GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 16, NO. 4, 1058, doi:10.1029/2001GB001811, 2002

Emissions of N_2O and NO from fertilized fields: Summary of available measurement data

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Received 17 October 2001; revised 27 February 2002; accepted 27 February 2002; published 18 October 2002.

[1] Information from 846 N_2O emission measurements in agricultural fields and 99 measurements for NO emissions was summarized to assess the influence of various factors regulating emissions from mineral soils. The data indicate that there is a strong increase of both N_2O and NO emissions accompanying N application rates, and soils with high organic-C content show higher emissions than less fertile soils. A fine soil texture, restricted drainage, and neutral to slightly acidic conditions favor N_2O emission, while (though not significant) a good soil drainage, coarse texture, and neutral soil reaction favor NO emission. Fertilizer type and crop type are important factors for N_2O but not for NO, while the fertilizer application mode has a significant influence on NO only. Regarding the measurements, longer measurement periods yield more of the fertilization effect on N_2O and NO emissions, and intensive measurements ($\geq$1 per day) yield lower emissions than less intensive measurements (2–3 per week). The available data can be used to develop simple models based on the major regulating factors which describe the spatial variability of emissions of N_2O and NO with less uncertainty than emission factor approaches based on country N inputs, as currently used in national emission inventories. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 1615 Global Change: Biogeochemical processes (4805); *KEYWORDS:* animal manure, gas emission, fertilizer, nitric oxide, nitrous oxide

Citation: Bouwman, A. F., L. J. M. Boumans, and N. H. Batjes, Emissions of N_2O and NO from fertilized fields: Summary of available measurement data, *Global Biogeochem. Cycles*, *16*(4), 1058, doi:10.1029/2001GB001811, 2002.

1. Introduction

[2] The acceleration of the global nitrogen (N) cycle due to human activities is probably the major cause of the increase in the atmospheric nitrous oxide (N_2O) concentration of 0.7 ppb per year and of the increasing injection of nitric oxide (NO) into the atmosphere. Nitrous oxide is one of the so-called greenhouse gases, constituting 6% of the anthropogenic greenhouse effect, and also contributing to the depletion of stratospheric ozone [*Intergovernmental Panel on Climate Change* (*IPCC*), 1996]. Although the individual sources of N_2O are poorly known, the most important natural sources are generally accepted as being soils and oceans, while the use of N fertilizers and animal manure are the main anthropogenic sources responsible for the atmospheric increase [*IPCC*, 2001]. Nitric oxide participates in the regulation of the oxidant balance of the atmosphere. In the atmosphere, NO is oxidized to NO_2. Redeposition of NO_x (NO and NO_2 are collectively denoted as NO_x) contributes to acidification and eutrophication of ecosystems. Agricultural fields are not major sources of NO worldwide. However, being the dominant source in regions away from fossil fuel combustion sources, agricultural NO emissions play an important role in local tropospheric ozone chemistry.

[3] In this study we have concentrated on the direct emissions of N_2O and NO from soils caused by the application of mineral fertilizers and animal manure. Indirect emissions of N_2O are not considered. Indirect emissions occur through degassing of N_2O from aquifers and surface waters, stemming from N_2O dissolved in water leaching from soils, or from denitrification in groundwater of N leached from fertilized soils. In addition, experiments in grazed grasslands are not considered since such systems are not within the scope of this study.

[4] The bacterial processes of denitrification and nitrification are the dominant sources of N_2O and NO in most soil systems, while denitrification is also a sink for N_2O. Nitrification is an aerobic process which is relatively constant across ecosystems. The availability of ammonium (NH_4^+) and oxygen is the most important factor controlling soil

0886-6236/02/2001GB001811

nitrification [*Firestone and Davidson*, 1989]. Denitrification is an anaerobic process, and rates are temporally and spatially more variable. The major controls on biological denitrification include the availability of carbon (C), and NO_3^- and other N oxides, and the oxygen supply [*Tiedje*, 1988].

[5] N_2, N_2O, and NO can also be produced during chemical decomposition of HNO_2 under limited oxygen conditions and at low soil pH [*Bremner*, 1997; *McKenney and Drury*, 1997; *Neff et al.*, 1995; *Veldkamp and Keller*, 1997b]. Uptake of NO and NO_2 by plants determines the net exchange of NO_x at the Earth's surface.

[6] The conceptual ''hole in the pipe'' (HIP) model proposed by *Firestone and Davidson* [1989] has proven useful in understanding nitrification and denitrification processes, and associated short-term fluxes of NO and N_2O at the field scale [*Davidson and Verchot*, 2000]. The HIP model can also capture a large fraction of the variation in N_2O and NO emissions for larger scales and can be used to demonstrate how emissions might be managed or mitigated [*Davidson et al.*, 2000]. The HIP model considers a fluid flowing through a leaky pipe, whereby rates of nitrification and denitrification are found analogous to the flow of N through the pipe, while the size of the holes determines the relative amounts of N_2O and NO that leak out compared to the total N flow.

[7] In agricultural soils the flow of N through the pipe is primarily determined by the application of synthetic fertilizers and animal manure, and biological N fixation by leguminous crops. Other sources of N include atmospheric deposition and mineralization of soil organic matter and crop residues. The availability of N for nitrification and denitrification is also determined by the loss of N via ammonia (NH_3) volatilization. Total N gas production and N_2O emission, in particular, may increase with the N application rate [*Chantigny et al.*, 1998], possibly in a nonlinear fashion [*Erickson et al.*, 2001].

[8] The speed of the N flow through the pipe is strongly related to temperature, which controls soil processes at all levels by governing organic matter decomposition, denitrification, and nitrification rates. The importance of the holes in the process pipe is determined by the N flow rate. At low flow rates the NO and N_2O losses will be low regardless of the size of the holes. During denitrification the ratio of N_2O/N_2 generally increases with decreasing temperature [*Firestone and Davidson*, 1989; *Keeney et al.*, 1979]. Observations show NO emissions to increase with soil temperature [*Saad and Conrad*, 1993; *Williams and Fehsenfeld*, 1991], although this relationship is uncertain [*Meixner*, 1994].

[9] The N flow may be temporally influenced by weather conditions. In climates where soil N temporarily accumulates due to wet-dry or freeze-thaw cycles, the autumn, early spring, and winter periods may account for an important part of the annual N_2O emission from agricultural fields [*Kaiser and Ruser*, 2000; *Lemke et al.*, 1998; *Röver et al.*, 1998; *Van Bochove et al.*, 2000; *Wagner-Riddle and Thurtell*, 1998]. Wetting of dry soils causes pulses in N mineralization, nitrification, and NO [*Johansson and Sanhueza*, 1988] and N_2O fluxes [*Letey et al.*, 1981].

