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Modeling global annual N_2O and NO emissions from fertilized fields

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[1] Information from 846 N_2O emission measurements in agricultural fields and 99 measurements for NO emissions was used to describe the influence of various factors regulating emissions from mineral soils in models for calculating global N_2O and NO emissions. Only those factors having a significant influence on N_2O and NO emissions were included in the models. For N_2O these were (1) environmental factors (climate, soil organic C content, soil texture, drainage and soil pH); (2) management-related factors (N application rate per fertilizer type, type of crop, with major differences between grass, legumes and other annual crops); and (3) factors related to the measurements (length of measurement period and frequency of measurements). The most important controls on NO emission include the N application rate per fertilizer type, soil organic-C content and soil drainage. Calculated global annual N_2O-N and NO-N emissions from fertilized agricultural fields amount to 2.8 and 1.6 Mtonne, respectively. The global mean fertilizer-induced emissions for N_2O and NO amount to 0.9% and 0.7%, respectively, of the N applied. These overall results account for the spatial variability of the main N_2O and NO emission controls on the landscape scale. *INDEX TERMS:* 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 1610 Global Change: Atmosphere (0315, 0325); 1615 Global Change: Biogeochemical processes (4805); *KEYWORDS:* animal manure, gas emission, fertilizer, global model, nitric oxide (NO), nitrous oxide (N_2O)

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1. Introduction

[2] Human activities are 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*), 2001]. Although the N_2O budget has been the least well constrained of the global trace gas budgets, it is generally accepted that the use of mineral N fertilizers and animal manure is the major anthropogenic source of N_2O [*IPCC*, 2001; *Mosier et al.*, 1998]. Nitric oxide participates in the regulation of the oxidant balance of the atmosphere. In the atmosphere NO is oxidized to NO_2. Re-deposition of NO_x (NO and NO_2 are collectively denoted as NO_x) contributes to acidification and eutrophication of ecosystems [*Vitousek et al.*, 1997]. Agricultural fields may not be a major source 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] The current guidelines [*IPCC et al.*, 1997] for calculating national direct N_2O emissions from the application of mineral N fertilizers and animal manure (i.e., excluding emissions from groundwater or surface water resulting from N being leached from agricultural soils) include a default global emission factor of 1.25% (0.25–2.25%) for the fertilizer-induced emission (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. 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 pre-agricultural times.

[4] Although countries can use their own emission factor based on local measurements, most global extrapolations are based on the default [*Kroeze et al.*, 1999; *Mosier et al.*, 1998]. The same default is used to calculate anthropogenic N_2O emissions from N inputs from crop residues and biological N fixation, while for atmospheric N deposition a somewhat smaller emission factor is proposed. A similar

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emission factor was proposed for NO emissions due to N application [*Veldkamp and Keller*, 1997]. This approach is subject to criticism because it ignores heterogeneity of environmental and management conditions [*Smith et al.*, 1998] and it does not yield the total emission required for estimating the global atmospheric N_2O budget.

[5] In a recent paper we summarized measurement data collected from the literature, emphasizing the main regulating factors of N_2O and NO emissions [*Bouwman et al.*, 2002]. In this paper we use the same data set of measurements to develop models for calculating global N_2O and NO accounting for the spatial variability of the main emission controls on the landscape scale. We concentrate on soil gaseous emissions aggregated to seasonal or annual timescales. On such temporal scales integrated gas fluxes may be strongly related to "average" biophysical conditions [*Schimel and Panikov*, 1999]. This makes empirical relationships between gas fluxes and environmental and management conditions useful for bridging the gap between site and landscape scales. A prerequisite for using empirical relationships to calculate N_2O and NO emissions is to have data which sufficiently cover the heterogeneity of environmental and management conditions occurring in agricultural landscapes. We use the Residual Maximum Likelihood (REML) technique rather than a multiple linear regression approach, as REML is considered more appropriate for handling problems of controlling factors in case of scant measurement and ancillary data or limited spatial and temporal coverage [*Payne et al.*, 2000].

2. Materials and Methods

[6] We used data on emission measurements from the peer-reviewed literature. The complete data set with references can be obtained from http://www.rivm.nl/ieweb and is summarized by *Food and Agriculture Organization of the United Nations* (*FAO*)/*International Fertilizer Industry Association* (*IFA*) [2001] and *Bouwman et al.* [2002]. The experiments represent a range of different measurement techniques to measure fluxes for different crops and uncropped systems, different soil types, climates, fertilizer types and N application rates, and methods and timing of fertilizer application.

[7] The first step in data handling consisted of the rational exclusion of several factors and factor classes: (1) measurements that included the use of such chemicals as nitrification inhibitors since their use is still very limited on the global scale [*Trenkel*, 1997]; (2) soil type and crop-residue management, because of the scanty data from the literature for these factors; (3) organic soils, because the median emission rates calculated with the REML procedure for mineral soils were reduced considerably by excluding 50 measurements from 13 studies on N_2O emissions from organic soils [*Bouwman et al.*, 2002]; and (4) measurements of emissions from grazing systems, because in many cases the N inputs from animal excreta were not accounted for.

[8] The reduced data set includes data on 846 N_2O measurements from 126 different studies and 99 NO measurements from 29 studies. The factors considered are climate, soil organic-C content, soil-N content, soil pH, texture and drainage, crop type, fertilizer type, N-application rate, mode and timing of fertilizer application, measurement technique and frequency, and length of the measurement period. N inputs from biological N fixation and N deposition could not be included in the data set due to the lack of data.

[9] Contrary to many studies using regression analysis [*Bouwman*, 1996; *Davidson and Verchot*, 2000; *Veldkamp and Keller*, 1997], we used the Residual Maximum Likelihood (REML) directive of Genstat [*Payne et al.*, 2000] for developing models relating gas emissions to controlling factors. REML is appropriate for analyzing unbalanced data sets with missing values. By assuming all factor classes to have an equal number of observations, REML balances the emission for factors not represented by the full range of environmental and management conditions.

