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Controls and models for estimating direct nitrous oxide emissions from temperate and sub-boreal agricultural mineral soils in Europe

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Abstract. Based on a review of N_2O field studies in Europe, major soil, climate and management controls of N_2O release from agricultural mineral soils in the European Union have been identified. Data for these N_2O emission drivers can easily be gathered from statistical services. Using stepwise multivariate linear regression analysis, empirical first order models of N_2O emissions have been established which allow – in contrast to existing large-scale approaches – a regionally disaggregated estimation of N_2O emissions at sub-national, national and continental level in the temperate and boreal climate regions of Europe. Arable soils showed lower mean and maximum emissions in oceanic temperate climate ("Temperate West") than in pre-alpine temperate and sub-boreal climate ("Sub-boreal Europe"). Therefore, two separate regression models were developed. Nitrous oxide emissions from arable soils the Temperate West amount to an average flux rate below 2 kg N_2O-N ha^{-1} yr^{-1} and rarely exceed 5 kg N_2O-N ha^{-1} yr^{-1}. They are modelled by the parameters fertiliser, topsoil organic carbon and sand content. In Sub-boreal European arable soils, N_2O emissions vary in a much wider range between 0 and 27 kg N_2O-N ha^{-1} yr^{-1} in dependence of available nitrogen, represented in the model by fertiliser and topsoil nitrogen content. Compared to existing methods for large scale inventories, the regression models allow a better regional fit to measured values since they integrate additional driving forces for N_2O emissions. For grasslands, a fertiliser-based model was established which yields higher emission estimates than existing ones. Due to an extreme variability, no climate, soil nor management parameters could be included in the empirical grasslands model.

Introduction

Nitrous oxide is a trace gas emitted along with chemical and biological processes. It participates in stratospheric ozone depletion as well as in the greenhouse effect and has a 296 times higher global warming potential than CO_2 (Houghton 2001). Therefore it belongs to the basket of trace gases addressed within the Kyoto Protocol (UNFCCC 1997). First incomplete investigations showed that in 1999, agriculture accounted for approximately half of the anthropogenic N_2O emissions in the European Union, with agricultural soils dominating the sources (EEA-European Environment Agency 2001).

Controls of soilborne N_2O emissions

Denitrification and nitrification have been identified as the principal processes of N_2O production in soils (e. g. Bremner (1997)). Whilst these microbial processes and their controls are well understood the tremendous temporal and spatial variability of N_2O emission rates poses an unresolved challenge to modelling, monitoring and prediction. Nitrous oxide emissions from soils arise from low, relatively constant, continuous emissions and – generally more important – from short emission peaks commonly associated with denitrification (Firestone and Davidson 1989) or both denitrification and nitrification. The ultimate drivers of N_2O emissions act at a proximal scale but are highly interlinked with soil conditions and management expanding over local to regional dimensions.

Proximal soil factors drive the microbial processes of N_2O production and consumption at the micro scale (10^{-3} m). Substrate availability, oxygen availability, soil moisture and soil temperature directly control the hourly and diurnal variation of N_2O fluxes (Figure 1). In fertilised soils, the denitrification rate is most commonly limited by oxygen supply and secondly by the availability of organic carbon as a reductant and by nitrate availability (Tiedje 1988). Furthermore the N_2O/N_2 ratio produced during denitrification increases with an excess of oxidants (nitrate, nitrite) over reductants, at low temperatures, and whenever a factor reduces the rate of overall reduction in soil (Betlach and Tiedje 1981). These proximal physical and chemical factors are themselves controlled by biological drivers supplying substrate such as readily degradable organic carbon and by the oxygen demand of decomposing organisms and roots. In general, N_2O production increases along with increasing rates of nitrification and denitrification and N_2O/N_2 product ratios. However, the proximal drivers interact with each other and also depend on larger scale factors. Oxygen availability, for instance, is driven by O_2 consumption through microbial and root activity as well as by diffusion constraints through soil structure and soil water content. The latter is again determined by the water balance as a function of local factors such as precipitation, interflow, drainage rate and evapotranspiration, which again depend on climate, position in the landscape, soil texture, crop type, season etc. (Figure 1).

Local factors ($1–10^3$ m) govern N_2O emission rates on a daily or weekly time scale. Farm management contributes to the emissions, but the driving forces of the microbial activity intimately link also to climate, weather, site properties (Smith et al. 1998 Skiba and Smith 2000) and land use history (Mosier et al. 1998b).

Soil

Many studies have documented the particular importance for N_2O emissions of elevated levels of soil moisture and soil nitrate concentration and hence of conditions favourable for denitrification (Yamulki et al. 1995 Ambus and Christensen 1995 Clayton et al. 1997 Skiba et al. 1994). Among the soil chemical characteristics affecting N_2O formation, transport, and emission (Hutchinson and Davidson 1993 Granli and Bøckman 1994), nitrogen availability measured as ammonium and nitrate concentrations in topsoil were shown to correlate with N_2O emissions (Kaiser et al. 1996 Skiba et al. 1998 Smith et al. 1998). Soil texture and clay content (Kaiser et al. 1996), respectively, as well as drainage status have been proven as useful proxies for O_2 availability (Hutchinson and Davidson 1993 Granli and Bøckman 1994). The effect of soil moisture changes on N_2O depends on the state of water-filled pore space (WFPS). In dry soils, a rising WFPS will lead to an increase in N_2O emission by enhanced denitrification, but above 80–90% WFPS, N_2O release declines due to a sharp decrease of the N_2O/N_2 ratio (Linn and Doran 1984). In the case of WFPS, positive as well as negative interactions with N_2O emissions may occur. Such ambiguity greatly restricts a simple generalisation of the influence of many parameters on N_2O release (Figure 1). Both the direction of the influence as well as the importance of a parameter vary in a complex pattern in space and time.

