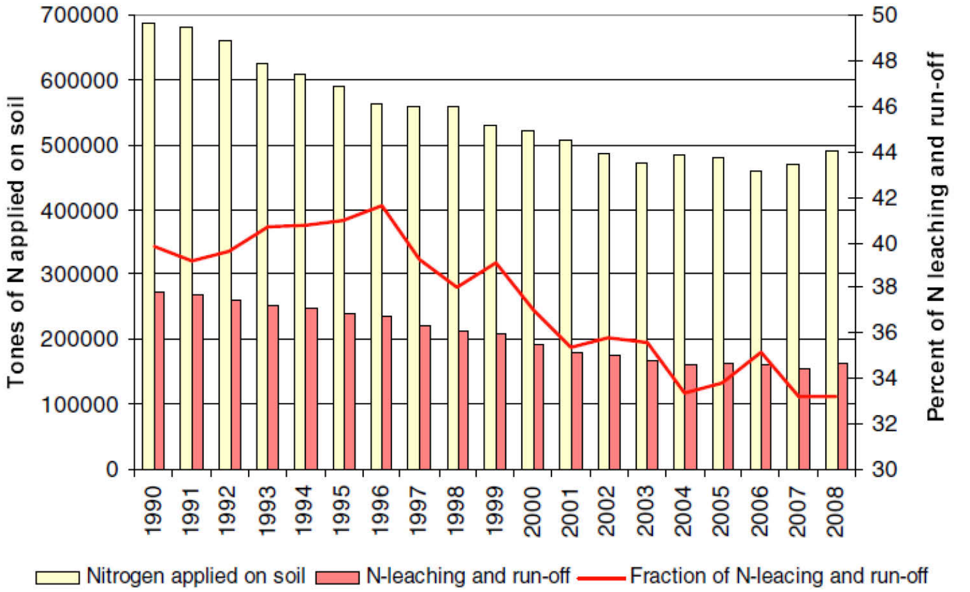


Figure 6.5 Nitrogen applied to agricultural soils and N-leaching from 1990 to 2008.

Figure 1 Figure 6.5 of the Danish report to UNFCC showing the N applied to agricultural soils and the N leaching in percentage of N applied from 1990 to 2008

Germany

Germany uses the IPCC 2006 emission factors for indirect N_2O emissions (EF5): 0.0075 kg kg^{-1} N. Germany considers the IPCC 2006 emission factor as state of the art and better underpinned than the IPCC 1996 emission factor. This justification is based on the scientific paper of Weymann et al. (2008) in which groundwater N_2O emission factors were derived in four sand and gravel aquifers in northern Germany.

Canada

A modified IPCC Tier 1 methodology is used to estimate indirect N_2O emissions from leaching, runoff and erosion of fertilizers, manure and crop residue N from agricultural soils. Indirect N_2O emissions from runoff and leaching of nitrogen at the ecodistrict level are estimated using FracLEACH multiplied by the amount of synthetic fertilizer nitrogen, non-volatilized manure nitrogen, and crop residue nitrogen and by the IPCC 1996 default emission factor of 0.025 kg N_2O-N per kg N (IPCC 2006).

It is assumed that FracLEACH would vary among ecodistricts from 0.05 (such as in the Prairie region of Canada) to 0.3. For ecodistricts with no moisture deficit during the growing season (May through October), the maximum FracLEACH value of 0.3 recommended by the IPCC 2006 Guidelines is assigned. The minimum FracLEACH value of 0.05 is assigned to ecodistricts with the greatest moisture deficit. For the remaining ecodistricts, FracLEACH is estimated by the linear extrapolation of the two endpoints described above (see copy of the report of Canada to UNFCCC in 2010 on the following page).

Finland

It is assumed that N leaching is less in Finnish conditions than according to the IPCC default value for FracLEACH. A value of 15% is used, based on a study of Rekolainen et al. (1993).

New Zealand

New Zeland uses a FracLEACH of 0.07 as it best reflects New Zealand's national circumstances. This value is based on extensively reviewed literature and field studies (Carran et al., 1995; de Klein et al., 2003; Muller et al., 1995; Thomas et al., 2005). New Zealand uses the default IPCC 1996 emission factor of 0.025 kg N_2O-N per kg N.

United Kingdom

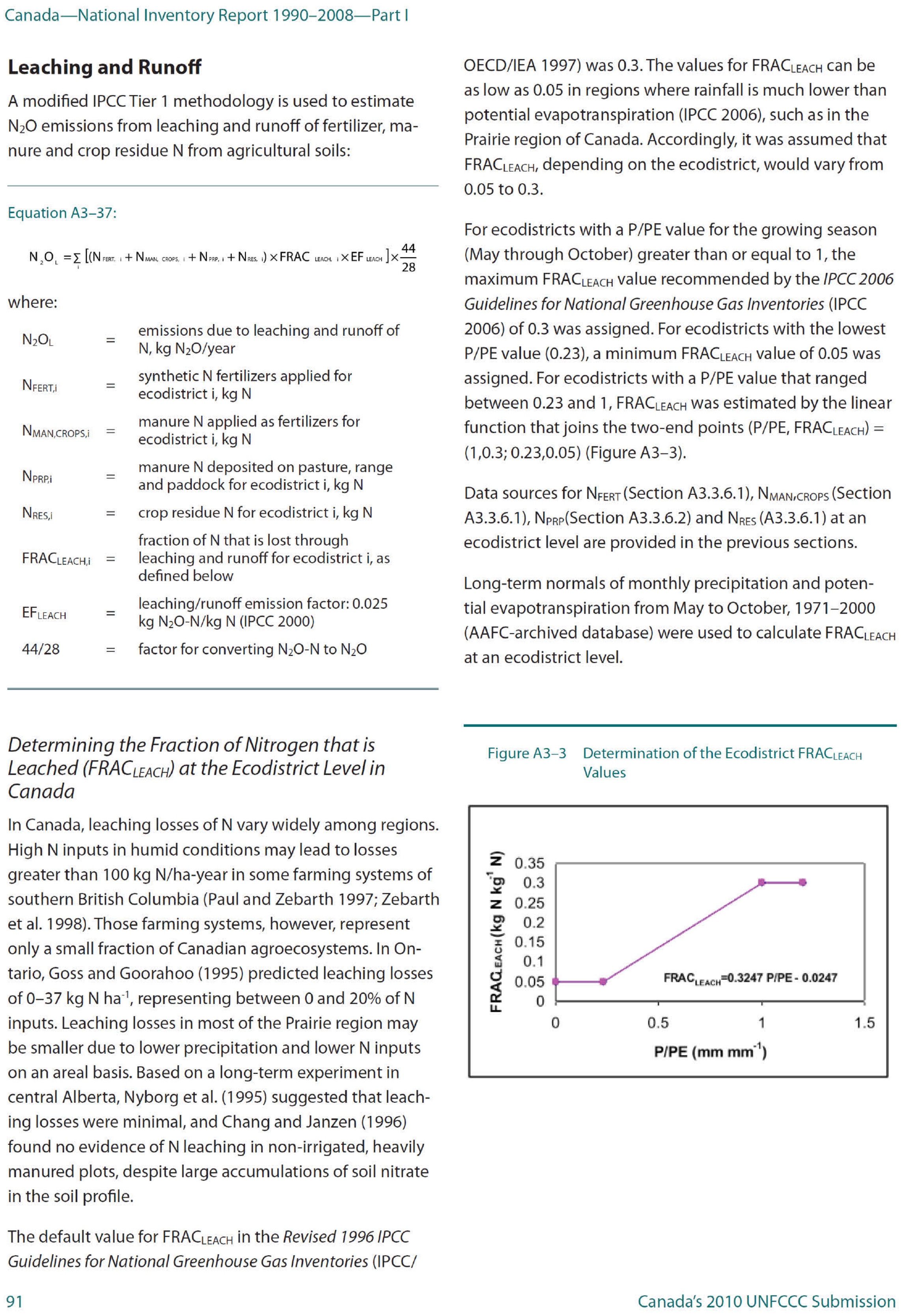
The UK uses IPCC 1996 methodology. However, it is indicated that UK emission factors are currently under review for EF5, and FracLEACH. This suggests that UK has proposed a methodology to calculate leaching, based on field measurements.

Switzerland

FracLEACH is set as 0.2 instead of the IPCC default of 0.3 (Prasuhn and Mohni, 2003). This value is extrapolated from long-term monitoring and modeling studies from the canton of Berne. According to Schmid et al. (2000), the default value of IPCC leads to an overestimation of the emissions from leaching and run-off. The default value is based on a global model which assumes that 30% of nitrogen from synthetic fertilizer and atmospheric deposition is reaching water bodies. According to Schmid et al. (2000) this amount is not representative for N-excretion of livestock animals in Switzerland. Switzerland uses the IPCC 1996 emission factor EF5 of 0.025 kg N_2O-N per kg N.

USA

The FracLEACH factors were based on regional cattle runoff data from EPA's Office of Water (EPA, 2002). EPA's Office of Water estimates the amount of runoff from beef, dairy and heifer operations in five geographic regions of the country (EPA, 2002). These estimates were used to develop U.S. runoff factors by animal type, Waste Management System and region. Nitrogen losses from leaching are believed to be small in comparison to the runoff losses. Therefore, FracLEACH was set equal to the runoff loss factor. The nitrogen losses from volatilization and runoff/leaching used by the U.S. are presented in Table 14. This Table indicates that USA do not consider runoff/leaching related to N fertilizer use. The U.S. use IPCC-2006 default factors for indirect N_2O emission factors to estimate indirect N_2O emission: 0.0075 kg N_2O per kg N for runoff/leaching.



Leaching and Runoff

A modified IPCC Tier 1 methodology is used to estimate N_2O emissions from leaching and runoff of fertilizer, manure and crop residue N from agricultural soils:

Equation A3–37:

$$N_2O_L = \sum_i [(N_{FERT,i} + N_{MAN,CROPS,i} + N_{PRP,i} + N_{RES,i}) \times FRAC_{LEACH,i} \times EF_{LEACH}] \times \frac{44}{28}$$

where:

N_2O_L = emissions due to leaching and runoff of N, kg N_2O/year

$N_{FERT,i}$ = synthetic N fertilizers applied for ecodistrict i, kg N

$N_{MAN,CROPS,i}$ = manure N applied as fertilizers for ecodistrict i, kg N

$N_{PRP,i}$ = manure N deposited on pasture, range and paddock for ecodistrict i, kg N

$N_{RES,i}$ = crop residue N for ecodistrict i, kg N

$FRAC_{LEACH,i}$ = fraction of N that is lost through leaching and runoff for ecodistrict i, as defined below

EF_{LEACH} = leaching/runoff emission factor: 0.025 kg N_2O-N/kg N (IPCC 2000)

44/28 = factor for converting N_2O-N to N_2O

Determining the Fraction of Nitrogen that is Leached ($FRAC_{LEACH}$) at the Ecodistrict Level in Canada

In Canada, leaching losses of N vary widely among regions. High N inputs in humid conditions may lead to losses greater than 100 kg N/ha-year in some farming systems of southern British Columbia (Paul and Zebarth 1997; Zebarth et al. 1998). Those farming systems, however, represent only a small fraction of Canadian agroecosystems. In Ontario, Goss and Goorahoo (1995) predicted leaching losses of 0–37 kg N ha^{-1}, representing between 0 and 20% of N inputs. Leaching losses in most of the Prairie region may be smaller due to lower precipitation and lower N inputs on an areal basis. Based on a long-term experiment in central Alberta, Nyborg et al. (1995) suggested that leaching losses were minimal, and Chang and Janzen (1996) found no evidence of N leaching in non-irrigated, heavily manured plots, despite large accumulations of soil nitrate in the soil profile.

The default value for $FRAC_{LEACH}$ in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD/IEA 1997) was 0.3. The values for $FRAC_{LEACH}$ can be as low as 0.05 in regions where rainfall is much lower than potential evapotranspiration (IPCC 2006), such as in the Prairie region of Canada. Accordingly, it was assumed that $FRAC_{LEACH}$, depending on the ecodistrict, would vary from 0.05 to 0.3.

For ecodistricts with a P/PE value for the growing season (May through October) greater than or equal to 1, the maximum $FRAC_{LEACH}$ value recommended by the *IPCC 2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) of 0.3 was assigned. For ecodistricts with the lowest P/PE value (0.23), a minimum $FRAC_{LEACH}$ value of 0.05 was assigned. For ecodistricts with a P/PE value that ranged between 0.23 and 1, $FRAC_{LEACH}$ was estimated by the linear function that joins the two-end points (P/PE, $FRAC_{LEACH}$) = (1,0.3; 0.23,0.05) (Figure A3–3).

Data sources for N_{FERT} (Section A3.3.6.1), $N_{MAN,CROPS}$ (Section A3.3.6.1), N_{PRP}(Section A3.3.6.2) and N_{RES} (A3.3.6.1) at an ecodistrict level are provided in the previous sections.