[10] Classes were used for all factors except for the N application•fertilizer type interaction which was included as a continuous variable. This is because of the numerical problems (colinearity) around zero-N application rates (control plots, leguminous crops), which always occur in combination with the fertilizer type "none" and the class "not relevant" for fertilizer application mode and timing. To avoid this type of problem, each zero-N application was numerically combined with all fertilizer types, except type "none," keeping the values of all other factors the same as in the original data. The influence of each zero-N application on the model was restored by weighting. As each fertilizer type has the same emission at an N application rate of zero, the factors "N-application rate" and fertilizer type were incorporated as an interaction without main effects. Climate types were aggregated into two classes (i.e., temperate and (sub) tropical), because some climate types were underrepresented in the data set. Factor classes for NO are identical to those for N_2O, except for soil organic-C content, N content and pH (aggregated classes).

[11] The N_2O and NO emissions were log-transformed to reduce the effect of extreme values. The residual distribution with log-transformed values is closer to a normal distribution than that for the untransformed values. Back-transformation yields values resembling a median value for the emission.

[12] Analysis of the log-transformed emissions for mineral soils consisted of the determination of the significance of the various factors considered, model development and uncertainty analysis.

[13] The most important factors in the data set explaining log-transformed emissions were selected on the basis of the WALD statistic ($P<0.005$). REML can handle both fixed and random effects. The "research paper" is the random-effect component, while the fixed-effect component is a linear combination of controlling factors of N_2O and NO emissions considered.

[14] All the factors with significant effects ($P<0.005$) on emissions were used to develop models for N_2O and NO. The emission of N_2O-N or NO-N in kg ha^{-1} is calculated as follows:

$$Emission = e^{constant + \sum_{1}^{n=i} Factor\ class(i)} \quad (1)$$

For N_2O the factors with a significant effect are the interaction N-application rate•fertilizer type, climate, soil organic-C content, soil texture, drainage and pH, crop type, length and frequency of measurement period; for NO these were the interaction N-application rate•fertilizer type, soil organic-C content and drainage.

[15] We did not look to see if specific combinations of factor classes give different emissions (interaction effects). Reasons for this were that (1) analyzing the data set for all such combinations is complicated given the number of factors and classes and (2) we did not have a priori knowledge of such combinations.

[16] Since the REML procedure gives no standard errors for estimations, these were calculated for N_2O with a multiple regression model to indicate the uncertainty in our global estimates. The factor ''research paper'' was used for weighting on the basis of the 353 complete records in the data set, with values for all the factors with a significant influence.

[17] Finally, the REML-based models for N_2O and NO were used to calculate global emissions and FIE from fertilized crops and grasslands in a geographical information system with 0.5 by 0.5 degree resolution data on soil properties [*Batjes*, 1997], climate types [*FAO*, 1996a], rice-growing areas, leguminous crops, other (upland) crops and grasslands [*Zuidema et al.*, 1994]. These were updated with statistical data for 1995 on land use (FAO, FAOSTAT database collections, 2000, available at http://www.apps.fao.org) (hereinafter referred to as FAO, database, 2000), combined with country data on mineral N-fertilizer use [*FAO et al.*, 1999; *International Fertilizer Industry Association* (*IFA*), 1999; FAO, database, 2000], animal populations for dairy and nondairy cattle, pigs, poultry, sheep and goats (FAO, database, 2000), and animal N excretion and animal-waste management systems [*FAO*, 1996b; *Mosier et al.*, 1998]. Since mineral N fertilizer application rates in wetland rice cultivation differ from other crops in many countries, we separated wetland rice from total rice areas, and upland rice was added to the category of ''other upland crops.''

[18] Equation (1) implies that the calculated emission increases more than proportional with the N application rate. Hence, we can not use mean country N application rates calculated as total N use divided by the total arable area. In the absence of information on application rates for each grid cell, we used country data for each crop type on N application rates and areas actually fertilized and excluded fallow areas and areas not fertilized. Country data on mineral N-fertilizer application rates and areas of fertilized grasslands, rice and leguminous crops were taken from a recent inventory [*FAO et al.*, 1999]; for other upland crops, data are available for 39 (mostly developing) countries, where less than 100% of the crop area is fertilized. For other developing countries, N application rates for other upland crops were assumed to be equal to those calculated for their respective world regions from country estimates [*FAO et al.*, 1999]. The fraction of the area that is actually fertilized was calculated so as to arrive at the reported total mineral N fertilizer use per country [*IFA*, 1999; FAO, database, 2000]. For developed countries we excluded fallow areas calculated from land-use statistics (FAO, database, 2000) from the upland crops and considered the harvested crop area as the area actually fertilized. For the former Soviet Union we assumed mineral N-fertilizer application rates to be equal to those in Eastern Europe.

[19] Animal manure available for application as fertilizer is calculated as total animal manure production, excluding manure used as fuel, manure excreted during grazing, and ammonia volatilization from stored manure on the basis of animal waste management systems [*FAO*, 1996b; *Mosier et al.*, 1998]. Due to lack of data, we ignored the use of ''night soil'' (human excreta) as a fertilizer, which is important in some countries such as China. On the basis of country surface N balances [*Van Drecht et al.*, 2001], the application of animal manure to grasslands was assumed to be 5% of the available manure in developing countries, 25% in the former Soviet Union and 50% in other developed countries; for some developing countries where grassland-based livestock production is not important, the N application to grasslands was assumed to be 0–5%. The remaining available manure was allocated to crops in proportion to the area of each crop category. Animal manure application to grasslands is assumed to occur in mixed farming systems that are defined as grasslands occurring in grid cells where the arable land coverage exceeds 35% in developed countries and 15% in developing countries. For a number of countries with dominant intensive grassland-based livestock production [*FAO*, 1996b] the total grassland area was included.

[20] For leguminous crops the animal manure N was allocated to the total area for this crop category in each grid cell. For the other upland crops and wetland rice the fraction of each cell receiving animal manure was calculated from N application rates, which were assumed to be equal to those for mineral N fertilizers; for animal manure application to grasslands, rates of 50% of those for upland crops were assumed. We assumed that the areas fertilized with mineral N fertilizers and animal manure would always overlap in countries where not all agricultural land is fertilized; in other words, the most intensive production systems received inputs from both sources.

[21] FIE was calculated for each 0.5 by 0.5 degree grid cell as the emission from the fertilized area minus the emission for zero-N application from the same area, all other conditions being equal. FIE is presented as the global aggregated mean for different fertilizer types expressed as percentage of the N applied. In calculating FIE we excluded the areas with pulses and soybeans (leguminous crops). These crops generally receive small amounts of N as a starter, and rely mostly on symbiotic N fixation. It is therefore not possible to attribute the emission to the mineral N fertilizer or animal manure application.