Management

The N_2O production conditions differ in arable land from those in grassland. Perennials have a longer growing season and therefore a prolonged nitrogen uptake as compared to annual summer crops and no period of bare soil without N uptake by crops. This helps to avoid the accumulation of mineral nitrogen in soil as it may happen after harvest of annual cultures in autumn. Grassland soils tend to accumulate more available carbon in the topsoil layer than arable soils (WBGU 1998), which in turn tend to have smaller C/N ratios as a result of carbon depletion and intensive fertilisation (Tisdall and Oades 1982). Furthermore, in the temperate and boreal regions of Europe, grasslands tend to cover the temporarily wet or poorer soils or higher elevations (EEA-European Environment Agency 1995). To account for these different patterns, arable lands and grasslands need to be addressed separately. Culture-dependent differences in N_2O emissions from arable soils arise from the temporal and spatial adaptation of nitrogen fertilisation to crop demands, i.e. preferential application in spring or summer, soil compaction by tractor traffic, and the amount, the C/N ratio and timing of crop residues (Flessa et al. 1998). The decay of nitrogen-rich crop residues (like from rapeseed or potato) may lead to high post-harvest emissions (Flessa et al. 1998 Flessa and Beese 1995 Smith et al. 1998). Similarly, in root and tuber cultures, soil compaction by frequent traffic and fertiliser spread between the crop rows may increase the N_2O release during the cropping season (Kaiser et al. 1998 Ruser et al. 1996). Hence, in accordance with Smith et al. (1998), lower annual N_2O emissions are expected for soils cultivated with cereals than with oilseeds or root and tuber crops.

Nitrogen input is a principal control of N_2O emissions. The effect of nitrogen fertiliser application has been excessively reviewed in the past (Bouwman 1996 Eichner 1990). The annual amount of nitrogen input to a field through fertilisation, nitrogen fixation and crop residues is being recommended world-wide to estimate direct N_2O emissions from agricultural soils in national inventories (IPCC 1997). In general, an increase of N input will increase both the nitrification and denitrification rates as well as the N_2O/N_2 ratio.

Manure as well as combined manure and synthetic fertilisers may lead to higher N_2O emissions directly after application than synthetic fertilisers alone (Bouwman 1996 Clayton et al. 1997 Kaiser et al. 1996). In contrast to (Eichner 1990), in re-

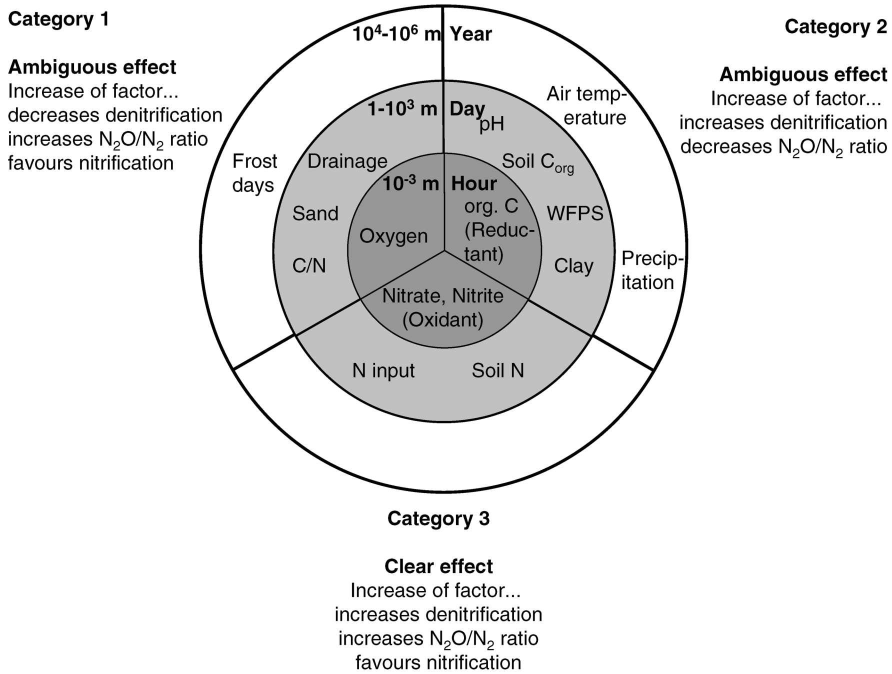

Figure 1. Scheme of factors regulating denitrification in agricultural soil; WFPS: water-filled pore space.

cent studies, the various forms of synthetic nitrogen fertiliser commonly applied in Europe resulted in similar emission factors (Bouwman 1996 Hénault et al. 1998 Eichner 1990 Michel and Wozniak 1998). In the latter studies, emission factors depend more on the soil (Hénault et al. 1998) and weather conditions (Flessa et al. 1995) during and after application or both (Clayton et al. 1997 Smith et al. 1998) rather than on fertiliser type alone.

Climate

Climatic features affect N_2O emissions at the regional to continental scale by setting a general framework for average, maximum and minimum precipitation, air temperatures and temperature changes (Figure 1).

Extreme events produce large portions of the annual N_2O emissions within a few days only. They typically occur either in winter during freeze-thaw cycles or in summer through rewetting of dry soil, driven by climate and weather parameters as well as in situations with elevated mineral nitrogen concentrations in moist soils after fertilisation or during the decomposition of crop residues, controlled by management and its interaction with climate, soil and site parameters. The debate about the physical and biochemical mechanisms of freeze-thaw cycles is still ongoing. Field experiments suggest that the N_2O is of microbial origin rather than from chemodenitrification (Röver et al. 1998). Extreme N_2O emission events occurring after a period of significant soil freezing and/or snow cover have been documented for a variety of climatic conditions throughout Europe (Denmark: Christensen and Tiedje (1990), France: Hénault et al. (1998), Northern Germany: Ernst (1997), Heinemeyer et al. (1996) and Kaiser and Heinemeyer (1996), Röver et al. (1998) and Southern Germany: Flessa et al. (1995) and Ruser (1999)). In contrast, Armstrong (1983) and Yamulki et al. (1995) reported no emission peak after light freezing of a well-drained surface soil for a week.

Emissions during the 3 to 4 winter months have been reported in the range of 7 to 92% of the annual N_2O release with a mean of 48% (± 19%), exceeding in average the emissions during the growing season. In dry continental conditions (USA and Canada: Chang et al. (1998) and Kessavalou et al. (1998)) or in well-drained soils under climate without severe frost (UK: Armstrong (1983) and Yamulki et al. (1995)), monthly N_2O emissions in winter do not exceed 30% of the average monthly emissions in the rest of the year. According to the studies cited above, elsewhere in Europe, monthly N_2O emissions in winter are similar to those in other months (mean N_2O emission in winter months is 120% the one in other months, median: 86%, range 50–312%).

