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N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions

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Abstract

The number of published N_2O and NO emissions measurements is increasing steadily, providing additional information about driving factors of these emissions and allowing an improvement of statistical N-emission models. We summarized information from 1008 N_2O and 189 NO emission measurements for agricultural fields, and 207 N_2O and 210 NO measurements for soils under natural vegetation. The factors that significantly influence agricultural N_2O emissions were N application rate, crop type, fertilizer type, soil organic C content, soil pH and texture, and those for NO emissions include N application rate, soil N content and climate. Compared to an earlier analysis the 20% increase in the number of N_2O measurements for agriculture did not yield more insight or reduced uncertainty, because the representation of environmental and management conditions in agro-ecosystems did not improve, while for NO emissions the additional measurements in agricultural systems did yield a considerable improvement. N_2O emissions from soils under natural vegetation are significantly influenced by vegetation type, soil organic C content, soil pH, bulk density and drainage, while vegetation type and soil C content are major factors for NO emissions. Statistical models of these factors were used to calculate global annual emissions from fertilized cropland (3.3 Tg N_2O-N and 1.4 Tg NO-N) and grassland (0.8 Tg N_2O-N and 0.4 Tg NO-N). Global emissions were not calculated for soils under natural vegetation due to lack of data for many vegetation types.

Introduction

Human activities like fertilizer application, and fossil fuel combustion have caused a major increase in both nitrous oxide (N_2O) and nitric oxide (NO) emissions. The atmospheric increase of N_2O by 0.7 ppbv per year causes 6% of the anthropogenic greenhouse effect and also contributes to stratospheric ozone depletion (IPCC 2001). NO is involved in the regional balance of oxidants of the atmosphere and its re-deposition causes eutrophication and acidification of ecosystems. Natural sources of N_2O are soils and oceans, and the anthropogenic increase is mainly caused by accelerated soil emissions through the application of N fertilizers and animal manure in agriculture. NO emissions mainly stem from fossil fuel combustion, while soil emissions (both natural and accelerated by fertilizer addition) are dominant in remote areas. Despite more than three decades of research yielding numerous publications on N_2O and NO flux measurements, the contribution of individual sources is still uncertain (IPCC 2001).

In soils N_2O and NO are intermediate products of nitrification and denitrification, while denitrification is also a sink for N_2O (Tiedje 1988). The controlling factors of N_2O and NO emissions have been reviewed elsewhere (for example, Firestone and Davidson 1989; Robertson 1989; Bouwman et al. 1993; Mosier et al. 1996; Bremner 1997; Freney 1997; Bouwman et al. 2002a).

One way to learn about the processes and factors responsible for N_2O and NO emissions is by developing process-based ecosystem models such as Daycent (Parton et al. 1996) and DNDC (Li and Aber 2000). Parallel to these process-based models, it is useful to summarize the emission measurement data with statistical techniques to identify correlations between controlling factors and emissions. These approaches can be used to develop emission factors such as those used by IPCC (Bouwman 1996; Mosier et al. 1998) or simple statistical models that describe the variation of N_2O and NO fluxes at larger scales which can be used to assess management or mitigation options (Bouwman et al. 2002b; Freibauer and Kaltschmitt 2003). In addition, statistical approaches are useful to validate process-based models and to point to problems of biases and underrepresentation in the data for specific climate or land use conditions.

For N_2O and NO emissions from agricultural soils measurement data have recently been summarized (Bouwman et al. 2002a) and an empirical model has been developed (Bouwman et al. 2002b). For N_2O and NO emissions from soils under natural vegetation no regional or global statistical emission model is known to the authors. The aim of this study is to identify the factors with significant influence on N_2O and NO emissions from agricultural fields and soils under natural vegetation, and to develop statistical models for estimating annual emissions. For N_2O and NO emissions from soils under natural ecosystems this study is the first comprehensive statistical analysis of published measurement data, and for agricultural systems the data set used by Bouwman et al. (2002a) was extended for this study.

Data and methods

Data set

We extended the N_2O and NO emission data set presented by Bouwman et al. (2002a) with data for N_2O and NO emissions from soils under natural vegetation and added more measurements for agricultural fields. The data set contains results from field studies that were published in the peer-reviewed literature, including various parameters related to climate, soil, management and measurement technique. The full data set can be obtained from http://www.mnp.nl/en/publications/2006.

The emissions are given as the sum of emissions over the reported measurement period, and for measurements covering more than one year the values were converted to one year. Unless indicated otherwise, hereafter the term 'emission' always refers to the emission during the time period covered by the experiment.

The data set is unbalanced as the combinations of classes are not represented by equal numbers in all experiments, it is biased as some categories are not represented at all, and it has many missing values as most studies do not report all parameters included in the data set. Similar to Bouwman et al. (2002a), classes were designed with – as far as possible – both similar ranges and balanced numbers of measurements. Only in two cases we had to use different classifications for N_2O and NO emissions from soils under natural vegetation than for agricultural measurements.

For agricultural fields the factor climate was classified according to de Pauw et al. (1996) and grouped into temperate continental, temperate oceanic, subtropical and tropical. The data for soils under natural vegetation have an unbalanced representation of these four climate classes, and the factor climate was therefore further aggregated to temperate and tropical. Arid, polar and boreal climates were not part of the final data set due to lack or complete absence of measurement data. Annual precipitation and mean annual temperature from the literature reference itself was included as a factor as well as climate data for the geographical location of the measurement sites from the 0.5×0.5 degree data provided by New et al. (1999).

The data set contains 1125 measurements for N_2O and 199 for NO from agricultural fields, which is a considerable improvement compared to the 846 (N_2O) and 99 (NO) measurements used by Bouwman et al. (2002a). Some variables and classes were excluded from the analysis before summarizing and analyzing the data: (i) Organic soils, as they are known to have very high N-emission and because they strongly influenced the predicted emissions for mineral soils. (ii) Experiments with chemicals or additives like nitrification inhibitors were excluded, because their use is still very limited at the global scale (Trenkel 1997). (iii) Grazing systems, because the N from animal excretion is often not provided. The reduced data set has 1008 measurements for agricultural N_2O from 204 references and 189 measurements for agricultural NO from 58 references.

For soils under natural vegetation the data set includes 247 N_2O emission measurements and 231 NO emission measurements. Some variables and classes were excluded before summarizing and analyzing the data: (i) Organic soils (for the same reason as above for agricultural fields). (ii) The classes deciduous-legume (Alder) forest, marsh, mixed forest and 'other types' which include only two or three measurements. (iii) Two measurements with N_2O uptake >0.4 kg ha^{-1} of N, which caused the predicted emissions to be mostly negative. The reduced data set for soils under natural vegetation has 207 measurements for N_2O from 72 references and 210 measurements for NO from 52 references.

N deposition is not considered because of limited information provided in the references. However, most N_2O and NO emission measurements from soils under deciduous and coniferous forests stem from regions with N inputs from atmospheric deposition >10 kg ha^{-1} yr^{-1}, which is a threshold above which changes to sensitive ecosystems may occur (Bobbink et al. 1998). Therefore the data represent only N-affected coniferous and deciduous forests. The measurements from all other vegetation classes are not or only slightly affected by N deposition and are therefore represent the natural state of those systems.

Data analysis

A statistical analysis of the data set based on the above classification was done to identify factors with a significant influence on N_2O and NO emissions and to develop empirical models for N_2O and NO emissions. We used the REML directive of Genstat (Payne et al. 2000) which is more appropriate for analyzing unbalanced data sets with missing values than regression analysis. Emissions are balanced by assuming all factor classes to have an equal number of observations. Balanced emission rates should therefore be used as relative values for comparing the different controlling factors or factor classes.

The emissions were first log-transformed as this resulted in a distribution that is closer to a normal one than the untransformed data. Log transformation requires manipulation of negative and zero fluxes. We used values for the minimum detectable fluxes of 1.67 ng m^{-2} s^{-1} for N_2O-N measurements (Verchot et al. 1999) and 0.44 ng m^{-2} s^{-1} for NO-N (Meixner et al. 1997) for closed chamber measurements (N_2O) and open chambers with forced flow-through (NO) (the most common types for these gases in our data set). For all measured fluxes smaller than this detectable weekly flux of 0.01 kg N_2O-N ha^{-1} and 0.003 kg NO-N ha^{-1}, we set the emissions to these values.

Initially, all factors in the data set were included in the REML analysis. They were treated as fixed terms, i.e. the REML directive assigns a value to each class of each factor, so that the resulting model with the best possible fit is:

$$\log(N_{\text{emission}}) = A + \sum_{i=1}^{n} E_i \qquad (1)$$

where N_{emission} is the emission of N_2O or NO expressed in kg ha^{-1} of N over the time period covered by the measurements, A is a constant and E_i is the effect value for factor i.