[22] Prior to upscaling with the models, assumptions had to be made for some factors. The data set of measurements for wetland rice is dominated by experiments during the crop season when fields are inundated. Anaerobic conditions prevail under such conditions; for this reason, calculated N_2O emissions from wet rice fields are lower than for

Table 1. Values for the Terms of the Models for N_2O and NO

Factor/Factor Class	N[a]	Value
N_2O Model		
Constant		−0.4136
N-rate ● Fertilizer Type Interaction[b]		
AA	38	0.0056
AF	59	0.0051
AN	117	0.0061
CAN	61	0.0037
NF	53	0.0034
Mix	25	0.0065
NP	16	0.0039
U	98	0.0051
AM	74	0.0021
AMF	41	0.0042
Crop type		
Grass	177	−1.268
Grass-clover	16	−1.242
Leguminous crops	36	−0.023
Other upland crops	512	0
Wetland rice	61	−2.536
Soil texture		
Coarse	447	−0.008
Medium	147	−0.472
Fine	134	0
Soil organic carbon, content, %		
SOC ≤ 1.0	92	0
1.0 < SOC ≤ 3.0	353	0.140
3.0 < SOC ≤ 6.0	126	0.580
SOC > 6	18	1.045
Soil drainage		
Poor	193	0
Good	460	−0.420
Soil pH		
pH ≤ 5.5	93	0.000
5.5 < pH ≤ 7.3	359	0.109
pH > 7.3	109	−0.352
Climate type[c]		
TE	650	0
STR	196	0.824
Length of experiment, days		
<120	343	0
120–180	132	0.004
180–240	42	0.487
240–300	34	0.657
>300	277	0.825
Frequency of measurements[d]		
>1 meas/day	140	0
1 meas/day	286	0.125
1 meas/2–3 day	78	1.639
1 meas/3–7 day	262	0.825
<1 meas/week	46	0.788
NO Model		
Constant		−1.527
N-rate ● fertilizer type interaction[b]		
AA	2	0.0051
AF	14	0.0056
AN	17	0.0040
CAN	5	0.0062
NF	15	0.0054
Mix	1	0.0078
U	19	0.0061
AM	3	0.0016
Soil organic carbon, content, %		
SOC ≤ 3.0	47	0
SOC > 3.0	8	2.571
Soil drainage		
Poor	7	0
Good	60	0.946

Notes to Table 1.

[a] N, number of observations.

[b] Mineral N fertilizers include: AA, anhydrous ammonia; AF, ammonium-based fertilizers; AN, ammonium nitrate; CAN, calcium ammonium nitrate; NF, nitrate-based fertilizers; Mix, mix of various fertilizers; NP, ammonium phosphates; U, urea and urine; UAN, urea-ammonium nitrate; animal manure and combinations: AM, animal manure; AMF, combinations of animal manure and mineral N fertilizers. In the REML models, the values presented are multiplied by the N application rate for the fertilizer type under consideration. In the data for NO the number of observations is nil for the fertilizer types NP and AMF; the value estimated by the REML procedure for the interaction N-rate · fertilizer type for both fertilizer types is 0.0055, based on all fertilizer types.

[c] TE, temperate climates, including temperate oceanic and continental, cool tropical, boreal and polar/alpine; STR, (sub-) tropical climates, including subtropics winter rains, subtropics summer rains, tropics, warm humid, and tropics warm seasonal dry [*FAO*, 1996a].

[d] Meas, measurement. Frequencies of one, or more than one, 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.

upland crops (Table 1). For wetland rice we therefore used the factor class value of "other upland crops" to account for the observed important contribution of emissions during the post-harvest period when fields are drained [*Bronson et al.*, 1997; *Byrnes et al.*, 1993]. To obtain estimates of annual N_2O emissions, we used the value of the model term for measurements covering a period of >300 days; for the frequency of measurements, we used the values for more than one measurement per day, which were significantly different from the values for lower frequencies.

3. Results

[23] The factors found to have a significant effect ($P<0.005$) on N_2O emissions include climate, soil factors (soil texture, drainage, soil organic-C content, and pH), management-related factors (i.e., N application rate per fertilizer type and crop type), and factors related to the measurements (i.e., length of experiment and frequency of measurements).

[24] The factors with a significant effect ($P<0.005$) on NO emissions include the N-application rate per fertilizer type, soil organic-C content and drainage. Contrary to N_2O, the influence of climate was not significant for NO. Differences in soil texture had no significant effect on NO emission, probably because soil organic-C content and drainage explain most of the variability.

[25] Both N_2O and NO emissions increase with N application rate (Table 1; Figures 1a and 1e). Soils with high organic C contents are prone to high N_2O and NO emissions (Table 1) reflecting the influence of soil fertility. A fine soil texture and restricted drainage favor N_2O emission (Table 1; Figures 1b and 1d). Contrary to N_2O, NO emissions from well-drained soils exceed those from poorly drained soils (Table 1; Figures 1e and 1f). Furthermore, a neutral to slightly acidic soil reaction favors N_2O emission.

[26] N_2O emissions are significantly higher in tropical than in temperate climates (Figure 1c), while climate has no significant influence on NO emission.

[27] There are important differences between fertilizer types. The lowest estimates for N_2O are for animal manure (AM), while ammonium nitrate (AN) and mixes of mineral

fertilizers (Mix) have the highest emissions. For the fertilizer types that are well represented in the data for NO, urea gives highest NO emissions and somewhat lower values for ammonium and nitrate-based fertilizers. Hence, ammonium-based fertilizers give high emissions of both N_2O and NO, while those for nitrate-based fertilizers are high for NO but low for N_2O.

[28] N_2O emissions from grasslands appear to be lower than those from croplands, assuming that all other conditions are identical, confirming a study based on a subset of our data [*Bouwman*, 1996]. N_2O emissions for measurements covering periods of at least one year exceed those based on shorter measuring periods. The length of the measurement period is not significant for NO. Measurement frequencies of at least one per day in periods with high flux rates (e.g., periods following fertilizer application or rainfall events) and lower frequencies in periods with low flux rates give smaller N_2O emissions than lower frequencies.