Quantification of soilborne N_2O emissions

World wide activities are ongoing to quantify the various sources of N_2O. Available inventories of direct N_2O release from agricultural soils were so far based upon the amount of nitrogen added to soil via fertilisation, atmospheric deposition and crop residues or upon land use classes (e.g. Kroeze (1994) and Bouwman (1996), Mosier et al. (1996), IPCC (1997), Mosier et al. (1998a)). National inventories of direct N_2O emissions from agricultural mineral soils most commonly apply the approach (1) by Bouwman (1996), which aims to capture the entire N_2O flux, or (2) by IPCC (1997), which addresses the human-induced portion of the N_2O flux only:

$$E_{N_2O} = 1 + 0.0125 \cdot N_{fert} \tag{1}$$

$$E_{N_2O} = 0.0125 \cdot (N_{SN} + N_{AW} + N_{BN} + N_{CR}) \tag{2}$$

With

E_{N_2O} = Emission of N_2O [kg N_2O–N ha^{-1} yr^{-1}]
N_{fert} = N input by synthetic fertiliser and manure [kg N ha^{-1} yr^{-1}]
N_{SN} = N input by synthetic fertiliser [kg N ha^{-1} yr^{-1}]
N_{AW} = N input by manure [kg N ha^{-1} yr^{-1}]
N_{BN} = N input by biological N fixation [kg N ha^{-1} yr^{-1}]
N_{CR} = N input by crop residues [kg N ha^{-1} yr^{-1}]

However, according to the current state of knowledge outlined above, various additional controlling factors should be considered to improve the accuracy of such inventories (Mosier et al. 1996). Also, in order to reduce the heterogeneity of the N_2O data, CORINAIR (EEA-European Environment Agency 2000) recommends to define different agro-ecological zones taking account of the varying climatic conditions within a country. Agriculture releases N_2O directly from soils and manure but also indirectly through nitrogen losses as ammonia or nitrate, producing N_2O elsewhere in affected ecosystems (Mosier et al. 1998a Groffman et al. 1998 Nevison 2000). The lack of data restricts the reliability of estimates of indirect agricultural N_2O emissions (Nevison 2000), but a wealth of European measurement data allows to improve regional estimates of direct agricultural soilborne N_2O emissions.

Consequently, this paper aims to analyse the influence of climatic, soil and management parameters on direct annual N_2O emissions from agricultural soils in the European Union and to develop a detailed methodology for inventories of direct N_2O emissions from agricultural soils applicable at sub-national, national and continental levels.

Since the proximal controls of N_2O vary too much for large scale flux estimates by inventories, the use of proxy variables acting at the local, regional or continental scale is more practicable (Figure 1). Here we quantify the influence of various proxy climate, soil and management parameters on the magnitude of annual N_2O emissions from agricultural soils in the European Union. These proxies shall be commonly reported in the literature and be easily accessible at statistical services or derived from soil maps in order to serve as a feasible and transparent basis for inventory calculations.

Material and methods

The literature was reviewed for European field data of N_2O fluxes and additional site information. The study focuses on cultivated mineral soils in order to reduce the heterogeneity of N_2O flux controls. This restriction to mineral soils is justified since N_2O fluxes from cultivated organic soils are driven by “fossil” carbon and nitrogen from peat oxidation after drainage and mechanical soil disturbance rather than by recently added substrates (Kasimir Klemedtsson et al. 1997). The investigation extends over the European temperate and boreal regions only because the two available studies in Mediterranean climate (Arcara et al. 1999 Teira-Esmatges et al. 1998) span over less than five months only.

Nitrous oxide and site data

Data from field experiments based on in-situ measurements with micrometeorological and chamber techniques were admitted since these methods agree reasonably in field intercomparisons (Christensen et al. 1996 Smith et al. 1994). Actually, most of the used data have been measured discontinuously by closed chamber methods with GC-ECD analysis.

Temporal representation

The discontinuity and limited duration of the field studies produces an intrinsic uncertainty in the data through the interpolation and extrapolation of the measured emission rates. At a Southern German site, for instance, Ruser (1999) calculated an average overestimation of the N_2O flux by 26% by weekly measurements at noon in relation to continuous sampling. The N_2O emissions underlying this study were typically measured in weekly intervals. The uncertainty in the literature data through interpolation can *post hoc* not be quantified, but needs to be kept in mind during modelling and the interpretation of models. We identified 163 (52 sites) annual records in Europe which in many cases, however, sample winter data at intervals of several weeks only and incompletely report site and management conditions. These investigations thus provide only rough estimates of the total annual N_2O emissions as do extrapolations from shorter, but more intensively sampled measurement periods. Therefore, field studies with a measurement period of more than five months were considered. The number of data sets expanded to 256 (69 sites) records with an average measurement period of 10 to 11 months, greatly improving the information about soil properties and management. Emissions reported for periods shorter than one year were proportionally extrapolated to annual estimates, applying the findings above that average monthly N_2O release in winter compare to those in other months in most of Europe. This strategy minimises the inevitable error connected with the temporal extrapolation of the reported data.

Further sources of uncertainty in the temporal dimension lie inherently in the reported data, like measurement errors, basically errors due to sampling design or leakiness of a chamber. The available N_2O data always represent a logistically constrained compromise between addressing temporal and spatial variability. Given the uncertainty in annual N_2O emission rates an accurate assessment of the magnitude of emissions on large scale remains difficult and demands for a careful interpretation of the gathered results.

Spatial representation

The spatial variability of the measurements indicated in the literature ranges from 15 to 350%, averaging around 70% for 3 to 8 replicates. Evidently, micro scale variability in N_2O fluxes and their controls generates a wide scatter in the data which models based on local and regional site characteristics cannot explain. The database is biased in space since studies from Germany are over-represented. The number of annual N_2O data per site also varies between 1 and 15. Furthermore, measurements are concentrated around research centres in Europe so their spatial distribution is uneven and not random. This underlines the necessity to include site parameters in a sound generalisation towards regions not yet covered by measurements.

The distribution of arable crops in the studies analysed here corresponds well to the distribution of their cultivated areas in the EU 15 except for leguminous crops being undersampled.

Occasionally, studies do not give full information on climate, soil and management. In particular, soil chemical and soil physical parameters are reported in about half of the studies only. Some gaps could be filled by personal communications with the authors as well as by soil and climate maps.