[10] The size of the holes in the HIP model is determined by many factors such as soil water and oxygen, and gas diffusion and soil reaction (pH). Soil-water content has been shown to influence N_2O and NO emissions from well-drained soils. Optimum conditions for NO production are at 30–60% water-filled pore space (WFPS) and for N_2O production at 60–80% WFPS [*Davidson*, 1991]. The optimum conditions for denitrification (WFPS of 80–100%) are generally found where oxygen supply is limited by restricted gas diffusion caused by, for example, high soil-water content, impeded drainage, shallow groundwater, or soil compaction. Under such conditions the probability of N_2O and NO being reconsumed by denitrifiers is greatly enhanced, leading to low N_2O and NO emissions [*Davidson*, 1991; *Skiba et al.*, 1997]; uptake of N_2O from the atmosphere may even occur [*Ryden*, 1981, 1983].

[11] The oxygen and moisture status and gas diffusion in agricultural soils depend on soil texture and drainage. Fine-textured soils have more capillary pores within aggregates holding water more tightly than do sandy soils. As a result, anaerobic conditions may be more easily reached and maintained for longer periods within aggregates in fine-textured soils than in coarse-textured soils. Hence, if soils are not completely water-saturated, restricted drainage and fine soil texture are prone to high N_2O emission, while well-drained coarse textured soils favor high NO emission.

[12] Heterogeneity of soil conditions often results in ''hot spots'' of denitrification activity created by decomposing organic matter which generates anaerobic microsites [*Dowdell and Smith*, 1974; *Duxbury et al.*, 1982; *Myrold and Tiedje*, 1985; *Parkin*, 1987; *Remde et al.*, 1993; *Schmidt et al.*, 1988]. This phenomenon explains the observed high spatial variability of soil denitrification.

[13] Soil pH has a marked effect on denitrification, with lower rates more under acid than under slightly alkaline conditions [*Simek et al.*, 2000; *Yamulki et al.*, 1997], but the N_2O fraction may be larger at low soil pH [*Brumme and Beese*, 1992; *Eaton and Patriquin*, 1989; *Focht*, 1974; *Goodroad and Keeney*, 1984; *Martikainen*, 1985]. Emissions of N_2O and NO decrease with increasing pH in acidic soils, and increase when the pH of alkaline soils is decreased [*Nägele and Conrad*, 1990].

[14] Many factors associated with crop, soil, water, and fertilizer management influence soil conditions and processes, and thus N_2O and NO emissions. Nitrous oxide fluxes from wetland rice systems during the growing season are generally lower than those from upland fields [*Cai et al.*, 1997; *Keertsinghe et al.*, 1993; *Smith et al.*, 1982; *Xu et al.*, 1997]. This is caused by the anaerobic conditions prevailing in wetland rice systems. However, aerobic conditions after draining the field during the post-harvest fallow period allow for nitrification of NH_4^+ mineralized from soil organic matter, and residues of rice and aquatic biota, as well as subsequent denitrification. Therefore N_2O emissions from drained wetland rice soils during the fallow period may be much higher than during the crop season [*Bronson et al.*, 1997; *Byrnes et al.*, 1993].

[15] Another group of crops requiring special attention are N-fixing leguminous crops such as alfalfa, soybeans, pulses, and clovers. Usually these crops receive no or only small N fertilizer inputs as a starter [*Food and Agriculture Organization* (*FAO*)/*International Fertilizer Industry Association*

(*IFA*)/*International Fertilizer Development Center* (*IFDC*), 1999], but their emissions of N_2O are of the same magnitude as those of fertilized nonleguminous crops [*Bremner et al.*, 1980; *Duxbury et al.*, 1982; *Jacinthe and Dick*, 1997].

[16] Fertilizer application timing and mode influence the NH_3 volatilization and the efficiency of plant uptake, hence availability of N for nitrification and denitrification. Timing and matching the N application with plant needs is important, because any prolongation of the period in which NH_4^+-based fertilizers can undergo nitrification or NO_3^-based fertilizers can be denitrified, without competition from plant uptake, is likely to increase emissions of NO and N_2O [*Chantigny et al.*, 1998; *Ortiz-Monasterio et al.*, 1996; *Smith et al.*, 1997]. Generally, N_2O emission from subsurface applied or injected N fertilizers is higher and NO emissions lower than from broadcast synthetic fertilizers and animal manure [*Ellis et al.*, 1998; *Flessa and Beese*, 2000; *Kessavalou et al.*, 1998; *Smith et al.*, 1998].

[17] Crop residues in agricultural fields are important sources of C and N for nitrification and denitrification. Higher denitrification [*Shelton et al.*, 2000] and N_2O and NO emission [*Cochran et al.*, 1997; *Slemr et al.*, 1984; *Vos et al.*, 1994] were observed after retaining or incorporating residues on the land instead of removing them.

[18] Tillage also affects the conditions for N_2O and NO emissions from soils. Higher N_2O losses were observed for no-tillage when compared to conventional tillage [*MacKenzie et al.*, 1997, 1998; *Palma et al.*, 1997] due to higher denitrification activity [*Rodriguez and Giambiagi*, 1995; *Weier et al.*, 1996]. However, N_2O losses from no-tillage systems may be lower than those from tilled soils when fields have not been cultivated for a number of years [*Jacinthe and Dick*, 1997]. An increase in NO emission caused by plowing has been observed under temperate [*Slemr and Seiler*, 1991] and tropical climatic conditions [*Sanhueza et al.*, 1994].

[19] Finally, the measurement technique is important when assessing literature data on N_2O and NO emissions. Detailed information on the various measurement techniques are given by *Lapitan et al.* [1999]. The majority of N_2O and NO emission measurements in field studies are based on chamber techniques involving the use of enclosures placed over the soil surface. Temporal and spatial variability of N_2O and NO fluxes are major problems in making estimates of gas fluxes from a plot based on enclosure measurements. Important aspects are the size of the enclosure and the number of enclosures within a plot as well as the frequency of measurements. For example, reducing the frequency from more than once per day to daily sampling resulted in a calculated emission from any chamber, which may vary by as much as 20%. [*Brumme and Beese*, 1992] reported that one flux measurement per week between 0630 and 1130 local time resulted in 6–49% higher emission estimates for N_2O from fertilized fields than for five measurements per day. [*Veldkamp and Keller*, 1997b] found that monthly measurements yielded lower N_2O emission estimates than one measurement every 2–3 days. Finally, N fertilization has an effect on N_2O emissions that lasts longer than the crop growing period. Therefore, the period covered by the measurements determines the amount of fertilizer N recovered as N_2O [*Bouwman*, 1996].

[20] Relationships between N application rate and emission were established by *Eichner* [1990] and *Bouwman* [1996] for N_2O and by *Veldkamp and Keller* [1997a] for NO using the concept of fertilizer-induced emission factor (FIE). FIE is defined as the emission from fertilized plots minus the emission from unfertilized control plots (all other conditions being equal to those of the fertilized plot), expressed as a percentage of the N applied. The emission factor for N_2O proposed by *Bouwman* [1996] was adopted by the *IPCC* [1997] as a default method to calculate national anthropogenic emissions of N_2O from the use of fertilizers and animal manure. FIE is supposed to represent the anthropogenic emission caused by N application, although the emission from control plots may not be the same as the "natural" emission of the original vegetation in preagricultural times.