[29] We estimated that about 69% of the world's arable land and 8% of grasslands are fertilized with N fertilizers and manure (Table 2). Intensive fertilization of grasslands only occurs in Europe. The global annual emission from fertilized fields calculated with the model for N_2O is 2.8 Mtonne N_2O-N (Table 2), including 0.1 Mtonne from grasslands, 0.4 Mtonne from wetland rice, 0.2 Mtonne from leguminous crops and 2.0 Mtonne from other upland crops. The calculated annual N_2O emission rates vary strongly in space (Figure 2). N_2O emission rates for grasslands are either of the same magnitude or exceed those for fertilized crops in some countries where the inherently lower emission rates for grasslands (Table 1) are balanced by high N application rates. The global annual N_2O-N emission calculated for the total arable land area (1436 Mha including fallow and unfertilized areas) is 3.4 Mtonne.

[30] The calculated mean global FIE for N_2O is 0.9% of the N applied (Table 3). The mean FIE for mineral N fertilizers is 1.0% of the N application, with important differences occurring between fertilizer types (Table 3). The highest FIE was calculated for other straight N (1.2%) and urea (1.1%), and the lowest (0.7%) for calcium ammonium nitrate.

[31] The global annual NO-N emission from fertilized fields calculated with the NO model is 1.6 Mtonne (Table 2), including 0.2 Mtonne from grasslands, 0.2 Mtonne from wetland rice, 0.1 Mtonne from leguminous crops and 1.1 Mtonne from other upland crops. The global annual NO-N emission calculated for the total arable land area is 1.7 Mtonne.

[32] The calculated mean global FIE for NO is 0.7% of the N input (Table 3). The highest FIE was calculated for the category of other straight N fertilizers, and the lowest FIEs for animal manure and anhydrous ammonia (Table 3). However, the number of measurements for some of the fertilizers is very small and results are less reliable than those for N_2O.

[33] The 95% confidence interval for N_2O-N emissions, computed with multilinear regression, is −40% to +70%. The uncertainty of the REML model is probably smaller than that for the regression model as it is based on a larger data set. The number of complete records in the data set for NO is too small to estimate the uncertainty.

4. Discussion

[34] The models for N_2O and NO presented in this paper are in close agreement with the data summary presented by *Bouwman et al.* [2002]. Small differences stem from differences in the way the data were handled. The main difference is that the N application•fertilizer type interaction was included as a continuous variable for the model development to avoid problems of colinearity (see section 2). To the contrary, fertilizer types and N application rates were treated as separate factors with classes in the data summary of *Bouwman et al.* [2002]. For N_2O the same factors had a significant influence on emissions in the data summary and the N_2O model. However, for NO the data summary indicated that soil organic C content, N application rate and mode of application, and length of measurement period and frequency of measurements had a significant influence. In the NO model the factors related to the measurements are not significant, while soil drainage is significant in the model and not in the data summary.

[35] There are many similarities in the models for N_2O and NO. We see that there is a strong increase of both N_2O and NO emissions accompanying N application rates. Soil drainage and texture are indicators of the soil oxygen and moisture status and gas diffusion in agricultural soils. 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. A neutral to slightly acidic soil reaction (soil pH) is favorable for N_2O emission. Soil reaction is known to influence the $N_2O:N_2$ ratio, with a larger $N_2O:N_2$ ratio under more acidic conditions [*Bouwman et al.*, 2002]. Soil pH has no significant influence on NO emissions.

[36] The finding that N_2O emissions in tropical climates exceed those in temperate climates is in agreement with literature reporting that temperature controls soil processes at all levels by governing organic matter decomposition, denitrification and nitrification rates [*Bouwman et al.*, 2002]. The results indicate that grasslands have lower N_2O emissions than croplands. Grasses have a longer growing season than crops, which could lead to more efficient N uptake than in cropped fields. In addition, denitrification may be more important in grasslands than in croplands because of larger amounts of available carbon. However, in conditions where oxygen is more limiting the $N_2O:N_2$ ratio may be lower in grasslands than in croplands. Hence, where occurrence of fertilized grasslands prevails in areas with poorly drained soils or soils rich in organic carbon, N_2O emissions may exceed those from crop cultivation on well-drained soils.

[37] In general ammonium-based fertilizers give high emissions of both N_2O and NO, while those for nitrate-