The factor 'reference' was handled as a random effect. Random effects are used in REML when subgroups may have specific effects on the results, but where group membership cannot be surveyed (i.e. new measurements cannot be assigned to existing groups). Including random effects may increase the uncertainty of a prediction but decrease the deviance of the model.

We analyzed the significance of factors in two ways. First, significant variables were identified by creating a model that contained all factors. Secondly – in order to exclude interaction effects – factors were added one by one to a core model, only keeping the significant ones in the model before adding the next one. The reason for this stepwise procedure is that in the model with all factors some may not be significant if there are too many other non-significant factors included. REML tests the significance by (i) adding the factors one after the other to the model, whereby the results depend on the order of the factors, and by (ii) dropping one variable at a time from the full model. The Wald statistics tool is used to calculate the change in deviance for a full model and a reduced model excluding one factor. The significance is tested by comparing the change in deviance with the chi-Square probability (see e.g. Snedecor and Cochran 1980), indicating the chance that the full model is significantly different from the reduced one ($P \leq 0.05$). Thus a model only containing the significant factors is obtained.

A data summary for these significant variables was compiled by calculating means (MEA) and medians (MED) in order to investigate the skewness of the data set. In addition, balanced medians (BMED) and balanced means (BMEA) were calculated for all classes from the statistical (balanced) REML model with the significant factors. As log transformation conserves the median, the model described above can be used to calculate the balanced median (BMED) by back-transformation of the REML results. For balanced means (BMEA) a model was fitted with the same fixed terms, but without prior log transformation of emissions. A comparison between these balanced values and the mean and median values can be used to analyze the unbalanced features of the data set. The values in the summary tables are mean and median emissions calculated by averaging reported emission values each having a specific length of experiment. Therefore mean and median emissions represent an average measurement period for the factor class considered.

For the significant factors we assessed the significance of differences between factor classes. Predicted means (not back-transformed) and standard errors of differences were calculated for all factor classes, assuming average values for all other classes. The difference between two factor classes is significant if it is larger than the standard error of the difference times the excentricity (μ). For classes that are expected to have different emissions than another factor class, a one-tailed test with $\mu = 1.64$ is used. If there is no expectation, the test is two-tailed with $\mu = 1.96$.

The 95% confidence interval was calculated as the prediction plus or minus 1.96 times the standard error. Back-transformation of the prediction and its upper and lower bound yield the emission and the confidence interval, whereby upper and lower range of the confidence interval differ after back-transformation. Since the confidence interval is different for each combination of factor classes, we present the average for all factor class combinations that are covered in the data set.

Estimating global annual emissions

We used global 0.5×0.5 degree resolution data for soil properties (Batjes 2002), climate (de Pauw et al. 1996), land use and vegetation for the year 1995 (IMAGE-team 2001) and fertilizer and manure application (Bouwman et al. 2005). The categories of the global land use and vegetation maps were grouped into the classes used in the statistical model. We used country data on harvested areas and fertilizer use for 1998 (1997–1999 average) obtained from Bruinsma (2003) and FAO (2004) to correct the land use maps, and allocated fertilizer use by crop on the basis of IFA/IFDC/FAO (2003). By using harvested areas the cropping intensity may exceed 100% in countries with multiple cropping, such as China and India. To identify areas affected by high N deposition we used estimates of atmospheric N deposition from the STOCHEM model (Collins et al. 1997) as described by Bouwman et al. (2002c).

More spatial detail was considered not realistic since data on agricultural management are available at the scale of countries at best. For example, no statistical information is available for fertilizer application mode, while fertilizer application rates from IFA/IFDC/FAO (2003) are based on expert knowledge for about 90 countries and animal manure application rates are based on information for world regions.

Fertilizer-induced emissions (FIE) were calculated for each grid cell as the emission with N application minus the emissions for the same area under zero N application (all other factors being equal) and expressed as a percentage of the N applied as fertilizer or animal manure. FIE expresses the anthropogenic N_2O emission from fertilizer, animal manure and other N inputs according to IPCC (1997). The exponential nature of the model causes FIE rates to be positively correlated to background emissions.

Results and discussion

Agricultural fields

Controlling factors for N_2O

Crop type, fertilizer type and N application rate are significant management-related factors for N_2O emissions. MEA and MED values for N application rate increase along with N inputs, except for the classes <100 kg ha^{-1} (Table 1). This is caused by the unbalanced features of the data, because values for BMEA and BMED increase almost linearly along with N application rate. Differences between most classes are significant (Table 2). These results show that the N application is a major control of N_2O emissions from agricultural soils and confirms earlier work based on smaller data sets (Bouwman 1996; Bouwman et al. 2002a).

For fertilizer type, only ANP (lowest BMED value) and CAN (highest BMED) are significantly different from most other fertilizer types (Table 2). Except for CAN and ANP the pronounced differences for MEA and MED between fertilizer types almost disappear after balancing.

For crop type, some differences between classes in MEA values can be explained by outliers and the unbalanced features of the data set, as MED and BMED values are similar (for example legumes compared to none, and grassland compared to cereals, Table 1). A consistent picture for MED and BMED is found for wetland rice with lowest, and cereals and grass with somewhat lower values compared to legumes. Wetland rice, cereals and grass significantly differ from all other crop types and among each other (Table 2), only the difference between cereals and grass is not significant. The factor crop type reflects various differences between crops. Legumes are N fixing crops and generally receive no or small amounts of N fertilizer but the input from N fixation gives rise to high N_2O emissions. Inundation in wetland rice promote anaerobic conditions, whereby N_2O is more likely to be re-consumed before being emitted from the soil (Davidson 1991). High N_2O emissions after drainage of the paddy field (Bronson et al. 1997) are not included in most measurements in our data set. Low N_2O emissions from grassland may be related to the long growing season of grass and higher N uptake than in crops with shorter growing periods.

From the factors related to soil conditions, soil organic C content, soil pH, and soil texture were found to have a significant influence on N_2O emissions (Table 1). For soil organic C content MEA, MED and BMED show continuously increasing emissions with increasing C content (Table 1). The class with C content >3% is significantly different from both other classes (Table 2). The increase of emissions along with soil organic C reflects the positive correlation between soil organic C content and rates of nitrification and denitrification (Tiedje 1988).

For soil pH the MEA, MED, BMEA and BMED all clearly show lowest emissions for pH values >7.3 (Table 2). The two classes with lower pH show similar values within unbalanced and balanced means and medians, whereby the medians are lower than the means. The pH class >7.3 is also significantly different from the two classes with lower pH (Table 2). The N_2O emissions from acidic soils exceed those from alkaline soils and reflect the reported higher N_2O emission from nitrification (Martikainen and Boer 1993) or higher N_2O:N_2 fraction for denitrification (Alexander 1977) at low pH compared to high pH.

The data for soil texture seem to be unbalanced as MEA and MED values are lowest for fine textured soils, BMEA values are similar in all classes. However, the balancing of logarithmic emissions leads to significantly higher BMED values for fine textured soils than for coarse and medium textures (Tables 1 and 2). Fine-textured soils have more capillary pores within aggregates than do sandy soils, thereby holding soil water more tightly. Anaerobic conditions may be more easily reached and maintained for longer periods within aggregates in fine-textured soils than in coarse-textured soils (Bouwman et al. 1993).

Climate type is a significant factor, and MEA, BMEA and BMED values for N_2O emissions from agricultural fields are highest for subtropical

Table 1. Number of observations (*N*), minimum (Min), maximum (Max), mean (MEA), median (MED), balanced mean (BMEA) and balanced median (BMED, back-transformed after log-transformation) emissions[a] for those factors with a significant influence on N_2O emissions from agricultural fields.