[21] In spite of the wealth of available information from individual research papers as discussed above, the FIE approach ignores the role of environmental and management factors that control N_2O and NO emissions. The objective of this study was to summarize the measurements and ancilliary data on N_2O and NO fluxes from fertilized fields, so as to assess the main factors regulating N_2O and NO fluxes. The methods used for summarizing the data set compiled from literature data are presented in section 2. Section 3 discusses the results, while conclusions are presented in section 4.

2. Data and Methods Used

2.1. Handling the Measurement Data From the Literature

[22] We used data from field studies from the peer-reviewed literature. The complete data set with references can be obtained from http://www.rivm.nl/ieweb and is described by *FAO*/*IFA* [2001]. The data set includes literature reference; location of the Measurement; climate; soil type, texture, organic C content, N content, drainage, and pH; residues left in the field; crop; fertilizer type; N application rate; method and timing of fertilizer application; NH_4^+ application rate (for organic fertilizers), N_2O/NO emission/denitrification (expressed as total over the measurement period, as % of N rate, and as % of N rate accounting for control); measurement technique; length of measurement period; frequency of the measurements; and additional information, such as year/season of measurement, information on soil, crop or fertilizer management, specific characteristics of the fertilizer used, and specific weather events important for explaining the measured emissions. The measurements that included the use of such chemicals as nitrification inhibitors were also collected, but excluded from our study because their use is still very limited on the global scale [*Trenkel*, 1997]. The resulting data set comprises 896 N_2O emission measurements from 139 studies and 99 NO measurements from 29 studies. The experiments represent a range of different measurement techniques to measure fluxes for different crops and uncropped systems, different soil types, climates, fertilizer

Table 1. Codes and Names of Climate Types[a]

Code	Climate Type
Clim1	temperate continental
Clim2	temperate oceanic
Clim3	subtropical, summer rains
Clim4	subtropical, winter rains
Clim5	tropical, warm humid
Clim6	tropical, warm seasonal dry
Clim7	cool tropics
Clim8	boreal

[a] Based on *FAO* [1996] using criteria of the Agro-Ecological Zones approach of the Food and Agriculture Organization [*de Pauw et al.*, 1996].

types, and N application rates, and methods and timing of fertilizer application.

[23] The factors selected for the data summary include the climate, crop type, fertilizer type, application rate, mode and timing of application, soil organic-C content, soil N content, pH, texture and drainage, measurement technique and frequency, and length of the measurement period. The factors soil type and crop residue management were excluded from the data summary, because the literature data were scant for these factors.

[24] Classifications were used for all factors. The classification used for climate is presented in Table 1. Differences in soil conditions are described using functional groupings based on soil texture, drainage, soil organic-C and soil-N content, and soil reaction (pH). Although soil analytical methods varied between laboratories [*Pleijsier*, 1989], these differences could not be explicitly considered. The classification chosen for soil organic-C and soil-N content, and soil pH is commensurate with the classes used in the global 0.5° × 0.5° soil database [*Batjes*, 1997]. This database is used for extrapolation using models developed on the basis of the same data set of measurements [*Bouwman et al.*, 2002]. Soils were grouped for organic-C content as follows: ≤ 1, 1.0–3.0, 3.0–6.0, and >6%. The classification for soil N is<0.05, 0.05–0.15, 0.15–0.3, and >0.3%. Three soil pH classes were used: $pH \leq 5.5$, $5.5 < pH \leq 7.3$, and $pH > 7.3$. Soil texture was classified as coarse (including sand, loamy sand, sandy loam, loam, silt loam, and silt), medium (sandy clay loam, clay loam, and silty clay loam), and fine (sandy clay, silty clay, and clay). This classification is based on clay content, which is often the only value reported in the literature used, and differs from the textural classes used in, for example, the FAO Soil Map of the World [*FAO-UNESCO*, 1974]. Soil drainage was put in two classes, i.e., well-drained soils and poorly drained soils (i.e., any soil type with imperfect to poor drainage).

[25] The classification of other factors was chosen in order to achieve a balance in the number of measurements in each class. Crops were grouped into five crop types, i.e., grass, grass-clover mixtures, wetland rice, leguminous crops, and "other upland crops." Fertilizer types, application mode, and classes for timing of fertilizer application were also grouped (Table 2). For N application rate we used the following classes: 0, 1–50, 50–100, 100–150, 150–200, 200–250, and >250 kg N ha^{-1}.

[26] The grouping of measurement techniques is presented in Table 3. The classes used for the length of the measurement period were <120, 120–180, 180–240, 240–300, and >300 days. Many studies have used variable measurement frequencies, with more intensive measurements shortly after fertilization, and lower frequencies when emission rates dropped to background levels. In such cases we selected the highest frequency. The frequency of the measurements was grouped as follows: more than one measurement per day (>1 m/d), one per day (1 m/d), one every 2–3 days (1 m/2–3 d), one every 3–7 days (1 m/3–7 d), and less than one per week (<1m/w).

[27] In the case of NO, there were only a limited number of observations for some of the above classes. Soil-N content was therefore excluded from the summary for NO, while a different grouping was used for soil organic-C content (<3%, >3%), soil pH ($pH < 5.5$; $pH > 5.5$), N application rate (0, 1–100, 100–200, and >200 kg N ha^{-1}), and length of the experiment (<120 days, >120 days).

[28] Lack of information on such items as soil pH, soil organic-C and soil-N content, soil texture, drainage, fertilizer type, application mode, timing of application, frequency of measurements, length of measurement period, and N-application rate was indicated in the data set by flagging as NK (not known). In other cases, flagging with NR (not relevant) was used, for example, fertilizer type and application mode in the case of zero fertilizer application.