Long-term normals of monthly precipitation and potential evapotranspiration from May to October, 1971–2000 (AAFC-archived database) were used to calculate $FRAC_{LEACH}$ at an ecodistrict level.

Figure A3–3 Determination of the Ecodistrict $FRAC_{LEACH}$ Values

Table 14

Factors for calculation of indirect N2O emissions, used in the U.S. (Source: U.S. report to UNFCC).

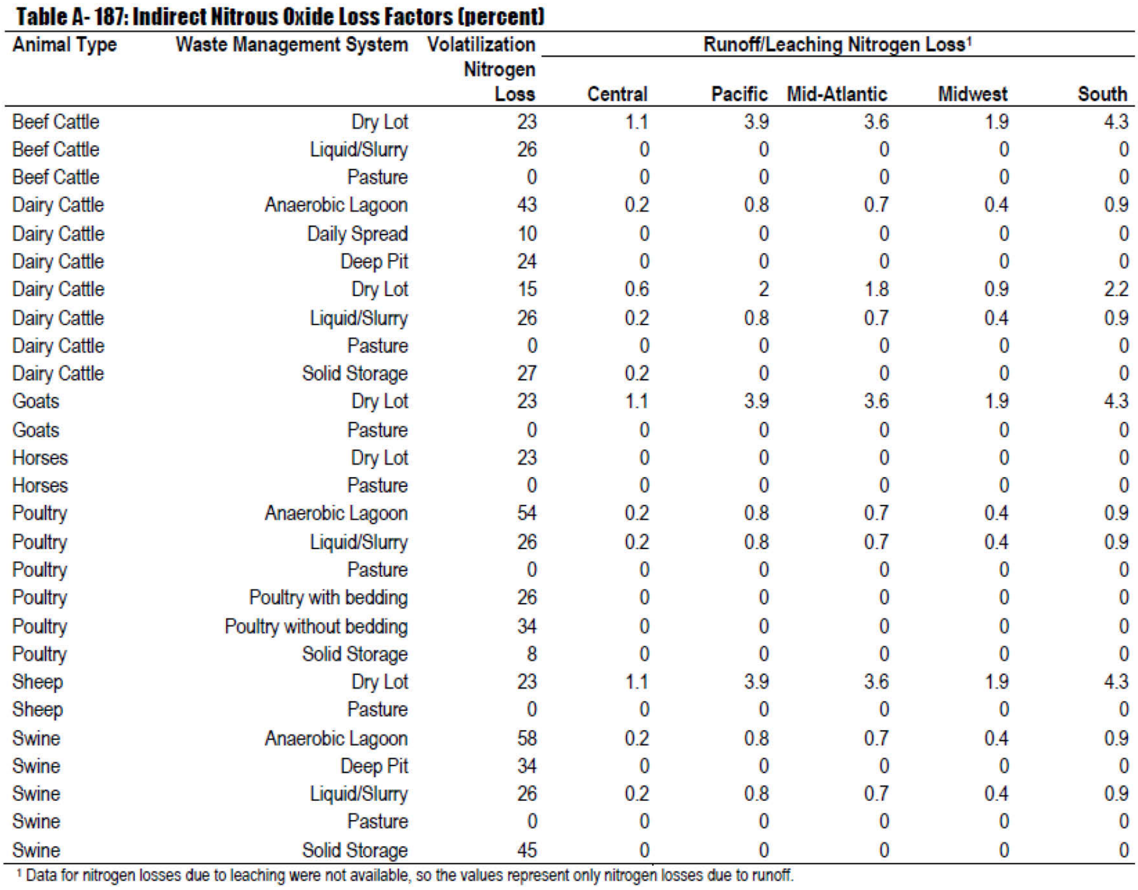


Table A- 187: Indirect Nitrous Oxide Loss Factors (percent)

Animal Type	Waste Management System	Volatilization Nitrogen Loss	Runoff/Leaching Nitrogen Loss[1]				
			Central	Pacific	Mid-Atlantic	Midwest	South
Beef Cattle	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Beef Cattle	Liquid/Slurry	26	0	0	0	0	0
Beef Cattle	Pasture	0	0	0	0	0	0
Dairy Cattle	Anaerobic Lagoon	43	0.2	0.8	0.7	0.4	0.9
Dairy Cattle	Daily Spread	10	0	0	0	0	0
Dairy Cattle	Deep Pit	24	0	0	0	0	0
Dairy Cattle	Dry Lot	15	0.6	2	1.8	0.9	2.2
Dairy Cattle	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Dairy Cattle	Pasture	0	0	0	0	0	0
Dairy Cattle	Solid Storage	27	0.2	0	0	0	0
Goats	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Goats	Pasture	0	0	0	0	0	0
Horses	Dry Lot	23	0	0	0	0	0
Horses	Pasture	0	0	0	0	0	0
Poultry	Anaerobic Lagoon	54	0.2	0.8	0.7	0.4	0.9
Poultry	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Poultry	Pasture	0	0	0	0	0	0
Poultry	Poultry with bedding	26	0	0	0	0	0
Poultry	Poultry without bedding	34	0	0	0	0	0
Poultry	Solid Storage	8	0	0	0	0	0
Sheep	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Sheep	Pasture	0	0	0	0	0	0
Swine	Anaerobic Lagoon	58	0.2	0.8	0.7	0.4	0.9
Swine	Deep Pit	34	0	0	0	0	0
Swine	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Swine	Pasture	0	0	0	0	0	0
Swine	Solid Storage	45	0	0	0	0	0

[1] Data for nitrogen losses due to leaching were not available, so the values represent only nitrogen losses due to runoff.

3.3 Country specific FracLEACH for the Netherlands

3.3.1 Introduction

In the Netherlands two models are used in manure policy, i.e.

- the WOG-model[8], a model developed to underpin N application standards in the Netherlands. In this model, leaching fractions based on N surplus are used to calculate nitrate leaching.
- the STONE-model, a model used to evaluate nitrate leaching at the manure policy in the Netherlands. The submodel ANIMO is used to calculate the nitrate leaching.

3.3.2 WOG-model

The relationships between N use and soil N surplus, soil N surplus and N leaching, and N leaching and N concentration in groundwater have to be known to derive environmentally sound N use standards. A method

---

[8] WOG; Werkgroep Onderbouwing Gebruiksnormen van de Commissie van Deskundigen Meststoffenwet (CDM). Working Group of the Scientific Committee of the Manure Act (CDM) to underpin application standards (www.cdm.wur.nl)

was derived to calculate nitrate leaching from the root zone of agricultural land as a fraction of the nitrogen surplus on the soil balance (Fraters et al. (2007; 2011; Schröder et al., 2007; 2010). Below some paragraphs are cited from the draft paper of Fraters et al. (2011).

The nitrate-N leaching as fraction of the N surplus of the soil N balance was calculated for grassland and arable land on a well and deeply drained sand soil, which is the most vulnerable soil to nitrate leaching. Data on farm practices and water quality from commercial dairy farms and arable farms were used, which participated in the Minerals Policy Monitoring Program (LMM) from the start (1991) to 2005. A procedure was developed to account for the presence of other soils types and different land use types on LMM farms in nitrate leaching calculations. The nitrate leaching expressed as fraction of the N surplus on the soil balances was almost twice as high for arable land (average leaching fraction is 0.89, standard deviation 0.15) than for grassland (average leaching fraction is 0.46, standard deviation 0.09).

For each farm the distribution over the different groundwater regime classes (GRCs) and soil types were determined using the national GRC map and the soil map (Boumans et al., 2005). In total, eleven GRCs were distinguished on the map. GRC 1-6 are commonly natural poorly drained soils with shallow groundwater levels (ALG < 1.20 m) and GRC 10 and 11 well and deeply drained soils (AHG > 0.80 m). GRC 7-9 are moderately drained soils with intermediate groundwater levels (ALG > 1.20 6m and AHG < 0.80 m). Four soil types were distinguished based on clay and organic matter content. The N surplus and nitrate concentration were averaged per year for all arable farms and all dairy farms before analyzes. Data were averages for arable farms (no grassland) and dairy farms (mainly grassland) separately. Nitrate leaching fractions (NLFs) were calculated for a reference soil per individual year and separately for arable land and grassland. The soil selected as reference was a soil most vulnerable for nitrate leaching, i.e. a well and deeply drained sandy soil (GRC 11). The relationship for non-reference sandy soils, i.e. sandy soils not well and deeply drained, was calculated using the relationship derived for the reference soil and a set of independently derived factors accounting for the effect of soil drainage (Boumans et al., 1989). The nitrate leaching fraction was calculated as the ratio of nitrate-N leaching (kg per ha per year) and the N surplus on the soil balance (kg per ha per year). N-leaching and soil N surplus were averaged over farms.

The N surplus on the soil balance was calculated by adding the following items to the N surplus on the farm gate balance: the net N mineralization, atmospheric N deposition and biological N fixation and by subtracting from it the NH_3-N losses from housing and storage of manure, from application of artificial fertilizers and manure and from manure excreted during grazing (Schröder et al., 2009).

Table 15 shows the nitrate leaching fractions for sandy soils, i.e. the fraction of the N surplus that leaches to groundwater. The leaching fractions for sandy soils ranges from 0.02 for grassland on wet sandy soil to 0.89 for arable land on dry sandy soil. The leaching fraction for grassland on peat soil is 0.04 and that for arable land on clay soil 0.36 and that for grassland on clay soil 0.12.

Table 15

Fraction of the N surplus that leaches to groundwater for arable land and grassland on sandy soil in the Netherlands for different groundwater regime classes (Fraters et al., 2011).

	Groundwater Regime Class								
	1-3	4	5	6	7	8	9	10	11
Arable land	0.04	0.07	0.28	0.38	0.45	0.43	0.58	0.73	0.89
Grassland	0.02	0.04	0.14	0.20	0.23	0.22	0.30	0.38	0.46

3.3.3 **STONE-model**

STONE comprises of a national scale soil and land use schematization (Figure 2), results of a hydrological model and simulation modules for nitrogen deposition, crop uptake, fertilizer and manure distribution, and for the simulation of nutrient dynamics in soils (ANIMO). The fertilizer and manure distribution is calculated with the MAMBO-model. Results of the MAMBO model are calibrated and validated yearly with data of manure transports in the Netherlands (Luesink and Kruseman, 2007; Luesink et al., 2008).

ANIMO is a detailed process oriented simulation model for evaluation of nitrate leaching to groundwater, and N- and P-loads on surface waters. The model is primarily used for the ex-ante evaluation of fertilization policy and legislation at regional and national scale. ANIMO aims to quantify the leaching of nutrients a function of fertilization level, soil and water management and land use and for a wide range of soil types and different hydrological conditions.

ANIMO is a one-dimensional mechanistic and deterministic model at field scale for calculating the cycling of C, N and P in soils and N and P emissions to ground and surface waters. It was first developed in the mid-1980s and has been updated regularly since then (e.g. Rijtema and Kroes, 1991; Rijtema et al. 1999; Groenendijk et al. 2005; Kroes and Roelsma, 2007; Wolf et al., 2003). The following description is taken mainly from Wolf et al. (2003). The relevant parts of the model are: (1) the organic C cycle, (2) the N cycle, and (3) the P cycle.

In the organic C cycle, the following processes are described: (a) application of various organic materials, (b) decomposition of fresh organic materials in soils and transformation to humus, and (c) turnover of humus. The organic part of the N and the P cycle in the soil runs largely parallel to the organic C cycle. In the inorganic part of the N cycle, the following processes are described: (a) addition of mineral N in fertilizers and N precipitation; (b) ammonium-N volatilisation; (c) ammonium sorption; (d) nitrification of ammonium; (e) denitrification; and (f) N uptake by crop. Groenendijk et al. (2005), De Willigen et al., (2007) and Vinten (1999) gave a more detailed description of the C and N cycling within the ANIMO model. A number of ANIMO applications for modelling N leaching (including hydrology) are given by Hack-ten Broeke et al., (1999), Hack-ten Broeke and De Groot (1998), Marinov et al. (2005) and Vinten (1999). A detailed description of ANIMO is given on www.animo.wur.nl/. A user's guide and technical reference are available (Renaud et al., 2005).

The STONE-model is validated (and partly calibrated) using the data of the Minerals Policy Monitoring Program (LMM), except for loess soils (Overbeek et al., 2001; Wolf et al., 2003) This means that both WOG-model and STONE make use of these LMM data.