Factor/factor class	*N*	Min	Max	MEA	MED	BMEA	BMED
N Application rate (kg ha^{-1})							
0–1	255	−0.60	9.00	1.09	0.56	−0.47	0.29
1–50	30	0.01	3.10	1.03	0.94	1.31	0.61
50–100	160	−0.75	12.93	1.62	0.80	1.61	0.71
100–150	183	−0.01	16.31	1.58	0.87	2.13	0.89
150–200	113	0.00	16.78	2.52	1.14	2.52	1.11
200–250	79	0.01	15.60	2.64	1.42	2.83	1.41
> 250	188	0.00	56.00	7.50	3.88	5.59	2.26
Soil organic C content (%)							
< 1	82	0.01	5.20	1.07	0.59	2.22	0.71
1–3	447	−0.75	31.73	2.11	0.95	1.69	0.71
> 3	180	−0.60	30.40	2.93	1.51	2.74	1.34
Soil pH							
< 5.5	95	0.00	24.20	2.78	0.91	2.63	1.08
5.5–7.3	465	−0.75	41.80	2.49	1.10	2.74	1.02
> 7.3	144	0.00	26.90	1.87	0.65	1.28	0.61
Texture							
Coarse	509	−0.60	46.44	3.21	1.20	2.48	0.80
Medium	219	0.00	56.00	2.56	1.25	2.04	0.68
Fine	158	−0.75	19.00	1.77	0.94	2.14	1.24
Climate							
Temp_C	464	−0.07	56.00	2.17	1.11	1.86	0.77
Temp_O	268	−0.60	31.73	2.80	1.15	1.20	0.71
S-Trop.	144	0.00	41.80	4.27	1.16	3.72	1.72
Trop.	132	−0.75	46.44	2.93	0.98	2.09	0.63
Crop type							
Cereals	184	0.00	56.00	2.09	0.92	2.09	0.77
Grass	282	−0.60	46.44	3.49	1.11	2.57	0.63
Legume	36	0.00	4.20	1.53	1.31	2.70	1.58
Other	289	0.00	41.80	3.39	1.60	2.62	1.16
W-Rice	79	−0.75	4.72	0.79	0.53	0.58	0.31
None	107	0.01	19.60	2.29	1.16	2.74	1.64
Fertilizer type							
AA	38	0.05	19.60	4.07	2.59	3.42	1.04
OAF	74	0.01	36.54	0.97	0.35	1.75	0.82
AN	131	0.00	30.40	3.20	1.41	2.73	1.12
CAN	73	0.05	11.20	2.58	1.80	2.37	1.56
KN	58	0.00	41.80	5.62	1.09	3.41	0.79
Mix	45	0.00	16.78	4.05	3.06	2.09	1.13
OS	48	0.00	31.73	5.64	3.35	2.70	0.81
Organic	88	0.03	56.00	4.49	1.00	2.97	1.15
U	131	−0.01	46.44	2.22	0.69	2.30	0.96
UAN	40	0.03	16.03	3.15	2.70	2.40	0.78
ANP	6	0.06	7.00	1.48	0.36	−1.73	0.26
Length of experiment (days)							
0–50	175	−0.01	16.31	1.19	0.16	1.20	0.28
50–100	111	0.00	15.00	1.15	0.36	1.09	0.61
100–200	311	−0.06	19.60	1.86	0.91	1.76	0.92
200–300	77	−0.10	41.80	5.85	2.10	3.73	1.61
> 300	334	−0.75	56.00	4.18	2.10	3.31	2.08

[a]Emissions in kg N_2O-N ha^{-1} during the experimental period.

Table 2. Significance of differences between classes for BMED for N_2O emissions from agricultural fields for those factors with a significant influence.

Factor/factor class	*N*	Factor class									
N Application rate (kg ha^-1^)		0–1	1–50	50–100	100–150	150–200	200–250				
0–1	255										
1–50	30	●									
50–100	160	●	○								
100–150	183	●	●	●							
150–200	113	●	●	●	○						
200–250	79	●	●	●	●	○					
> 250	188	●	●	●	●	●	●				
Soil organic C content (%)		< 1	1–3								
< 1	82										
1–3	447	○									
> 3	180	●	●								
Soil pH		< 5.5	5.5–7.3								
< 5.5	95										
5.5–7.3	465	□									
> 7.3	144	■	■								
Texture		Coarse	Medium								
Coarse	509										
Medium	219	□									
Fine	158	■	■								
Climate		Temp_C	Temp_O	S-Trop.							
Temp_C	464										
Temp_O	268	□									
S-Trop.	144	■	■								
Trop.	132	□	□	■							
Crop type		Cereals	Grass	Leg.	Other	W-Rice					
Cereals	184										
Grass	282	□									
Legumes	36	■	■								
Other	289	■	■	□							
W-Rice	79	■	■	■	■						
None	107	■	■	□	□	■					
Fertilizer type		AA	OAF	AN	CAN	KN	Mix	OS	Org.	U	UAN
AA	38										
OAF	74	□									
AN	131	□	□								
CAN	73	□	■	□							
KN	58	□	□	□	■						
Mix	45	□	□	□	□	□					
OS	48	□	□	□	■	□	□				
Organic	88	□	□	□	□	■	□	□			
U	131	□	□	□	■	□	□	□	□		
UAN	40	□	□	□	■	□	□	□	□	□	
ANP	6	■	■	■	■	■	■	□	■	■	□
Length of experiment (days)		0–50	50–100	100–200	200–300						
0–50	175										
50–100	111	●									
100–200	311	●	●								
200–300	77	●	●	●							
> 300	334	●	●	●	○						

Solid = significant; open = not significant; circle = one-tailed test with excentricity = 1.64; cube = two-tailed test with excentricity = 1.96.

climates, while the differences between the other classes are small (Table 1). Only the BMED for subtropical climates is significantly different for the other climate types (Table 2). Surprisingly the BMED values for N_2O for tropical climates are similar to those in temperate and lower than in subtropical climates. Although not significantly different, the BMED for continental temperate climates is higher than for oceanic temperate climates, reflecting the higher winter emissions due to temporary accumulation of soil N due to freeze-thaw cycles (Kaiser and Ruser 2000).

The length of the experiment is the only measurement-related factor with a significant influence on N_2O emissions (Table 1). As expected, N_2O emissions increase with the length of the measurement period and for BMED the observed increase is almost linear. Emissions for short measurement periods tend to be disproportionately high as studies often cover the high emission period directly after N application. Differences between classes are significant in all cases but one (Table 2).

Controlling factors for NO

N application rate, soil N content, climate and length of the experiment were found to have a significant influence on NO emissions from agricultural fields (Table 3). The values of MEA, MED, BMEA and BMED generally increase along with the amount of N fertilizer applied, though only MEA and MED values for N application rates > 200 kg ha^{-1} are markedly higher than the other classes. However, after balancing only the lowest N application rate is significantly different from the others (Table 4). This may indicate that the number of measurements is too small to describe the high variability of NO emissions in the data set. However, NO emissions that increase along with N application rate are in agreement with the findings for N_2O.

MEA, MED, BMEA and BMED for soil N content $> 0.2\%$ exceed values for the two classes with lower soil N content. Emissions for soil N content $> 0.2\%$ differ significantly from the class with 0.05–0.2% N, and the difference between the two lower classes is also significant (Table 4). The influence of soil N content reflects the positive effect of soil organic matter on nitrification and denitrification, similar to soil organic C for N_2O emissions.

The patterns of MEA, MED, BMEA and BMED for the factor climate type vary (Table 4). MEA, MED and BMED are highest for NO

Table 3. Number of observations (*N*), maximum (Max), minimum (Min), mean (MEA), median (MED), balanced mean (BMEA) and balanced median (BMED, back-transformed after log transformation) emissions[a] for those factors with a significant influence on NO emissions from agricultural fields.

Factor/factor class	*N*	Min	Max	MEA	MED	BMEA	BMED
N Application rate (kg ha^{-1})							
0–1	56	−0.18	2.62	0.35	0.09	1.61	0.10
1–100	46	0.00	4.48	0.61	0.15	2.20	0.41
100–200	56	0.00	3.00	0.38	0.14	2.15	0.53
> 200	31	0.00	32.00	3.43	0.97	3.37	0.74
Soil N content (%)							
< 0.05	12	0.01	1.05	0.24	0.15	1.65	0.37
0.05–0.2	18	0.00	0.47	0.08	0.03	1.93	0.14
> 0.2	11	0.00	32.00	4.07	1.21	3.41	0.85
Climate							
Temp_C	71	−0.18	4.48	0.37	0.11	1.57	0.17
Temp_O	22	0.00	32.00	1.69	0.19	4.21	0.30
S-Trop.	53	0.00	8.00	0.70	0.31	1.56	0.40
Trop.	43	0.00	10.70	1.74	0.54	2.00	0.78
Length of experiment (days)							
0–50	107	−0.03	2.62	0.22	0.05	2.04	0.08
50–100	19	0.03	2.54	0.73	0.34	1.71	0.53
100–200	33	−0.18	6.29	1.00	0.42	1.75	0.30
200–300	7	0.28	1.13	0.55	0.39	2.00	0.36
> 300	22	0.24	32.00	4.13	1.90	4.17	1.21

[a]Emissions in kg NO-N ha^{-1} during the experimental period.

emissions from tropical systems, and temperate oceanic and subtropical climates show intermediate values of BMED. The two tropical climate types are significantly different from the temperate continental climate type, while the other differences are not significant (Table 4). Higher emissions for tropical than for temperate climates reflect the observed positive relationship between temperature and NO emission (Williams and Fehsenfeld 1991; Saad and Conrad 1993), and this finding is consistent with for example Yienger and Levy (1995) and Davidson and Kingerlee (1997).