[29] In the data set the emissions of N_2O and NO are expressed as (1) the total emission during the measurement

Table 2. Codes and Corresponding Name or Description of Fertilizer Types, Chemical Additives, Fertilizer Application Mode, and Method Used in Data Set and Text

Code	Fertilizer Type	Code	Fertilizer Application Mode and Timing
AA	anhydrous ammonia, incl. aqueous ammonia	br	broadcast/broadcast to floodwater
AF	ammonium bicarbonate, ammonium chloride, ammonium sulphate	bpi	broadcast to floodwater at panicle initiation
AN	ammonium nitrate	i	incorporated
CAN	calcium ammonium nitrate (or combinations of AN and $CaCO_3$)	s	fertilizer applied in solution
NF	calcium nitrate, potassium nitrate, sodium nitrate	single	single application
Mix	combination of various synthetic fertilizers	single/ps	single, but part of split application scheme
NP	ammonium phosphate and other NP fertilizers	split	split application, aggregate
AM	animal manure and other organic fertilizers		
AMF	combinations of synthetic fertilizers and animal manure and other organic fertilizers		
U	urea, urine		
UAN	urea-ammonium nitrate		
None	no fertilizer		

Table 3. Codes Used for The Various Measurement Techniques

Code	Explanation
c	chamber technique, closed
o	chamber technique, open
co	soil core incubation method
g	soil N_2/N_2O gradient method, based on gas concentration gradient in the soil profile
m	micrometeorological technique

period, (2) the emission expressed as percent of applied fertilizer N, and (3) the fertilizer-induced emission [*Bouwman*, 1996; *Veldkamp and Keller*, 1997a]. We based our data summary on the total emission during the measurement period and not the fertilizer-induced emission. The reason is that many studies had no control measurements included; hence the data set contains a much smaller amount of data for fertilizer-induced emissions than for total emissions. In addition, when using fertilizer-induced emissions the information on controlling factors enclosed in the measurement data for control plots is lost.

2.2. Data Summary

[30] On the basis of the above classification for the different factors, we summarized the data set by calculating the mean (MEA) and median (MED) of the N_2O and NO emissions for each factor class. Differences between MEA and MED indicate the skewness of the distribution of the data. In addition, we calculated balanced mean and median values (BMEA and BMED, respectively) of the N_2O and NO emissions with the Residual Maximum Likelihood (REML) procedure, using Genstat release 4.2 [*Payne et al.*, 2000]. The REML procedure is appropriate for analyzing unbalanced data sets with missing values. REML can handle both fixed and random effects. The "research paper" is modeled as random effect, while the fixed-effects are a linear combination of controlling factors of N_2O and NO emissions considered. BMEA and BMED values are estimated mean values assuming that all factor classes have an equal number of observations in the data set.

[31] BMEA and BMED values indicate unbalanced features of MEA and MED, respectively, for factor classes that are represented by a (small) part of the full range of conditions. If, for example, the emission measurements for a factor class of soil drainage were made under specific conditions (such as soil pH, soil texture, and N application rate), the REML procedure corrects the estimate for soil drainage on the basis of all the information present in the data set. Balanced medians (BMED) were calculated using log-transformed emissions. The residual distribution of the REML with log-transformed values is closer to a symmetric or normal distribution than that for the untransformed values. Back-transformation of calculated balanced means for log-transformed values yields values resembling a balanced median value for the emission.

[32] MEA, MED, BMEA, and BMED are estimates for each factor class of the emission of N_2O and NO. These estimates represent the emission for average conditions for all other factors. For example, an estimate for the factor class "poor drainage" represents the emission for the mean value of emissions for all N application rates, soil organic-C contents, textures, lengths of the measurement period, etc. The absolute values are therefore less meaningful than the differences between factors and factor classes.

[33] The factors N application rate, fertilizer type, fertilizer application mode, and timing of fertilizer application are numerically related. A zero N application rate (control plots, leguminous crops) always occurs in combination with fertilizer type "None" and the class "NR" of the other factors. This presents numerical problems (colinearity) when using the REML procedure. Therefore, BMEAs and BMEDs for the factor N application were calculated without the factors related to fertilizer management but with all other factors. In all other cases the calculation of BMEA and BMED values included all factors.

[34] We determined the significance of the influence of the factors considered on BMED values of emissions using the Wald statistic ($P < 0.05$). We also calculated the standard errors of differences between the values for BMED for the classes of each factor. The BMED value of one factor class is significantly greater that that of another factor class if the standard error of the difference between transformed values times the excentricity (u) for a normal distribution is smaller that the actual difference. For cases where according to the information provided in the introduction the BMED value of a factor class is expected to exceed that of another factor class, a one-tailed test was done with $u = 1.64$; the test was two-tailed in cases where a priori information is lacking to develop such a hypothesis, and $u = 1.96$.

[35] The number of studies (43) in which both N_2O and NO were measured is much smaller than the individual data sets for N_2O and NO. In addition, the ancilliary data is incomplete in many cases and the data therefore severely unbalanced. We therefore only assessed the influence of soil drainage and soil texture on the basis of median values.

3. Results and Discussion

[36] In the following sections we will successively discuss the factors with a significant influence on N_2O and NO emissions, including (1) factors related to soil conditions (sections 3.1.1 and 3.2.1); (2) management-related factors (sections 3.1.2 and 3.2.2); and, (3) factors related to measurements (sections 3.1.3 and 3.2.3). For the factors with significant influence we discuss the differences in the BMED values between the factor classes and characteristic features of the MEA, MED, and BMEA values. Section 3.3 describes the results obtained on the basis of measurements that included both N_2O and NO. In section 3.4 we discuss the importance of the classification of the factors on the results.

3.1. Factors Controlling N_2O Emissions

[37] We first assessed the factor soil texture (Table 4). Results reveal that organic soils used for crop production show very high emissions compared to mineral soils, particularly when they are drained [*Duxbury et al.*, 1982; *Kasimir-Klemedtsson et al.*, 1997; *Terry et al.*, 1981; *Velthof et al.*, 1996]. Inherently, exclusion of organic soils from the

Table 4. Mean, Median, Balanced Mean and Balanced Median N_2O Emissions Calculated for the Factor Soil Texture[a]

Data Set	Property[b]	Soil Texture Class			
		Coarse	Medium	Fine	Organic
Including organic soils	N	447	147	134	50
	MEA	2.8	2.6	1.9	32.2
	MED	1.2	1.3	0.9	15.7
	BMEA	4.3	5.9	6.4	30.2
	BMED	1.2	0.9	1.4	5.8
Excluding organic soils[c]	BMEA	2.1	1.9	2.9	–
	BMED	1.1	0.7	1.2	–

[a] Emissions in kg N ha^{-1} for the factor soil texture, based on mean values for all other factors.

[b] N, number of observations; MEA, mean; MED, median; BMEA, balanced mean; BMED, balanced median (back-transformed after log-transformation). BMEA and BMED were calculated with the REML procedure (see section 2.2).

[c] The values for MEA and MED are identical when organic soils are included or excluded from the data summary.

analysis does not influence the means (MEA) and medians (MED) calculated for mineral soils. However, the balanced mean (BMEA) and balanced median (BMED) values for mineral soils are reduced considerably by excluding organic soils. To eliminate this effect, 50 N_2O measurements from 13 studies for organic soils were excluded from the data summary. The number of N_2O measurements for mineral soils remaining in the data set is 846 from 126 different studies. The calculated values for MEA, MED, BMEA, and BMED for the measured N_2O emissions for all systems, except organic soils and grazing, are presented for N_2O in Table 5 for those factors with a significant effect on BMED emissions.