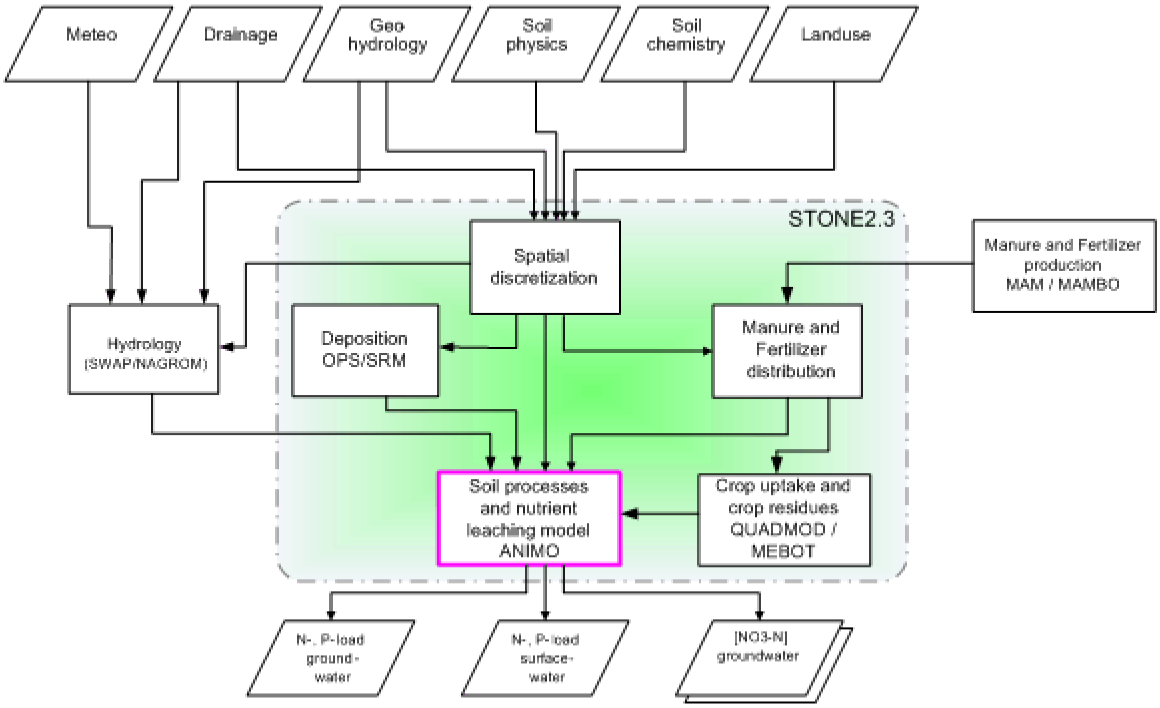


Figure 2
Schematic presentation of the STONE-mode.

3.3.4 **Comparison of both models**

The major differences between WOG-model and STONE-model are:

- Type of modeling.
  - The WOG-model is a static model, i.e. it calculates the leaching from the nitrogen surplus on the soil balance on a annual basis using fixed leaching fractions for different soil-crop combinations.
  - STONE/ANIMO is a detailed process oriented simulation model and, by that, needs more input data than the WOG-model.
- Scale: the WOG-model has been developed for calculations on the crop/field level and the STONE-model for the regional/national scale.
- STONE includes a module to calculate the surface runoff (overland flow[9]), so that STONE can calculate both leaching to groundwater and surface runoff. The leaching fractions of the WOG-model are based on leaching to groundwater, thus excluding surface runoff.

The WOG-model is derived from the data of the Minerals Policy Monitoring Program (LMM) and the STONE-model is validated (and partly calibrated) using these data (except for loess soils). This means that both WOG-

---

[9] Surface runoff is the overland flow and does not include drainage to surface water or horizontal leaching through the upper zones of the soil

model and STONE-model make use of these LMM data. The measurement of nitrate concentrations are carried out in the upper meter of the groundwater in LMM. Thus, the WOG-model calculates the leaching of nitrate to the upper meter of the groundwater. STONE-model is validated for the nitrate concentration in the upper groundwater, but is able to calculate the nitrate concentration in other soil and groundwater layers. For calculation of FracLEACH, the nitrate concentration calculated with STONE of the upper meter of ground water is considered, because this is the layer for which STONE has been validated and because this N can be considered as leached (i.e. it out of reach of roots of crops).

In a brainstorm session (27th August 2010), four scientists[10] have discussed the advantages and disadvantages of using the WOG-model and STONE-model for calculation of FracLEACH in the Netherlands in the method for quantification of the indirect N_2O emission. The major conclusions are:

- The calculation of N leaching using the IPCC methodology in which the leaching is calculated from the total N input and a FracLEACH is a relatively rough method, because it does not account for differences in crop N uptake. A high N application rate will not result in higher leaching if the N uptake is also high. Both the calculation of leaching in the WOG-model and that in the STONE-model are based on the surplus of N (i.e. the difference between the total N input to the soil and the N output by the harvested crop). The N surplus is a much better indicator for the risk of leaching than the N input, because it not only considers the N input via fertilizer and manures, but also the N output via harvested crop.
- Furthermore, the WOG-model and STONE-model are based on data specific for the Netherlands (soil, climate, crop, nutrient management). It is concluded that a methodology in which N leaching is derived from WOG-model or STONE-model will result in a more reliable estimate of the N leaching than the default method of IPCC, using a FracLEACH of 0.3 of the total N input.
- The calculation of FracLEACH using the IPCC-2006 method is based on the total N input to the soil and that of IPCC-1996 method on the total N fertilizer input to soil and the N excretion by livestock, and thus includes also the gaseous N losses which take places in housing and manure storage. The IPCC 2006 method is conceptually better and preferred, because it relates to the N leaching to the N input to the soil.
- Both the WOG-model and STONE-model can be used to calculate a country specific FracLEACH for the Netherlands.
- Although both methods can be used to calculate every year a FracLEACH, there was a general agreement during the discussion that it is better to use an average FracLEACH derived from calculations over several years. This is because part of the input parameters are not year specific. Moreover, in case of STONE, the leaching found in one year is caused by N inputs in the years before. Thus, the average FracLEACH of several years is the most robust estimator of FracLEACH. It is recommended to check (and if necessary update) the factor if new modelling results are available, e.g. results of from the Evaluation of the Fertiliser Act (about once in six years). However, it is not expected that FracLEACH will strongly change.
- The FracLEACH using the WOG-model can be calculated as follows:
  - The leaching fractions in percentage of the N surplus are available for grassland and arable land for different soil types and, for sand, for different groundwater classes.
  - The N inputs to soils are limited in the future by the application standards for mineral N fertilizer and manure. If it is assumed that the N inputs to crops is equal to these standards, the N surplus for each soil-crop combination can be calculated using the crop model of the WOG-model (Schröder et al., 2009; Van Dijk and Schröder, 2007).
  - If the N inputs and N surplus are known for crops and soils, the leaching fractions in percentage of the N surplus for each soil-crop combination can be transformed in a FracLEACH of the N input.

---

[10] D. Fraters, RIVM; P. Groenedijk (Alterra, Wageningen UR); J. Schröder (Plant Research International, Wageningen UR); G. Velthof (Alterra, Wageningen UR)

  - The average FracLEACH can be calculated using the FracLEACH of each soil-crop combination and the area of these combinations in the Netherlands.
- The FracLEACH using the STONE-model can be calculated as follows:
  - The total leaching of nitrate to the upper part of the groundwater and the runoff (over land flow) of total N in agricultural soils in the Netherlands is calculated for a number of years.
  - The total N inputs as fertilizer, manure, and grazing are also available for these years.
  - The FracLEACH is calculated for each year as: total N leaching/total N input.
  - All the required data and STONE results are available (Groenendijk et al., 2008) http://content.alterra.wur.nl/Webdocs/PDFFiles/Alterrarapporten/AlterraRapport1820.pdf).

Comparison of both models:
- Both models are described in scientific papers and detailed descriptions in reports are available. Both are acceptable approaches for a scientific reviews.
- The approach of the WOG-model is more simple and transparent than that of the STONE-model and more easy to describe.
- The STONE-model is used for the regional and national scale and the WOG-model for the field scale. An average FracLEACH for the Netherlands has to be calculated. The STONE-model is better equipped to calculate an average FracLEACH for the Netherlands (e.g. it includes detailed maps of soil types, land use and groundwater levels). The focus of the WOG-model is the crop or field scale. It is possible to scale the results of the WOG-model up to regional or national level, but this will demand for additional data (not part of the common WOG modeling system).
- STONE contains a fertilizer and manure distribution model, which is also used by the Emisison Registration for the calculation of regional ammonia emissions (the model MAMBO).
- The STONE-model includes both a calculation module for leaching and for surface runoff (overland flow); the leaching fractions of the WOG-model are only based on leaching to groundwater.

It was concluded that STONE is more suitable for calculation of an average FracLEACH in the Netherlands than the WOG-model.

3.3.5 **Country specific FracLEACH for the Netherlands**

In this paragraph, the FracLEACH calculated using STONE results, based on the IPCC 1996 method.

The average leaching of nitrate to the upper part of the groundwater and the runoff (over land flow) of total N in agricultural soils in the Netherlands was calculated for three periods using the STONE 2.3 and the recorded data for rainfall and temperature:
- 1987 - 1991: to be used as the average for the year 1990.
- 1992 - 1997: the period with relative high N inputs to soils and in which farmers were obliged to apply manure with a low ammonia emission technique (this was not yet obliged in 1990). This has resulted in lower gaseous N emissions and, by that, to higher N inputs to soil.
- 1998 - 2008: the period in which the N inputs to soils strongly decreased in the Netherlands. Low ammonia emission application techniques were obliged in this period.

The average FracLEACH for the Netherlands was calculated by dividing the total leaching and runoff in the Netherlands calculated with STONE with the total N inputs according to the Pollutant Release and Transfer Register (Van der Maas, 2010; Table 16). The N inputs of the Pollutant Release and Transfer Register were used in the calculations to be consistent with other calculations of N emissions in which the N inputs are used.

The FracLEACH (based on IPCC-1996 methodology) was 0.14 for 1987-1991, 0.13 for the period 1992 - 1997, and 0.12 for the period 1998 - 2008 (Table 17). A rough calculation with the WOG-model for several combinations or crop-soil-grondwater level combinations, also show that FracLEACH was lower than 0.3 (data not shown). The FracLEACH calculated with the WOG-model was somewhat smaller than that of STONE.

Clearly, the average FracLEACH obtained for the Netherlands is smaller than the default IPCC factor of 0.3. This is mainly due to the large area of soils with a high denitrification capacity (and low N leaching) in the Netherlands: clay, peat, and wet sandy soils and grasslands (Figure 3). The FracLEACH ranged from < 0.01 for soil with a high denitrification capacity (peat, clay, and wet sandy soils) to about 0.4 for dry sand soils, i.e. soils with a low denitrification capacity (Figure 3). The denitrification capacity of grassland is higher than of arable land (because of the higher organic matter contents of grasslands than of arable land), by which the FracLEACH of grassland is lower than that of arable land. The high FracLEACH for the dry sand soils are in agreement with the relatively high FracLEACH for the well drained sandy soils in Denmark (Figure 1).

Figure 4 shows the average area of grassland and arable land on clay, peat and sandy soils in the Netherlands. The area of soils and land use with al relatively low FracLEACH is relatively large. The FracLEACH for more than 80% of the area of agricultural soils in the Netherlands is smaller than the default factor 0.3 and the FRACleach is less than 0.1 in about 60% of the agricultural soils.

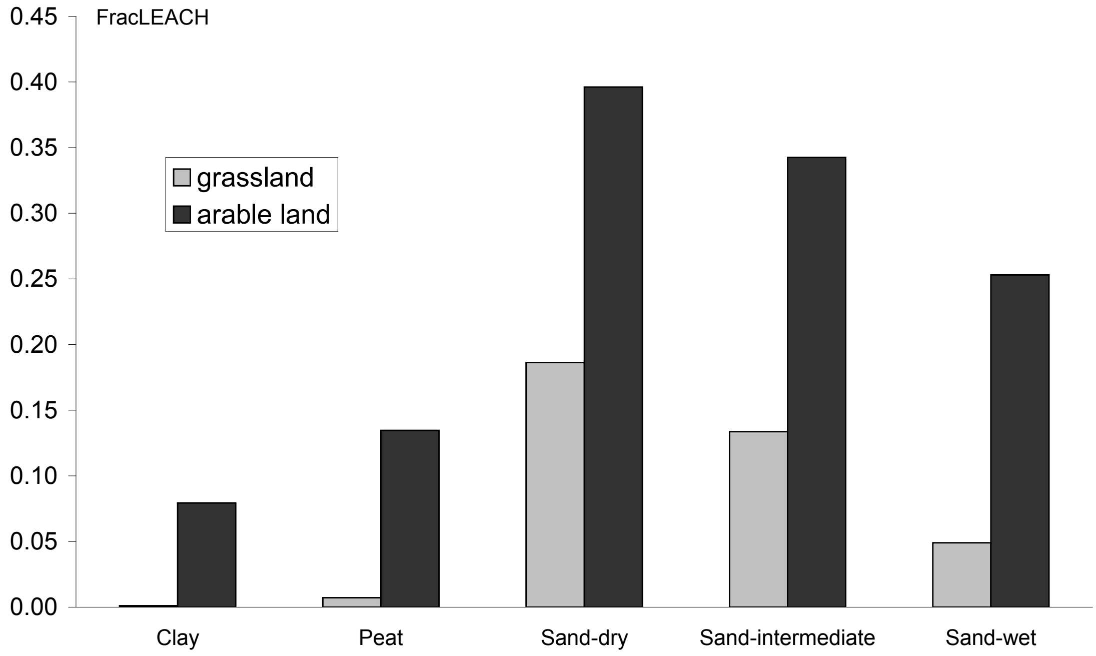


Figure 3

.Average calculated leaching fraction (FracLEACH) for arable land and grassland on clay, peat and sandy soils. The sandy soils are split in three wetness classes ('dry is deep groundwater, i.e. deeper than óne meter during whole year, and 'wet' is shallow groundwater, i.e. within the upper meter of the soil during winter. 'Intermediate' is between 'dry' and 'wet')

