# Estimation of $N_2O$ emission factors for soils depending on environmental conditions and crop management

Jan Peter Lesschen and Gerard Velthof

*Alterra, Wageningen UR, PO Box 47, 6700 AA, Wageningen, The Netherlands*

Keywords: emission factor, $N_2O$, driving factors

## ABSTRACT:

Nitrous oxide ($N_2O$) contributes 8% to anthropogenic global warming, of which about one third are direct emissions of agricultural soils. These $N_2O$ emissions are often estimated using the default IPCC 2006 emission factor of 1% of the amount of N applied for mineral fertilizer, manure and crop residues. However, a large variation in emission factors exists due to differences in environment (e.g. weather and soil conditions), crops (grassland, arable land, crop residues) and management (e.g. type of manure and fertilizer, application rates, time of application). We developed a simple approach to determine $N_2O$ emission factors that depend on environmental, crop and management factors.

The main factors controlling $N_2O$ emission are nitrate content, oxygen content, available C content, temperature and pH. The starting point of the method was a two-year monitoring study of Velthof et al. (1996), who found an emission factor of exactly 1% for grassland on a sandy soil fertilized with calcium ammonium nitrate. The conditions of this experiment were set as the reference from which the effects of other environmental conditions and management on the $N_2O$ emission factor were estimated. Based on literature and expert knowledge we determined for 19 sources of N input, three soil types, two land use types, three precipitation classes, two pH classes and three temperature classes the effect on the default emission factor. The calculated $N_2O$ emission factors ranged from 0 to 10%. The emission factors derived from this inference scheme can improve predictions of $N_2O$ emissions with integrated large-scale models.

## 1 INTRODUCTION

Nitrous oxide ($N_2O$) is one of the major greenhouse gasses with a contribution of 7.9 % to the anthropogenic global warming (IPCC, 2007). The majority of $N_2O$ is emitted by agriculture and about one third is direct emission from agricultural soils. The nitrous oxide emissions from soil-applied fertilizer and manures are often estimated using a default emission factor. In the IPCC 2006 guidelines a default emission factor for N inputs from mineral fertilisers, organic amendments and crop residues of 1% is used, i.e. the fertilizer-derived $N_2O$ emission is equal to 1% of the amount of N applied. This factor is based on analyses of a large number of measurements (Bouwman et al., 2002a,b; Stehfest and Bouwman, 2006; Novoa and Tejeda, 2006).

However, this is an average emission factor, whereas in reality a large variation in emission factors exists (Stehfest and Bouwman, 2006; Flechard et al., 2007). This variation is due to environmental factors (e.g. climate and soil conditions), crop factors (e.g. crop type and crop residues) and management factors (e.g. type of manure and fertilizer, application rate, time of application).

In this paper we elaborate a simple approach to estimate $N_2O$ emission using emission factors that dependent on environmental and management factors. The approach is based on literature data and expert knowledge and is intended for implementation in large-scale models such as INTEGRATOR and MITERRA-Europe. This paper starts with the conceptual framework and a summarized literature review to quantify the $N_2O$ emission from different sources and the effects of environmental conditions on $N_2O$ emissions. The methodology results in an inference scheme for $N_2O$ emission factors of the different sources of N input and for the different environmental conditions and management factors. Finally, we compare the calculated $N_2O$ emissions from the INTEGRATOR model, which adopted the new approach for the calculation of $N_2O$ emissions from agricultural soils (Kros et al., 2009) with the results from the MITERRA-Europe model which uses the default IPCC emission factor (Velthof et al., 2009).

# 2 METHODOLOGY

## 2.1 *Conceptual framework*

The major factors that control $N_2O$ emission are nitrogen input and nitrate content, oxygen content, available C content, temperature and pH. Table 1 gives an overview of the effects of the controlling factors on denitrification and on the $N_2O/N_2$ ratio of denitrification. The categorization and parameterisation of these factors and their effect on $N_2O$ emission is based on a literature study and expert knowledge. In the following paragraphs a description and a comprehensive literature review of the effects on the $N_2O$ emissions are given for each of the controlling factors.