3.1.1. Factors Related to Soil Conditions

[38] Soil organic carbon content, soil pH, texture, and drainage have a significant influence on the BMED values of N_2O emissions. Only the BMED values for soils with 3–6 and >6% soil organic C are significantly higher from soils with C content of 1–3% (Table 6). Values for MEA, MED, BMEA, and BMED all indicate increasing N_2O emission along with increasing soil organic-C content.

[39] Contrary to the MEA values for the soil pH factor, which are highest at low pH, the MED, BMEA, and BMED are highest for soils with an intermediate soil pH (5.5–7.3). Apparently, the N_2O losses in acid to near-neutral soils exceed those in acid or alkaline soils, which agrees with the reviewed literature.

[40] The BMED values for fine (58%) and coarse (49%) textured soils are significantly higher than those for medium soil texture (Table 6), while those for poorly drained soils are significantly higher (35%) than those from well-drained

Table 5. Number of Observations (N), Mean (MEA), Median (MED), Balanced Mean (BMEA), and Balanced Median (BMED, Back-Transformed After Log-Transformation) Values for N_2O Emissions From the Data Set Used Excluding Measurements With Grazing and Fertilizer Type CAN With Grazing, and Organic Soil Texture[a]

Factor/Factor Class	N	MEA	MED	BMEA	BMED
N Application Rate, kg/ha					
0	206	1.1	0.6	0.5	0.5
1–50	33	1.6	1.2	1.8	1.0
50–100	184	1.5	0.7	1.8	1.0
100–150	113	1.9	1.2	2.0	1.2
150–200	98	2.4	1.2	2.3	1.4
200–250	56	3.3	1.4	3.1	1.9
>250	156	6.8	4.1	5.4	3.5
Soil Organic-C Content, %					
<1.0	92	1.3	0.8	1.8	0.8
1.0–3.0	353	2.0	1.0	1.4	0.7
3.0–6.0	126	2.7	1.5	1.9	1.1
>6.0	18	5.0	1.6	4.2	1.7
Soil Texture Class					
Fine	134	1.9	0.9	2.9	1.2
Coarse	447	2.8	1.2	2.1	1.1
Medium	147	2.6	1.3	1.9	0.7
Soil Drainage					
Poor	193	2.8	1.4	2.4	1.1
Well	460	2.6	1.1	2.2	0.8
Soil pH					
<5.5	93	2.8	1.0	2.7	1.1
5.5–7.3	359	2.3	1.1	3.1	1.1
>7.3	109	2.0	0.7	1.1	0.8
Fertilizer Type[b]					
AA	38	4.4	2.7	4.4	1.2
AF	59	0.6	0.4	1.4	1.0
AN	117	3.0	1.4	2.7	1.0
CAN	61	2.3	1.7	1.5	0.9
NF	53	2.6	0.7	2.0	0.6
Mix	25	3.4	2.2	2.8	1.5
NP	16	3.8	3.0	1.2	0.6
AM	74	4.7	1.0	2.6	1.0
AMF	41	5.9	4.2	3.0	1.2
U	98	1.9	0.7	1.7	1.0
UAN	37	3.2	2.7	2.8	0.8
Crop Type					
Other upland crops	512	2.9	1.3	3.0	2.0
Grass	177	3.3	1.4	2.5	0.9
Grass/clover	16	1.1	0.9	1.0	0.7
Legume	36	1.3	1.1	3.4	2.7
Wetland rice	61	0.7	0.5	1.7	0.3
Length of Experiment, Days					
<120	343	1.4	0.5	1.7	0.6
120–180	132	2.3	1.2	1.7	0.7
180–240	42	2.1	1.2	1.9	1.0
240–300	34	2.6	1.3	2.2	1.2
>300	277	4.5	2.3	4.0	1.8
Frequency of Measurements[c]					
>1 meas/day	140	1.5	0.8	1.9	0.9
1 meas/day	286	2.9	1.1	2.9	0.8
1 meas/2–3 day	78	2.6	1.1	2.9	1.8
1 meas/3–7 day	262	2.8	1.3	3.0	1.2
<1 meas/week	46	4.5	2.0	2.5	1.3

Notes to Table 5.

[a] Values of N_2O-N emissions in kg ha^{-1} for each factor class, based on mean values for all other factors.

[b] See Table 2 for abbreviations.

[c] Meas, measurement. Frequencies of 1, or more than 1, per day are generally used in periods with high emission rates, such as after rainfall events or fertilizer application; when emissions drop to background levels, the frequency in many experiments is lower.

Table 6. Significance of Difference Between BMED Values of N_2O Emissions for Factor Classes for Those Factors With Significant Influence

Factor/Factor Class	N	Factor class									
N application rate (kg/ha)		0	1–50	50–100	100–150	150–200	200–250				
0	206										
1–50	33	a1									
50–100	184	a1	b1								
100–150	113	a1	b1	a1							
150–200	98	a1	a1	a1	b1						
200–250	56	a1	a1	a1	a1	a1					
>250	156	a1	a1	a1	a1	a1	a1				
Soil organic-C content (%)		<1.0	1.0–3.0	3.0–6.0							
<1.0	92										
1.0–3.0	353	b1									
3.0–6.0	126	b1	a1								
>6.0	18	b1	a1	b1							
Soil texture class		Fine	Coarse								
Fine	134										
Coarse	447	b1									
Medium	147	a1	a2								
Soil drainage		Poor									
Poor	193										
Well	460	a1									
Soil pH		<5.5	5.5–7.3								
<5.5	93										
5.5–7.3	359	b1									
>7.3	109	a1	a1								
Fertilizer type		AA	AF	AN	CAN	NF	Mix	NP	AM	AMF	U
AA	38										
AF	59	b2									
AN	117	b2	b2								
CAN	61	b2	b2	b2							
NF	53	a2	a2	a2	b2						
Mix	25	b2	b2	b2	b2	a2					
NP	16	a2	b2	b2	b2	b2	a2				
AM	74	b2	b2	b2	b2	a2	b2	b2			
AMF	41	b2	b2	b2	b2	a2	b2	a2	b2		
U	98	b2	b2	b2	b2	a2	b2	b2	b2	b2	
UAN	37	b2	b2	b2	b2	b2	b2	b2	b2	b2	b2
Crop type		Other upland	Grass	Grass/legume	Legume						
Other upland crops	512										
Grass	177	a2									
Grass/clover	16	a2	b2								
Legume	36	b2	a2	a2							
Wetland rice	61	a2	a2	b2	a2						
Length of experiment (days)		<120	120–180	180–240	240–300						
<120	343										
120–180	132	b1									
180–240	42	a1	a1								
240–300	34	a1	a1	b1							
>300	277	a1	a1	a1	a1						
Frequency of measurements		>1 m/d	1 m/d	1m/2–3 d	1m/3–7 d						
>1 meas/d	140										
1 meas/d	286	b2									
1 meas/2–3 d	78	a2	a2								
1 meas/3–7 d	262	b2	b2	b2							
<1 meas/w	46	b2	b2	b2	b2						

a = significant; b = not significant; 1 = one-tailed test with excentricity = 1.64; 2 = two-tailed test with excentricity = 1.96. See Table 3 for abbreviations of fertilizer types.

soils. Soils with pH>7.3 give significantly lower (33%) emissions than soils with pH $\leq$ 7.3.