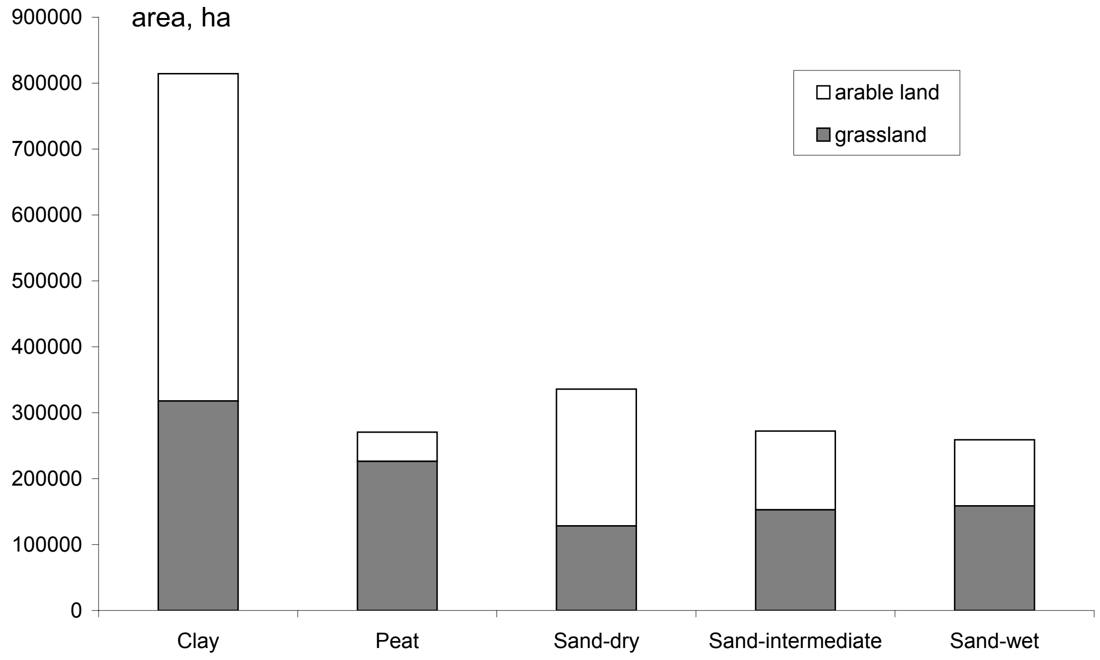


Figure 4
Average area of grassland and arable land on on clay, peat and sandy soils in the Netherlands (Source: STONE 2.3).

Table 16
Input of N (in million kg N) to agricultural soil in the Netherlands (Source: National Inventory report 2010, Van der Maas et al., 2010).

Year	Manure	Manure exported from the Netherlands	Mineral N- fertilizer	Sewage sludge	Total
1987	656		494		1150
1988	639		449		1088
1989	634		434		1069
1990	694	6	412	5	1105
1991	719	7	400	5	1118
1992	718	11	392	6	1104
1993	711	15	390	4	1089
1994	682	21	372	3	1035
1995	680	22	406	2	1065
1996	668	13	389	2	1046
1997	645	11	401	1	1035
1998	602	10	403	1	996
1999	585	13	383	1	956
2000	549	15	340	2	875
2001	542	18	298	1	824
2002	505	20	292	2	779
2003	479	12	291	2	760
2004	467	16	301	1	753
2005	479	15	279	1	744
2006	471	16	288	1	744
2007	480	29	258	1	709
2008	491	31	238	1	700
2009	498	31	238	1	707

Table 17
Total leaching to the upper part of the groundwater and runoff in the Netherlands (in kg N) from agricultural soils (all crops, soils, and groundwater classes), calculated with STONE, the total N inputs according to Pollutant Release and Transfer Register), and the calculated FracLEACH, for three periods.

Period	leaching, kg N	runoff, kg N	leaching + runoff, kg N	N input, kg N	FracLEACH
1987-1991	149,215,822	5,435,772	154,651,594	1,106,031,134	0.14
1992-1997	139,741,969	963,588	140,705,557	1,062,537,589	0.13
1998-2008	94,232,689	816,949	95,049,639	803,817,864	0.12

3.4 Emission factor for indirect N_2O emission (EF5)

The overall value for the emission factor for leached N (EF5) has been changed in IPCC 2006 compared to IPCC 1996 from 0.025 to 0.0075 kg N_2O-N per kg N leached. This emission factor incorporates three components: EF5g, EF5r and EF5e, which are the emission factors for groundwater and surface drainage, rivers, and estuaries, respectively. IPCC 2006 suggested that the previously used emission factor for groundwater and surface drainage (EF5g; 0.015) was too high and should be reduced to 0.0025 kg N_2O- N per kg leached N. The emission factor for rivers (EF5r) has also been reduced from 0.0075 kg N_2O-N per kg N to 0.0025 kg N_2O-N per kg N in the water. The value for estuaries (EF5e) remains at 0.0025 kg N_2O-N per kg N.

Kroeze et al. (2010) indicated that the emission factors according the IPCC 2006 methodology for aquatic sources of N_2O have been an issue of debate (Mosier et al., 1998; Kroeze et al., 2005; De Klein et al., 2007). They stated that the current version (2006) of the IPCC Guidelines recognizes that the current (2006) default value may be too low for some rivers. Weymann et al. (2008) determined experimentally groundwater N_2O emission factors for four sand and gravel aquifers in northern Germany. They concluded that their observations support the lower EF5 factor in IPCC 2006 in comparison to IPCC 1996.

In the Dutch protocol, the IPCC 1996 emission factor of 0.025 kg N_2O-N per kg N leached is used. This emission factor is much higher than the emission factor of 0.0075 kg N_2O-N per kg N leached in the IPCC 2006 methodology. Adopting this new IPCC factor for indirect emissions by the Netherlands will result in a strong decrease in the indirect N_2O emission related to leaching.

There are several studies carried out in the Netherlands in which N_2O emission from surface waters or groundwater was measured (e.g. De Wilde, 1999; Van Beek, 2007; Hefting, 2003). However, these studies do not relate the total N_2O emission to the amount of leached nitrate. Moreover, these studies only focus on a small part of the N leaching pathway (e.g. Van Beek (2007) on ditches in peat area, De Wilde (1999) on marine systems, and Hefting (2003) on riparian buffer zones).

The model STONE calculates the denitrification in the groundwater and in the water flow towards the surface waters (see paragraph 3.3.3). However, STONE only calculates total denitrification losses (=N_2 + N_2O) and is not parametrized to calculate the N_2O emission derived from leached nitrogen. There is no model available that calculates the N_2O emission from groundwater and surface waters in the Netherlands.

Concluding, there are no results from the Netherlands (both measurements and modeling) to derive a specific N_2O emission factors for the indirect N_2O emission from leached nitrate in the Netherlands.

3.5 Recommendations

3.5.1 **FracLEACH**

It is recommended to use the STONE model to calculate N leaching and runoff for three periods:

- 1987 - 1991: to be used as the average for the year 1990
- 1992 - 1997: the period with relative high N inputs to soils and in which farmers were obliged to apply manure with a low ammonia emission technique (this was not yet obliged in 1990).
- 1998 - 2008: the period in which the N inputs to soils strongly decreased in the Netherlands. Also the low ammonia emission application techniques are obliged.

The FracLEACH can be calculated using the leaching and runoff derived from the STONE model and the total N inputs according to the data derived from the Pollutant Release and Transfer Register (www.emissieregistratie.nl).

The FracLEACH (based on the IPCC-1996 methodology) was calculated for three periods: 0.14 for 1987-1991, 0.13 for the period 1992-1997, and 0.12 for the period 1998-2008.

3.5.2 **EF5**

There are no results from the Netherlands (both measurements and modeling) to derive specific N_2O emission factors for the indirect N_2O emission from leached nitrate in the Netherlands (EF5). For the first budget beriod of the Kyoto protocol (2008-2012), the Netherlands is obliged to use the IPCC-1996 method. However, it is recommended to use the IPCC-2006 emission factors for indirect N_2O emission derived from leached nitrate in the following budget period, as the most recent scientific insights are used for underpinning the IPCC-2006 emission factor.

Literature

Abbasi, M.K. and W.A. Adams, 2000. Gaseous N emissions during simultaneous nitrification - denitrification associated with mineral N fertilization to a grassland soil under field conditions. *Soil Biol. Biochem.* 32, pp. 1251-1259

Ambus, P., J.M. Jensen, A. Prieme, K. Pilegaard and A. Kjoller, 2001. Assessment of CH_4 and N_2O fluxes in a Danish beech (Fagus sylvatica) forest and an adjacent N-fertilised barley (Hordeum vulgare) field: effects of sewage sludge amendments. *Nutr. Cycl. Agroecosys*. 60, pp. 15-21.

Anger, M., C. Hoffman and W. Kühbauch, 2003. Nitrous oxide emissions from artificial urine patches applied to different N-fertilized swards and estimated annual N_2O emissions for differently fertilized pastures in an upland location in Germany. *Soil Use and Management* 19, pp. 104-111.

Arah, J.R.M., K.A. Smith, I.J. Crighton and H.S. Li, 1991. Nitrous oxide production and denitrification in Scottish arable soils. *Soil Sci.* 42, pp. 351-367.

Ball, B.C., G.W. Horgan and J.P. Parker, 2000. Short-range spatial variation of nitrous oxide fluxes in relation to compaction and straw residues. *European Journal of Soil Science* 51, pp. 607-616.

Beek, C.L.M. van, 2007. *Nutrient losses from grassland on peat soil*. PhD Thesis Wageningen University.

Boumans, L.J.M., C.R. Meinardi and G.J.W. Krajenbrink 1989. *Nitraatgehalten en kwaliteit van het grondwater onder grasland in de zandgebieden [Nitrate concentration and the quality of shallow groundwater of grassland in the sandy areas of the Netherlands].* Bilthoven, the Netherlands, RIVM report no. 728472013, 43 pp. (in Dutch).

Boumans, L.J.M., B. Fraters and G. van Drecht, 2005. Nitrate leaching in agriculture to upper groundwater in the Sandy regions of the Netherlands during the 1992-1995 period. *Environmental Monitoring and Assessment* 102, pp. 225-241.

Burford, J.R., R.J. Dowdell and R. and Crees, 1981. Emission of nitrous oxide to the atmosphere from direct drilled and ploughed clay soils. *J. Sci. Food Agric.* 32, pp. 219-223.

Carran, R.A., P.W. Theobold and J.P. Evans, 1995. Emissions of nitrous oxide from some grazed pasture soils. *New Zealand and Australian Journal of Soil Research* 33, pp. 341-352.

Chadwick, D.R., B.F. Pain S.K.E. and Brookman, 2000. Nitrous oxide and methane emissions following application of animal manures to grassland. *J. Environ. Qual.* 29, pp. 277-287.

Christensen, S., 1983. Nitrous oxide emission from a soil under permanent grass: seasonal and diurnal fluctuations as influenced by manuring and fertilization. *Soil Biol. Biochem.* 15, pp. 531-536.
Clayton, H., J.R.M. Arah and K.A. Smith, 1994. Measurement of nitrous oxide emissions from fertilised grassland using closed chambers. *J. Geophys. Res.* 99, pp. 16599-16607.

Clayton, H., I.P. McTaggart, J. Parker, L. Swan and K.A. Smith, 1997. Nitrous oxide emissions from fertilized grassland: a 2-year study of the effects of N fertilizer form and environmental conditions. *Biol. Fertil. Soils* 25, pp. 252-260.

Clemens, J., R. Vandré, M. Kaupenjohann and H. Goldbach, 1997. Ammonia and nitrous oxide emissions after landspreading of manure as influenced by application technique and dry matter-reduction. II. Short term nitrous oxide emissions. *Z. Pflanzenernähr. Bodenk.* 160, pp. 491-496.

Colbourn, P. and I.W. Harper, 1987. Denitrification in drained and undrained arable clay soil. *J. Soil Sci.* 38, pp. 531-539.

Colbourn, P., M.M. Iqbal and I.W. Harper, 1984. Denitrification losses from 15N labelled calcium fertilizer in a clay soil in the field. *J. Soil Sci.* 35, pp. 539-547.

Conrad, R., W. Seiler and G. Bunse, 1983. Factors influencing the loss of fertilizer nitrogen in the atmosphere as N_2O. *J. Geophys. Res*. 88, pp. 6709-6718.