Table 1. Effect of changes in factors on denitrification and on the $N_2O/N_2$ ratio of denitrification (Firestone et al., 1980; Granli and Bøckman, 1994; Sahrawat and Keeney, 1986; Tiedje, 1988).

| | Effect on denitrification | effect on $N_2O/N_2$ ratio |
|---|---|---|
| increasing $NO_3^-$ content | + | + |
| increasing oxygen content | - | + |
| increasing available organic carbon content | + | - |
| increasing temperature | + | - |
| decreasing pH | - | + |

Starting point of the methodology is the average emission factor for a certain reference situation from which the effects of environmental factors on the emission factor are estimated. As starting point the emission factor for fertilizer of 1 % of the applied N is used, which is often found in studies (e.g. Stehfest and Bouwman, 2006). In a two-year monitoring study of Velthof et al. (1996) the emission factor of grassland on a sandy soil fertilized with calcium ammonium nitrate was exactly 1 %. Therefore this experiment was used as the reference situation and the starting point for the inference scheme. The conditions of this reference are: grassland on a well drained sandy soil, neutral pH (pH > 5), relatively wet conditions (average precipitation of 600-900 mm per year), an average annual temperature of 8-12°C, and fertilized with calcium ammonium nitrate fertilizer. Also in other studies with intensively managed grassland in NW Europe an emission factor of about 1% is often found (e.g. Clayton et al., 1997; Flechard et al., 2007).

## 2.2 *Nitrogen input and nitrate content*

The most important sources for nitrogen in soils are mineral fertilizers, manure, nitrogen excreted during grazing, atmospheric deposition, biological N fixation, and mineralization of soil organic N. Many studies indicate that the type of nitrogen affects $N_2O$ emission. Therefore we distinguished the following six nitrogen sources in the inference scheme:

- Three types of mineral fertilizer: only ammonium containing fertilizer, nitrate containing fertilizer and urea
- Three types of manure: pig, poultry, and cattle. Moreover, the type of manure (slurry or solid) and method of application (incorporation and surface-application) are distinguished.
- Grazing
- Biological N fixation
- Three types of crop residues: cereals, vegetables and arable crops
- Atmospheric N deposition
- Net mineralization of soil organic N

Mineral fertilizer

Many types of fertilizers are used in agriculture, but the most common fertilizers are: ammonium nitrate based fertilizers, nitrate based fertilizers, ammonium based fertilizers and Urea and urea based fertilizers. Statistical analyses on the database with measurements of $N_2O$ emissions (Bouwman, 1996; Stehfest and Bouwman, 2006) show no clear significant effect of fertilizer type on $N_2O$ emission. However, some studies in which mineral fertilizers are compared in one experiment sometimes show large differences. In incubation studies, the $N_2O$ emission from nitrate based fertilizer is much higher than from ammonium based fertilizer at wet conditions (Figure 1). The grassland studies of Clayton et al. (1997), Dobbie and Smith (2003) and Velthof et al. (1997) also point at much higher $N_2O$ emissions from nitrate based fertilizer than from fertilizer only containing ammonium, especially during wet conditions. Based on the differences found in literature we made the following assumptions for the inference scheme: for grassland, the emission factor for nitrate fertilizer is two times that of ammonium fertilizers; for arable land, the emission factor of nitrate fertilizer is 1.25 times that of ammonium fertilizer; and in the dry areas of Europe (low precipitation class), the emission factor for urea is 1.5 times that of ammonium fertilizer on both grassland and arable land.