[41] The data for soil texture seem to be unbalanced, because MEA and MED values for coarse and medium soil texture exceed those for fine soil texture while BMEA and BMED for fine texture are higher than for the other texture classes. The discontinuity in the data (fine > coarse > medium) is apparent in MEA, BMEA, and BMED, but not in MED. Possible causes of this feature, which contradicts the expected increase of emissions with increasing clay content (see introduction), may be the classification of soil texture in three classes, which may be too coarse to separate the texture effect. In addition, the information on soil texture provided in the literature is often vague or incomplete, and interpretation is difficult.

[42] Emissions from poorly drained soils exceed those from well-drained soils in all cases. This result is consistent with the general recognition that the denitrification process

dominates and N_2O emissions are higher when oxygen availability is restricted than in the case of ample oxygen supply.

3.1.2. Factors Related to Management

[43] The factors with a significant influence on N_2O emissions include the N application rate, fertilizer type, and crop type. The N application rate has a significant influence on the BMED values of N_2O emissions. Differences between the BMED values for the classes of N rate are significant in most cases (Table 6).

[44] BMEA and BMED values for the N application rate show a consistent pattern, with nearly constant emissions below 100 kg N ha^{-1}, and increasing emissions along with the N application at rates >100 kg N ha^{-1}. A possible explanation for the small differences between N application rates of 1–50, 50–100, and 100–150 kg $ha^{-1}yr^{-1}$ may be the fact that the inputs from atmospheric N deposition are ignored in all reports. The majority of the measurements stem from industrialized countries, where the relative contribution of N deposition to total N inputs is particularly important at low N application rates. Values for unbalanced MEA and MED show a similar pattern, except for the application rates 1–50 kg N ha^{-1}, which show higher values than those for 50–100 kg N ha^{-1}. The trend in the emission is highest at application rates >250 kg N ha^{-1}.

[45] Because we had no a priori expectations regarding differences between fertilizer types, two-tailed tests were done resulting in significant differences in only a few cases (Table 6). The highest BMED value was calculated for mixed fertilizers (Mix), which is only significantly higher than NF and NP. BMED for the nitrate-based fertilizers (NF) are significantly lower than respectively AA, AF, AN, Mix, AM, AMF, and U. The BMED for NP is even lower than that for NF, but due to the smaller number of observations the standard error is larger, so only the differences between NP and AA, Mix and AMF are significant. Emissions for leguminous crops and other upland crops are significantly different (higher) from those for grass, grass/clover, and wetland rice. The difference of 37% between the BMED values for legumes and other upland crops is not significant.

[46] All the values (Table 5) show consistent differences between fertilizer types. The highest values for MEA were calculated for organic fertilizers (AM) and combinations of organic and synthetic fertilizers (AMF), while lowest values for MEA were calculated for the ammonium-based fertilizers (AF). The MED values are highest for AMF, and lowest again for AF. The values for BMEA are highest for AMF, while NP fertilizers have the lowest value. The differences between the BMED and BMEA values among fertilizer types are less pronounced than for MED.

[47] Grass shows the highest values for MEA and MED, followed by the "other upland crops" class. Balancing changes this pattern. BMEA and BMED show highest values for leguminous crops, followed by other upland crops, grass, wetland rice, and grass-clover mixtures. It should be noted that most measurements in rice fields are from inundated fields during the growing season, giving rise to low emissions (see introduction). Lower emissions for grass than for other upland crops can result from more efficient N uptake by grass as a result of longer growing periods, particularly in temperate and tropical seasonal climates.

[48] Mode and timing of fertilizer application have no significant influence on N_2O emissions. Broadcasting and incorporation have similar values and application in solution has a somewhat lower value for BMED. This contrasts some literature reporting that incorporation of fertilizer leads to higher N_2O emission than broadcasting. However, the depth of incorporation is known to influence the amount of N_2O that escapes, and the influence of topsoil characteristics that determine gas exchange are included in the BMED values of soil texture. In addition, the fertilizer AA is always injected, and the effect of the application mode is probably included in the BMED values for this fertilizer type.

[49] Single applications lead to somewhat higher emission than single application as part of a split application scheme (results not presented). The results for BMED for single and split application are similar. This is not in line with the literature, possibly because most experiments with split application schemes were made in a few locations in Germany only. The influence of the local climatic (cold winters with high winter emissions of N_2O), N application rate (split applications generally in lower classes of N application rate), and the length of measurement period (mostly 1 year or more, so that winter emissions are included) may not have been separated completely from the factors fertilizer application mode and timing by the REML procedure.

3.1.3. Factors Related to the Measurements

[50] The factors with a significant influence on N_2O emissions are the length of the measurement period and the frequency of measurements (Table 5). With some exceptions, emissions for long measurement periods are significantly higher than those for shorter measurement periods (Table 6). This confirms the findings of *Bouwman* [1996] based on a subset of our data. The BMED value for measurements covering more than 300 days (mostly 365 or more) exceeds those for periods of 240–300, 180–240, and <180 days by 54, 72, and 172%, respectively, all differences being significant. Many measurements cover less than 180 days, apparently recording only part of the annual emission and probably only part of the fertilizer effect.

[51] Although the emissions for the classes of frequency of measurements vary strongly, only those for a frequency of one measurement per 2–3 days are significantly higher than those for higher or lower frequencies (Table 6). The differences between the BMED values are in general agreement with the findings of *Veldkamp and Keller* [1997b] and *Brumme and Beese* [1992].

[52] Measurements covering >300 days show the highest MEA, MED, BMEA, and BMED values (Table 5). In most cases there is an increasing trend of measured N_2O, along with the length of the measurement period. In general, high-frequency measurements (>1 measurement per day) show lower values for MEA, MED, BMEA, and BMED than measurements with lower frequency (<1 per day). For MEA and MED, there is a clear tendency of high emission with less frequent measurements. However, this pattern changes by balancing into one with highest emissions at intermediate

Table 7. Number of Observations (N), Mean (MEA), Median (MED), Balanced Mean (BMEA) and Balanced Median (BMED, Back-Transformed After Log-Transformation) Values for NO Emissions From the Data Set Used Excluding Measurements With Grazing And Fertilizer Type CAN With Grazing, and Organic Soil Texture[a]

Factor/Factor Class	N	MEA	MED	BMEA	BMED
		N Application Rate, kg/ha			
0	21	0.3	0.1	1.7	0.4
1–100	45	0.5	0.1	2.4	0.9
100–200	16	0.5	0.6	2.5	1.1
>200	17	5.4	2.8	4.3	2.1
		Soil Organic-C Content, %			
<3.0	47	0.5	0.1	0.2	0.3
>3.0	8	4.5	0.4	0.5	0.9
		Fertilizer Application Mode[b]			
br	27	1.1	0.8	1.4	0.9
bpi	0	–	–	–	–
i	8	5.5	0.4	−1.1	0.2
s	33	0.1	0.0	−0.3	0.3
		Length of Experiment, Days			
<120	64	0.4	0.1	−1.2	0.3
>120	35	3.0	0.8	1.9	0.8
		Frequency of Measurements[c]			
>1 meas/d	51	0.2	0.1	−1.0	0.3
1 meas/d	20	2.9	1.1	1.2	0.9
1 meas/2–3 d	8	4.6	0.4	7.1	1.0
1 meas/3–7 d	10	0.9	0.7	−2.0	0.6
<1 meas/w	2	0.7	0.7	−1.6	0.6

[a] Values of NO-N emissions in kg ha^{-1} for each factor class, based on mean values for all other factors.