Dijk, W. van and J.J. Schröder 2007*. Adviezen voor stikstofgebruiksnormen voor akker- en tuinbouwgewassen op zand- en lössgrond bij verschillende uitgangspunten*. AGV PPO nr. 371, Praktijkonderzoek Plant & Omgeving B.V., Lelystad.

Dobbie, K.E. and K.A. Smith, 2003a. Nitrous oxide emission factors for agricultural soil in Great Brain: the impact of soil water-filled pore space and other controlling variables. *Glob. Change Biol.* 9, pp. 204-218.

Dobbie, K.E., I.P. McTaggart and K.A.Smith, 1999. Nitrous oxide emissions from intensive agricultural systems: variations between crops and seasons, key driving variables, and mean emission factors. *Journal of Geophysical Research* 104, pp. 26891-26899.

Dolfing, J., P.J. Kuikman, G.L. Velthof and K.A. Zwart (unpublished). Effect of sugar beet and barley residues on nitrous oxide emission from soils. Unpublished (concept paper available in Reductie Plan Overige Broeikasgassen Landbouw map 3: achtergrond documentatie. Alterra, Wageningen).

Eggington, G.M. and K.A. Smith, 1986. Nitrous oxide emission from a grassland soil fertilized with manure and calcium nitrate. *J. Soil Sci*. 37, pp. 59-67.

Ellis, S., S, Yamulki, E. Dixon, R. Harrison and S.C. Jarvis, 1998. Denitrification and N2O emissions from a UK pasture soil following the early spring application of cattle manure and mineral fertilizer. *Plant Soil* 202, pp. 15-25.

EPA, 2002. *Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations*. U.S. Environmental Protection Agency. EPA-821-R-03-004. December 2002.

Fraters, B., L.J.M. Boumans, T.C. van Leeuwen and J.W. Reijs, 2011. *Relationship between nitrate leaching and nitrogen surpluses for arable land and grassland on sandy soils* (Scientific publication in preparation).

Fraters, B., L.J.M. Boumans, T.C. van Leeuwen and J.W. Reijs, 2007. *De uitspoeling van het stikstofoverschot naar grond- en oppervlaktewater op landbouwbedrijven*. RIVM Rapport 680716002/2007, RIVM, Bilhoven.

Glatzel, S. and K. Stahr, 2001. Methane and nitrous oxide exchange in differently fertilized grassland in southern Germany. *Plant and Soil* 231, pp. 21-35.

Goossens, A., A. De Visscher, P. Boeckx and O. van Cleemput, 2001. Two-year field study on the emission of N2O from coarse and middle-textured Belgian soils with different land use. *Nutr. Cycl. Agroecosyst.* 60, pp. 23-34.

Groenendijk, P., L.V. Renaud and J. Roelsma, 2005. *Prediction of Nitrogen and Phosphorus leaching to groundwater and surface waters; Process descriptions of the Animo4.0 model.* Wageningen, Alterra - Report 983, 114 pp.

Groenendijk, P., L.V. Renaud, J. Roelsma, G.M.C.M. Janssen, S. Janssen, R. Heerdink, J. Griffioen and B. van der Grift. 2008. A new compliance checking level for nitrate in groundwater. Modelling nitrate leaching and the fate of nitrogen in the upper five meter of the groundwater system. Alterra, Alterra report 1820, 215 p. http://content.alterra.wur.nl/Webdocs/PDFFiles/Alterrarapporten/AlterraRapport1820.pdf).

Groenigen, J.W. van, G.J. Kasper, G.L. Velthof, A. van den Pol van Dasselaar and P.J. and Kuikman, 2004. Nitrous oxide emissions from silage maize fields under different mineral nitrogen fertilizer and manure applications *Plant and Soil* 263, pp. 101-111

Groenigen, J.W. van, P.J. Kuikman, W.K.M. de Groot G.L. and Velthof, 2005. Nitrous oxide emission from urine-treated soil as influenced by urine composition and soil physical conditions. *Soil Biology and Biochemistry* 37, pp. 463-473.

Hack-ten Broeke M.J.D. and W.J.M. de Groot, 1998. Evaluation of nitrate leaching risk at site and farm level. *Nutrient Cycling in Agroecosystems* 50, pp. 271-276.

Hack-ten Broeke, M.J.D. A.G.T. Schut and J. Bouma, 1999. Effects on nitrate leaching and yield potential of implementing newly developed sustainable land use systems for dairy farming on sandy soils in the Netherlands. *Geoderma* 91, pp. 217-35.

Hénault, C., X. Devis, J.L. Lucas and J.C. Germon, 1998. Influence on different agricultural practices (type of crop, form of N-fertilizer) on soil nitrous oxide emissions. *Biol. Fertil. Soils* 27, pp. 299-306.

Hefting, M.M., 2003. Nitrogen transformation and retention in riparian buffer PhD. Thesis University Utrecht.

Hoek, K.W. van der, M.W. van Schijndel and P.J. Kuikman, 2007. *Direct and indirect nitrous oxide emissions from agricultural soils, 1990 - 2003.* Background document on the calculation method for the Dutch National Inventory Report. RIVM rapport 680125003; MNP rapport 500080003

Hoving, I.E. and G.L. Velthof, 2006. *Landbouw- en milieukundige effecten van graslandvernieuwing op zand- en kleigrond.* Praktijk Rapport 83. Animal Science Group, Lelystad.

Jambert, C., R. Delmas, D. Serca, L. Thouron, L., Labroue and L. Delprat, L., 1997. N_2O and CH_4 emissions from fertilized agricultural soils in southwest France. *Nutrient Cycling in Agroecosystems* 48, pp. 105-114.

Jørgensen, R.N., B.J. Jørgensen, N.E. Nielsen, M. Maag and A.M. Lind, 1997. N2O emission from energy crop fields of Miscanthus Giganteous and winter rye. *Atmospheric Environment* 31(18), pp. 2899-2904.

Kaiser, E.A., K. Kohrs, E. Kücke, E., Schnug, J.C. Munch and O. Heinemeyer, 1996. Nitrous oxide from cultivated soils: influence of different N-fetilizer types. In: *Transactions of the 9th Nitrogen Workshop*, eds. B. Diekkrüger, O. Heinemeyer and R. Nieder, pp. 149-152. Braunschweig, September. Technische Universität Braunschweig.

Kaiser, E.A., M. Kohrs, M. Kücke, E. Schnug, J.C. Munch and O. Heinemeyer, 1998. Nitrous oxide release from arable soil: importance of different perennial forage crops. *Biol. Fert. Soils* 28, pp. 36-43.

Kamp, T., H. Steindl, R.E. Hantschel, F. Beese and J.C. Munch, 1998. Nitrous oxide emissions from a fallow and wheat field as affected by increased soil temperatures. *Biol. Fertil. Soils* 27, pp. 307-314.

Kersebaum, K. Ch., et al., (Eds.), *Modelling Water and Nutrient Dynamics in Soil-Crop Systems*. Springer. pp. 111-128.

Klein, C.A.M. de, L. Barton, R.R. Sherlock, Z. Li and R.P. Littlejohn, 2003. Estimating a nitrous oxide emission factor for animal urine from some New Zealand pastoral soils. *Australian Journal of Soil Research* 41, pp. 381-399.

Klein C.A.M. de, R.S.A. Novoa, S. Ogle, K.A. Smith, P. Rochette, T.C. Wirth, B.G. McConkey, A. Mosier, K. Rypdal, M. Walsh et al., 2007. Chapter 11: N_2O emissions from managed soils, and CO2 emissions from lime and urea application. In: 2006 *IPCC guidelines for national greenhouse gas inventories.*

Kroes, J.G. and J. Roelsma, 2007. Simulation of water and nitrogen flows on field scale: application of the SWAP-ANIMO model for the Müncheberg data set. In:

Kroeze, C. 1994. *Nitrous oxide (N_2O). Emission inventory and options for control in the Netherlands.* Report nr. 773001004. RIVM. Bilthoven, the Netherlands.

Kroeze, C, E. Dumont and S.P. Seitzinger, 2005. New estimates of global emissions of N_2O from rivers, estuaries and continental shelves. *Environ Sci.* 2 (2-3), pp. 159-167.

Kroeze, C., E. Dumont and S.P. Seitzinger, 2010. Future trends in emissions of N_2O from rivers and estuaries. *Journal of Integrative Environmental Sciences* 7. 2, pp. 71-78.

Kuikman, P.J., K.W. van der Hoek, A. Smit and K.A. Zwart, 2006. *Update of emission factors for direct emissions of nitrous oxide from agricultural soils on the basis of measurements in the Netherland*s. Alterra report 1217, Alterra, Wageningen.

Luesink, H.H. and G. Kruseman. 2007. Emission inventories. pp. 45-67 In: Starmans. D.A.J. and K.W. Van der Hoek. *Ammonia the case of the Netherlands*. Wageningen Academic Publishers. The Netherlands.

Luesink, H.H., P.W. Blokland, J.N. Bosma en M.W. Hoogeveen, 2008. *Monitoring manure market 2007, background.* The Hague, LEI, Report 2008-041, 142 p.

Maas, C.W.M. van der, P.W.H.G. Coenen, P.J. Zijlema, K. Baas, G. van den Berghe, G.J. van den Born, A.T. Brandt, R. Dröge, B. Guis, G. Geilenkirchen, R. te Molder, D.S. Nijdam, C.J. Peek, S.M. van der Sluis, 2010. *Greenhouse Gas Emissons in the Netherlands 1990-2008*. Report nr. 500080017

Marinov, D., D. Querner and J. Roelsma, 2005. Simulation of water flow and nitrogen transport for a Bulgarian experimental plot using SWAP and ANIMO models. *Journal of Contaminant Hydrology* 77, pp. 145 - 164.

McTaggart, I.P., H. Clayton, J. Parker, L. Swan and K.A. Smith, 1997. Nitrous oxide emissions from grassland and spring barley, following N fertilizer application with and without nitrification inhibitors. *Biol. Fertil. Soils* 25, pp. 261-268.

Mosier, A, C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger and O. van Cleemput, 1998. Closing the global N2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. *Nutrient Cycl Agroecosystems*. 52, pp. 225-248.

Myers, R.A. en P. Pepin, 1990. The robustness of lognormal-based estimators of abundance. *Biometrics* 46, 1185-1 p.192.

Misselbrook, T.H., D.R. Chadwick, B.F. Pain and D.M. Headon, 1998. Dietary manipulation as a means of decreasing N losses and methane emissions and improving herbage N uptake following application of pig manure to grassland. *J. Agric. Sci.* 130, pp. 183-191.

Mogge, B., E.A. Kaiser and J.C. and Munch, 1999. Nitrous oxide emissions and denitrification N-losses from agricultural soils in the Bornhöved Lake region (Northern Germany): influence of organic fertilizers and land-use. *Soil Biol. Biochem.* 31, pp. 1245-1252.

Muller, C., R.R. Sherlock and P.H. Williams, 1995. Direct field measurements of nitrous oxide emissions from urine-affected and urine-unaffected pasture in Canterbury. In: *Proceedings of the Workshop on Fertilizer Requirements of Grazed Pasture and Field Crops: Macro and Micronutrients*. Currie LD, Loganathan P (eds). Occasional Report No. 8, ISSN 0112-9902: 7. Palmerston North: Massey University, pp. 243-34.

Overbeek, G.B.J., A. Tiktak, A.H.W. Beusen and P.J.T.M. van Puijenbroek 2001. Partial Validation of the Dutch Model for Emission and Transport of Nutrients (STONE). *The ScientificWorld* 1(S2), pp. 194-199.

Parkin, T.B., J.J. Meisinger, S.T. Chester, J.L. Starr and J.A. Robinson, 1988. Evaluation of statistical estimation methods for lognormally distributed variables. *Soil Science Society of America Journal* 52, pp. 323-329.

Pauwelyn, J. and S. Depuyd, 1997. *Studie der kwantificering van de nutriëntenverliezen per stroombekken naar het oppervlaktewater door landbouwactiviteiten in Vlaanderen: een praktijkgericht onderzoek ter ondersteuning van het milieu- en landbouwbeleid*. Instituut voor Scheikundig Onderzoek. 54 p.

Petersen, S.O., 1999. Nitrous oxide emissions from manure and inorganic fertilizers applied to spring barley. J. Environ. Qual. 28, 1610-1618.

Prasuhn, V., R. Mohni, 2003. *GIS-gestützte Abschätzung der Phosphor- und Stickstoffeinträge aus diffusen Quellen in die Gewässer des Kantons Bern.* FAL, interner Bericht z.H. Amt für Gewässerschutz und Abfallwirtschaft, Kanton Bern. Zürich-Reckenholz.

Rekolainen, S., M. Posch and E. Turtola, 1993. Mitigation of agricultural water pollution in Finland: an evaluation of management practices. *Wat. Sci. Tech. Vol.* 28, pp. 529-538.