MEA, MED and BMED increase along with the length of the measurement period, but this trend is not continuous because of the small number of measurements in most classes. The shortest measurement period (0–50 days) has the largest number of measurements, and is significantly different from the other classes. Furthermore, only emissions for measurements covering > 300 days are significantly different from those for 100–200 days (Table 4).

Table 4. Significance of differences between classes for BMED of NO emissions from agricultural fields for factors with a significant influence.

Factor/factor class	*N*	Factor class			
N Application rate (kg ha⁻1)		0–1	1–100	100–200	
0–1	56				
1–100	46	●			
100–200	56	●	○		
> 200	31	●	○	○	
Soil N content (%)		< 0.05	0.05–0.2		
< 0.05	12				
0.05–0.2	18	●			
> 0.2	11	○	●		
Climate		Temp_C	Temp_O	S-Trop.	
Temp_C	71				
Temp_O	22	□			
S-Trop.	53	■	□		
Trop.	43	■	□	□	
Length of experiment (days)		0–50	50–100	100–200	200–300
0–50	107				
50–100	19	●			
100–200	33	●			
200–300	7	●	○	○	
> 300	22	●	○	●	○

Solid = significant; open = not significant; circle = one-tailed test with excentricity = 1.64; cube = two-tailed test with excentricity = 1.96.

Estimation of global annual N_2O emissions

The summary model excludes the factor fertilizer type, because there is no information about crop-specific use of different fertilizer types at the global scale, and because differences between most fertilizer types are not significant. Furthermore, the summary model handles N application rate as a continuous variable, while this factor was classified in the data summary for presentation purposes. The effect values for the factors of the summary model are listed in Table 5. For length of experiment we use the class > 300 days to calculate annual emissions.

The N_2O emissions calculated with the summary model for agriculture and grassland show that the broad patterns are mainly governed by N application rate, while at smaller scales spatial variability is determined by differences in soil parameters (Figure 1). Differences between crop types mainly follow the effect values (Table 5),

Table 5. Effect values and constant for the N_2O and NO summary model used for global emissions from agricultural fields.

Factor/factor class	N_2O model		NO model	
Constant	−1.5160			−2.9950
N Application rate per kg N ha^{-1}	0.0038			0.0061
Soil organic C content (for N_2O)/soil N content (for NO) (%)				
	< 1	0	< 0.05	0
	1–3	0.0526	0.05–0.2	−1.0211
	> 3	0.6334	> 0.2	0.7892
Soil pH				
< 5.5		0		
5.5–7.3		−0.0693		
> 7.3		−0.4836		
Texture				
Coarse		0		
Medium		−0.1528		
Fine		0.4312		
Climate				
Temp_C		0		0
Temp_O		0.0226		0.3511
S-Trop.		0.6117		0.5189
Trop.		−0.3022		1.1167
Crop type				
Cereals		0		
Grass		−0.3502		
Legume		0.3783		
Other		0.4420		
W-Rice		−0.8850		
None		0.5870		
Length of experiment				
Per year (> 300 days)		1.9910		2.5440

though lower crop-specific effects for grassland are compensated for by higher fertilizer application rates in some regions, and higher crop-specific effects for legumes are compensated for by lower fertilizer application rates (data not shown). Highest emission rates are calculated for other crops, cereals and legumes in Europe and China.

High synthetic fertilizer inputs in crop systems in East Asia, South Asia, North America and Europe are reflected in the high emission sums for these regions (Table 6). Even though more than one crop is grown each year in large parts of China and India, the aggregated emission rates are suppressed by wide-spread rice cultivation. For grassland the highest input of synthetic fertilizer is in Europe, and animal manure is important in Europe and North America, leading to high emissions in these regions. Some regions with low N application rates exhibit high N_2O emission sums because of the vast areas of grassland (e.g. the former USSR).

The global annual N_2O-N emission from fertilized crops is 3.3 Tg with 0.1 Tg from rice crops, 0.4 Tg from legumes, 1 Tg from cereals and 1.9 Tg from others crops (Table 6). Global annual emissions from grassland amount to 0.8 Tg N_2O-N. The mean global FIE (see Section 'Estimating global annual emissions') is 0.91% of the N applied in cropland (excluding legumes) and grassland.

The average 95% confidence interval for calculated N_2O emissions is −51% to +107%. This uncertainty is comparable to that obtained by Bouwman et al. (2002b) and that used as an uncertainty range by IPCC (1997).

Estimation of global annual NO emissions

In the summary model the factor N application rate was – as for N_2O – included as a continuous variable, and for length of experiment we used the class > 300 days to calculate annual emissions. As no global map of soil N content was available we used the map of soil organic C content assuming a C/N ratio of 10 globally based on Brady (1990) as a proxy for soil N content.

Similar to N_2O, broad patterns of NO emissions from agricultural soils are mainly governed by N application rate, while at smaller scales spatial variability is mainly determined by differences in soil organic N content (Figure 2). As crop type is not a model factor, differences between crops are due to crop-specific fertilizer application rates (data not shown). Highest emission rates are calculated for all non-rice crops in Europe, and intermediate values are observed in Northern America and China (Figure 2). In spite of the low

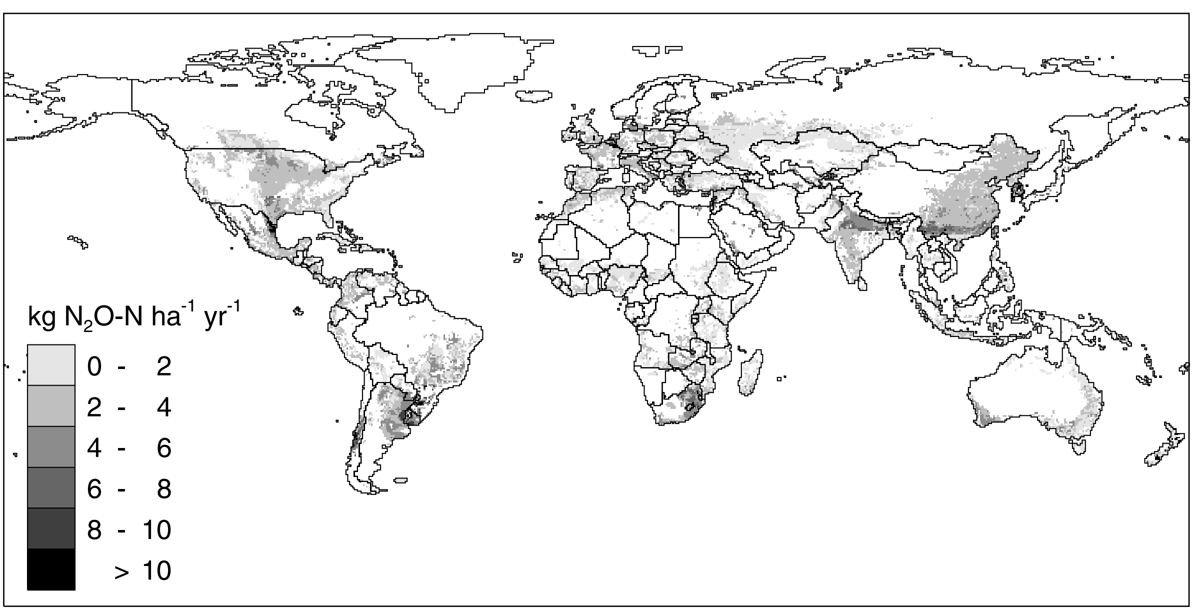

Figure 1. Simulated annual N_2O emission rates for agriculture and grassland. Values are weighted averages over the crop and grassland areas within one grid cell and refer to land use in 1998.

Table 6. Total fertilized area, N fertilizer and animal manure application, N_2O and NO emissions for arable land and grassland for nine world regions[a].