[b] See Table 2 for abbreviations.

[c] Meas, measurement. Frequencies of 1, or more than 1, per day are generally used in periods with high emission rates, such as after rainfall events or fertilizer application; when emissions drop to background levels, the frequency in many experiments is lower.

frequency (1 measurement in 2–3 days), and lowest values for $\geq$1 measurement per day.

3.2. Factors Controlling NO Emissions

[53] The data set for NO includes only measurements for mineral soils. The values calculated for MEA, MED, BMEA, and BMED for the measured emissions are presented in Table 7.

3.2.1. Factors Related to Soil Conditions

[54] The soil organic C content significantly influences NO emission. The BMED value for soils with >3% is significantly higher (216%) than that for soils with <3% soil organic C (Table 8), which is in agreement with our findings for N_2O emissions. For soils with organic-C content >3%, the values for MEA, MED, BMEA, and BMED are all higher than those for the class <3%.

[55] Although the results for MEA, MED, and BMED suggest that coarse textured soils are more prone to high NO emissions than medium and fine textured soils, and that well drained soils show higher emissions than poorly drained soils, the influence of these factors on BMED values is not significant.

3.2.2. Factors Related to Management

[56] Fertilizer application rate and mode of application have a significant influence on NO emissions (Table 7). The differences between BMED values for the classes of N application rate are significant in most cases, except for the difference between 100–200 and 1–100 kg N ha^{-1} (Table 8).

[57] The values for MEA, MED, and BMEA for N application rate do not show a consistent pattern (Table 7). Balancing corrects this apparent discrepancy, and BMED shows a clear increase of emissions with increasing N application rate which is strongest at high N application rates.

[58] The value for BMED for broadcasting is significantly higher than those for incorporation and solution (Table 8), differences being 263 and 163%, respectively (Table 7). Broadcasting N fertilizer results in higher values for MED, BMEA, and BMED than incorporation and fertilizer applied in solution. The number of measurements for incorporation is smaller and the results more uncertain than for the other application modes.

3.2.3. Factors Related to the Measurements

[59] Both the length of the experiment and the frequency of measurements have a significant influence on NO emissions. The BMED value for experiments covering >120 days is significantly higher (177%) than that for measurements covering <120 days (Tables 7 and 8). For the frequency of measurements, the BMED values for 1 measurement per day is significantly higher than that for >1 measurement per day. Differences between BMED values for frequencies of less than 1 measurement per day and 1 or more per day are not significant due to the small number of observations.

[60] Most measurements covered less than 120 days, and values for MEA, MED, BMEA, and BMED for this class are lower than for measurements covering >120 days. The data available for measurement periods of >300 days is scarce, but results (not shown) suggest that the effect of N application on NO emissions is not as long-lasting as for

Table 8. Significance of Difference Between BMED Values of NO Emissions for Factor Classes for Those Factors With Significant Influence

Factor/Factor Class	N	Factor Class			
N application rate (kg/ha)		0	1–100	100–200	
0	21				
1–100	45	a1			
100–200	16	a1	b1		
>200	17	a1	a1	a1	
Soil organic-C content (%)		<3.0			
<3.0	47				
>3.0	8	a1			
Fertilizer application mode		br	bpi	i	
br	27				
bpi	0	-			
i	8	a1	-		
s	33	a2	-	b2	
Length of experiment (days)		<120			
<120	64				
>120	35	a1			
Frequency of measurements		>1 m/d	1 m/d	1m/2–3 d	
>1 meas/d	51				
1 meas/d	20	a2			
1 meas/2–3 d	8	b2	b2		
1 meas/3–7 d	10	b2	b2	b2	
<1meas/w	2	b2	b2	b2	b2

a = significant; b = not significant; 1 = one-tailed test with excentricity = 1.64; 2 = two-tailed test with excentricity = 1.96.

See Table 2 for abbreviations of fertilizer application mode.

Table 9. Number of Measurements and Median Values of Emissions of NO and N_2O for the Subset of Data Containing Measurements of Both NO and N_2O and the Full Data Sets of Measurements of N_2O and NO for Different Soil Textural and Drainage Classes

Factor	Factor Class	N[a]	NO Emission, kg N ha^{-1}	N[a]	N_2O Emission, kg N ha^{-1}
			Data With Both NO and N_2O Measurements		
Texture	coarse	25	0.7	25	1.4
	medium	7	0.5	7	1.6
	fine	4	0.0	4	0.1
Drainage	good	34	0.6	34	1.2
	poor	5	0.5	5	2.3
			Full Data Set for NO and N_2O		
Texture	coarse	71	0.2	447	1.2
	medium	13	0.2	147	1.3
	fine	5	0.0	134	0.9
Drainage	good	60	0.4	460	1.1
	poor	7	0.5	193	1.4

[a] N, number of observations.

N_2O. High-frequency measurements (>1 measurement per day) of NO emission have lower values for MEA, MED, and BMED than measurements with lower frequencies, which, in general, is in agreement with the results for BMED for N_2O.

3.3. N_2O + NO Emissions

[61] The number of studies in which both N_2O and NO emissions (N_2O + NO data set) were measured is very limited (43), with only four data lines with data on all the factors. These unbalanced features as well as the outliers present in the subset of measurement data cause the REML procedure to fail to separate the influence of factors that were well-represented, such as soil texture and soil drainage, on NO, N_2O, NO + N_2O, or the ratios NO:N_2O or NO/(NO + N_2O).

[62] We therefore compared the median values for the emission for the factors soil texture and soil drainage of the N_2O + NO data set with the complete data sets for NO and N_2O (Table 9). It should be noted that soil texture and soil drainage were factors that had no significant influence on NO emissions (section 3.2.1). Nevertheless, the available data suggest that N_2O generally dominates the total N gas production confirming data presented by *Davidson et al.* [2000], and that this is more apparent in fine textured and poorly drained soils than in coarse and medium textured and well-drained soils. The small number of measurements (four in the NO + N_2O data set and five in the full NO data set) for fine-textured soil suggests very low NO emissions, while a poor soil drainage does not lead to such low NO emission values on the basis of five (NO + N_2O data set) and seven measurements (full NO data set).