Statistical analyses

In order to derive empirical models of soilborne N_2O emissions in the European Union, the collected data sets were statistically analysed as follows:

1. Homogeneous climate and land use groups were formed by a hierarchical cluster analysis with N_2O emissions, land use type (arable land or grassland), and frost class (Table 1) as sorting variables, taking account of the recommendation by EEA-European Environment Agency (2000) to separate various agroecological zones if necessary.
2. A set of potential controlling factors was selected based on the analysis above (Table 1) for which data are frequently reported in the literature and, for the purpose of inventories, information can be commonly gathered from national statistics and maps. The correlation with N_2O emissions and intercorrelations among the variables were tested with a bivariate non-parametric rank correlation analysis, using Spearman's Rho.
3. Then the quantitative relation between annual N_2O emissions and each of the variables was determined by univariate linear regression analysis.
4. Finally, the dependence of annual N_2O emissions from combinations of variables was tested by multiple linear regression analysis with stepwise selection of independent variables (Norusis 1993). Here the analysis was restricted to complete data sets. The remaining data sets with information gaps in some of the controlling factors were used for validation of the multivariate models.

All steps were applied to all data sets as well as separately to each homogeneous group of data sets. The regression analyses were performed with weighted data sets in order to assure an equal representation of all sites. A site was defined by the same climatic and soil properties, but eventually differing measurement years and fertilisation rates. Weighing the data sets by the inverse number of data sets per site avoided to optimise the models towards the conditions at the few excessively studied sites (Braunschweig/Germany, Edinburgh/UK, Göttingen/Germany, Longchamp/France, and Munich/Germany) but rather optimised the models to fit best to many sites. Tests with randomly chosen subsets of sites proved that the weighted regression analyses produced stable correlations and coefficients in contrast to non-weighted regression runs where in turn the regression coefficients depended on the choice of sites in the test regression runs.

The coefficient of determination R^2 of the regression model and the regression coefficients r^2 of the respective variables describe the degree of linear association (Neter et al. 1996). The reliability of a model or parameter is given as its significance, tested by either F- or t-tests ($^{*} = p < 0.05$; $^{**} = p < 0.01$; $^{***} = p < 0.001$). Correlation and regression analysis filters out those parameters interacting with N_2O emissions in a relatively uniform and homogeneous pattern over a wide range of environmental conditions. Parameters of which the impact and importance varies in space and time cannot be considered due to non-linear behaviour. The linear approach used in this study drastically simplifies the real situation but allows to estimate the annual N_2O flux when detailed local site data are unavailable. All statistical tests were performed with the software SPSS 9.0 for Windows.

The regression models were validated with independent test sites. The uncertainty in the predicted N_2O emissions exceeds the mean standard error of the regression (Neter et al. 1996). The prediction uncertainty for the validation test sites was quantified by Bonferroni simultaneous prediction limits (Neter et al. 1996) using the software Mathematica 3.0. In analogy to the procedure described by Fonseca and Parresol (2001), the prediction interval was obtained as

$$N_2O_{pred} \pm se_{pred} \cdot B \tag{3}$$

where N_2O_{pred} is the predicted emission in kg N_2O-N ha^{-1} yr^{-1}, se_{pred} the standard error of the prediction (Neter et al. 1996 Fonseca and Parresol 2001) and B the Bonferroni value for simultaneous prediction limits:

$$B = t(1 - p/2; \quad n - a) \tag{4}$$

was derived from tables of the t-distribution (Neter et al. 1996) for a given Type I error p, for n regression observations and for a parameters in the regression equation.

Results

Homogeneous climatic groups

The cluster analysis sorted the data sets into classes according basically to annual N_2O emission levels. When attributing sites to the classes, the first class contained most arable temperate sites with 90% of annual mean emissions below 3 kg N_2O-N ha^{-1} yr^{-1} and maximum emission rates below 10 kg N_2O-N ha^{-1} yr^{-1}. Some Southern German sites bearing extended snow cover in winter fell into joint classes with the sub-boreal sites achieving in general mean annual emissions above 3 kg N_2O-N ha^{-1} yr^{-1} and maximum rates above 10 kg N_2O-N ha^{-1} yr^{-1}. Therefore, the arable sites were separated into two distinct climatic groups: 1) Temperate Western Europe (all temperate EU except alpine and extensively snow-covered pre-alpine regions, "Temperate West") and 2) Temperate-moist-subcontinental (e.g. Germany South of 49° N), sub-alpine and sub-boreal regions ("Sub-boreal"). In contrast, the classification of grassland sites did not follow a spatial pattern but rather soil and management properties. The grassland sites all joined low to moderate emission classes with few exceptional data sets on poorly drained or excessively fertilised (> 500 kg N input per year) sites. This allows to choose a uniform climatic group for European grassland soils (Table 2).

Table 1. Potential controlling factors to describe N_2O emissions.

Category*	Parameter	Unit
Climate		
2	Annual precipitation	mm
2	Mean air temperature	°C
1	Frost class	classes: 0 = no significant frost; 1 = periodical frost with shallow snow cover; 2 = regular frost with high snow cover
Soil		
2	Drainage class	classes: 0 = well drained; 1 = moderately; 2 = poorly; 3 = very poorly
2	Texture	% clay
1		% sand
?		% silt
2	Carbon content of topsoil	%
3	Nitrogen content of topsoil	%
1	C/N ratio	1
2	pH	1
Management		
?	Crop type[a]	classes: 0 = fallow; 1 = cereals; 2 = oilseeds; 3 = roots/tubers; 4 = legumes
3	Total N-fertiliser applied	kg N ha^{-1} yr^{-1}
?	Fertiliser type	classes: 1 = synthetic; 2 = organic; 3 = synthetic + organic 11 = synthetic nitrate; 12 = synthetic ammonium
?	Application mode	classes: 1 = split application; 2 = all at once

*parameter category in Figure 1
[a] applies to arable soils only

Importance of controlling factors

Univariate regression analyses identified a set of factors out of those of Table 1 with a significant quantitative linear statistical relationship with annual N_2O flux rates (Table 3). The other parameters did not reveal statistically significant correlations.

Table 2. Annual N_2O emissions in European homogeneous climatic groups.