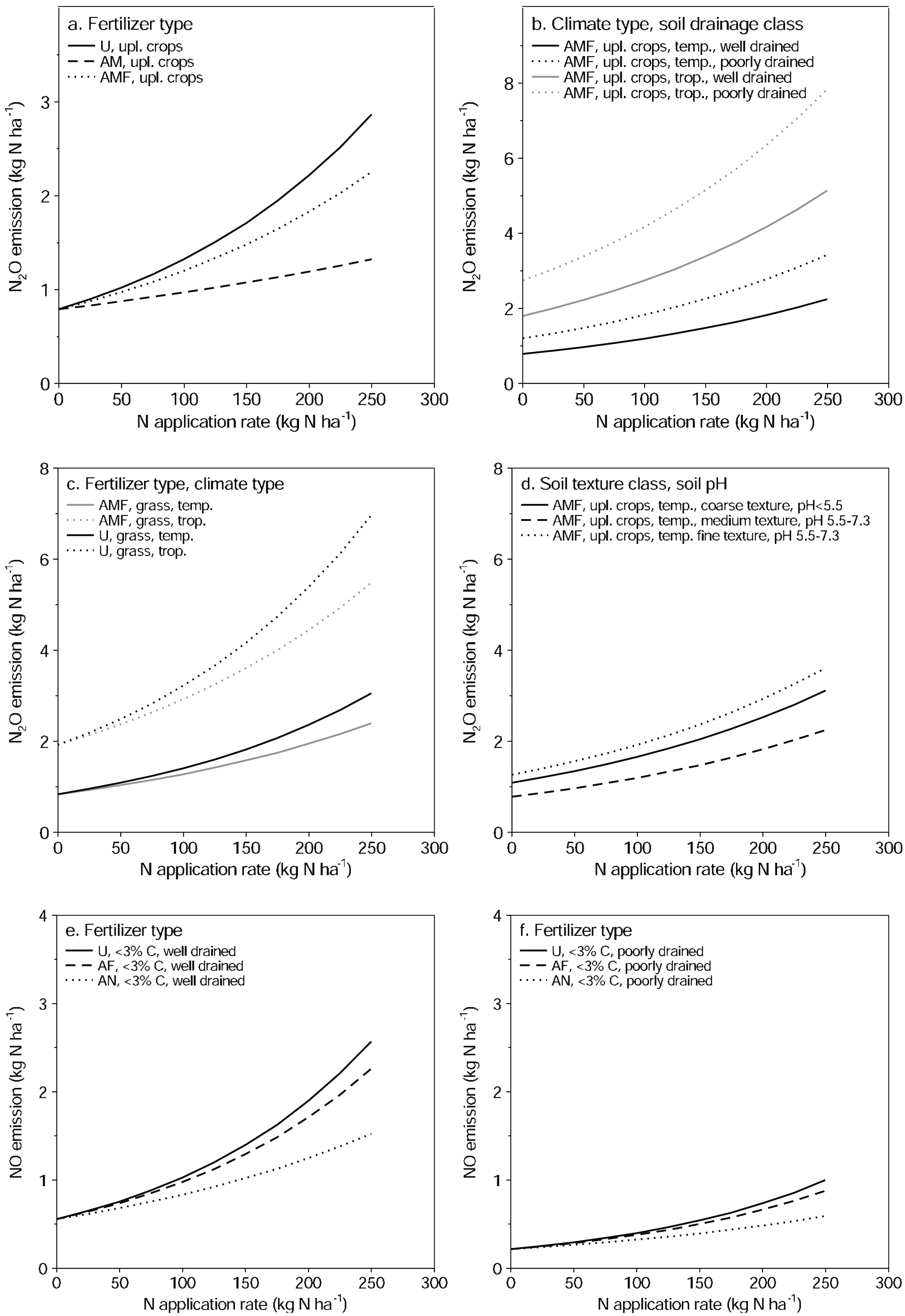
a. Fertilizer type
U, upl. crops
AM, upl. crops
AMF, upl. crops
b. Climate type, soil drainage class
AMF, upl. crops, temp., well drained
AMF, upl. crops, temp., poorly drained
AMF, upl. crops, trop., well drained
AMF, upl. crops, trop., poorly drained
c. Fertilizer type, climate type
AMF, grass, temp.
AMF, grass, trop.
U, grass, temp.
U, grass, trop.
d. Soil texture class, soil pH
AMF, upl. crops, temp., coarse texture, pH<5.5
AMF, upl. crops, temp., medium texture, pH 5.5-7.3
AMF, upl. crops, temp. fine texture, pH 5.5-7.3
e. Fertilizer type
U, <3% C, well drained
AF, <3% C, well drained
AN, <3% C, well drained
f. Fertilizer type
U, <3% C, poorly drained
AF, <3% C, poorly drained
AN, <3% C, poorly drained
N2O emission (kg N ha-1)
NO emission (kg N ha-1)
N application rate (kg N ha-1)
0
50
100
150
200
250
300
1
2
3
4
6
8

Table 2. Total Arable and Grassland Area and Estimated Fertilized Area, Application of N Fertilizers and Animal Manure, and Emission of N_2O and NO From the Areas Fertilized for Nine World Regions[a]

	Arable Land						Grassland					
Region	Area, Mha	Fertilized Area, %	Fertilizer N[b]	Animal Manure N[b]	N_2O-N Emission[b]	NO-N Emission[b]	Area, Mha	Fertilized Area (%)	Fertilizer N[b]	Animal Manure N[b]	N_2O-N Emission[b]	NO-N Emission[b]
North America	236	64	12699	1820	295	207	271	13	0	1816	14	32
Latin America	151	73	3834	5412	309	114	590	2	32	287	8	11
North Africa and Middle East	80	70	3596	1755	111	81	246	3	54	88	2	4
West, East and Southern Africa	158	53	911	2669	182	57	825	1	54	143	6	7
Europe	138	73	8245	4567	250	142	83	76	3293	4513	48	79
Former USSR	230	35	1864	3848	109	77	372	20	606	1292	22	43
South Asia	207	97	12549	9683	634	202	52	2	0	16	1	0
East Asia	95	100	24329	9906	501	376	495	4	0	479	6	8
Southeast Asia, Oceania and Japan	140	71	5356	3617	301	113	484	10	496	779	32	40
World[a]	1435	68	73384	43277	2692	1369	3417	8	4536	9414	138	225

[a] Totals shown for the world may differ from the sum of values for the nine different regions due to rounding.
[b] In ktonne yr^{-1}.

based fertilizers are high for NO but low for N_2O. The difference between the N_2O emission from AN and calcium ammonium nitrate (CAN) may be caused by the influence of calcium on soil pH in the vicinity of the fertilizer grains (see influence of soil pH, with lower emissions for alkaline conditions).

[38] The length of the measurement period is significant for N_2O but not for NO. NO emissions may be concentrated in the growing season; climatic conditions for the climate types differ less during this season than during other periods like winter, spring and autumn. Hence, for NO, shorter measurement periods may account for most of the effect of N fertilization. However, NO emission measurements covering periods in the order of one year are scarce, and our results for NO are less reliable than those for N_2O.

[39] Problems caused by correlation between independent variables are accounted for in the procedure followed and is indicated by the Wald statistic. This statistic indicates the influence of an independent variable on the dependent variable (emission) given the set of other independent variables. For example, consider measured N_2O emissions in relation to the C and N contents of soils. As C/N ratios are relatively constant across mineral soils and climates, we have seen that after C, incorporation of N does not improve the model.

[40] Our estimated mean global FIE for N_2O from N fertilizers is 22% lower than the default IPCC estimate [*IPCC et al.*, 1997], while for animal manure our estimate (0.8%) is 37% lower. Consequently, our estimate would lead to a reduction in the global annual FIE from N fertilizers and animal manure of 0.5 Mtonne, compared to the default IPCC method [*Mosier et al.*, 1998]. Our uncertainty range of −40% to +70% in the N_2O emission is lower than the −80% to +100% range reported for the default global emission factor [*Bouwman*, 1996; *IPCC et al.*, 1997].