Region	Cropland					Grassland[b]				
	Area (Mha)	N fertilizer (Gg y^{-1})	N manure (Gg y^{-1})	N_2O-N emission (Gg y^{-1})	NO-N emission (Gg y^{-1})	Area (Mha)	N fertilizer (Gg y^{-1})	N manure (Gg y^{-1})	N_2O -N emission (Gg y^{-1})	NO-N emission (Gg y^{-1})
North America	134	13,545	2532	459	116	173	0	1577	240	86
Latin America	116	5699	3373	363	177	73	55	145	79	58
North Africa and Middle East	61	4163	1271	150	50	30	23	50	32	12
West, East and Southern Africa	164	1202	1523	294	179	61	31	51	56	58
Europe	98	9231	3581	330	144	71	2418	1935	99	57
Former USSR	104	2132	2355	177	64	75	393	493	69	41
South Asia	219	15,686	6715	617	265	20	0	229	22	14
East Asia	216	25,323	6986	677	173	75	0	193	79	22
Southeast Asia, Oceania and Japan	118	7082	2631	278	220	97	138	144	134	70
World	1229	84,063	30,968	3345	1388	677	3058	4816	809	417

[a]Totals for the world may differ from the sum of regional values due to rounding.
[b]This includes grassland where manure or fertilizer is applied; grazing land only receiving N input from animal excretion during grazing is excluded.

fertilizer input, the NO emissions in many tropical countries are rather high due to the high effect value for tropical climate (Figure 2 and Table 5). High NO emissions from South Korea (also observed for N_2O emissions) reflect high fertilizer input rates in this country (IFA/IFDC/FAO 2003).

Tropical and subtropical climates promote high NO emissions while fertilizer application rates are generally low in these regions. Therefore, the correlation between N fertilizer application and the emission sum is not as strong as observed for N_2O (Table 6). Among the highest emissions come from South and East Asia, where fertilizer application rates are comparable to those in industrialized countries (Table 6). However, high emissions are also calculated for Latin America, Africa, and Oceania, where fertilizer input is rather low. For grasslands, which generally have lower fertilizer and manure application rates, the same can be seen, with high emissions from Latin America, Africa and Oceania (Table 6).

The global annual NO-N emission from fertilized crops is 1.4 Tg (Table 6), with 0.1 Tg from rice crops, 0.1 Tg from legumes, 0.4 Tg from cereals and 0.7 Tg from others crops, and total emissions from grassland amount to 0.4 Tg NO-N (Table 6). Our estimated global annual emission from agricultural systems therefore is 1.8 Tg NO-N. The calculated FIE for NO from agriculture and grassland excluding legumes is 0.55%.

The relative 95%-confidence interval is −80% and +406% for NO emissions from agricultural fields. NO emission estimates are more uncertain than those for N_2O because of the smaller number of available measurements in our data set. There is no uncertainty estimate from the literature to compare with, because Bouwman et al. (2002b) did not assess the uncertainty (due to the limited number of available measurements), while Veldkamp and Keller (1997) obtained an R^2 value, which is not a true estimate of the uncertainty.

Soils under natural vegetation

Controlling factors for N_2O

Soil organic C content, soil pH, bulk density, drainage, vegetation type, length of the measurement period and frequency of the measurements have a significant influence on N_2O emissions from

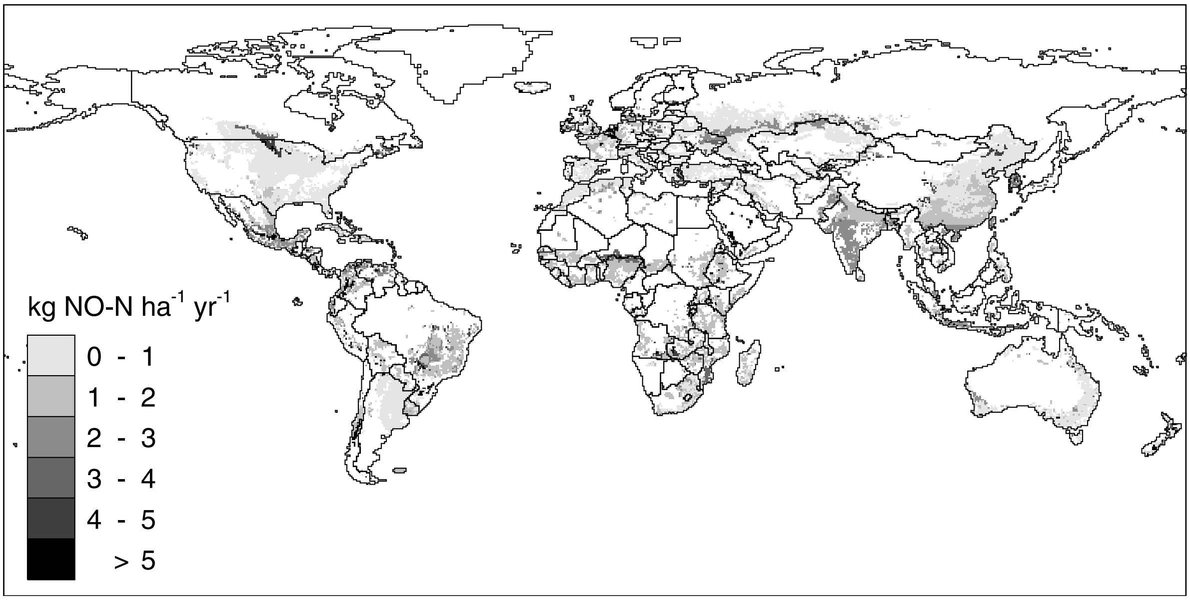

Figure 2. Simulated annual NO emission rates for agriculture and grassland. Values are weighted averages over the crop and grassland areas within one grid cell and refer to land use in 1998.

soils under natural vegetation (Table 7). MEA, MED, BMEA and BMED show continuously increasing emissions with increasing soil organic C content, indicating that the data set is well-balanced. The classes with C content >1% are significantly different from the class <1% (Table 8). These findings agree with those for N_2O emissions from agricultural soils and literature (Tiedje 1988).

For soil pH the values for MEA, BMEA and BMED indicate decreasing N_2O emissions with increasing pH (Table 7), and the BMED for pH > 7.3 is significantly different from both other classes (Table 8). This also is consistent with the findings for agricultural emissions.

The factors bulk density and drainage have an effect on soil hydrological conditions and gas exchange. N_2O emissions decrease along with soil bulk density as is apparent for MEA, MED, BMEA and BMED. Classes with bulk density >1 g m^{-3} are significantly different from those with bulk density <1 g m^{-3} (Table 8). MEA and MED values for the factor soil drainage class show lower emissions for poorly drained soils. However, BMEA and BMED are significantly higher for poorly drained than for well-drained soils (Table 8), which may be attributed to the small number of measurements from poorly drained soils. In general, poor drainage and high bulk density both limit gas diffusion. Under low gas diffusivity N_2O is more likely to be re-consumed before being emitted from the soil (Davidson 1991).

For vegetation type the patterns of MEA, MED, BMEA and MED are not consistent as the data are highly unbalanced (Table 7). For BMED the hierarchy of emissions is rainforest > coniferous/deciduous forest (N affected) > savannah/tropical dry forest. Emissions of N_2O from rainforest are significantly higher than from grassland, savannah and tropical dry forest, and emissions from grassland are significantly lower than those from deciduous forest and rainforest (Table 8). Climate is not a significant factor for soils under natural vegetation. However, climate is partly represented by the factor vegetation type in many cases, since most grassland sites in our data set are from temperate regions. High values for tropical rainforest reflect that these forests generally cycle 2–4 times more N between soil and vegetation than do most temperate ecosystems (Vitousek 1984; Jordan 1985; Vitousek and Sanford 1986). Part of this difference may be related to the presence and N fixation activity of leguminous species which are generally more abundant in tropical than in temperate ecosystems (Crews 1999). An important anthropogenic N input to 'natural'

Table 7. Number of observations (*N*), minimum (Min), maximum (Max), mean (MEA), median (MED), balanced mean (BMEA) and balanced median (BMED, back-transformed after log transformation) emissions for those factors with a significant influence on N_2O emissions[a] from soils under natural vegetation.