Manure

The effect of manure on $N_2O$ emissions is affected by many factors, such as animal type, storage type (slurry, liquid, solid, grazing), feeding, treatment and application technique (Chadwick et al., 2000; Flessa and Beese, 2000; Velthof et al., 2003). Relatively low $N_2O$ emissions (<1% of the N applied) have been found for animal manures applied to grassland (Velthof et al., 1997; Chadwick et al., 2000). In these soils, $N_2O$ emission from $NO_3$ containing mineral fertilizers are often (much) higher than from animal manures. In an incubation experiment of Velthof et al. (2003), the $N_2O$ emission factor was highest for pig slurry (7.3-13.9%) than for cattle slurry (1.8-3.0%) and for poultry manure (0.5-1.9%). The differences in emission can be explained by the composition of the manure (e.g. fraction of ammonia in total N, degradability of organic matter). Emission of $N_2O$ from soil applied animal manures is controlled by the amount of applied N and C. The higher the amount of applied mineral N and easily mineralizable N, the higher the risk on $N_2O$ emission. The portion of $NH_4$ in total N is higher for slurries than for solid manures and is higher for pig manure than for cattle and poultry manure. Injection or incorporation of manure may increase $N_2O$ emission and denitrification compared to surface-applied manure (e.g. Flessa and Beese, 2000; Velthof et al., 2003). In the model, it is assumed that pig slurry injected to grassland has an emission factor of 0.75%, i.e. less than a nitrate containing fertilizer. The ratio in emission factor between the different manure types is poultry manure : solid cattle manure : solid pig manure : cattle slurry : pig slurry = 1 : 1 : 1 : 2 : 3. It is assumed that on average, the $N_2O$ emission factor for manure that is injected or incorporated in the soil, is a factor 1.5 times that of surface-applied manure.

Grazing

A review of Oenema et al. (2001) of published data on $N_2O$ emissions from urine and dung show that $N_2O$ emission from dung pats ranges from 0.1 to 0.7 percent and emissions of $N_2O$ from urine patches range from 0.0 to 15.5%. This wide range has been attributed to variations in urine composition, soil type and environmental conditions. In a study of Velthof et al. (1996), the emission factor for grazing was on average two times that of fertilizer application. Therefore we assumed that the emission factor for grazing is two times the emission factor of nitrate fertilizer.

Biological N fixation

Biological N fixation can be an important source of N in soils. The fixed can be readily taken up by the crop (grass, soya, pulses etc.), which suggests that the N is efficiently used, which may reduce the $N_2O$ emission. It is assumed that the emission factor in grass clover swards for biological N fixation is equal to that of ammonium fertilizer. For all other crops, no additional $N_2O$ emission from biologically fixed N is accounted for. Only the crop residues are a source of $N_2O$.

Crop residues

Crop residues incorporated in the soil are a potentially important source of $N_2O$. Crop residues may affect the $N_2O$ emission from soils in three ways: i) supply of easily mineralizable N, that may be transformed into mineral N, ii) supply of easily mineralizable C, which may enhance denitrifier activity and, thereby, $N_2O$ emission from both soil mineral N and crop residue N, and iii) locally increase the oxygen consumption in the soil. Velthof et al. (2002) showed large differences in $N_2O$ emission from crop residues. The following emission factors are assumed: 0.2% for crop residues of cereals, 2% for crop residues of vegetables and 1% for crop residues of other arable crops.

Atmospheric deposition

The major form of atmospheric nitrogen is ammonium. The amount of N deposited is small in comparison to N applied via manures and fertilizers. In regions with high intensive livestock systems, deposition may be higher than 30 kg N per ha per year, but in most countries atmospheric deposition is less than 20 kg N per ha per year, which is evenly distributed through a year. Therefore it is assumed that the emission factor for atmospheric N deposition is lower than that of ammonium fertilizers, i.e. 0.75 times that of ammonium fertilizer.

Mineralization of soil organic matter

In mineral soil, the soil organic N contents are generally more or less stable, so that the net mineralization is zero. Systems that have net mineralization are drained peat soil (Histosols) and permanent grasslands that are converted into arable land. In both systems high $N_2O$ emission have been measured. It is assumed that on average 2.6% of the N that is mineralized is emitted as $N_2O$.

## 2.3 *Oxygen content*

We used indirect parameters for the effects of oxygen content, i.e.