[41] The global annual NO-N emission calculated for the total arable land area (1.7 Mtonne) is two-thirds lower than the 5.0 Mtonne estimate for crops based on emission rates for temperate and tropical climates from a recent emission inventory [*Davidson and Kingerlee*, 1997] applied to the same area. Our estimated FIE for NO of 0.7% of the N applied is 40% higher than a recent estimate of 0.5% [*Veldkamp and Keller*, 1997].

[42] Inherently, the data set used is not reflective of all management and environmental conditions found in the world's agricultural systems. For example, many fertilizer types with small use have been studied intensively, and measurements in tropical systems are underrepresented.

[43] Our data set is dominated by measurements in industrialized countries with high atmospheric-N deposition rates [*Bouwman and Van Vuuren*, 1999]. We may therefore overestimate emissions in countries with low deposition rates. Despite this possible overestimation, our estimated

Figure 1. (opposie) Examples of calculations using the models for N_2O and NO for selected combinations of factor classes: (a) N_2O emission for three N fertilizer types (U, urea; AM, animal manure; AMF, combinations of animal manure and N fertilizers) and varying N application rates for the category of "other upland crops" (i.e., upland crops excluding leguminous crops, medium soil texture, 1–3% soil organic C, pH 5.5–7.3, good soil drainage and temperate climate; (b) N_2O emission for AMF and varying N application rates for "other upland crops," medium soil texture, 1–3% soil organic C, pH 5.5–7.3, for temperate and tropical climates, and good and poor soil drainage; (c) N_2O emission for U and AMF and varying N application rates for grass, fine soil texture, poor soil drainage, >3% soil organic C, pH 5.5–7.3, and temperate and tropical climates; (d) N_2O emission for AMF and varying N application rates for "other upland crops," good soil drainage, temperate climate and different soil pH and texture classes; (e) NO emission for three N fertilizer types and varying N application rates, <3% soil organic C and good soil drainage; (f) NO emission for three N fertilizer types and varying N application rates, <3% soil organic C and poor soil drainage. See color version of this figure at back of this issue.

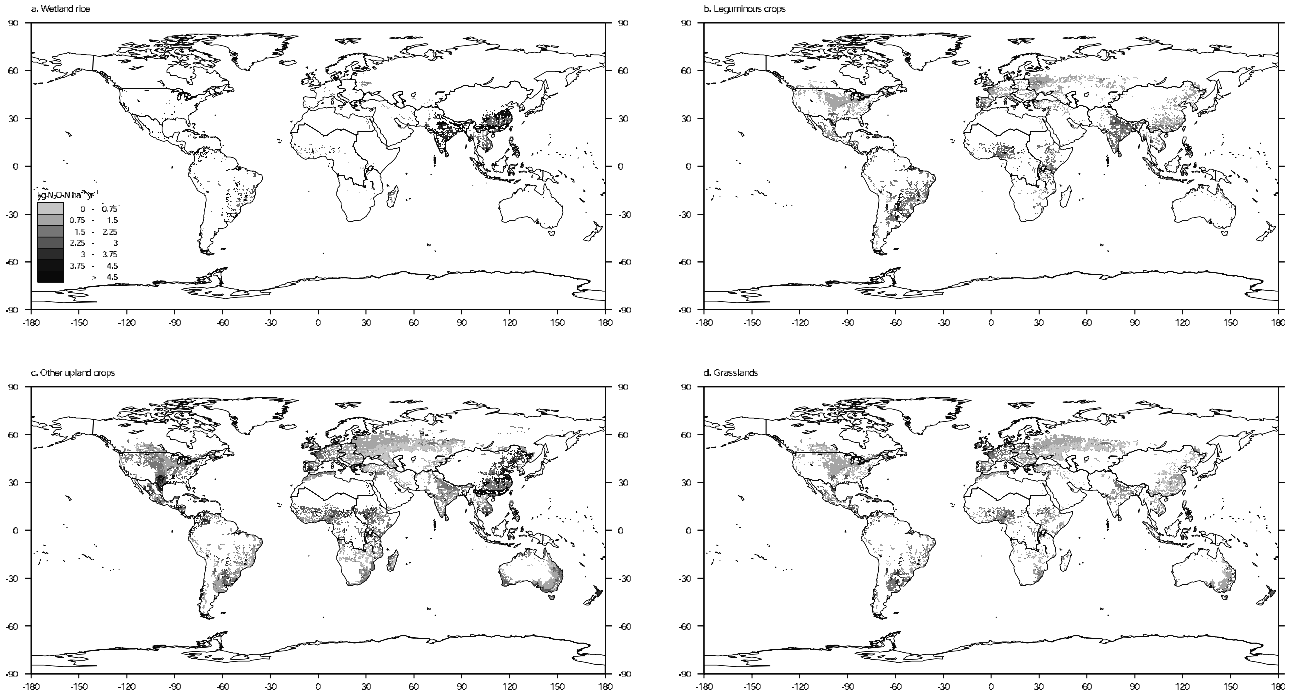

Figure 2. Annual N_2O emission rates for grid cells with fertilized areas of (a) wetland rice, (b) leguminous crops, (c) other upland crops and (d) grasslands. See color version of this figure at back of this issue.

mean FIE for N_2O from N fertilizers of 1% of the N application is 22% lower than the default IPCC estimate [*IPCC et al.*, 1997], while for animal manure this is 37% lower. In addition to N deposition, crop residues have contributed in many experiments to the observed emissions. The separate treatment of N inputs from crop residues in the IPCC guidelines may therefore lead to overestimation of anthropogenic N_2O emissions.

[44] A further point is that in about 30% of the global 128 Mha of leguminous crops on the average 28 kg ha^{-1} of fertilizer N is applied per year, while in some countries N fertilizer application rates are comparable to those of non-leguminous crops [*FAO et al.*, 1999]. In addition, varying quantities of animal manure are used. Attributing the total N_2O emission to biological N fixation as proposed in the IPCC guidelines is, therefore, not correct for fertilized leguminous crops.

[45] Our approach is based on areas that are actually fertilized with corresponding N application rates for the categories grasslands, wetland rice, legumes, and other upland crops. However, there may also be variation in fertilizer and manure management within countries. We recognize this problem, but the associated error in the extrapolated emission estimates is considered acceptable when compared to other uncertainties related to agricultural management in global upscaling.