Region	Number of data sets (sites)	Mean	Median	Range
		---------[kg N_2O–N ha^{-1} yr^{-1}]----------		
Arable soils				
Temperate West	91 (27)	1.8	1.5	0.0–8.0
Sub-boreal	67 (13)	6.5	5.3	0.0–27
Total	158 (40)	3.6	2.0	0.0–27
Grassland soils				
Temperate and Sub-boreal Total	64 (29)	3.6	2.3	0.0–21

Many of the parameters tested (Table 1) are intercorrelated. So the emission factors given in Table 3 should be interpreted with some precaution since the statistical significance does not indicate any causal relationship. A given parameter represents a set of typical site conditions which must always be kept in mind. In general, the parameters displayed in Table 3 show highly significant, but relative low regression coefficients due to the facts that the data sets are widely scattered and some important sources of uncertainty like the interannual variability and microscale spatial variability in N_2O flux rates have been disregarded as separate factors in the analyses.

Climate

Climate plays a key role in determining the maximum measured annual N_2O release from arable sites upon which the distinction of homogeneous climatic site groups (cf. above) was based. Within the homogeneous climatic groups, no significant quantitative relationship was found between annual precipitation, air temperature or frost and N_2O emissions from arable nor from grassland soils. Evidently, the scale and the general nature of the tested climate factors is too unspecific for a significant linear interaction with local soil processes.

Soil

In accordance with Kaiser et al. (1996), among the soil physical characteristics, the clay fraction best explains annual N_2O emission rates. The sand content correlates negatively with N_2O release in Temperate Western arable soils. These parameters can be interpreted as indicators of oxygen availability (Hutchinson and Davidson 1993). Among the soil chemical characteristics, the topsoil nitrogen content best predicts N_2O emissions, which is a proxy for substrate limitation. Topsoil carbon content and pH also link with N_2O emissions, but at lower r^2. Unfortunately, precise information about the site properties has been documented in about half of the grassland studies only, restricting the scope of the analyses. The negative correlation of the silt content in grassland soils might be attributed to the interrelation with fertiliser amount (Table 3).

Table 3. Significant emission factors based on univariate regression analysis.

Parameter	Emission factors	Descriptives (N° of data sets)	Significant ($p < 0.05$) intercorrelations with
All arable and grassland soils			
Drainage class	1.7 ± 0.5 kg N_2O-N (class number)$^{-1}$	r^2=0.05*** (212)	Soil C, soil N, fertiliser, clay, silt, sand
Clay	6.2 ± 3.2 kg N_2O-N%$^{-1}$ clay	r^2=0.05** (130)	Drainage class, silt, sand, soil N, soil C/N, soil pH
Soil C	0.64 ± 0.25 kg N_2O-N%$^{-1}$ soil C	r^2=0.03* (219)	Drainage class, silt, sand, soil N, soil C/N, soil pH, fertiliser
Fertiliser	0.014 ± 0.002 kg N_2O-N kg^{-1} N-input	r^2=0.15*** (242)	Drainage class, soil C, fertiliser type, crop type
All arable soils			
Clay	0.17 ± 0.5 kg N_2O-N%$^{-1}$ clay	r^2=0.08** (107)	Drainage class, silt, sand, soil N, soil C/N, soil pH
Silt	0.065 ± 0.025 kg N_2O-N%$^{-1}$ silt	r^2=0.06** (107)	Drainage class, clay, sand, soil C, soil C/N, soil pH, fertiliser type
Sand	–0.065 ± 0.019 kg N_2O-N%$^{-1}$ sand	r^2=0.10*** (107)	Drainage class, clay, silt, soil C, soil C/N, soil pH
Soil N	27 ± 10 kg N_2O-N%$^{-1}$ soil N	r^2=0.06** (132)	Clay, soil C, C/N, soil pH, crop type
Soil C/N	–0.38 ± 0.17 kg N_2O-N (C/N)$^{-1}$	r^2=0.04* (130)	Clay, silt, sand, soil C, soil N, soil pH
Fertiliser	0.013 ± 0.006 kg N_2O-N kg^{-1} N-input	r^2=0.03* (169)	Fertiliser type, crop type
Fertiliser type	3.5 ± 0.7 kg N_2O-N (fertiliser class)$^{-1}$	r^2=0.15*** (130)	Drainage class, silt, fertiliser
Arable soils Temperate West			
Clay	0.075 ± 0.019 kg N_2O-N%$^{-1}$ clay	r^2=0.20*** (65)	Drainage class, silt, sand, soil N, soil C/N, soil pH
Silt	0.019 ± 0.010 kg N_2O-N%$^{-1}$ silt	r^2=0.05* (65)	Drainage class, clay, sand, soil C, soil C/N, fertiliser type
Sand	–0. 025 ± 0.007 kg N_2O-N%$^{-1}$ sand	r^2=0.17*** (65)	Drainage class, clay, silt, soil N, soil C/N, soil pH
Soil C	0.65 ± 0.13 kg N_2O-N%$^{-1}$ soil C	r^2=0.21*** (100)	Silt, soil N, soil C/N, soil pH
Soil N	17 ± 3 kg N_2O-N%$^{-1}$ soil N	r^2=0.25*** (84)	Clay, sand, soil C, soil C/N, soil pH
Soil C/N	–0.32 ± 0.03 kg N_2O-N (C/N)$^{-1}$	r^2=0.07* (106)	Clay, sand, soil C, soil N, soil pH
Soil pH	0.47 ± 0.16 kg N_2O-N (pH)$^{-1}$	r^2=0.07** (118)	Clay, sand, soil C, soil N, soil C/N
Fertiliser	0.003 ± 0.002 kg N_2O-N kg^{-1} N-input	r^2=0.01 (106)	Fertiliser type, crop type
Crop type	0.63 ± 0.23 kg N_2O-N (crop class)$^{-1}$	r^2=0.07** (102)	Fertiliser type
Arable soils Sub-boreal Climate			
Fertiliser	0.039 ± 0.008 kg N_2O-N kg^{-1} N-input	r^2=0.30*** (62)	Fertiliser type
Grassland soils			
Drainage class	3.2 ± 0.7 kg N_2O-N (drainage class)$^{-1}$	r^2=0.32*** (42)	Clay, sand, soil N, fertiliser
Soil pH	2.3 ± 0.6 kg N_2O-N (pH)$^{-1}$	r^2=0.20*** (52)	Clay, sand, soil C/N, fertiliser type
Fertiliser	0.015 ± 0.003 kg N_2O-N kg^{-1} N-input	r^2=0.23*** (72)	Air temperature, drainage class, fertiliser type

Table 4. Fertiliser-derived N_2O emission estimates [kg N_2O-N ha^{-1} yr^{-1}].