- Soil type: texture, biological oxygen consumption by degradation of organic matter, and groundwater level control the oxygen content
- Precipitation: higher precipitation increases the risk on anaerobic conditions
- Land use: grasslands contain more organic C and have a higher oxygen consumption than arable land (paragraph 2.4)
- Manure application technique: the depth of application affects oxygen content (paragraph 2.2)
- Temperature: higher temperatures result in a higher oxygen demand (paragraph 2.5)

In general, $N_2O$ emission increases with higher clay content of the soil, because the chance on anaerobic conditions increases (Granli and Bøckman, 1994). However, under strict anaerobic conditions, $N_2O$ is reduced to $N_2$. Thus, during wet conditions less $N_2O$ will be produced in heavy textured soils than in light textured soils. Peat soils have a higher $N_2O$ emission than sand and clay soils because of i) the higher organic matter content with related higher denitrification potential (Velthof et al., 1996) and ii) the higher groundwater level (wet conditions). We used the following ratios for the relative emission factor of soil types: sand : clay : peat = 1 : 1.5 : 2.

Precipitation is an important indicator for the risk of anaerobic conditions in soils. We defined three precipitation classes, based on the annual precipitation distribution in Europe: high: > 900 mm $yr^{-1}$, medium: 600 – 900 mm $yr^{-1}$ and low: < 600 mm $yr^{-1}$. The relative emission factors increase when the precipitation increases. The following ratios were used: high : medium : low = 2 : 1 : 0.5.

## 2.4 *Available organic carbon content*

We used indirect parameters for the effects of available carbon content, i.e.

- Soil type: peat soils much higher than clay and sand (paragraph 2.3)
- Land use: grassland higher than arable land
- Three manure types (paragraph 2.2)
- Three crop residue types (paragraph 2.2)

There are several mechanisms make $N_2O$ emission from permanent grasslands differ from those of arable cropping systems. First of all the organic matter content of grasslands is higher than in arable cropping systems (e.g. Jenkinson, 1988). This difference is mainly due to the absence of soil tillage in permanent grasslands, in combination with a high C input by crop residues and manure. In addition the organic matter of grasslands is much more available for bacteria because of the continuous high input of fresh organic matter via root exudates and manure. The potential denitrification rate is therefore higher for grasslands than for arable land (Bijay-Singh et al., 1988). Because of the higher availability of C in grassland soils, the application of C via manure has less effect on $N_2O$ emission from grasslands than from arable land (e.g. Velthof et al., 1997). Furthermore, grassland has a dense rooting system which is active during large part of the year. Therefore, applied mineral N is rapidly (within a few days – weeks) taken up by the grass or immobilized in the rooting system (Huntjes, 1971). By contrast, in arable cropping systems, mineral fertilizer and manure are often applied before sowing of planting of the crop and it takes longer before the crop can absorb the applied N. In this period, N contents in the soil remain high for a relatively long period and applied ammonium can be nitrified.

## 2.5 *Temperature*

The temperature affects directly the activity of the nitrifying and denitrifying bacteria and the ratio $N_2O/N_2$, i.e. this ratio decreases when the temperature decreases. Moreover, temperature controls biological oxygen consumption and this may also affect the emission of $N_2O$ (see oxygen). Because of these opposite effects on $N_2O$ emission, the net temperature effect on $N_2O$ emission is limited to a range of about 5 to 15 °C, but may sharply increase at higher temperatures (e.g. Keeney et al., 1979). At low temperatures, still $N_2O$ may be emitted, but at low rates. We defined three temperature classes (average annual temperature): < 8 °C, 8-12 °C and > 12 °C. The relative emission factors increase when temperature increases. The following ratios were used: < 8 °C : 8-12 °C : > 12 °C = 0.75 : 1 : 1.25.

## 2.6 *pH*

The pH directly affects the activity of nitrifying and denitrifying bacteria (e.g. Granli and Bøckman, 1994). Optimum activities are found in the range of pH 7-8. However, the reduction of $N_2O$ to $N_2$ is more sensitive to acidic conditions than the reduction of $NO_3$ to $N_2O$, by which the ratio $N_2O/N_2$ strongly increases at decreasing pH. It assumed that in acid soils (pH < 5) the $N_2O$ emission is 25% lower than in other soils, because of the limitation for denitrification and nitrification. For soils with a pH of 5 and higher no net effect is assumed, i.e. the effect of change in activity of denitrifiers is counterbalanced by the change in $N_2O/N_2$ ratio.

