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A REGIONALLY DISAGGREGATED INVENTORY OF NITROUS OXIDE EMISSIONS FROM AGRICULTURAL SOILS IN GERMANY – A GIS-BASED EMPIRICAL APPROACH

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With 8 figures, 3 tables and 1 appendix
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Summary: Nitrous oxide (N_2O) is a potent greenhouse gas, which has to be included in national inventories because it is contributing to global warming. It primarily originates from agriculturally managed soils. These represent area sources, which are much more difficult to account for than point sources, such as power plants or industrial sources. The Intergovernmental Panel on Climate Change provides a default emission factor but also the plea for more sophisticated ways of calculating N_2O emissions from agricultural land use, in particular from industrialized nations. To fulfill this plea, already some approaches developed for use in Germany and elsewhere, which are more process based to a certain degree, have been published. However, these predominately require a high information input for model runs and site-specific calibration. In the present paper, we demonstrate the advantage of an empirical approach. This contribution introduces an approach for estimating N_2O emissions in a regionally disaggregated manner by calculating emission factors based on 86 empirical measurements of N_2O fluxes. These emission factors are calculated separately for distinct regions of Germany based on climate characteristics (precipitation and days of frost) and soil aeration. By combining these calculated emission factors with datasets on land use, nitrogen input, climate characteristics and soil, the N_2O emission fluxes for Germany are estimated in a spatially disaggregated manner at the county (Landkreis) level, only accounting for agricultural land use and excluding forest and urban areas. This approach yields an emission estimate of 53.38 Gg N_2O-N. For comparison purposes, this contribution also estimates N_2O emissions using a spatially disaggregated version of the IPCC guidelines to determine emissions for the national greenhouse gas inventories, which results in an estimated emission of 35.70 Gg N_2O-N for Germany. The results of these emission estimates suggest that the N_2O emissions from agricultural land use are underestimated in the official national greenhouse gas inventory if the simple, single-emission-factor based method is used.

Zusammenfassung: Lachgas (N_2O) ist ein starkes Treibhausgas, das zur Erderwärmung beiträgt und in nationalen Treibhausgasinventaren berücksichtigt werden muss. Es entsteht hauptsächlich in landwirtschaftlich genutzten Böden. Diese Flächenquellen sind deutlich schwerer zu berücksichtigen als Punktquellen wie Industrie oder Kraftwerke. Das Intergovernmental Panel on Climate Change (IPCC) gibt einen Standard-Emissionsfaktor vor, bittet aber auch um ausgefeiltere Methoden, N_2O-Emissionen aus landwirtschaftlichen Böden zu berechnen, insbesondere für industrialisierte Nationen. Aufgrund dessen gibt es einige Ansätze für Deutschland, die zu einem gewissen Grad prozessorientiert sind, allerdings große Mengen an Eingabeinformationen für Modellläufe und ortsspezifische Kalibrierung benötigen. Hier präsentieren wir die Vorteile eines empirischen Ansatzes. Dieser Beitrag stellt einen Ansatz vor, der es ermöglicht, N_2O-Emissionen räumlich disaggregiert abzuschätzen. Dies wird durch die Ermittlung von Emissionsfaktoren anhand von 86 Messreihen über N_2O-Flüsse ermöglicht. Die Emissionsfaktoren werden jeweils für eindeutig über klimatische Charakteristika bzw. den Status der Bodendurchlüftung abgegrenzte Regionen Deutschlands bestimmt. Indem diese Emissionsfaktoren mit Datensätzen über Landnutzung, Stickstoffeintrag, Klimacharakteristika und Bodeneigenschaften verknüpft werden, können N_2O-Emissionsflüsse für Deutschland regional disaggregiert auf Kreisebene abgeschätzt werden. Dabei wird nur landwirtschaftliche Landnutzung berücksichtigt, Wald- und Siedlungsflächen werden ignoriert. Dieser Ansatz schätzt die Emissionen auf 53.38 Gg N_2O-N. Für Vergleichszwecke wird auch eine Methode vorgestellt, die die Vorgaben des IPCC zur Erstellung nationaler Treibhausgasinventare für N_2O-Emissionen aus landwirtschaftlich genutzten Böden räumlich disaggregiert umsetzt, dies resultiert in einer Schätzung von 35.70 Gg N_2O-N-Emissionen für Deutschland. Die Gesamtsumme der abgeschätzten N_2O-Emissionen deutet darauf hin, dass die N_2O-Emissionen aus landwirtschaftlich genutzten Böden in Deutschland im nationalen Treibhausgasinventar deutlich unterschätzt werden, wenn die einfache auf einem Emissionsfaktor basierende IPCC Methode genutzt würde.