Factor class	N	Min	Max	MEA	MED	BMEA	BMED
Soil organic C content (%)							
< 1	5	0.02	0.16	0.06	0.03	0.64	0.06
1–3	38	0.00	2.43	0.36	0.06	0.89	0.12
> 3	44	0.00	7.45	1.07	0.31	1.04	0.19
Soil pH							
< 5.5	109	−0.03	7.45	0.52	0.04	1.32	0.27
5.5–7.3	29	0.00	1.28	0.24	0.11	0.94	0.21
> 7.3	4	0.02	0.04	0.03	0.04	0.32	0.02
Bulk density ($g\ cm^{-3}$)							
0.5–1	26	0.02	6.89	1.18	0.55	1.19	0.33
1–1.25	58	0.00	7.45	0.43	0.05	0.79	0.08
> 1.25	8	0.00	0.31	0.05	0.01	0.59	0.05
Drainage							
P	14	0.00	1.08	0.25	0.08	1.13	0.19
W	121	−0.03	7.45	0.55	0.08	0.58	0.07
Vegetation type							
Coniferous	51	−0.03	2.10	0.13	0.01	0.92	0.14
Deciduous	18	0.00	1.15	0.48	0.46	0.42	0.15
Grass	31	0.00	1.08	0.11	0.06	0.63	0.07
Rain forest	77	0.00	7.45	0.85	0.21	1.37	0.24
Savannah	17	0.00	0.09	0.02	0.02	0.93	0.07
Tropical dry forest	13	0.01	0.70	0.11	0.04	0.87	0.08
Length of experiment (days)							
0–50	122	0.00	1.08	0.06	0.02	−1.04	0.01
50–100	10	0.13	3.19	0.90	0.35	−1.60	0.09
100–200	21	−0.03	1.90	0.29	0.10	1.95	0.15
200–300	11	0.00	2.72	0.81	0.35	2.36	0.27
> 300	43	0.01	7.45	1.29	0.67	2.62	0.41
Frequency of measurements							
> 1 per day	75	0.00	7.45	0.40	0.03	1.92	0.17
Daily	54	0.00	1.08	0.09	0.02	1.69	0.18
Every 2–3 days	6	0.03	0.31	0.14	0.09	2.40	0.24
Every 4–7 days	14	0.08	2.20	0.74	0.30	−0.78	0.08
< 1 per week	58	−0.03	5.86	0.69	0.26	−0.94	0.03

[a]Emissions in kg N_2O-N ha^{-1} during the experimental period.

ecosystems is atmospheric N deposition, causing the high values we find for the N-affected temperate forests as observed by many authors (for example, Brumme and Beese 1992).

As expected, N_2O emissions increase with the length of the experiment, confirming our results for agricultural fields. There is a continuous trend for BMED, while for MEA, MED, and BMEA the class 50–100 days breaks the otherwise continuous increase. The differences between classes are significant in most cases (Table 8). The factor frequency of the measurements also has a significant influence on N_2O emissions (Table 7), but only the class with less than one measurement per week is significantly lower than the other classes (Table 8).

Controlling factors for NO

Soil organic C content, vegetation type and length of experiment have a significant influence on NO emissions from soils under natural vegetation. MEA, MED, BMEA, and BMED continuously increase along with soil C content (Table 9), whereby the class > 3% C is significantly different from both other classes (Table 10). This finding is consistent with the results for N_2O emissions from agricultural fields and soils under natural vegetation. Soil organic C content is a general indicator of soil fertility, similar to soil N content for NO emissions from agricultural fields.

For the factor vegetation type MEA is highest for NO emissions from coniferous, deciduous and

Table 8. Significance of differences between classes for BMED of N_2O emissions from soils under natural vegetation for factors with a significant influence.

Factor/factor class	N	Factor class				
Soil organic C content (%)		< 1	1–3			
< 1	5					
1–3	38	●				
> 3	44	●	○			
Soil pH		< 5.5	5.5–7.3			
< 5.5	109					
5.5–7.3	29	□				
> 7.3	4	■	■			
Bulk density ($g\ cm^{-3}$)		0.5–1	1–1.25			
0.5–1	26					
1–1.25	58	■				
> 1.25	8	■	□			
Drainage			P			
P	14					
W	121	■				
Vegetation type		Coniferous	Deciduous	Grass	Rain forest	Savannah
Coniferous	51					
Deciduous	18	□				
Grass	31	□	■			
Rain forest	77	□	□	■		
Savannah	17	□	□	□	■	
Tropical dry forest	13	□	□	□	■	□
Length of experiment (days)		0–50	50–100	100–200	200–300	
0–50	122					
50–100	10	●				
100–200	21	●	○			
200–300	11	●	●	○		
> 300	43	●	●	●	○	
Frequency of measurements		1	2	3	4	
> 1 per day	75					
Daily	54	□				
Every 2–3 days	6	□	□			
Every 4–7 days	14	□	□	□		
< 1 per week	58	■	■	■	■	

Solid = significant; open = not significant; circle = one-tailed test with excentricity = 1.64; cube = two-tailed test with excentricity = 1.96.

tropical dry forest, while MED values for these classes are low, indicating skewness of the data (Table 9). BMEA and BMED for tropical systems differ from MEA and MED, indicating unbalanced features of the data set. Most tropical emission measurements stem from soils with a C content >3%. As emissions are positively correlated with soil organic C content this causes the observed reduction of balanced values. BMED values are highest for coniferous forest, intermediate for savannah, grassland and deciduous forest, and lowest for tropical rainforest. Most classes are significantly different from two or three other classes (Table 10). Vegetation type is also a representation of climate in many cases (tropical rainforest, savanna and dry forests, temperate coniferous and deciduous). Our results for savannas confirm literature reporting high emissions of NO for climates with wet-dry cycles (Davidson and Kingerlee 1997), and high values for temperate N-affected forests reflect the accelerated N cycling due to atmospheric N deposition.

Finally, our results indicate that the length of the experiment is a significant factor, similar to our results for N_2O and NO from agricultural fields and N_2O emissions from soils under natural vegetation. The NO experiments generally cover shorter periods than N_2O measurements (see Table 9; the class 0–50 days has by far the largest number). BMEA and BMED increase along with

Table 9. Number of observations (*N*), minimum (Min), maximum (Max), mean (MEA), median (MED), balanced mean (BMEA), balanced median (BMED, back-transformed after log transformation) for those factors with a significant influence on NO emissions[a] from soils under natural vegetation.

Factor class	N7	Min	Max	MEA	MED	BMEA	BMED
Soil organic C content (%)							
< 1	31	0.00	0.20	0.01	0.00	1.01	0.13
1–3	52	0.00	3.38	0.19	0.01	1.02	0.14
> 3	25	0.00	10.85	1.09	0.10	1.31	0.48
Vegetation type							
Coniferous	53	0.00	8.04	0.47	0.01	2.01	0.45
Deciduous	10	0.00	2.49	0.40	0.01	0.88	0.17
Grass	43	0.00	0.69	0.08	0.00	1.02	0.29
Rain forest	33	0.00	2.38	0.39	0.04	0.39	0.11
Savannah	60	0.00	3.38	0.11	0.00	1.11	0.29
Tropical dry forest	11	0.00	10.85	1.30	0.02	1.26	0.10
Length of experiment (days)							
0–50	168	0.00	0.47	0.02	0.00	0.09	0.01
50–100	8	0.08	2.82	0.69	0.45	0.59	0.26
100–200	5	0.16	1.31	0.62	0.43	1.32	0.33
200–300	6	0.18	1.09	0.66	0.58	1.38	0.47
> 300	23	0.00	10.85	2.15	0.82	2.19	0.60

[a]Emissions in kg NO-N ha^{-1} during the experimental period.

Table 10. Significance of differences between classes for BMED of NO emissions from soils under natural vegetation for factors with a significant influence.

Factor/factor class	N	Factor class				
Soil organic C content (%)		< 1	1–3			
< 1	31					
1–3	52	○				
> 3	25	●	●			
Vegetation type		Coniferous	Deciduous	Grass	Rain forest	Savannah
Coniferous	36					
Deciduous	0	■				
Grass	21	□	□			
Rain forest	59	■	□	■		
Savannah	31	□	□	□	■	
Tropical dry forest	10	■	□	■	□	■
Length of experiment (days)		0–50	50–100	100–200	200–300	
0–50	168					
50–100	8	●				
100–200	5	●	○			
200–300	6	●	○	○		
> 300	23	●	○	○	○	

Solid = significant; open = not significant; circle = one-tailed test with excentricity = 1.64; cube = two-tailed test with excentricity = 1.96.

the length of experiment, and for MEA and MED the continuous increase is only disturbed by the class 100–200 days.

Estimation of global annual N_2O and NO emissions

The effect values for the parameters in the summary models for N_2O and NO emissions are listed in Table 11. For the factor length of experiment we used the effect values for the class > 300 days to calculate annual emissions, and for frequency of experiment we used >1 measurement per day.

Given the high uncertainty of the summary models and the limited representation of different ecosystems and climatic zones in the data set we regard the global emission maps (Figures 3 and 4) as an illustration of the interacting effect of significant factors at the global scale and not as reliable estimates of natural N_2O emission rates.