Renaud, L.V., J. Roelsma and P. Groenendijk, 2005. *User's guide of the ANIMO4.0 nutrient leaching model.* Wageningen, Alterra - Report 224, 184 pp. www.animo.wur.nl/availabilityandsupport.htm

Rijtema, P.E. and J.G. Kroes, 1991. Some results of nitrogen simulations with the model ANIMO. *Fertilizer Research* 27, pp. 189-198.

Rijtema, P.E., P. Groenendijk and J.G. Kroes, 1999. Environmental impact of land use in rural regions. The Development, Validation and Application of Model Tools for Management and Policy Analysis. *Series on Environmental Science and Management* vol. 1, Imperial College Press, Imperial College, London, UK, p. 321.

Rohde, L., M. Pell and S. Yamulki, 2006. Nitrous oxide, methane and ammonia emissions following manure spreading on grassland. *Soil Use and Management* 22, 229-237.

Ryden, J.C., 1981. N_2O exchange between a grassland soil and the atmosphere. *Nature* 292, pp. 235-237.

Ryden, J.C., 1983. Denitrification loss from a grassland soil in the field receiving different rates of nitrogen as ammonium nitrate. *J. Soil Sci.* 34, pp. 355-365.

Schils, R.L.M., J.W. van Groenigen, G.L. Velthof and P.J. Kuikman., 2008. Nitrous oxide emissions from multiple combined applications of fertiliser and cattle manure to grassland. *Plant and Soil* 310, pp. 89-101.

Schils, R.L.M., J.W. van Groenigen, G.L. Velthof and P.J. Kuikman, 2010. Fertilising practices to reduce nitrous oxide emissions from managed grasslands. *Grassland Science in Europe,* Vol. 15, pp. 81-83.

Schmid, M., A. Neftel and J. Fuhrer, 2000. Lachgasemissionen aus der Schweizer Landwirtschaft. [Emissions de protoxyde d'azote de l'agriculture Suisse].
Schriftenreihe der FAL 33. Zürich-Reckenholz. http://www.environment-switzerland.ch/climatereporting/00545/01913/index.html?lang=en

Schröder, J.J., H.F.M. Aarts, J.C. van Middelkoop, R.L.M. Schils, G.L. Velthof, B. Fraters and W.J. Willems, 2007. Permissible manure and fertilizer use in dairy farming systems on sandy soils in The Netherlands to comply with the Nitrates Directive target. *European Journal of Agronomy* 27, pp. 102-114.

Schröder, J.J., H.F.M. Aarts, J.C. van Middelkoop, G.L. Velthof, J.W. Reijs and B. Fraters, 2009. *Nitrates Directive requires limited inputs of manure and mineral fertilizer nitrogen in dairy farming systems*. Wageningen, the Netherlands, Plant Research International, Report 222, 46 pp.

Seiler, W. and R. Conrad, 1981. Field measurements of natural and fertilizer-induced N_2O release rates from soils. *J. Air Pollut. Control Assoc.* 31, pp. 767-772.

Skiba, U.M., K.J. Hargreaves, D. Fowler and K.A. Smith, 1992. Fluxes of nitric and nitrous oxides from agricultural soils in a cool temperate climate. *Atmos. Environ.* 26A, pp. 2477-2488.

Skiba, U.M., L.J. Sheppard, J. MacDonald and D. Fowler, 1998. Some key environmental variables controlling nitrous oxide emissions from agricultural and semi-natural soils in Scotland. *Atmospheric Environment* 32 (3), pp. 311-3320.

Slemr, F., R. Conrad and W. Seiler, 1984. Nitrous oxide emissions from fertilized and unfertilized soils in a subtropical region (Andalusia, Spain). *J. Atmos. Chem.* 1, 159-169.

Smith, K.A., P.E. Thomson, H., Clayton, I.P. McTaggart and F. Conen, 1998a. Effects of temperature, water content and nitrogen fertilization on emissions of nitrous oxide by soils. *Atmospheric Environment* 32(19), 3301-3309.

Smith, K.A., I.P. McTaggart, K.E. Dobbie and F. Conen, 1998b. Emissions of N_2O from Scottish agricultural soils, as a function of fertilizer N. *Nutrient Cycling in Agroecosystems* 52, pp. 123-130.

Stehfest, E. and L. Bouwman, 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. *Nutrient Cycling in Agroecosystems* 74, pp. 207-228.

Thomas, S.M., S.F. Ledgard and G.S. Francis, 2005. Improving Estimates of Nitrate Leaching for Quantifying New Zealand's Indirect Nitrous Oxide Emissions. *Nutrient Cycling in Agroecosystems* 73, pp. 213-226.

Velthof, G.L., A.B. Brader and O. Oenema, 1996. Seasonal variations in nitrous oxide losses from managed grasslands in the Netherlands. *Plant and Soil* 181: pp. 263-274.

Velthof, G.L., O. Oenema, R. Postma and M.L. van Beusichem, 1997. Effects of type and amount of applied nitrogen fertilizer on nitrous oxide fluxes from intensively managed grassland. *Nutrient Cycling in Agroecosystems* 46: pp. 257-267.

Velthof, G.L., J. Dolfing, G.J. Kasper, J.W. van Groenigen, W.J.M. de Groot, A. van den Pol-Van Dasselaar and P.J. Kuikman, 2003. *Beperking van lachgasemissie uit bemeste landbouwgronden.* Eindrapport Reductieplan Overige Broeikasgassen Landbouw Cluster 1 Alterra rapport 560.2, 58 pp.

Velthof, G.L., P.J. Kuikman and O. Oenema, 2003. Nitrous oxide emission from animal manures applied to soil under controlled conditions. *Biology and Fertility of Soil* 37, pp. 221-230.

Velthof, G.L., I.E. Hoving, J. Dolfing, A. Smit, P.J. Kuikman and O. Oenema, 2010a. Method and timing of grassland renovation affects herbage yield, nitrate leaching, and nitrous oxide emission in intensively managed grasslands. *Nutrient Cycling in Agroecosystems* 86: 401-412.

Velthof, G.L., J. Mosquera, J. Huis in 't Veld and E. Hummelink, 2010b. *Effect of manure application technique on nitrous oxide emission from agricultural soils*. Wageningen, Alterra, Alterra-report 1992, 74 p.

Velthof, G.L. and J. Mosquera, 2011) The impact of manure application technique on nitrous oxide emission from agricultural soils. *Agriculture, Ecosystems and Environment* (Accepted).

Vinten, A.J.A., 1999. Predicting Nitrate Leaching from Drained Arable Soils Derived from Glacial Till. *Journal of Environmental Quality* 28, pp. 988-996.

Webster, C.P. and R.J. Dowdell, 1982. Nitrous oxide emission from permanent grass swards. *J. Sci. Food Agric.* 33, pp. 227-230.

Weslien, P., L. Klemedtsson, L, Svensson, B. Galle, A. Kasimir-Klemedtsson and A. Gustafsson, A., 1998. Nitrogen losses following application of pig manure to arable land. *Soil Use and Management* 14, pp. 200-208.

Weymann, D., R. Well, H. Flessa, C. von der Heide, M. Deurer, K. Meyer, C. Konrad, and W. Walther, 2008. Groundwater N_2O emission factors of nitrate-contaminated aquifers as derived from denitrification progress and N_2O accumulation. *Biogeosciences* 5, pp. 1215-1226.

Wilde, H. de, 1999. Nitrous oxide and methane in marine systems. PhD thesis University of Groningen.

Wolf, J, A.H.W. Beusen, P. Goenedijk, T. Kroon, R. Rötter and H. van Zeijt, 2003. The integrated modeling system STONE for calculating nutrient emissions from agricultures in the Netherlands. *Environ Model Software* 18, pp. 597-617.

Wulf, S., M. Maeting and J. Clemens, 2002. Application technique and manure co-fermentation effects on ammonia, nitrous oxide, and methane emissions after spreading: II. Greenhouse gas emissions. *J. Environ. Qual.* 31, pp.1795-1801.

Yamulki, S. and S.C. Jarvis, 2002. Short-term effects of tillage and compaction on nitrous oxide, nitric oxide, nitrogen dioxide, methane and carbon dioxide fluxes from grassland. *Biol. Fertil. Soils* 36, pp. 224-231.

Yamulki, S., K.W.T. Goulding, C.P. Webster and R.M. Harrison, 1995. Studies on NO and N2O fluxes from a wheat field. *Atmospheric Environment* 29, pp. 1627-1635.

Appendix 1 N_2O-N emission factors derived from field experiments in the Netherlands

N_2O-N emission factor, % of N applied = [(N_2O-N fertilized) - (N_2O-N unfertilized)]/(amount of N applied) * 100

N source	Application rate kg N/ha	Land use	Soil type	Location	Year	Period	Manure application method	N_2O emission factor, % of N applied	Source	Comment
CAN	313	grassland	sand	Heino	1992/1993	1 year		0.60	Velthof et al. (1996)	
CAN	426	grassland	sand	Heino	1993/1994	1 year		1.30	Velthof et al. (1996)	
CAN	277	grassland	clay	Lelystad	1992/1993	1 year		1.40	Velthof et al. (1996)	
CAN	437	grassland	clay	Lelystad	1993/1994	1 year		0.50	Velthof et al. (1996)	
CAN	266	grassland	peat	Zegveld	1992/1993	1 year		2.20	Velthof et al. (1996)	relatively shallow groundwater level
CAN	464	grassland	peat	Zegveld	1993/1994	1 year		1.70	Velthof et al. (1996)	relatively shallow groundwater level
CAN	161	grassland	peat	Zegveld	1992/1993	1 year		4.50	Velthof et al. (1996)	relatively deep groundwater level
CAN	323	grassland	peat	Zegveld	1993/1994	1 year		3.60	Velthof et al. (1996)	relatively deep groundwater level
CAN-grazing	753	grassland	sand	Heino	1992/1993	1 year	grazing	0.80	Velthof et al. (1996)	
CAN-grazing	727	grassland	sand	Heino	1993/1994	1 year	grazing	1.70	Velthof et al. (1996)	

CAN-grazing	557	grassland	clay	Lelystad	1992/1993	1 year	grazing	1.70	Velthof et al. (1996)	
CAN-grazing	730	grassland	clay	Lelystad	1993/1994	1 year	grazing	2.10	Velthof et al. (1996)	
CAN-grazing	521	grassland	peat	Zegveld	1992/1993	1 year	grazing	1.90	Velthof et al. (1996)	relatively shallow groundwater level
CAN-grazing	712	grassland	peat	Zegveld	1993/1994	1 year	grazing	2.20	Velthof et al. (1996)	relatively shallow groundwater level
CAN-grazing	356	grassland	peat	Zegveld	1992/1993	1 year	grazing	6.50	Velthof et al. (1996)	relatively deep groundwater level
CAN-grazing	544	grassland	peat	Zegveld	1993/1994	1 year	grazing	6.80	Velthof et al. (1996)	relatively deep groundwater level
Urine/dung	440	grassland	sand	Heino	1992/1993	1 year	grazing	1.00	Velthof et al. (1996)	
Urine/dung	301	grassland	sand	Heino	1993/1994	1 year	grazing	2.20	Velthof et al. (1996)	
Urine/dung	280	grassland	clay	Lelystad	1992/1993	1 year	grazing	2.00	Velthof et al. (1996)	
Urine/dung	293	grassland	clay	Lelystad	1993/1994	1 year	grazing	4.60	Velthof et al. (1996)	
Urine/dung	255	grassland	peat	Zegveld	1992/1993	1 year	grazing	1.50	Velthof et al. (1996)	relatively shallow groundwater level
Urine/dung	248	grassland	peat	Zegveld	1993/1994	1 year	grazing	3.10	Velthof et al. (1996)	relatively shallow groundwater level
Urine/dung	195	grassland	peat	Zegveld	1992/1993	1 year	grazing	8.10	Velthof et al. (1996)	relatively deep groundwater level
Urine/dung	221	grassland	peat	Zegveld	1993/1994	1 year	grazing	11.40	Velthof et al. (1996)	relatively deep groundwater level
CAN	220	grassland	clay	Lelystad	March - Nov 1993	8.5 months		0.40	Velthof et al. (1997)	
CAN	660	grassland	clay	Lelystad	March - Nov 1993	8.5 months		0.50	Velthof et al. (1997)	
CAN	880	grassland	clay	Lelystad	March - Nov 1993	8.5 months		0.50	Velthof et al. (1997)	
CAN	80	grassland	clay	Wageningen	March 1993	3.5 weeks		0.10	Velthof et al. (1997)	emission factor < 0.1%
CN	80	grassland	clay	Wageningen	March 1993	3.5 weeks		0.10	Velthof et al. (1997)	emission factor < 0.1%
AS	80	grassland	clay	Wageningen	March 1993	3.5 weeks		0.10	Velthof et al. (1997)	emission factor < 0.1%
Urea	80	grassland	clay	Wageningen	March 1993	3.5 weeks		0.10	Velthof et al. (1997)	emission factor < 0.1%