Keywords: Nitrous oxide, emission, disaggregation, regionalization, agriculture, Germany

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1 Introduction

Nitrous oxide (N_2O) is one of the four major greenhouse gases responsible for anthropogenic global warming and the major agricultural greenhouse gas. It contributes a radiative forcing of 0.16 ± 0.02 W/m^2, which corresponds to 6% of the total radiative forcing by long-lived greenhouse gases, and is involved in stratospheric ozone depletion (IPCC 2013; Crutzen 1970). One third of the agricultural N_2O emissions of are direct emissions from agriculturally used soils (Mosier et al. 1998), and the N_2O emissions from agricultural soils are a major source of the uncertainties in the German greenhouse gas inventory. Most of the N_2O emissions in soils result from the processes of nitrification and denitrification (Bremner 1997, 12). In agricultural soils, the supply of reactive nitrogen required for both processes is normally highly increased by fertilization. Firestone and Davidson (1989) have conceptualized the processes of N_2O release from soils by introducing the "Hole-in-the-Pipe Model". The processes of nitrification and denitrification are represented as pipes in which NH_4^+ is oxidized to NO_2^- or NO_3^-, and NO_3^- or NO_2^- is reduced to N_2, respectively (Bouwman 1998). The rate of flow through the pipes is dependent on the supply of reactive nitrogen (Davidson et al. 2000). N_2O escapes through holes in these pipes during both processes. The size of these "holes" is dependent on (a) soil parameters such as carbon content, soil pH and soil texture and (b) environmental conditions. Environmental conditions that are well known to have a clear influence on the production of N_2O in soils are (a) freezing-thawing cycles (Teepe et al. 2001) and (b) dry-wet cycles (Davidson et al. 1993). N_2O fluxes from spoil are dependent on N_2O production and N_2O consumption, which usually occur concurrently, particularly in highly structured soils. Consequently, N_2O emissions frequently exhibit extreme spatial and temporal variability (Röver et al. 1999), which cannot be explicitly predicted spatially. Frequently, peak emission events determine more than 50% of the annual emission rate (Papen and Butterbach-Bahl 1999; Teepe et al. 2000). In order to reduce the uncertainty of greenhouse gas inventories, research efforts therefore have to concentrate on these peak emission events, mainly using statistical probability, and introduce as many independent approaches as possible. The Intergovernmental Panel on Climate Change (IPCC) published guidelines for national greenhouse gas inventories in 2007 (IPCC 2007). For N_2O, the IPCC has introduced a multi-tiered approach. Tier 1 uses default emission factors in combination with country-specific activity data. For example, a static proportion of the applied reactive nitrogen is assumed to be emitted as N_2O. This tier is used when neither country-specific emissions factors nor activity data are available. This approach has obvious limitations because environmental factors are not considered at all. If rigorously documented, country-specific emission factors are available, they should be used; this represents a Tier 2 approach. Tier 3 approaches are modeling or measurement approaches that do not involve emission factors. Due to the high spatial variability of these environmental conditions, approaches that do not consider the variability of the spatial distribution of environmental factors determining the emissions, such as the Tier 1 approach, are unlikely to be useful for mitigation efforts (Freibauer and Kaltschmitt 2003). Therefore, the knowledge that the N_2O emission factors are not randomly distributed, but dependent on soil and climate characteristics have to be implemented consequently. This study presents an approach for estimating the N_2O emissions from agriculturally used soils in Germany on a national level in a regionally disaggregated manner in accordance with patterns found for the N_2O emissions when referring to soil and climate characteristics. Using regionalized emission factors based on climate and soil properties, this approach represents a Tier 2 approach for estimating N_2O emissions that should provide more accurate emission estimates because it is adapted to local mean climate conditions and soil aeration. This approach is based on the work of Jungkunst et al. (2006) which was a compilation of available empirical measurements. In this respect, this approach is related to the work of Dechow and Freibauer (2011), who used empirical measurements to develop a model based on weather, soil properties and management using fuzzy sets, a more complex approach than the one taken in this work. It requires more input variables, which could be applied to different years when compared with this approach, and therefore exhibits greater flexibility. However, it is unclear if these input parameters are available everywhere at any time in a meaningful resolution. In any case, many different approaches are currently desirable, and if they provide similar results, it will strengthen empirical approaches. Empirically based approaches stand in contrast to process-based modelings, such as DNDC (Li 2000), DAYCENT (Parton et al. 2001), *ecosys* (Grant and Pattey 1999) or CANDY (Franko et al. 1995), which represent Tier 3 approaches. Process-based models have also been used to estimate N_2O emissions at national and regional levels, for example DNDC in Cardenas et al. (2013), DNDC-Europe in Leip et al. (2011b) and LandscapeDNDC in Haas et al. (2013). In contrast to DNDC's regional mode, LandscapeDNDC simulates the single-site submodels for each time-step simultaneously instead of on a site-by-site basis; this allows two-way coupling to other regional models during each synchronized timestep.