As most measurements for coniferous and deciduous forests stem from areas with high atmospheric N deposition the estimation of global emissions excludes all temperate forests where N deposition is less than 10 kg N ha^{-1} y^{-1}. Hence, large areas in northern latitudes are not considered. The high effect value for tropical rainforest (Table 11) leads to high N_2O emissions from tropical regions (Figure 3). The N_2O emission rates calculated for tundra and grasslands in northern latitudes are comparable to those from tropical savanna and dry forest systems due to the combined effect of poorly drained soils and low soil bulk density. Low pH values, which are mainly found in tropical regions and high latitudes, are further causes of high emission rates in these two regions (Figure 3). The effect of the soil organic C content on simulated global emission patterns is not as strong as could be expected from the summary model, as soil organic C content exceeds 3% only in few regions according to the global input dataset.

Regarding NO emissions, variation in emissions can directly be attributed to the distribution of vegetation types and their effect values (Table 11 and Figure 4). Lowest emissions are calculated for rainforest and tropical dry forest. Higher NO-N emissions of about 0.6 kg ha^{-1} y^{-1} are estimated for temperate grasslands and savannah, which together cover the largest area included in the estimation. The soil organic C content in the data set often exceeds 3%, while in the global soil map it is lower than 3% in most areas. Therefore the statistical model produces lower estimates of NO (and also N_2O) emissions from soils under natural vegetation than one would conclude from the measurement data per se. The average 95%-confidence interval is −84% and +621% for N_2O, and −73% and +274% for NO emissions from soils under natural vegetation.

Table 11. Effect values for the N_2O and the NO model for soils under natural vegetation.

	N_2O model	NO model
Constant	−2.8900	−3.952
Soil organic C content (%)		
< 1	0	0
1–3	0.6683	0.0569
> 3	1.0918	1.3265
Soil pH		
< 5.5	0	
5.5–7.3	−0.2750	
> 7.3	−2.4179	
Bulk density (g cm^{-3})		
0–1	0.9941	
1–1.25	−0.3786	
> 1.25	−0.8597	
Drainage		
P	0	
W	−1.0462	
Vegetation type		
Coniferous	0	0
Deciduous	0.0115	−0.9540
Grass	−0.7941	−0.4335
Rain forest	0.4995	−1.4246
Savannah	−0.6881	−0.4238
Tropical dry forest	−0.5811	−1.5296
Length of experiment		
Per year (> 300 days)	3.6120	3.771
Frequency of experiment		
> daily	0	

Comparison with other studies

Agricultural fields

Compared to the data of Bouwman et al. (2002a) (which we will refer to as subset), the data set of N_2O measurements for agricultural fields was extended with 162 measurements, and the results are similar to those found with the data subset. The 20% increase in the number of measurements and re-classification of climate types cause small differences, i.e. climate is now a significant factor, while soil drainage is not significant as it was for the subset of data.

For N_2O there is only little reduction of the uncertainty due to the addition of new data, possibly because the subset had already a large number of measurements in primarily temperate climates, and additional measurements in the same climate types do not add much information. Unfortunately, the representation of tropical climates did not increase substantially (relative contribution of subtropical and tropical systems is 13 and 11% in the subset, and is now 14 and 13%, respectively), so the representation of global environmental conditions in agricultural systems has not really improved.

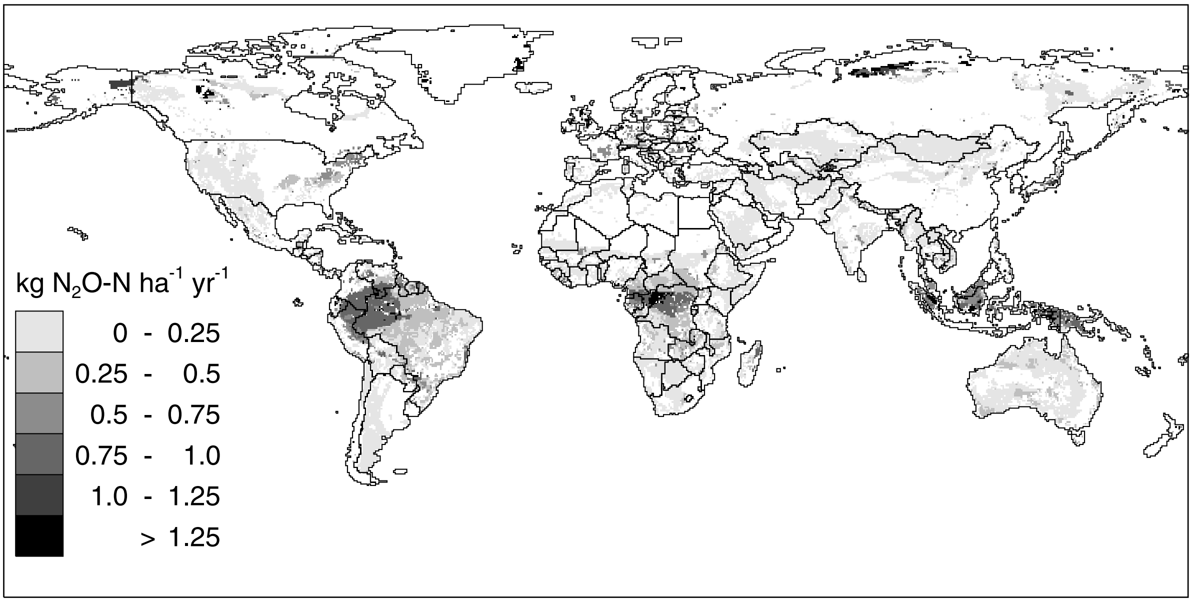

Figure 3. Simulated annual N_2O emission rates for natural ecosystems for 1998 land cover. Agricultural area, regrowth forest, arid climate and polar climate are excluded.

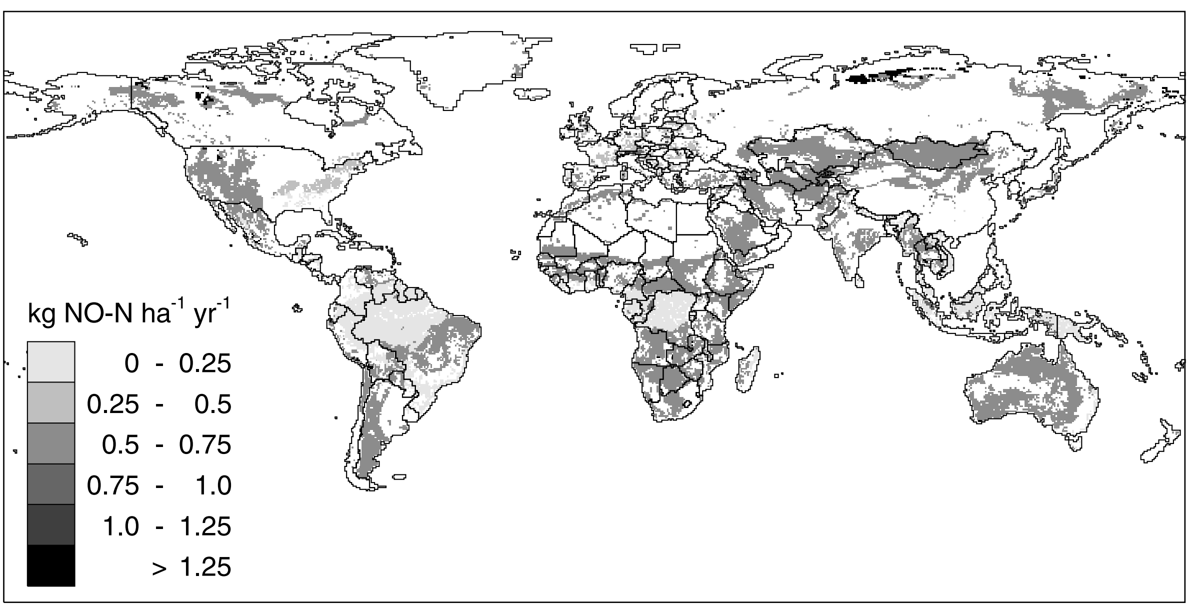

Figure 4. Simulated annual NO emission rates for natural ecosystems for 1998 land cover. Agricultural area, regrowth forest, arid climate and polar climate are excluded.

The global estimate for annual N_2O-N emissions from cropland (3.3 Tg) we obtain here exceeds that based on the subset. This difference is related to the summary model and the handling of the data. Although the models are quite similar, four different climate classes are now included, which results in more variation and higher emissions in sub-tropical and tropical climates. In addition, in this study we have a more detailed classification of crop types, which may lead to higher emission estimates in some regions.

Our estimate for annual global N_2O emissions from fertilized grassland differs from the results based on the data subset. In this study the grassland area of about 700 Mha includes primarily managed grassland in mixed agricultural systems, only excluding pastoral grazing land (Bouwman et al. 2005). In contrast, (Bouwman et al. 2002b) considered only those grassland areas receiving fertilizer N inputs and therefore obtained lower N_2O (and NO) emissions.