# 3 RESULTS

The resulting inference scheme gives the $N_2O$ emission factors for 19 different sources of N input, three soil types, two land use types, two pH classes, three precipitation classes and three temperature classes. This results in 2052 combinations with different emission factors. However, many of these combinations will in reality not occur. Since the entire inference scheme is too large to include in this paper, only a part of the scheme is shown in Table 3. This table shows how the inference scheme is build up, starting at the emission factor of 1.00 for grassland on sandy soils with a neutral pH, fertilized with nitrate fertilizer, an annual rainfall of 600-900 mm and an annual temperature of 8-12 $^{o}C$.

Table 3. Part of the resulting inference scheme for some of the N-input sources on grassland with sandy soils. The value 1.00 in bold is the starting point of the reference situation.

| Soil type | Land use | pH | Precipitation | temp | Emission factor in % of the N input | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $^{o}C$ | nitrate containing fertilizer | ammonium fertilizer | urea | pig slurry low NH3 application | cattle slurry low NH3 application |
| Sand | grassland | < 5 | < 600 mm/yr | < 8 | 0.28 | 0.14 | 0.21 | 0.21 | 0.14 |
| | | | | 8-12 | 0.38 | 0.19 | 0.28 | 0.28 | 0.19 |
| | | | | > 12 | 0.47 | 0.23 | 0.35 | 0.35 | 0.23 |
| | | | 600 - 900 | < 8 | 0.56 | 0.28 | 0.28 | 0.42 | 0.28 |
| | | | mm/yr | 8-12 | 0.75 | 0.38 | 0.38 | 0.56 | 0.38 |
| | | | | > 12 | 0.94 | 0.47 | 0.47 | 0.70 | 0.47 |
| | | | > 900 mm/yr | < 8 | 1.13 | 0.56 | 0.56 | 0.84 | 0.56 |
| | | | | 8-12 | 1.50 | 0.75 | 0.75 | 1.13 | 0.75 |
| | | | | > 12 | 1.88 | 0.94 | 0.94 | 1.41 | 0.94 |
| | | ≥ 5 | < 600 mm/yr | < 8 | 0.38 | 0.19 | 0.28 | 0.28 | 0.19 |
| | | | | 8-12 | 0.50 | 0.25 | 0.38 | 0.38 | 0.25 |
| | | | | > 12 | 0.63 | 0.31 | 0.47 | 0.47 | 0.31 |
| | | | 600 - 900 | < 8 | 0.75 | 0.38 | 0.38 | 0.56 | 0.38 |
| | | | mm/yr | 8-12 | **1.00** | 0.50 | 0.50 | 0.75 | 0.50 |
| | | | | > 12 | 1.25 | 0.63 | 0.63 | 0.94 | 0.63 |
| | | | > 900 mm/yr | < 8 | 1.50 | 0.75 | 0.75 | 1.13 | 0.75 |
| | | | | 8-12 | 2.00 | 1.00 | 1.00 | 1.50 | 1.00 |
| | | | | > 12 | 2.50 | 1.25 | 1.25 | 1.88 | 1.25 |

In Figure 1 the spatial pattern of $N_2O$ soil emissions from INTEGRATOR (Kros et al., 2009), which uses the differentiated $N_2O$ emission factors, is compared with the spatial pattern from MITERRA-Europe, which uses the default IPCC emission factor of 1%. INTEGRATOR calculates lower $N_2O$ emissions, especially in northern Europe, mainly because of lower emission factors due to the lower temperature influence. For some areas the effect of soil type on the $N_2O$ emission is clearly visible, e.g. in the Netherlands the highest $N_2O$ emissions are in the western part with mainly clay and peat soils, while the eastern and southern part with mainly sandy soils have lower emissions. With the default emission factor of MITERRA-Europe the regions with most manure have the highest emissions, although these are in the sand areas. The total $N_2O$ soil emission as calculated by INTEGRATOR is 292 kton $N_2O$-N for the EU27, whereas MITERRA-Europe calculates a total of 315 kton $N_2O$-N. Thus for total $N_2O$ emission both approaches give comparable results.