In this paper, emission factors are calculated for different soil aeration levels and three distinct climatic regions of Germany based on 86 empirical N_2O emission measurements taken at 30 locations throughout the country. Because this approach uses soil aeration and climate characteristics, which are ecosystem characteristics, it can be considered an "ecosystem approach" (Matson and Vitousek 1990; Bareth et al. 2001; Bareth and Glatzel 2006), which combines spatial datasets on land use, fertilizer utilization, and soil type and climate conditions. The key objective of this paper is therefore the introduction and presentation of a new method for estimating nitrous oxide emission factors at landscape to regional scales that should also provide an estimate of the total emissions as used in national greenhouse gas inventories. Furthermore, by calculating different scenarios based on realistic assumptions on climate and soil parameters, it should allow elucidation of the potentially most efficient mitigation options. According to Leip et al. (2011a), such estimates should be a focus of research because not many emission estimates are available on a regional level. Consequently, we are certain that taking spatial distribution of nitrogen input and emission factors into account is necessary, and therefore our objective is to demonstrate that a spatial disaggregation of emission factors in an ecological manner will aid in the reduction of national greenhouse gas inventories. In addition to other approaches, it will indicate how to deal best with the temporal and spatial unsteady nature of N_2O emissions for more accurate regional estimates.

2 Data and methodology

2.1 Data

The estimation of regionalized N_2O emissions by means of the approach presented in this paper depends on and requires the use of a multitude of spatial datasets:

To determine the areas of agricultural land use, the land cover dataset created by the "IMAGE & CORINE Land Cover 2006" project was used. It provides land use data for Europe in 44 classes with minimal mapping units of 25 ha and was derived from satellite images obtained by Landsat 7, IRS-P6 LISS III, SPOT-4 and SPOT-5 (Keil et al. 2011). The "VG250" dataset that is provided by the German Federal Agency for Cartography and Geodesy contains the administrative boundaries in Germany and was used for the regionalization along administrative boundaries, i.e. the boundaries of the federal states of Germany. For the regionalization based on climatic characteristics, two climate datasets provided by the German Weather Service (DWD) (DWD 1999; DWD 2001; DWD 2003) were used: The 30-year average precipitation in mm/m^2 for the period of 1961–1991 with an accuracy of 1 mm as well as the days of frost (minimum temperate <0 °C) per year for the period of 1961–1990 with an accuracy of 0.1 days. The Soil Map of Germany 1:1 000 000 (BÜK1000) was used to disaggregate with respect to soil properties. In it, the soils of Germany are classified into 71 soil mapping units (Hartwich et al. 1995). Data on nitrogen fertilizer usage was provided by the Thünen Institute (TI), an institution of the German Ministry of Food, Agriculture and Consumer Protection. This dataset provides the quantity of nitrogen-based fertilizer utilized in Germany on a district level, separated by fertilizer type. This dataset is based on the quantity of nitrogen fertilizer sold per state, which was broken down onto the district level using a simple key based on the spatial distribution of cultivated plants and their typical fertilizer requirements, as described in Rösemann et al. (2011). Figure 1 shows the quantity of fertilizer input per hectare of agricultural land use for each district of Germany.