[46] The models developed in this study are not suitable for predicting emissions from measurements reported in individual research papers for specific sites. Estimated emission rates for factor class combinations are, however, more relevant for upscaling to "landscape" conditions than those from individual measurements.

Table 3. Global Use of N Fertilizers and Animal Manure, and World-Average Fertilizer-Induced Emission (FIE) for N_2O and NO

Fertilizer Type[a]	Global N Use,[b] Mtonne yr^{-1}	FIE for N_2O,[c] %	FIE for NO,[c,d] %
Ammonium sulfate (AF)	2.4	1.0	0.7
Urea (U)	33.6	1.1	0.7
Ammonium nitrate (AN)	7.2	0.8	0.6
Calcium ammonium nitrate (CAN)	3.6	0.7	0.6
Ammonia, direct application (AA)	4.6	0.9	0.5
Nitrogen solutions (Mix)	4.0	1.0	0.7
Other straight N (AF)[e]	9.8	1.2	1.0
Ammonium phosphates (AP)	4.1	0.9	0.7
Other compound NP-N (AP)	1.7	0.9	0.6
Compound NK-N (NF)	0.0	0.9	0.8
Compound NPK-N (AP)	5.9	0.8	0.6
Total mineral N fertilizers	76.9	1.0	0.7
Animal manure (AM)	48.2	0.8	0.5
Total N fertilizers and animal manure	125.1	0.9	0.7

[a] Types of mineral N fertilizers are from statistics [*IFA*, 1999].

[b] Excluding the mineral N fertilizer and animal manure N applied annually to leguminous crops. On the global scale these quantities amount to 1 Mtonne of mineral N fertilizer and 4.7 Mtonne of animal manure N.

[c] Emissions are calculated for each grid cell for (1) areas where only mineral N fertilizers are applied using the value for the N-rate fertilizer type interaction (Table 1) for the fertilizer type indicated between parentheses; (2) areas where animal manure and mineral N fertilizers are applied in combination using the value for AMF; the calculated emission is attributed to the individual fertilizer types and AM on the basis of their application rates; and (3) areas where only animal manure is applied, using the value for AM.

[d] We have not taken account of possible uptake of NO by plant leaves. This may be particularly important in grasslands and perennial crops.

[e] Most of the other straight N (90%) is used in China, mainly (95%) in the form of ammonium bicarbonate. The remainder is mainly ammonium chloride. The AF factor value is used for both fertilizers.

5. Conclusions

[47] By developing models that summarize measurement data from the literature with the residual maximum likelihood (REML) procedure we account for the heterogeneity of environmental and management factors determining N_2O and NO emissions from agricultural fields.

[48] Climate, soil factors (soil texture, drainage, soil organic-C content, and pH), management-related factors (i.e., N application rate per fertilizer type and crop type), and factors related to the measurements (i.e., length of experiment and frequency of measurements) have a significant effect on N_2O emissions. N-application rate per fertilizer type, soil organic-C content and drainage have a significant influence on NO emissions. Contrary to N_2O, the influence of climate was not significant for NO.

[49] According to our analyses, N_2O emission estimates in agricultural fields should be based on measurements covering periods of at least 1 year, with a measurement frequency of at least one per day in periods with high flux rates (e.g., periods following fertilizer application or rainfall events) and lower frequencies in periods with low flux rates. The length of the measurement period is not significant for NO, but our results for NO are less reliable than those for N_2O.

[50] Although REML was developed for handling unbalanced data sets, additional observations for the currently underrepresented agricultural systems and geographic regions will allow refinement of the presented modeling approach. Since the data set is dominated by measurements in industrialized countries with high atmospheric-N deposition rates, we may overestimate emissions in countries with low deposition rates. The data analysis also suggests that the IPCC default approach could lead to overestimation of the contribution of crop residues to N_2O emissions. In addition, the calculation of the contribution of biological N fixation of N_2O emissions as proposed in the IPCC guidelines is not correct in many countries where leguminous crops are being fertilized with N.

[51] Our global aggregated estimates for FIE for N_2O for different fertilizer types are considerably lower than the default global FIE proposed by *IPCC et al.* [1997], while our estimate for the FIE for NO exceeds the one proposed by *Veldkamp and Keller* [1997]. The uncertainty in our estimates is much smaller than that of *IPCC et al.* [1997]. In addition, the global extrapolation using the REML models indicates a high spatial variability of mean annual N_2O and NO emissions, with important differences in both total emissions and the FIE between regions resulting from heterogeneity of management and environmental conditions. The data set of measurements and the approach followed in this study could therefore form a basis for an update of the IPCC methodology [*IPCC et al.*, 1997].