Area	Model	R^2	n
World (Bouwman 1996)	N_2O = 1 (−0.6 to 3.2) + 0.0125 (0.0025 to 0.0225)·fert	0.8^{***}	20
Arable + grassland soils, Europe	N_2O = 1.87^{***} (± 0.38) + 0.0138^{***} (± 0.002)·fert	0.15^{***}	242
Arable soils, Temperate West	N_2O = 1.84^{***} (± 0.37) + 0.0003 (± 0.002)·fert	n.s.	106
Arable soils, Sub-boreal	N_2O = 1.71 (± 0.93) + 0.0388^{***} (± 0.008)·fert	0.30^{***}	62
Grasslands, Temperate and Sub-boreal Europe	N_2O = 2.34^{***} (± 0.70) + 0.0152^{***} (± 0.003)·fert	0.23^{***}	72

N_2O = annual emission in kg N_2O-N ha^{-1} yr^{-1}
fert = annual fertiliser input in kg N ha^{-1} yr^{-1}
n = number of data sets
n.s. = not significant

Management

Fertilisation affects N_2O emissions through 1) adding nitrogen and 2) the form of the nitrogen and possible carbon source as a function of the fertiliser type.

Nitrogen input turned out as the most important control of N_2O emissions of agricultural soils in general. The amount of fertiliser yields highly significant and well correlated emissions factors for grassland soils but less so for arable soils. If arable soils are analysed separately, the emission factor for fertiliser is not significant if all arable soils are analysed jointly and even less in Temperate Western arable soils. In the latter region, statistically, the soil physical and chemical features become the dominant control of the annual N_2O emissions. They promote nitrification and denitrification as well as the partitioning between the two processes. This finding opposes the presently used default methods to estimate N_2O release from agricultural soils (IPCC 1997). However, nitrogen input by fertiliser explains a great portion of the variability in annual N_2O fluxes from Sub-boreal arable soils.

The mean fertiliser emission factors reported in the literature for European conditions are 0.013, 0.022, and 0.012 kg N_2O-N kg^{-1} nitrogen fertiliser in Temperate West arable, Sub-boreal arable, and grassland soils, respectively. They do not entirely agree with the calculated emission factors (Table 3) and the slope of the regressions (Table 4). Table 4 compares the regression equations for N input obtained in this study with the one of (Bouwman 1996). Interestingly, our emission factor for combined arable and grassland soils comes close to the one derived from annual studies world wide (Bouwman 1996), which also stem mainly from temperate climate regions. Hence, the emission factor of 0.0125 kg N_2O-N kg^{-1} nitrogen fertiliser (Bouwman 1996) as recommended for national greenhouse gas inventories in the IPCC methodology (IPCC 1997), seems appropriate for rough conservative emission estimates on a continental scale.

Measured N_2O emissions from unfertilised treatments show average fluxes of 0.7 (0 to 1.7) kg N_2O-N ha^{-1} a^{-1} for arable soils in the Temperate West, 2.3 (0 to 6.1) kg N_2O-N ha^{-1} a^{-1} in the Sub- Boreal region, and 1.2 (0 to 5.0) kg N_2O-N ha^{-1} a^{-1} in grassland soils. They follow the average magnitude of annual N_2O emissions as displayed in Table 2 but are not reflected by the intercept of the regressions in Table 4. The disaggregation of the data into arable lands in two regions and grassland, respectively, helps to understand regional variations in fertiliser-derived emissions. The lower R^2 highlights the importance of controls other than N input.

Fertiliser type. In our data base, the fertiliser type (mineral–organic–mineral plus organic) and the various forms of mineral fertilisers are highly intercorrelated with the amount of fertiliser added, so no meaningful analysis of the impact of fertiliser type on N_2O emissions was possible. In addition, most of the studies applied calcium-ammonium-nitrate fertiliser, so the analysis is also biased due to limited data for other fertiliser types. No significant correlation was found between the emission factors reported in the literature and the fertiliser types nor the mineral fertiliser form. As a result, in parallel with Bouwman (1996) and IPCC (1997), a uniform emission factor is used for all types of synthetic fertilisers as well as for manure.

In terms of crop type, in arable soils of the Temperate West, annual N_2O emissions from non-cereals (2.0 (0–8.7) kg N_2O-N ha^{-1} a^{-1}) exceed in general those of cereal fields (1.0 (0–5.2) kg N_2O-N ha^{-1} a^{-1}). However, the effect of crop type on N_2O emissions is masked by an intercorrelation with fertiliser amounts. Short-term and annual measurements on pea cultures (Duyzer 1996 Goossens and van Cleemput 2001) and grass-clover mixtures (Allen et al. 1996 Heinemeyer et al. 1996) do not exceed the N_2O release expected in non-leguminous crops. However, observations suggest extraordinary N_2O release in the season after the legumes (Goossens and van Cleemput 2001). These emissions have been attributed to the succeeding crop, masking the effect for our analysis.

Combined effects

In the previous sections, major controls of annual N_2O emissions from European agricultural soils have been identified. Using all parameters that were correlated with annual N_2O emissions of the respective homogeneous climate class, we deduced models of N_2O emissions by stepwise multivariate linear regression analysis (Table 5). Nitrogen input was treated as obligatory parameter in order to ensure comparability with the methods of Bouwman (1996) and IPCC (1997). The emission factors in the multivariate regression models match well with those in the univariate models (Table 3) indicating that the subsample of data sets in the combined models is representative for the whole set of available data and that the explanatory variables in the models are uncorrelated (Neter et al. 1996).

Compared to the fertiliser-based models in Table 4, the consideration of the combined effects of fertiliser, climate and soil clearly improves the model fit (Table 5) for N_2O emissions from arable soils. In consistence with the findings in sec-

Table 5. Regression models of annual N_2O emissions from agricultural mineral soils in Europe.