The source of the datasets concerning the atmospheric deposition of nitrogen is the work of Gauger et al. (2008) (for the years 1995, 1997 and 1999–2004) and Gauger (2010) (for the years 2005–2007). Both datasets provide (amongst other deposition loads) total atmospheric nitrogen deposition separately for nine land use classes derived from the CORINE Land Cover classes. In this paper, the deposition datasets for the land use "agricultural areas" will be used. Figure 2 shows the atmospheric deposition of nitrogen for agricultural land use in Germany for the year 2007.

2.2 Methodology

The emission measurements on fertilized fields summarized by Jungkunst et al. (2006) (measurement sites one through 27), along with the measurement of Pfab et al. (2010) (Site 28), Ludwig et al. (2011) (Site 29), Brümmer et al. (2010) (Site 30),

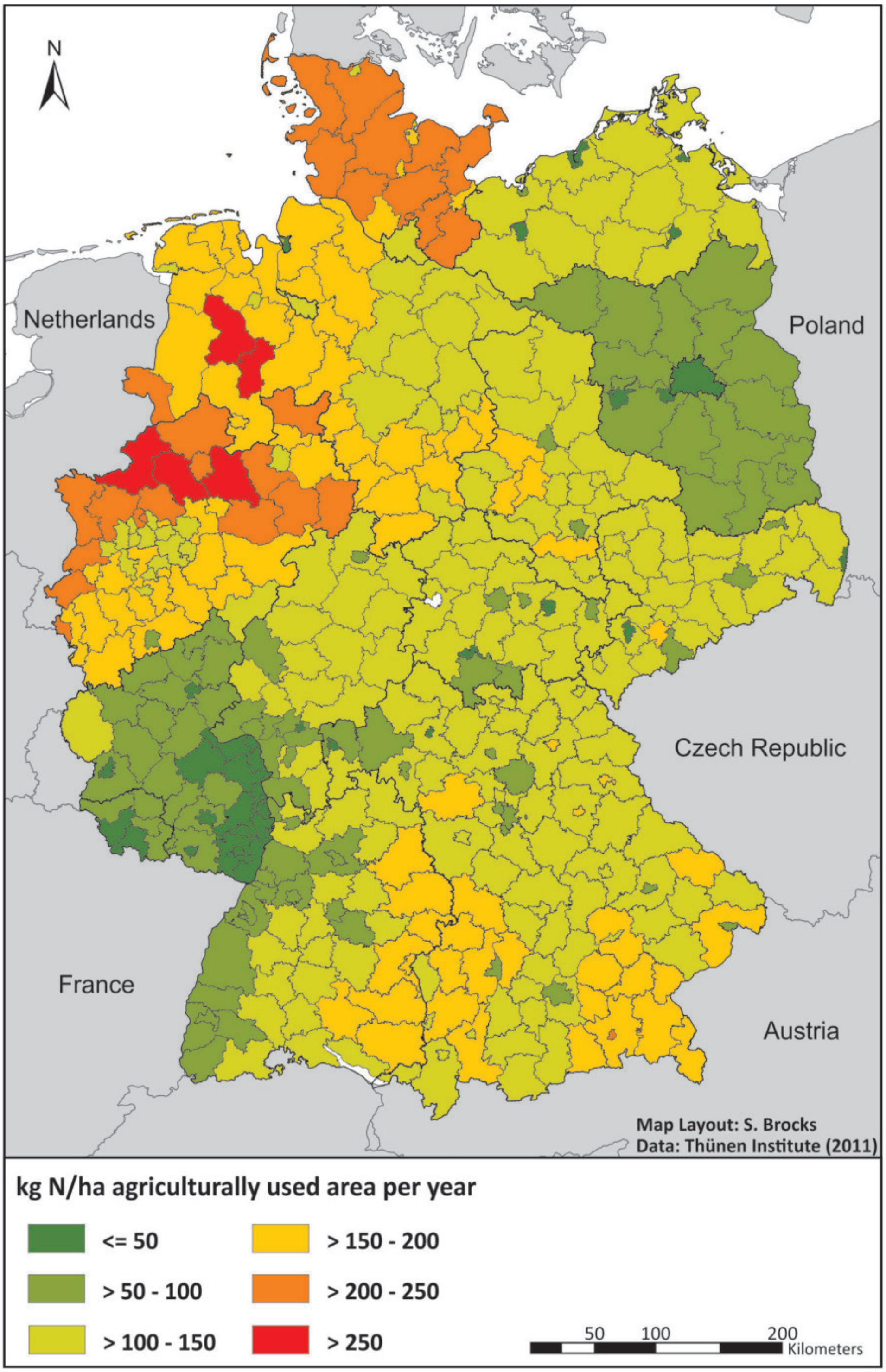

Fig. 1: Fertilizer input per hectare of agricultural land use

Schmeer et al. (2010) (site 31) and Dey (2013) (site 32), which all are shown in the appendix, were used to determine regionally disaggregated median N_2O emission factors. Measurement site 26 and other pasture sub-measurements from Jungkunst et al. (2006) were not considered if nitrogen input was only spec-

