

Estimation of N₂O emission factors for soils depending on environmental conditions and crop management

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Keywords: emission factor, N₂O, driving factors

ABSTRACT:

Nitrous oxide (N₂O) contributes 8% to anthropogenic global warming, of which about one third are direct emissions of agricultural soils. These N₂O 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 N₂O emission factors that depend on environmental, crop and management factors.

The main factors controlling N₂O 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 N₂O 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 N₂O emission factors ranged from 0 to 10%. The emission factors derived from this inference scheme can improve predictions of N₂O emissions with integrated large-scale models.

1 INTRODUCTION

Nitrous oxide (N₂O) is one of the major greenhouse gasses with a contribution of 7.9 % to the anthropogenic global warming (IPCC, 2007). The majority of N₂O 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 N₂O 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 Tejada, 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 N₂O 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 N₂O emission from different sources and the effects of environmental conditions on N₂O emissions. The methodology results in an inference scheme for N₂O emission factors of the different sources of N input and for the different environmental conditions and management factors. Finally, we compare the calculated N₂O emissions from the INTEGRATOR model, which adopted the new approach for the calculation of N₂O 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 N₂O 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 N₂O/N₂ ratio of denitrification. The categorization and parameterisation of these factors and their effect on N₂O 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 N₂O emissions are given for each of the controlling factors.

Table 1. Effect of changes in factors on denitrification and on the N₂O/N₂ ratio of denitrification (Firestone et al., 1980; Granli and Bøckman, 1994; Sahrawat and Keeney, 1986; Tiedje, 1988).

	Effect on denitrification	effect on N ₂ O/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 N₂O 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 N₂O emissions (Bouwman, 1996; Stehfest and Bouwman, 2006) show no clear significant effect of fertilizer type on N₂O emission. However, some studies in which mineral fertilizers are compared in one experiment sometimes show large differences. In incubation studies, the N₂O 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 N₂O 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 N₂O 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 N₂O 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, N₂O emission from NO₃ containing mineral fertilizers are often (much) higher than from animal manures. In an incubation experiment of Velthof et al. (2003), the N₂O 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 N₂O 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 N₂O emission. The portion of NH₄ 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 N₂O 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 N₂O 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 N₂O emissions from urine and dung show that N₂O emission from dung pats ranges from 0.1 to 0.7 percent and emissions of N₂O 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 N can be readily taken up by the crop (grass, soya, pulses etc.), which suggests that the N is efficiently used, which may reduce the N₂O 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 N₂O emission from biologically fixed N is accounted for. Only the crop residues are a source of N₂O.

Crop residues

Crop residues incorporated in the soil are a potentially important source of N₂O. Crop residues may affect the N₂O 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, N₂O 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 N₂O 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 N₂O emission have been measured. It is assumed that on average 2.6% of the N that is mineralized is emitted as N₂O.

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, N₂O 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, N₂O is reduced to N₂. Thus, during wet conditions less N₂O will be produced in heavy textured soils than in light textured soils. Peat soils have a higher N₂O 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 N₂O 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 N₂O 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 N₂O/N₂, i.e. this ratio decreases when the temperature decreases. Moreover, temperature controls biological oxygen consumption and this may also affect the emission of N₂O (see oxygen). Because of these opposite effects on N₂O emission, the net temperature effect on N₂O 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 N₂O 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 N₂O to N₂ is more sensitive to acidic conditions than the reduction of NO₃ to N₂O, by which the ratio N₂O/N₂ strongly increases at decreasing pH. It is assumed that in acid soils (pH < 5) the N₂O 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 N₂O/N₂ ratio.

3 RESULTS

The resulting inference scheme gives the N₂O 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 built 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 °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						
										°C	nitrate containing fertilizer
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 mm/yr	< 8	0.56	0.28	0.28	0.42	0.28		
				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 mm/yr	< 8				0.75	0.38	0.38	0.56	0.38		
	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 N₂O soil emissions from INTEGRATOR (Kros et al., 2009), which uses the differentiated N₂O emission factors, is compared with the spatial pattern from MITERRA-Europe, which uses the default IPCC emission factor of 1%. INTEGRATOR calculates lower N₂O 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 N₂O emission is clearly visible, e.g. in the Netherlands the highest N₂O 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 N₂O soil emission as calculated by INTEGRATOR is 292 kton N₂O-N for the EU27, whereas MITERRA-Europe calculates a total of 315 kton N₂O-N. Thus for total N₂O emission both approaches give comparable results.

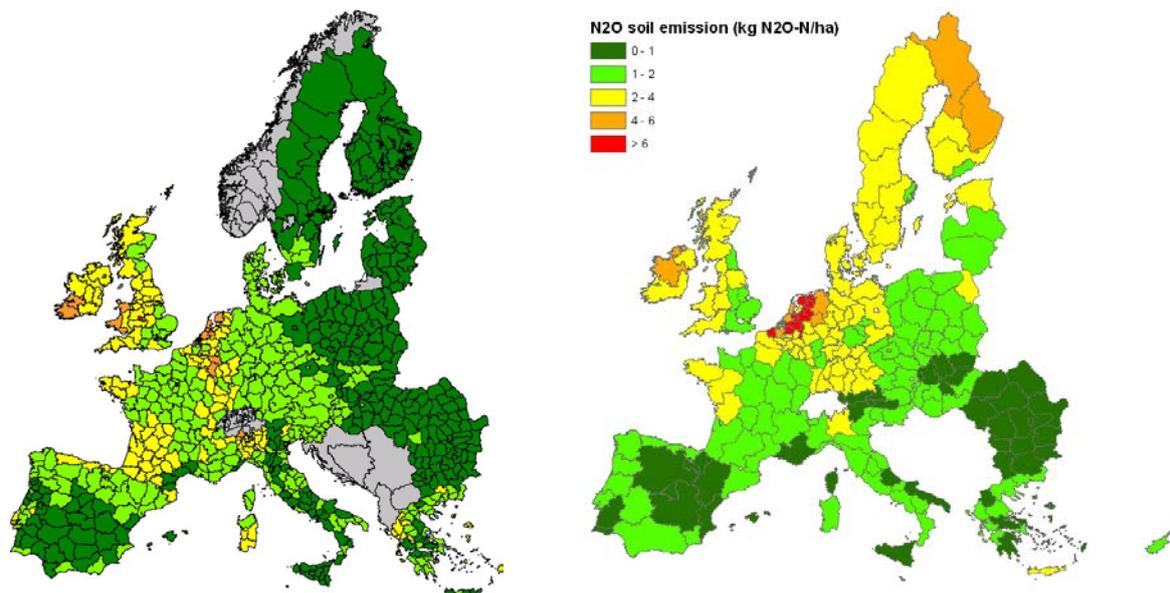


Figure 1. Comparison of calculated N₂O emissions based on differentiated N₂O emission factors from INTEGRATOR (left) with calculated emission factors from MITERRA-Europe based on the default emission factor of 1% (right).

4 DISCUSSION AND CONCLUSION

In this paper we developed a methodology for an inference scheme for N₂O 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 N₂O emission factors are disaggregated based on environmental and management related factors. The presented inference scheme of N₂O emission factors offers the possibility for European countries to use such a Tier 2 approach.

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