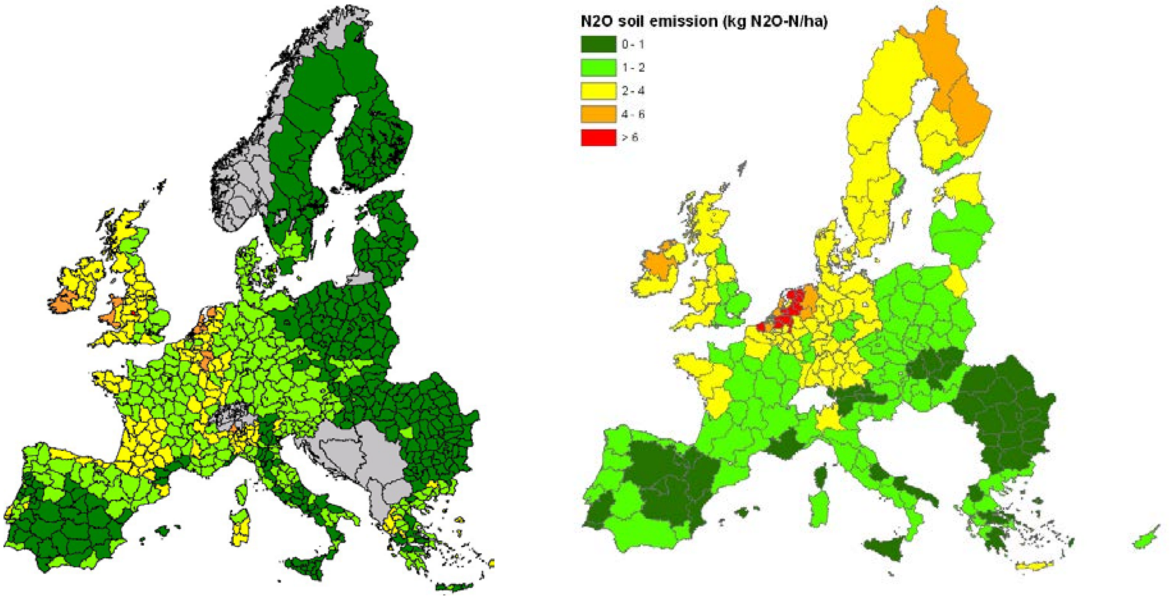


Figure 1. Comparison of calculated $N_2O$ emissions based on differentiated $N_2O$ emission factors from INTEGRATOR (left) with calculated emission factors from MITERRA-Europe based on the default emission factor of 1% (right).

## 4 DISCUSSION AND CONCLUSION

In this paper we developed a methodology for an inference scheme for $N_2O$ soil emission factors. Although this work is still in development and some factors might have to be slightly adapted, e.g. the effect of high emissions during thawing is not yet accounted for, the results show that the use of differentiated emission factors leads to a spatial pattern which takes account of the different environmental and management related factors. The major benefit of the presented approach with differentiated emission factors is that the effects of mitigation measures are expressed in the emission factor, e.g. changes in fertilizer type or incorporation of manure. Besides the influence of local environmental conditions, e.g. soil type and precipitation, is taken into account. IPCC also encourages countries to use a Tier 2 approach, in which $N_2O$ emission factors are disaggregated based on environmental and management related factors. The presented inference scheme of $N_2O$ emission factors offers the possibility for European countries to use such a Tier 2 approach.

## REFERENCES


Bouwman, A.F. (1996). Direct emissions of nitrous oxide from agricultural soils. Nutr. Cycl. Agroecosyst., 46, 53-70.

Bouwman, A.F., Boumans, L.J.M. and Batjes, N.H. (2002a). Emissions of $N_2O$ and NO from fertilised fields: Summary of available measurement data. Glob. Biogeochem. Cycles, 16(4), art. no. 1058.

Bouwman, A.F., Boumans, L.J.M. and Batjes, N.H. (2002b). Modeling global annual $N_2O$ and NO emissions from fertilised fields. Glob. Biogeochem. Cycles, 16(4), art. no. 1080

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

Clayton, H., I.P. McTaggart, J. Parker, L. Swan and K.A. Smith (1997). Nitrous oxide emissions from fertilised grassland: A 2-year study of the effects of N fertiliser form and environmental conditions. Biol. fertil. soils 25, 252-260.