Model [kg N_2O-N ha^{-1} yr^{-1}]	R^2	n
Arable soils, Temperate Western Europe		
N_2O (± 0.7) = 0.6 (± 0.5) + 0.002 (± 0.002)·fert + 1.27^{***} (± 0.28)·soil C–0.024^{***} (± 0.005)·sand	0.38^{***}	61
Arable soils, Sub-boreal Europe		
N_2O (± 1.6) = -1.3 (± 2.1) + 0.033^{***} (± 0.008)·fert + 28* (± 13)·soil N	0.31^{***}	46
Grassland soils, Temperate and Sub-boreal Europe		
N_2O (± 2.6) = 2.4^{***} (± 0.7) + 0.015^{***}(± 0.003)·fert	0.23^{***}	72

N_2O = annual emission in kg N_2O-N ha^{-1} yr^{-1}
fert = annual fertiliser input in kg N ha^{-1} yr^{-1}
soil N = total soil nitrogen content in % of soil weight
soil C = soil organic carbon content in topsoil in % of soil weight
sand = sand content in topsoil in % of soil weight
total soil nitrogen content in topsoil, in % of soil weight
n = number of data sets
(± x) = standard error of predictor variables and mean standard error of models

Table 6. Standardised coefficients in the regression models of Table 5 and the effect of their variation on annual N_2O emission estimates.

Region			Standardised coefficients				Effect on N_2O flux estimate in kg N_2O-N ha^{-1} yr^{-1}			
	Fert.	Soil C	Soil N	Sand	Fert.	Soil C	Soil N	Sand		
Arable soils, Temperate West			0.09	0.48		–0.47	0–1	0–4		0–2.4
Arable soils, Sub-boreal Europe			0.51		0.28		0–16		0–7	
Grassland soils			0.48				0–8			

tion 3.3, in Temperate Western arable soils, soil parameters exhibit a stronger relationship with annual N_2O emissions than fertiliser input (Table 6). This agrees with the findings of Kaiser et al. (1996) and Hénault et al. (1998). In Sub-boreal arable soils and grasslands, fertiliser remains the dominant controlling parameter (Table 6).

Discussion

Validation

The regression models of Table 5 may serve for estimating the average order of magnitude of annual N_2O emissions from agricultural mineral soils in the temperate and sub-boreal regions of Western Europe but are not designed for predicting fluxes from a given site. Nevertheless, they are validated against measured data

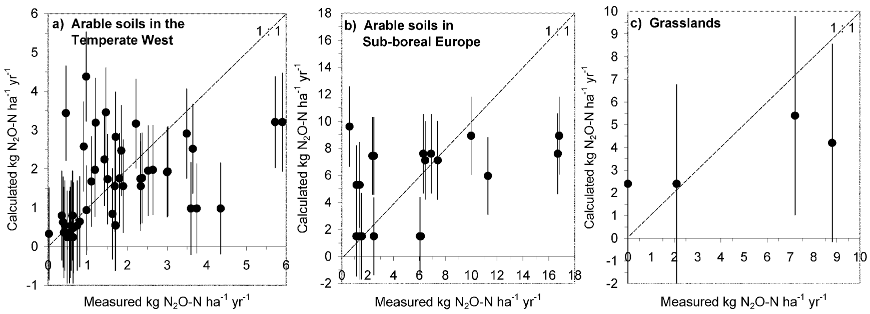

Figure 2. Validation of the multivariate regression models for a) arable soils in the Temperate West, b) arable soils in Sub-boreal Europe, and c) grasslands. Error bars indicate the prediction uncertainty for the validation test sites given by Bonferroni simultaneous prediction limits at $p < 0.1$.

from independent data sets (Figure 2). Overall, the range of the measured data is readily predicted by the models without, however, matching properly the observed annual N_2O fluxes on the test sites. Given the scatter in the data for model development, the prediction intervals $N_2O_{pred} \pm se_{pred} \cdot B$ are relatively large. The standard errors of the predictions se_{pred} slightly exceed those of the regression models, B is about 1.68 for $p < 0.1$. Consequently, the average prediction uncertainty is ± 1.2, ± 2.9, and ± 4.4 kg N_2O-N ha^{-1} yr^{-1} for arable soils in the Temperate West, arable Sub-boreal soils, and grasslands, respectively. For $p < 0.05$, B and consequently the prediction uncertainty both increase by ± 20%. The standard error of the grasslands model might decline in the future by accounting for site characteristics such as drainage status and management (pastures versus meadows). Obviously, the models allow to capture the correct order of magnitude of annual N_2O emissions when extrapolated in space and time over climate regions of Europe. Given the wide scatter, they suit less for predicting N_2O emissions at local scale.

Comparison with existing approaches

Existing approaches (IPCC 1997 Bouwman 1996) and the regression models developed in this study rely on relatively simple, linear statistical relations between annual N_2O emissions and some controls rather than on mechanistic process understanding. They should be able to generate the correct order of magnitude of measured values and the general patterns of low versus high annual gas fluxes. This hypothesis is tested for the three approaches mentioned, based on all available European data (Figure 3).

All models produce widely scattered results as compared to measured data (Figure 3). The Bouwman (1996) model (Figure 3a) estimates fluxes generally below 5 kg N_2O-N ha^{-1} a^{-1} but tends to overestimate small and underestimate higher fluxes, even in the Temperate West region. Both regression lines stay below the 1:1 line of measured versus modelled data. In contrast, the IPCC (1997) model (Figure 3b) captures at some extent the regional pattern of the measured data. It predicts the data in the Temperate West at an adequate magnitude while in Sub-boreal Europe,

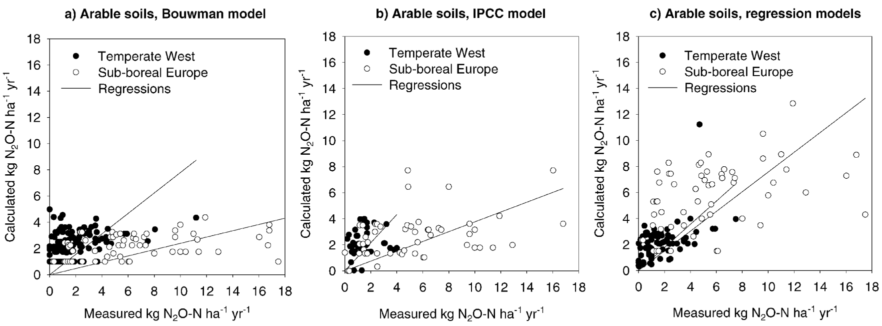

Figure 3. Comparison of measured N_2O emissions with estimates by existing models (Bouwman 1996 IPCC 1997) and by the new regression models.

it underestimates the measured data exceeding 8 kg N_2O-N ha^{-1} a^{-1}. The new regression models (Figure 3c) follow most closely the 1:1 line of measured versus modelled data in both climate regions. The models fit local measurements in the Temperate West with an average deviation of 1–2 kg N_2O-N ha^{-1} yr^{-1}. In the Sub-Boreal region, the new regression model is clearly superior to the other approaches although still substantial errors occur. It estimates local N_2O emissions with an average deviation of < 4 kg N_2O-N ha^{-1} yr^{-1}.