CAN	80	grassland	sand	Bennekom	March-April 1994	4 weeks		5.20	Velthof et al. (1997)	
CN	80	grassland	sand	Bennekom	March-April 1994	4 weeks		5.20	Velthof et al. (1997)	
AS	80	grassland	sand	Bennekom	March-April 1994	4 weeks		0.20	Velthof et al. (1997)	
AS+DCD	80	grassland	sand	Bennekom	March-April 1994	4 weeks		0.10	Velthof et al. (1997)	emission factor < 0.1%
Urea	80	grassland	sand	Bennekom	March-April 1994	4 weeks		0.10	Velthof et al. (1997)	emission factor < 0.1%
Cattle manure	90	grassland	sand	Bennekom	March-April 1994	4 weeks	surface-applied	0.10	Velthof et al. (1997)	emission factor < 0.1%; 15 m3/ha manure
Cattle manure	90	grassland	sand	Bennekom	March-April 1994	4 weeks	shallow injection	0.10	Velthof et al. (1997)	emission factor < 0.1%; 15 m3/ha manure
CAN	80	grassland	sand	Bennekom	June-July 1994	4.5 weeks		8.30	Velthof et al. (1997)	
CN	80	grassland	sand	Bennekom	June-July 1994	4.5 weeks		12.00	Velthof et al. (1997)	
AS	80	grassland	sand	Bennekom	June-July 1994	4.5 weeks		1.00	Velthof et al. (1997)	
AS+DCD	80	grassland	sand	Bennekom	June-July 1994	4.5 weeks		0.10	Velthof et al. (1997)	
Urea	80	grassland	sand	Bennekom	June-July 1994	4.5 weeks		0.70	Velthof et al. (1997)	
Cattle manure	90	grassland	sand	Bennekom	June-July 1994	4.5 weeks	surface-applied	0.10	Velthof et al. (1997)	emission factor < 0.1%; 15 m3 manure per ha
Cattle manure	90	grassland	sand	Bennekom	June-July 1994	4.5 weeks	shallow injection	0.10	Velthof et al. (1997)	emission factor < 0.1%; 15 m3 manure per ha
CAN	50	grassland	sand	Bennekom	April - June 1994	6.5 weeks		0.60	Velthof et al. (1997)	
CAN	100	grassland	sand	Bennekom	April - June 1994	6.5 weeks		1.20	Velthof et al. (1997)	
CAN	150	grassland	sand	Bennekom	April - June 1994	6.5 weeks		1.20	Velthof et al. (1997)	
CAN	200	grassland	sand	Bennekom	April - June 1994	6.5 weeks		2.30	Velthof et al. (1997)	
CAN	300	grassland	sand	Bennekom	April - June 1994	6.5 weeks		3.10	Velthof et al. (1997)	
Sugar beet leaves	138	arable land	sand	Wageningen	Sept 2000 - May 2001	9 months		0.29	Dolfing et al. unpublished	
Sugar beet leaves	145	arable land	clay	Marknesse	Sept 2000 - May 2001	9 months		0.06	Dolfing et al. unpublished	
Urine patch	186	grassland	sand	Wageningen	Aug 2000 - Sept 2001	13 months		0.92	Van Groenigen et al.(2005)	Synthetic urine

Urine patch	280	grassland	sand	Wageningen	Aug 2000 - Sept 2001	13 months		2.12	Van Groenigen et al.(2005)	
Urine patch	373	grassland	sand	Wageningen	Aug 2000 - Sept 2001	13 months		1.67	Van Groenigen et al.(2005)	
Urine patch	746	grassland	sand	Wageningen	Aug 2000 - Sept 2001	13 months		1.96	Van Groenigen et al.(2005)	
Urine patch	373	grassland	sand	Wageningen	Aug 2000 - Sept 2001	13 months		1.51	Van Groenigen et al.(2005)	N concentration 4.77 g N/l
Urine patch	373	grassland	sand	Wageningen	Aug 2000 - Sept 2001	13 months		1.67	Van Groenigen et al.(2005)	N concentration 18.65 g N/l
Urine patch	373	grassland	sand	Wageningen	Aug 2000 - Sept 2001	13 months		1.15	Van Groenigen et al.(2005)	N concentration 9.33 g N/l
CAN	320	grassland	sand	Wageningen	March - Oct 2000	8 months		0.52	Schils et al. (2010)	
CAN	320	grassland	sand	Wageningen	March - Oct 2000	8 months		0.34	Schils et al. (2010)	split in more dressings
AS	320	grassland	sand	Wageningen	March - Oct 2000	8 months		0.32	Schils et al. (2010)	
CAN	120	grassland	sand	Wageningen	March - Oct 2001	8 months		0.11	Schils et al. (2008)	
CAN	240	grassland	sand	Wageningen	March - Oct 2001	8 months		0.23	Schils et al. (2008)	
CAN	330	grassland	sand	Wageningen	March - Oct 2001	8 months		0.17	Schils et al. (2008)	
Cattle manure	375	grassland	sand	Wageningen	March - Oct 2001	8 months	shallow injection	0.11	Schils et al. (2008)	
CAN + cattle manure	495	grassland	sand	Wageningen	March - Oct 2001	8 months	shallow injection	0.17	Schils et al. (2008)	120 kg N as CAN and 375 as cattle manure; applied on same day
CAN + cattle manure	555	grassland	sand	Wageningen	March - Oct 2001	8 months	shallow injection	0.18	Schils et al. (2008)	180 kg N as CAN and 375 as cattle manure; applied on same day
CAN + cattle manure	615	grassland	sand	Wageningen	March - Oct 2001	8 months	shallow injection	0.22	Schils et al. (2008)	240 kg N as CAN and 375 as cattle manure; applied on same day
CAN	120	grassland	sand	Wageningen	March - Oct 2002	8 months		0.14	Schils et al. (2008)	

CAN	240	grassland	sand	Wageningen	March - Oct 2002	8 months		0.12	Schils et al. (2008)	
CAN	330	grassland	sand	Wageningen	March - Oct 2002	8 months		0.12	Schils et al. (2008)	
Cattle manure	444	grassland	sand	Wageningen	March - Oct 2002	8 months	shallow injection	0.12	Schils et al. (2008)	
CAN + cattle manure	564	grassland	sand	Wageningen	March - Oct 2002	8 months	shallow injection	0.10	Schils et al. (2008)	120 kg N as CAN and 375 as cattle manure; applied on same day
CAN + cattle manure	624	grassland	sand	Wageningen	March - Oct 2002	8 months	shallow injection	0.10	Schils et al. (2008)	180 kg N as CAN and 375 as cattle manure; applied on same day
CAN + cattle manure	684	grassland	sand	Wageningen	March - Oct 2002	8 months	shallow injection	0.15	Schils et al. (2008)	240 kg N as CAN and 375 as cattle manure; applied on same day
CAN + cattle manure	555	grassland	sand	Wageningen	March - Oct 2001	8 months	shallow injection	0.24	Schils et al. (2010)	180 kg N as CAN and 375 as cattle manure. Fertilser later applied than manure
AS	330	grassland	sand	Wageningen	March - Oct 2001	8 months		0.15	Schils et al. (2010)	
CAN + cattle manure	624	grassland	sand	Wageningen	March - Oct 2002	8 months	shallow injection	0.12	Schils et al. (2010)	180 kg N as CAN and 375 as cattle manure. Fertilser later applied than manure
AS	330	grassland	sand	Wageningen	March - Oct 2002	8 months		0.14	Schils et al. (2010)	
CAN	75	maize land	sand	Wageningen	May - Oct 2001	6 months		0.04	Van Groenigen et al. (2004)	
CAN	113	maize land	sand	Wageningen	May - Oct 2001	6 months		0.13	Van Groenigen et al. (2004)	
CAN	150	maize land	sand	Wageningen	May - Oct 2001	6 months		0.07	Van Groenigen et al. (2004)	
CAN	188	maize land	sand	Wageningen	May - Oct 2001	6 months		0.06	Van Groenigen et al.	

									(2004)	
Cattle manure	104	maize land	sand	Wageningen	May - Oct 2001	6 months	deep injection	0.31	Van Groenigen et al. (2004)	
Cattle manure	156	maize land	sand	Wageningen	May - Oct 2001	6 months	deep injection	0.73	Van Groenigen et al. (2004)	
Cattle manure	209	maize land	sand	Wageningen	May - Oct 2001	6 months	deep injection	0.75	Van Groenigen et al. (2004)	
Cattle manure	261	maize land	sand	Wageningen	May - Oct 2001	6 months	deep injection	0.68	Van Groenigen et al. (2004)	
CAN + cattle manure	194	maize land	sand	Wageningen	May - Oct 2001	6 months	deep injection	0.29	Van Groenigen et al. (2004)	38 kg N as CAN and 156 as cattle manure
CAN + cattle manure	179	maize land	sand	Wageningen	May - Oct 2001	6 months	deep injection	0.21	Van Groenigen et al. (2004)	75 kg N as CAN and 104 as cattle manure
CAN + cattle manure	165	maize land	sand	Wageningen	May - Oct 2001	6 months	deep injection	0.27	Van Groenigen et al. (2004)	113 kg N as CAN and 52 as cattle manure
CAN	75	maize land	clay	Goutum	May - Oct 2001	6 months		2.14	Van Groenigen et al. (2004)	
CAN	113	maize land	clay	Goutum	May - Oct 2001	6 months		0.48	Van Groenigen et al. (2004)	
CAN	150	maize land	clay	Goutum	May - Oct 2001	6 months		1.42	Van Groenigen et al. (2004)	
CAN	188	maize land	clay	Goutum	May - Oct 2001	6 months		0.66	Van Groenigen et al. (2004)	
Cattle manure	98	maize land	clay	Goutum	May - Oct 2001	6 months	deep injection	0.96	Van Groenigen et al. (2004)	
Cattle manure	147	maize land	clay	Goutum	May - Oct 2001	6 months	deep injection	0.95	Van Groenigen et al. (2004)	
Cattle manure	196	maize land	clay	Goutum	May - Oct 2001	6 months	deep injection	0.88	Van Groenigen et al. (2004)	

Cattle manure	245	maize land	clay	Goutum	May - Oct 2001	6 months	deep injection	2.03	Van Groenigen et al. (2004)	
CAN + cattle manure	185	maize land	clay	Goutum	May - Oct 2001	6 months	deep injection	1.01	Van Groenigen et al. (2004)	38 kg N as CAN and 147 as cattle manure
CAN + cattle manure	173	maize land	clay	Goutum	May - Oct 2001	6 months	deep injection	0.96	Van Groenigen et al. (2004)	75 kg N as CAN and 98 as cattle manure
CAN + cattle manure	162	maize land	clay	Goutum	May - Oct 2001	6 months	deep injection	3.11	Van Groenigen et al. (2004)	113 kg N as CAN and 49 as cattle manure
CAN	65	maize land	clay	Goutum	May - Oct 2001	6 months		3.90	Velthof et al. (2003)	
Cattle manure	120	maize land	clay	Goutum	May - Oct 2001	6 months	deep injection	1.45	Velthof et al. (2003)	Tractor with separate tank and injector
Cattle manure	120	maize land	clay	Goutum	May - Oct 2001	6 months	trailing shoe	-0.57	Velthof et al. (2003)	Narrow band with trailing shoe
Cattle manure	120	maize land	clay	Goutum	May - Oct 2001	6 months	deep injection	1.74	Velthof et al. (2003)	Application machine with tank and injector
CAN	150	grassland	clay	Goutum	Sept 2002 - Oct 2003	1 year		1.60	Velthof et al. (2010a)	EF calculated from Velthof et al. (2010a) and Hoving & Velthof (2006)
CAN	300	grassland	clay	Goutum	Sept 2002 - Oct 2003	1 year		0.63	Velthof et al. (2010a)	EF calculated from Velthof et al. (2010a) and Hoving & Velthof (2006)
CAN	180	grassland	sand	Heino	Sept 2002 - Oct 2003	1 year		0.50	Velthof et al. (2010a)	EF calculated from Velthof et al. (2010a) and Hoving & Velthof (2006)
CAN	310	grassland	sand	Heino	Sept 2002 - Oct 2003	1 year		0.26	Velthof et al. (2010a)	EF calculated from Velthof et al. (2010a) and Hoving & Velthof (2006)
CAN	180	grassland	sand	Maarheeze	Sept 2002 - Oct 2003	1 year		2.00	Velthof et al. (2010a)	EF calculated from Velthof et al. (2010a) and Hoving