3.4. Data Issues

3.4.1. Omissions

[63] There are many omissions in the information provided in the literature on several controlling factors of emissions. Several factors could not be used, or information had to be flagged as "not known." Many reports on measurements in grazing systems lack information on the N inputs. The information provided on soil type and other soil characteristics is often not comparable either because of differences in nomenclature or analytical methods. In many reports information on fertilizer type, application mode and timing, soil conditions, measurement technique, length of measurement period, and frequency of measurements are not specified. Our data set is dominated by measurements in industrialized countries with high atmospheric-N deposition rates [*Bouwman and van Vuuren*, 1999]. In none of the literature reports has this N source been accounted for. In addition to N deposition, crop residues and N fixation may have contributed in many experiments to the observed emissions, but their contribution to the N inputs has only rarely been reported. In future studies on N_2O and NO emissions, such information should be provided in order to allow for better comparison between measurements from different locations.

[64] There are also problems related to the unbalanced features of the data set used, the major ones for the factors climate and crop type. It is clear that the majority of measurements are from temperate regions, and that subtropical and tropical systems are underrepresented. For wetland rice cultivation, measurements on emissions during the post-harvest period when fields are drained are scarce. In addition, it is not clear if the measurement data represent the actual agricultural practices prevalent in the region of study. For example, most measurements study (part of) one crop season; our analysis, therefore, also concentrated on single crops. Measurements of emissions during complete crop rotations have only been measured in a few reports [e.g., *Kaiser and Ruser*, 2000]. The sequence of crops with their specific crop and fertilizer management practices may strongly determine the total N_2O and NO emissions over the rotation period, and estimations based on single crops may differ from those for complete crop rotations.

3.4.2. Influence of Classification

[65] Our results give a straightforward summary of the data, using classes for the factors that were chosen on the basis of practical considerations. The analysis is, however, sensitive to the classification of the data. For example, the classification used resulted in no significant influence of climate on the BMED values of N_2O emissions, although our results suggest that BMED values of N_2O-N emissions for temperate continental climates (0.9 kg ha^{-1}) exceed those for oceanic climates (0.8 kg ha^{-1}). This confirms the importance of N_2O emissions during the winter period in oceanic climates, as noted in section 1. The data also suggest that N_2O-N emissions from subtropical (1.6–1.9 kg ha^{-1}) and tropical climates (1.2 kg ha^{-1}) exceed those from temperate climates. Results are, however, uncertain due to the relatively small number of measurements in these climate types. Using the interaction "N application rate x fertilizer type" instead of the two separate factors, and grouping eight climate types into two, temperate and (sub)tropical, as done by *Bouwman et al.* [2002], resulted in a significant effect of the factor climate for N_2O. In addition, the factor drainage gave a significant effect on NO emissions.

4. Conclusions

[66] The major conclusions of our data summary relate to the influence of the various regulating factors on N_2O and

NO emissions and to possible alternatives to replace emission factor approaches currently used to estimate national emissions. Our results summarize emission measurements from the literature which represent a range of different measurement techniques to measure fluxes for different environmental and management conditions. This implies that our estimates cannot be compared with measurement data from individual fields. Merely, they indicate relative differences between factors and factor classes as they occur in the data set. The REML procedure is used to eliminate unbalanced features in the data set as much as possible.

[67] We see that there is a strong increase of both N_2O and NO emissions accompanying N application rates. Regarding soil factors, the data show that soils with high organic-C content show higher N_2O and NO emissions than less fertile soils. A fine soil texture, restricted drainage, and neutral to slightly acidic soil reaction are conditions that favor N_2O emission. In contrast, the data indicate (though no significant influences were seen) that a good soil drainage, coarse texture, and neutral soil reaction are conditions prone to high NO emission.

[68] Regarding management factors, there are significant differences between crop types and fertilizer types on N_2O emissions. N_2O emissions decrease in the order leguminous crops (generally not receiving N inputs from fertilizers), upland crops, grass, and wetland rice (during the growing season). For fertilizer types, the data indicate low values for nitrate-based fertilizers, and high values for ammonium-based synthetic fertilizers, animal manure, and animal manure applied in combination with synthetic fertilizers. For NO, fertilizer type and crop type had no significant influence on emissions. Application mode has a significant influence on NO emission, whereby broadcasting of N fertilizer results in higher NO emissions than incorporation or application in solution. Although the factor climate was found not to have a significant effect on N_2O emissions, the data suggest that emissions for oceanic climates are lower than those for continental climates where winter N_2O emissions strongly contribute to annual emissions, and that emissions from subtropical and tropical climates exceed those for temperate climates.

[69] With respect to measurement techniques, our results indicate that longer measurement periods yield more of the fertilization effect on N_2O and NO emissions, and intensive measurements ($\geq$1 per day) yield lower emissions than less intensive measurements of 2–3 measurements per week. However, differences are not significant for NO emissions for most frequency classes.

[70] We give a straightforward summary of the data, using classes for the factors that were chosen on the basis of practical considerations. The results are, however, sensitive to the classification of the factors, but this problem is not easily solved. In addition, the analysis is hampered by unbalanced features of the data set used. The major problems are seen for the factors climate and crop type, where some classes are clearly underrepresented. In addition, more studies that include measurements of both NO and N_2O are needed to establish more reliable relations for the sum of the two gases and their relative contribution as was concluded earlier [*Davidson et al.*, 2000].

[71] The concept of water-filled pore space used in the HIP model [*Davidson et al.*, 2000] cannot be used for temporal scales of growing seasons to 1 year or spatial scales of landscapes due to the temporal and spatial variability of soil moisture conditions. The factors climate, soil texture, and drainage that we distinguished indirectly reflect soil water and oxygen conditions. These and other soil factors (such as soil pH) and management-related factors can be used to define areas with specific combinations of climate, soil, and management conditions that influence N_2O and NO emissions. Our findings confirm the ideas and concepts that went into the HIP model [*Davidson et al.*, 2000], whereby the N inputs reflect the N flow through the pipes, climate governs the speed of the N flow, and the various soil and management factors reflect the size of the holes in the soil process pipes.

[72] A final major conclusion from our data summary is that the literature data provide a wealth of information that can be used to replace emission factor approaches, which express the anthropogenic N_2O emission as a percentage of the N input, by more sophisticated methods. The major improvement would involve describing the influence of the main factors that regulate N_2O and NO emissions at the scale of landscapes or functional units with similar climate, soil, and management conditions. This would result in model approaches that account for the spatial variability of emissions. A first attempt is a simple model describing the influence of the main regulators of annual N_2O and NO emissions, developed by *Bouwman et al.* [2002] on the basis of the data set summarized in this paper, to calculate N_2O and NO emissions from global agricultural fields.

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