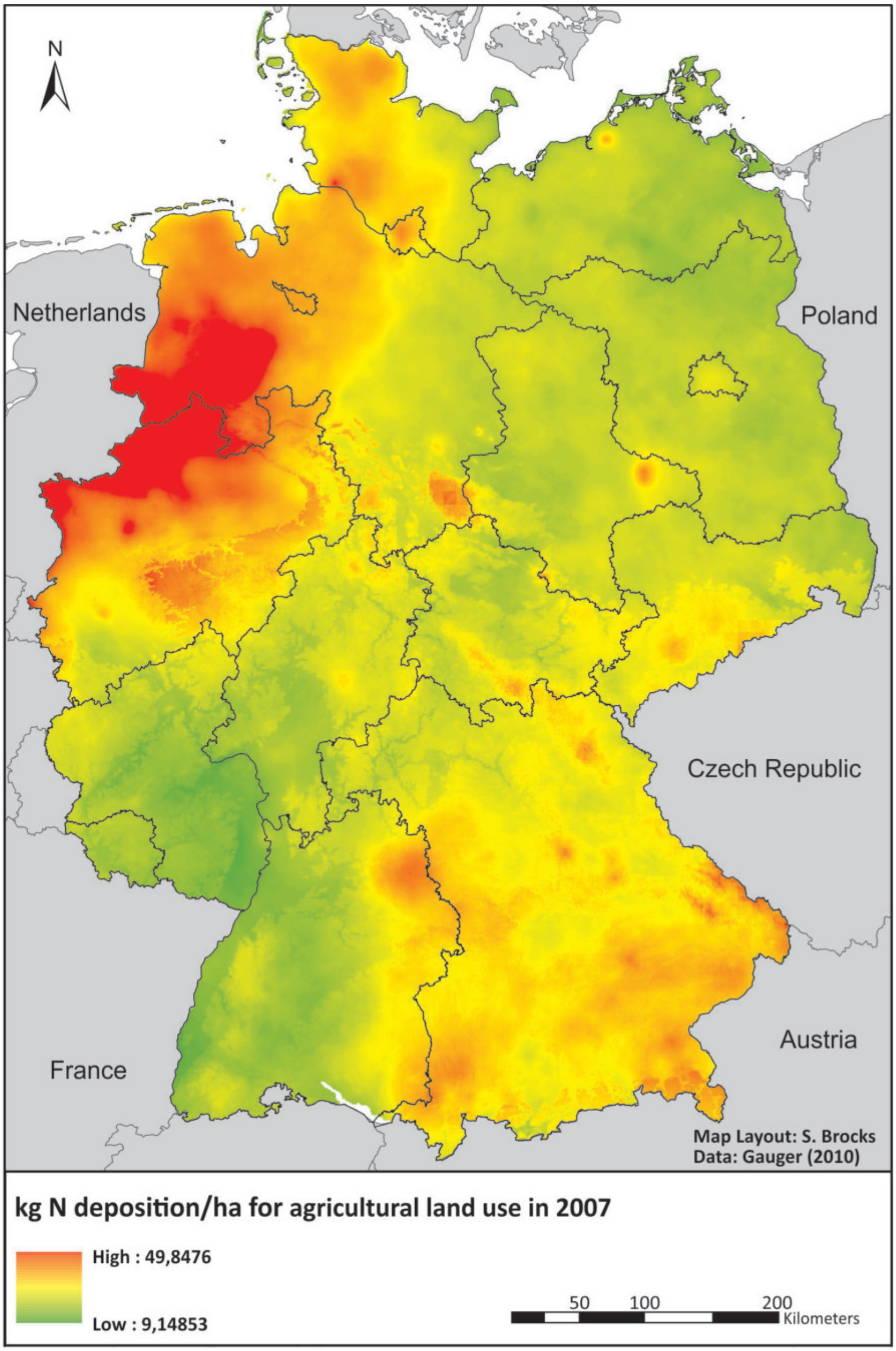

Fig. 2: Atmospheric deposition of nitrogen for agricultural land use in 2007

ified in terms of livestock units. For each measurement, two emission factors were determined by dividing the measured N_2O flux by the nitrogen input. One only considers the fertilizer nitrogen input, and the other additionally includes N_2O emissions due to atmospherically deposited nitrogen, which varies relevantly across Germany (Fig. 2). Therefore, regional variations were expected because of differing nitrogen input due to atmospheric deposition, even though this might not have a large effect on the total emission sums for Germany. The different types of fertilizer were summed up to an annual total nitrogen input per district. The emission factors, including the atmospherically deposited nitrogen, were calculated by adding the deposition values of the year in which the measurements were made (provided by Gauger et al. (2008) and Gauger (2010)) to the fertilizer nitrogen input. In this context, the total nitrogen input can be related to the measured N_2O fluxes. This contribution does not consider background emission fluxes as specified by Bouwman (1996) because atmospheric deposition of nitrogen impedes the detection of background emissions and recent research suggests that actual natural forests emit very little N_2O, even though they receive nitrogen input from atmospheric deposition (Jungkunst et al. 2012).

The locations of the measurement sites as well as the three regions defined by the climate-based disaggregation are shown in figure 3.

The regionalization based on soil aeration distinguishes between well-aerated soils and soils that exhibit redoximorphic properties. Fluvisols, Gleysols and Stagnosols have been classified as redoximorphic soils (34 measurements fall into this category); all others have been classified as well-aerated