Freibauer and Kaltschmitt (2003) used stepwise multivariate linear regression to analyze N_2O emissions from Europe. Results were based on measurements for arable sites in temperate oceanic (61) and temperate continental (46) climates, and for grassland sites (72). In our study we used available data from all over the world, with 464 measurements for temperate oceanic and 268 measurements for temperate continental climates. It is therefore difficult to compare our results in terms of uncertainty with those of Freibauer and Kaltschmitt (2003).

As Freibauer and Kaltschmitt (2003) did not calculate total European emissions, we can only compare the FIE estimates. Our estimate for FIE for N_2O is 0.91%. Based on their regression, Freibauer and Kaltschmitt (2003) calculate FIE values for N_2O for arable soils in temperate oceanic climates of 0.2, 0.8% in temperate continental climates, and 0.3% for grassland. This contradicts their mean FIE obtained directly from the literature (1.3, 2.2 and 1.2% for arable soils in temperate oceanic and temperate continental climates, and grassland, respectively). Our FIE and their direct mean values are consistent with the 1.25% currently used as default FIE by the IPCC methodology for national greenhouse gas inventories (Bouwman 1996; IPCC 1997), and with the 0.9% obtained by Bouwman et al. (2002b) based on the subset.

For NO emissions from agricultural soils 90 measurements were added compared to the subset (Table 12). This 91% increase resulted in soil drainage as a significant control of NO emissions, while for the subset this was soil organic C content. Furthermore, climate is a significant factor additional to the N application rate (significant for both the subset and extended data set). The frequency of measurements is no longer significant, while it was a major factor for the subset. We believe that results are less uncertain than those based on the subset. This does not mean that the data now represent the full variability of world agricultural systems, but temperate continental (36%), subtropical (28%) and tropical (23%) are better represented than in the subset.

Our estimated global annual NO emission sum from agricultural systems (1.8 Tg) is much lower than the 5 Tg estimate in the inventory of Davidson and Kingerlee (1997), also lower than the 2.6 Tg reported in a recent summary at the global N cycle (Galloway et al. 2004) and similar to the 1.6 Tg reported by Bouwman et al. (2002b). However, a proper comparison is difficult because of differences in the types and areas of grassland in the various studies.

The calculated FIE of 0.55% for NO from agriculture and grassland excluding legumes agrees with the estimate of 0.5% by (Veldkamp and Keller 1997) and is somewhat lower than the 0.7% of Bouwman et al. (2002b) based on a smaller data set.

Soils under natural vegetation

For global N_2O and NO emissions from soils under natural vegetation no purely statistical emission model has been developed so far, but empirical approaches have been applied both for global emissions of N_2O (Bouwman et al. 1993; Kreileman and Bouwman 1994) and NO (Yienger and Levy 1995). Additionally, process based models have been used to estimate N_2O emissions (Nevison and Holland 1997; Potter et al. 1997).

Table 12. Comparison of number of measurements of N_2O and NO for agricultural fields in this study and Bouwman et al. (2002a).

Crop type	Number of N_2O measurements		Number of NO measurements	
	2002	This study	2002	This study
Grass	193	282	23	55
Legumes	36	36	16	14
Wetland rice	61	79	2	2
All other (incl. 'not known')	556	611	58	118
Total	846	1008	99	189

The global N_2O emission rates calculated with our summary model differ from the pattern suggested by the above cited references. The main reason for this discrepancy is that both the empirical model (Bouwman et al. 1993) and the process models (Nevison and Holland 1997; Potter et al. 1997) strongly link N_2O emission rates to one or more of the parameters Normalized Difference Vegetation Index (NDVI), Net Primary Production (NPP), decomposition rate or temperature. All these parameters peak in tropical systems. In addition, high emissions are calculated by the statistical model for high latitudes due to the the impact of drainage class and bulk density. Therefore the emission sums and average emission rates for broad vegetation classes differ between Bouwman et al. (1993) and this study (Table 13). While Bouwman et al. (1993) covers the entire area of temperate forests and assumes no N deposition, here only N affected temperate forests are included with higher emission rates. For the three other vegetation classes the areas are not directly comparable because of different classifications (Table 13). The emission estimate for closed tropical rainforest is similar, while the emissions we calculate for open tropical forest and grassland/steppe are lower compared to Bouwman et al. (1993).

The patterns of global NO emissions from soil under natural vegetation calculated with the statistical model differ from both the empirical model (Yienger and Levy 1995) and the process-based approach (Potter et al. 1997). Analogous to N_2O, the NO emissions according to Potter et al. (1997) are strongly linked to NPP, decomposition rates and temperature, thus predicting highest emissions in tropical systems. In contrast, Yienger and Levy (1995) basically derived a biome-specific NO emission potential from a compilation of measurement data (which is highest for tropical systems), and superimposed a temperature response function. Though they additionally accounted for other effects like pulsing, this basic mechanism also causes their emission estimates to roughly increase with decreasing latitude.

A more recent biome stratification of NO emissions based on mean values and expert judgment covers a larger variety of systems though not deriving an empirical model (Davidson and Kingerlee 1997). Our calculated NO emissions are systematically lower than these values (Table 13), which can be attributed to the effect of soil organic C content and the log transformation that we used to reduce effects of outliers. However, the relative emission rates for vegetation classes are similar in both cases, with lowest emissions calculated for tropical rainforest. Given the high uncertainty range of the statistical model and the problematic interaction of the two parameters C content and vegetation class, we recognize that the estimation of global NO emissions from soils under natural vegetation presented is highly uncertain due to scarcity of data.

Table 13. Comparison of N_2O and NO emission estimates from soils under natural vegetation.

Vegetation classes	Area (Mha)	Emission (N_2O-N or NO-N)		Area (Mha)	Emission (N_2O-N or NO-N)	
		Gg y^{-1}	kg ha^{-1} y^{-1}		Gg y^{-1}	kg ha^{-1} y^{-1}
	This study			Bouwman et al. (1993)		
A. N_2O emission estimates						
Temperate forest[a]	230	147	0.64	2246	500	0.22
Open tropical forest[b]	1598	333	0.21	1028	1000	0.97
Closed tropical forest[c]	854	1170	1.37	1682	2300	1.37
Grassland/steppe	2765	403	0.15	3147	1500	0.48
	This study			Davidson and Kingerlee (1997)		
B. NO emission estimates						
Temperate forest[a]	230	105	0.46	100	300	3.00
Open tropical forest[b]	1598	670	0.42	2400	7400	3.08
Closed tropical forest[c]	854	186	0.22	1600	1320	0.83
Grassland/steppe	2765	1559	0.56	900	1100	1.22

[a]N affected temperate forest, except for the estimate of Bouwman et al. (1993) which covers the entire temperate forest area.
[b]Including shrubland, savanna and tropical woodland.
[c]Including warm humid, deciduous and montane tropical forest and warm mixed forest.

Conclusions

The analysis based on an extended version of the data set presented in Bouwman et al. (2002b) does not yield a considerable improvement or reduction of uncertainty in the N_2O emissions from agricultural fields compared to the reduced data set. This is because the representation of environmental and management conditions in agricultural systems did not improve. For NO emissions from agricultural fields the analysis is based on a much larger number of measurements (200%) compared to Bouwman et al. (2002b), now covering a higher diversity of environmental conditions. The uncertainty of NO emission estimates was considerably reduced compared to the previous analysis.

For agricultural N_2O a better understanding of important processes and better emission estimates can be expected by improving the representation of tropical and subtropical agricultural systems, and by including more measurements for legumes and for wetland rice covering also the post-drainage period. In contrast, agricultural NO measurements in the database already cover temperate and tropical systems likewise, but the number of measurements is substantially lower than for N_2O, which is reflected in a lower number of significant factors and a much higher uncertainty range.

For emissions from soils under natural vegetation this analysis is the first comprehensive statistical analysis of published measurement data (about 200 for both N_2O and NO). Given the incomplete coverage of global vegetation zones and the high uncertainty of the developed statistical models, global annual emissions cannot be calculated with this approach. Far more measurement data, and particularly a better representation of the vegetation types tropical dry forest, savanna, tundra and temperate ecosystems that are not affected by N deposition, preferably covering prolonged periods, are needed to understand the complexity of interactions.

The statistical models presented in this study are useful to estimate seasonal or annual N_2O and NO emissions based on site-specific environmental and management parameters, and as they include estimates of uncertainty, they can serve as a benchmark to process-based models applied at larger spatial scales.

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