Dobbie, K.E. and K.A. Smith (2003). Impact of different forms of N fertilizer on $N_2O$ emission from intensive grassland. Nutr. Cycl. Agroecosyst. 67, 37-46.

Firestone, M.K., R.B. Firestone and J.M. Tiedje, 1980. Nitrous oxide from soil denitrification: factors controlling its biological production. Science 208, 749-751.

Flechard, C.R., et al. (2007). Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe. Agric. ecosyt. eviron. 121 (1-2), 135-152.

Flessa, H. and F. Beese (2000). Laboratory estimates of trace gas emissions following surface application and injection of cattle slurry. J. Environ. Qual. 29, 262-268.

Granli, T. and O.C. Bøckman, 1994. Nitrous oxide from agriculture. Norwegian Journal of Agricultural Sciences Supplement 12, 7-128.

Huntjes, J.L.M. (1971). Influence of living plants on immobilisation of nitrogen in permanent pastures. Plant soil 34, 393-404.

IPCC, 2007. Climate change 2007: Synthesis report.

Jenkinson, D.S. (1988). Soil organic matter and its dynamics. In: Wild, A. (Ed). Russels's Soil Conditions and Plant Growth. New York, Longman, pp. 564-607.

Keeney, D.R., I.R. Fillery and G.P. Marx, (1979). Effect of temperature on the gaseous nitrogen products of denitrification in a silt loam soil. Soil Sci. Soc. Am. J. 43, 1124-1128.

Kros, H., W. de Vries, G.J. Reinds, J.P. Lesschen and G.L. Velthof (2009). Impacts of data aggregation on European wide predictions of nitrogen and green house gas fluxes in response to changes in livestock, land cover and land management. 5th International Symposium on Non-$CO_2$ Greenhouse Gasses: Science, Control, Policy and Implementation, 30 June-3 July 2009, Wageningen, the Netherlands.

Novoa, R. and Tejeda, H.R. (2006) Evaluation of the $N_2O$ emissions from N in plant residues as affected by environmental and management factors. Nutr. Cycl. Agroecosyst. 75, 29-46.

Oenema, O., A. Bannink, S.G. Sommer and G.L. Velthof (2001). Gaseous nitrogen emissions from livestock farming systems. In: Follet, R.F. and J.L. Hatfield (Eds). Nitrogen in the environment: sources, problems, and management. Amsterdam, Elsevier, pp. 255-289.

Sahrawat, K.L. and D.R. Keeney (1986). Nitrous oxide emission from soils. Adv. Soil. Sci. 4, 103-148.

Stehfest, E. and Bouwman, L. (2006). $N_2O$ and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutr. Cycl. Agroecosyst. 74, 207-228.

Tiedje, J.M. (1988). Ecology of denitrification and dissimilatory nitrate reduction to ammonium. In: Zehnder, A.J.B. (Ed). Biology of Anaerobic Microorganisms. New York, John Wiley and Sons, pp. 179-243.

Velthof GL, A.B. Brader and O. Oenema (1996). Seasonal variations in nitrous oxide losses from managed grasslands in the Netherlands. Plant and Soil 181, 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. Nutr. Cycl. Agroecosyst. 46(3), 257-267.

Velthof, G.L., P.J. Kuikman and O. Oenema (2002). Nitrous oxide emission from soils amended with crop residues. Nut.Cycl. Agroecosyst. 62, 249-261.

Velthof, G.L., P.J. Kuikman and O. Oenema (2003). Nitrous oxide emission from animal manures applied to soil under controlled conditions. Soil Biology Fert. 37(4), 221-230.

Velthof, G.L., D. Oudendag, H.P. Witzke, W.A.H. Asman, Z. Klimont and O. Oenema (2009). Integrated assessment of nitrogen emissions from agriculture in EU-27 using MITERRA-Europe. J. Environ. Qual. 38, 402-417.