										& Velthof (2006)
CAN	310	grassland	sand	Maarheeze	Sept 2002 - Oct 2003	1 year		1.65	Velthof et al. (2010a)	EF calculated from Velthof et al. (2010a) and Hoving & Velthof (2006)
CAN	174	grassland	clay	Wageningen	2007/2008	1 year		2.51	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	322	grassland	clay	Wageningen	2007/2008	1 year	shallow injection	0.41	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	322	grassland	clay	Wageningen	2007/2008	1 year	surface-applied	0.04	Velthof et al. (2010b); Velthof amd Mosquera (2011)	
CAN + cattle manure	460	grassland	clay	Wageningen	2007/2008	1 year	shallow injection	1.09	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN	174	grassland	sand	Wageningen	2007/2008	1 year		1.63	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	322	grassland	sand	Wageningen	2007/2008	1 year	shallow injection	0.70	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	322	grassland	sand	Wageningen	2007/2008	1 year	surface-applied	0.12	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN + cattle manure	460	grassland	sand	Wageningen	2007/2008	1 year	shallow injection	1.15	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN	102	maize land	sand	Wageningen	2007/2008	1 year		-0.19	Velthof et al. (2010b); Velthof and Mosquera	

									(2011)	
Cattle manure	166	maize land	sand	Wageningen	2007/2008	1 year	deep injection	0.89	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	166	maize land	sand	Wageningen	2007/2008	1 year	surface-applied	0.25	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Pig manure	249	maize land	sand	Wageningen	2007/2008	1 year	deep injection	7.03	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Pig manure	249	maize land	sand	Wageningen	2007/2008	1 year	surface-applied	1.08	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN	175	grassland	clay	Wageningen	2008/2009	1 year		1.98	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	330	grassland	clay	Wageningen	2008/2009	1 year	shallow injection	0.19	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	330	grassland	clay	Wageningen	2008/2009	1 year	surface-applied	0.17	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN + cattle manure	400	grassland	clay	Wageningen	2008/2009	1 year	shallow injection	0.44	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN	175	grassland	sand	Wageningen	2008/2009	1 year		1.52	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	330	grassland	sand	Wageningen	2008/2009	1 year	shallow injection	0.46	Velthof et al. (2010b); Velthof and Mosquera	

									(2011)	
Cattle manure	330	grassland	sand	Wageningen	2008/2009	1 year	surface-applied	0.06	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN + cattle manure	400	grassland	sand	Wageningen	2008/2009	1 year	shallow injection	1.42	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN	102	maize land	sand	Wageningen	2008/2009	1 year		0.44	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	182	maize land	sand	Wageningen	2008/2009	1 year	deep injection	0.85	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	182	maize land	sand	Wageningen	2008/2009	1 year	surface-applied	0.86	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Pig manure	188	maize land	sand	Wageningen	2008/2009	1 year	deep injection	1.43	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Pig manure	188	maize land	sand	Wageningen	2008/2009	1 year	surface-applied	1.35	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN	160	grassland	sand	Wageningen	March - Nov 2009	9 months		0.48	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	277	grassland	sand	Wageningen	March - Nov 2009	9 months	shallow injection	0.24	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	277	grassland	sand	Wageningen	March - Nov 2009	9 months	surface-applied	0.07	Velthof et al. (2010b); Velthof and Mosquera	

									(2011)	
CAN + cattle manure	336	grassland	sand	Wageningen	March - Nov 2009	9 months	shallow injection	0.34	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN	125	maize land	sand	Wageningen	March - Nov 2009	9 months		0.18	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	175	maize land	sand	Wageningen	March - Nov 2009	9 months	deep injection	0.86	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	175	maize land	sand	Wageningen	March - Nov 2009	9 months	surface-applied	0.19	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Pig manure	181	maize land	sand	Wageningen	March - Nov 2009	9 months	deep injection	1.14	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Pig manure	181	maize land	sand	Wageningen	March - Nov 2009	9 months	surface-applied	0.13	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN	50	arable land	sand	Wageningen	March - Nov 2009	9 months		0.16	Velthof et al. (2010b); Velthof and Mosquera (2011)	
CAN	200	arable land	sand	Wageningen	March - Nov 2009	9 months		0.53	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	100	arable land	sand	Wageningen	March - Nov 2009	9 months	deep injection	0.55	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Cattle manure	251	arable land	sand	Wageningen	March - Nov 2009	9 months	deep injection	1.68	Velthof et al. (2010b); Velthof and Mosquera	

									(2011)	
Pig manure	106	arable land	sand	Wageningen	March - Nov 2009	9 months	deep injection	1.11	Velthof et al. (2010b); Velthof and Mosquera (2011)	
Pig manure	266	arable land	sand	Wageningen	March - Nov 2009	9 months	deep injection	2.40	Velthof et al. (2010b); Velthof and Mosquera (2011)	

Appendix 2 Statistical analyzes

The emission factors in the data set were not normal distributed, i.e. most emission factors were low (< 0.5%) with a few high emission factors (see Table A1). This type of distribution is often shown for N_2O emissions. To stabilize the variance, all emission factors were log-transformed before statistical analyzis. However, two emission factors were negative (- 0.19 and - 0.57%), by which log-transformation could not be carried out. In order to obtain a data set with only positive values, a value of 0.6 was added to the data of emission factors. A Kolmogorov-smirnov test showed that the log-transformed data were better described by a normal distribution than the untransformed data. The log-transformed data were statistically analyzed.

The arithmetic mean was chosen as the estimator of the mean emissions factor, as it is a robust estimator of the mean for population of small size (Myers and Pepin, 1990; Parkin et al., 1988). It is an unbiased estimator of the population mean, regardless of the form of the underlying distribution. The lognormal mean or median may be biased when applied to non-lognormal distributions.

The data set of emission factors is derived from different studies, by which the number of data for a certain fertilizer, soil type, and land use type may strongly differ (see Tables 3, 4 and 5). Differences in N_2O emission factors between fertilizers/manure, manure application techniques, soil types, and land use types were statistically assessed for subsets of the data (see Table A2).

The differences in N_2O emission factors between two factors were assessed with a t-test and that for three factors with a Least Significant Difference (LSD)-test at $\alpha = 0.05$, using SAS 9.1.3. If the results were not statistically significant at $\alpha = 0.05$, it was assessed if the result were significant at $\alpha = 0.10$. Otherwise, the differences were considered as not significant. The results of the statistical analyzes are presented in Table A2.

Table A1
Distribution of emission factors of CAN and slurries in experiments of more than six months in the Netherlands.

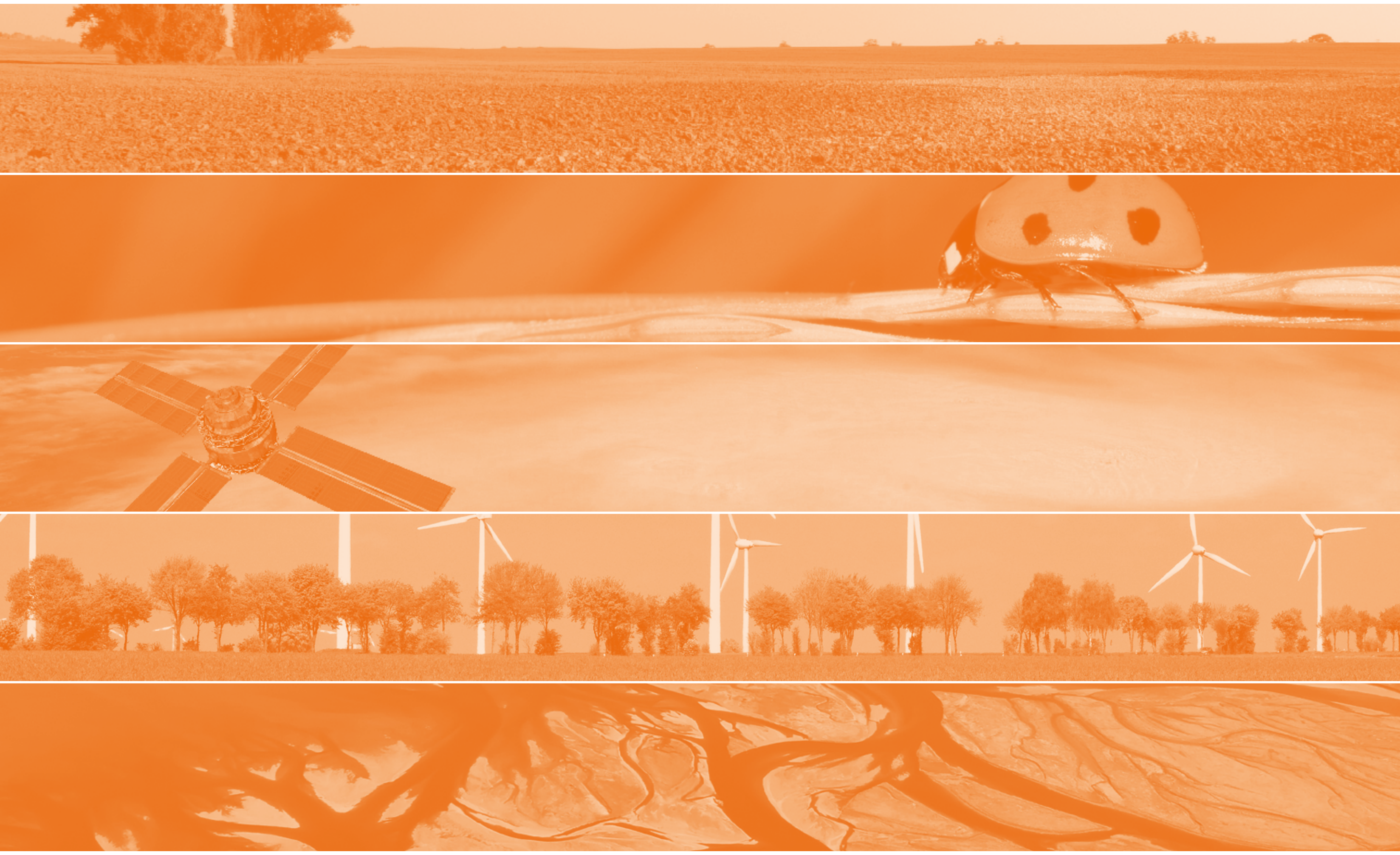
N_2O emission factor, % of N applied	*Frequency*
< 0.50	39
0.50 - 0.75	10
0.75 -1.00	7
1.00 - 1.25	3
1.25 -1.50	6
1.50 -1.75	6
1.75 - 2.00	2
2.00 - 3.00	4
> 3.00	2

Table A2

Results of statistical analyzes; t-test (for two comparisons) and LSD-test (for three comparisons) using SAS 9.1.3. The data subset for which the analyzis was carried out is indicated. All emission factors were log-transformed prior to the statistical analyzis.

Tested difference	Subset			Result	α
	Soil	Land use	Nitrogen source		
Peat, clay and sand for CAN for grassland	Peat, clay, sand	Grassland	CAN	Peat > Sand = Clay	α = 0.05
Clay and sand	Clay, sand	Grassland Arable land	CAN, manure applied with low ammonia technique and surface-applied	Not significant	α = 0.1
Clay and sand for CAN for grassland	Clay, sand	Grassland	CAN	Not significant	α = 0.1
Clay and sand for CAN for arable land	Clay, sand	Arable land	CAN	Clay > Sand	α = 0.05
Clay and sand for manure applied with low ammonia technique	Clay, sand	Grassland Arable land	Manure applied with low ammonia technique	Not significant	α = 0.1
Clay and sand for surface-applied manure	Clay, sand	Grassland Arable land	Manure surface-applied	Not significant	α = 0.1
Nitrogen sources for arable land	Mineral*	Arable land	CAN, manure injected and surface-applied	Not significant	α = 0.1
Manure application techniques for arable land	Mineral*	Arable land	Manure injected and surface-applied	Not significant	α = 0.1
Nitrogen source for grassland	Mineral*	Grassland	CAN, manure injected and surface-applied	CAN > manure	α = 0.05
Manure application techniques for grassland	Mineral*	Grassland	Manure applied with low ammonia technique and surface-applied	Application with low ammonia emission > surface application	α = 0.05
Land use for CAN	Mineral*	Grassland Arable land	CAN	Not significant	α = 0.05
Land use for manure applied with low ammonia technique	Mineral*	Grassland Arable land	Manure applied with low ammonia technique	Arable > grassland	α = 0.1
Land use for surface-applied manure	Mineral*	Grassland Arable land	Manure surface-applied	Arable > grassland	α = 0.05

**Mineral soils: data of sand and clay combined*



Alterra is part of the international expertise organisation Wageningen UR (University & Research centre). Our mission is 'To explore the potential of nature to improve the quality of life'. Within Wageningen UR, nine research institutes – both specialised and applied – have joined forces with Wageningen University and Van Hall Larenstein University of Applied Sciences to help answer the most important questions in the domain of healthy food and living environment. With approximately 40 locations (in the Netherlands, Brazil and China), 6,500 members of staff and 10,000 students, Wageningen UR is one of the leading organisations in its domain worldwide. The integral approach to problems and the cooperation between the exact sciences and the technological and social disciplines are at the heart of the Wageningen Approach.

Alterra is the research institute for our green living environment. We offer a combination of practical and scientific research in a multitude of disciplines related to the green world around us and the sustainable use of our living environment, such as flora and fauna, soil, water, the environment, geo-information and remote sensing, landscape and spatial planning, man and society.

More information: www.alterra.wur.nl/uk