For grasslands, the three approaches use N-input as control parameter only, with (Bouwman (1996) and the model developed here) or without (IPCC 1997) background emissions, so their general behaviour is similar. The new grassland model developed in this study estimates N_2O emissions at 1 to 2 kg N_2O-N ha^{-1} yr^{-1} above the Bouwman (1996), which in turn includes 1 kg N_2O-N ha^{-1} yr^{-1} background emissions not considered by the IPCC (1997) models (Figure 4). The regression model overestimates small annual N_2O fluxes while it better fits the average expected emission rates than Bouwman (1996) and IPCC (1997). The average deviation of estimates at local scale can exceed 4 kg N_2O-N ha^{-1} yr^{-1} in all models (Figure 4).

Summary and conclusions

Based on a review of N_2O field studies in Europe, the influence of soil, climate and management on the annual N_2O release from agricultural mineral soils in Europe was assessed. Using stepwise multivariate linear regression analysis, simple first order models of N_2O emissions were established suitable for the calculation of inventories from sub-national to continental scale in the European temperate and sub-boreal climatic regions. This method identifies statistical relations between annual N_2O emissions and some important controls and allows – in contrast to the approaches of Bouwman (1996) and IPCC (1997) – to quantify N_2O emissions from arable mineral soils with a variable background emission in dependence on site conditions and climate. We have shown that for improving estimates of N_2O

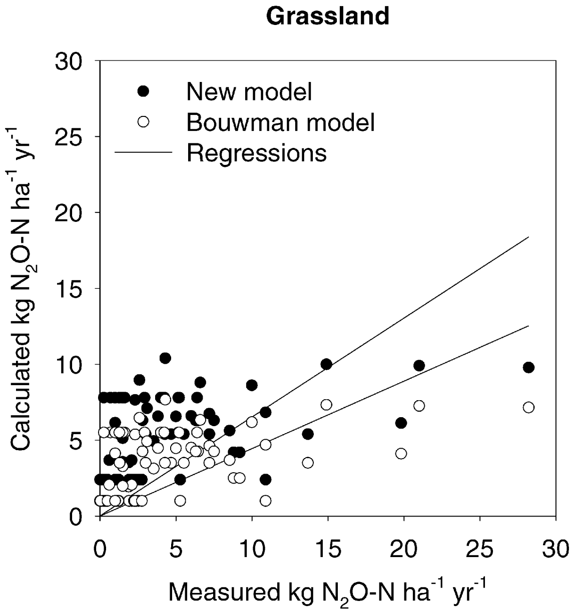

Figure 4. Comparison of measured N_2O emissions with modelled estimates by Bouwman (1996) and the new grassland model.

emissions it is necessary to stratify the agricultural soils of Europe on the basis of environmental and management characteristics. Climate proved important for N_2O emissions from arable fields but not for grasslands.

For modelling annual N_2O emissions on arable soils in Europe, two climate regions were distinguished, the "Temperate West" (UK, France, Belgium, The Netherlands, Denmark and Northern Germany) and the "Sub-boreal" region (Finland, Sweden, South Germany; no data available for Austria and Switzerland, which would be expected to fall in this group). Nitrogen input by fertiliser and soil characteristics (texture, soil organic carbon and soil nitrogen content) quantifiably determine the annual N_2O release rate. Each of these parameters allows to explain a small part of the variability in the N_2O data in at least one climate region, so in a whole, the multivariate models of Table 5 represent a clear improvement for the estimation of N_2O emissions from arable mineral soils in Europe in comparison to the currently used approaches based on N-input (Bouwman 1996 IPCC 1997). In contrast to existing large scale approaches, both the order of magnitude of fluxes and the reaction of flux rates to changes in controlling factors is roughly explained by the new models. For grasslands, the Bouwman (1996) model was modified towards higher emission estimates. The large variability in the database prevented from an incorporation of site and climate parameters, which would, however, be highly desirable for future improvement.

The relatively low values for R^2 suggest that some important controlling factors could not yet been integrated in the models, which were either not quantifiable due to their ambiguous interaction with N_2O production or not sufficiently documented in the literature. This restriction applies particularly to soil physical and chemical properties and organic carbon input by crop residues and manure. The lack of detailed site and management descriptions in the literature makes the interpretation and generalisation of local measurements difficult. In order to facilitate future synthesis, the following frame data should be given as a minimum in future studies: precipitation, position in the landscape (plane, top, slope, depression), soil type, detailed texture data, soil organic carbon and nitrogen in the topsoil, soil pH, drainage and soil moisture changes, N input, crop type, yields or N removed. Very few data are available from the Mediterranean region. Therefore, more long-term studies are urgently needed in Southern Europe for all typical crops before N_2O emissions can be generalised for this climate region. Also greater emphasis on leguminous crops is desired in order to understand the role of nitrogen fixation during an entire crop rotation.

Furthermore, the temporal variability of site conditions is not considered in these regression models, so changes of the importance of controls and the complex interactions among them are disregarded here. The mean standard error of the models is of the same order of magnitude as the temporal and spatial uncertainty in the underlying observations.

Despite of these restrictions to be overcome in future, major soil, climate and management controls of N_2O release from agricultural mineral soils in the European Union were identified, which can be easily gathered from statistical services, and empirical statistical models were established which allow–in contrast to existing large-scale approaches – a regionally disaggregated assessment of N_2O emissions from sub-national to continental scale.

We applied the regression equations in a GIS-based inventory of N_2O emissions from European agriculture (Freibauer (in press)). As a result, in EU-15 in 1995, agricultural soils emitted 419 Gg N_2O-N, which compares well to 380 Gg N_2O-N reported in official inventories based on the IPCC (1997) methodology (Ritter 1999). In contrast, as expected, results for national inventories differ considerably (Freibauer (in press)).

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