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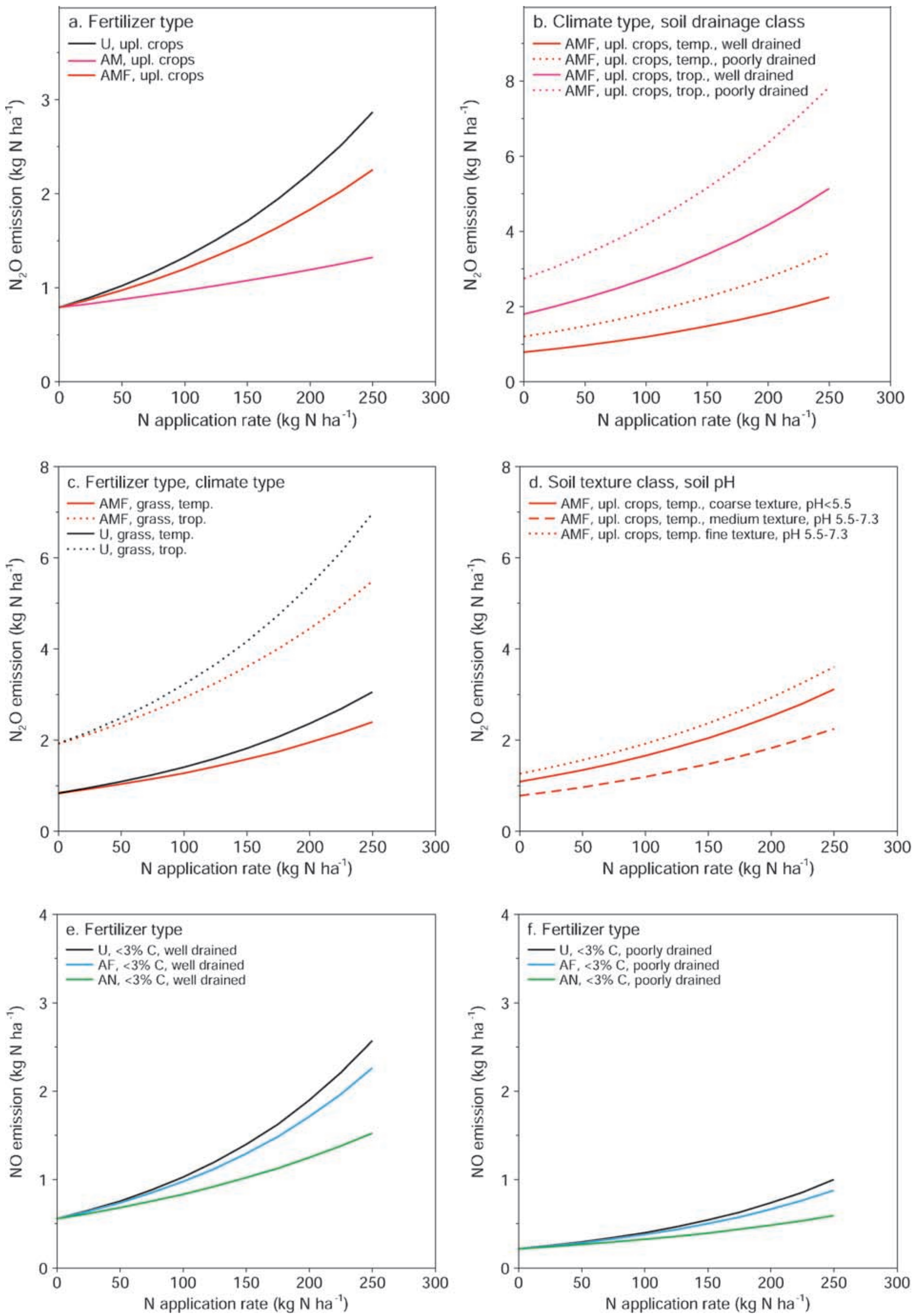
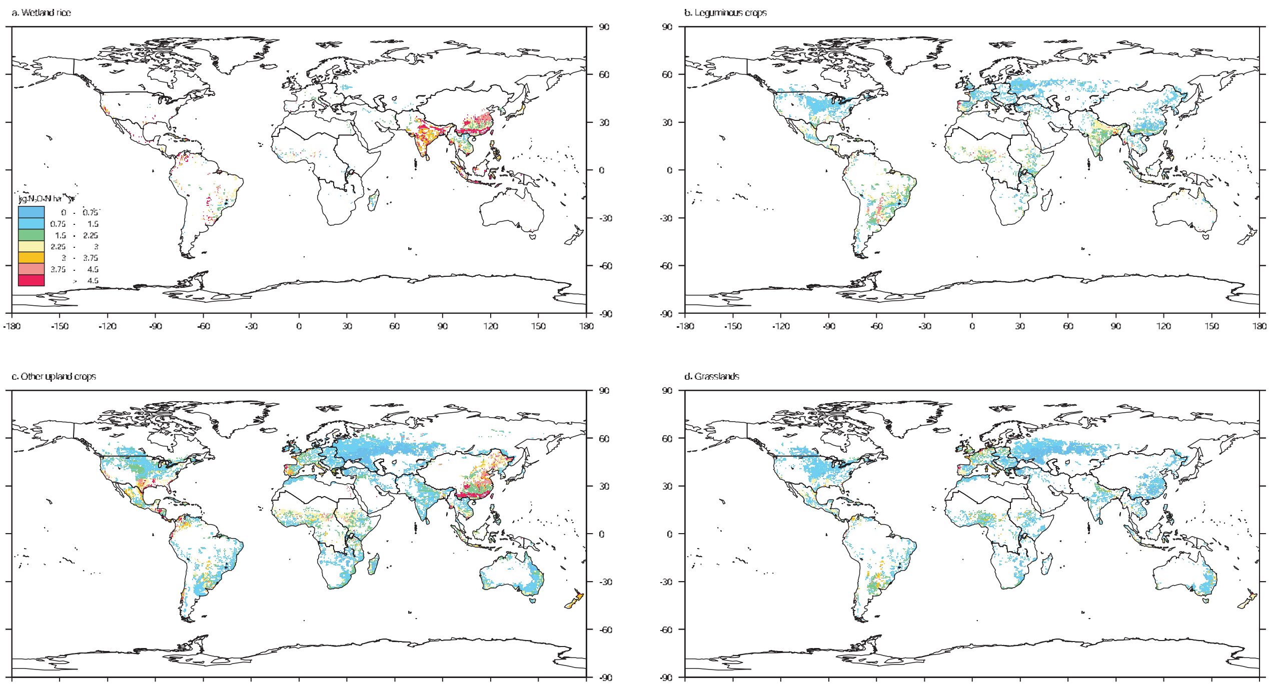

a. Fertilizer type
U, upl. crops
AM, upl. crops
AMF, upl. crops
b. Climate type, soil drainage class
AMF, upl. crops, temp., well drained
AMF, upl. crops, temp., poorly drained
AMF, upl. crops, trop., well drained
AMF, upl. crops, trop., poorly drained
c. Fertilizer type, climate type
AMF, grass, temp.
AMF, grass, trop.
U, grass, temp.
U, grass, trop.
d. Soil texture class, soil pH
AMF, upl. crops, temp., coarse texture, pH<5.5
AMF, upl. crops, temp., medium texture, pH 5.5-7.3
AMF, upl. crops, temp. fine texture, pH 5.5-7.3
e. Fertilizer type
U, <3% C, well drained
AF, <3% C, well drained
AN, <3% C, well drained
f. Fertilizer type
U, <3% C, poorly drained
AF, <3% C, poorly drained
AN, <3% C, poorly drained
N2O emission (kg N ha-1)
NO emission (kg N ha-1)
N application rate (kg N ha-1)
0
50
100
150
200
250
300



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