soils (56 measurements). Independently of climatic regions, the redoximorphic soil show a rather narrow variation of emission factors (Jungkunst et al. (2006) and this study). This is comprehensible because the N_2O emissions by soils are more directly dependent on actual soil conditions, particularly on soil aeration (Davidson and Verchot 2000), which is mainly driven by the prevailing soil water condition, rather than on the mean climatic conditions. Consequently, we calculated the mean and median emissions factors of the dataset in a two-tier hierarchy. First, the dataset was partitioned into samples taken at sites with redoximorphic soils and samples taken at sites with soils that are well-aerated. In a second step, the dataset of the samples with well-aerated soils was divided into three climate classes to regionalize the emissions based on climate conditions using temperature and precipitation to divide Germany into three regions in accordance with Jungkunst et al. (2006):

1. Cold: $\geq$ 100 days of frost per year (25 measurements belong to this class)
2. Warm-Wet: < 100 days of frost and $\geq$ 600 mm precipitation per year (21 measurements)
3. Warm-Dry: < 100 days of frost and $\leq$ 600 mm precipitation per year (10 measurements)

Figures 4 and 5 show the distribution of the measured emission factors for the different classes both for emission factors calculated from fertilizer nitrogen input and for emission factors calculated from fertilizer and atmospheric deposition nitrogen input (the upper and lower bounds of the boxes are the first and third quartile, the black bar shows the median, and the whiskers show the minimum and maximum data points, except in the presence of outliers; then they show the smallest and largest datums within 1.5 times the interquartile range, and outliers are plotted separately). The statistical analysis of the emission measurements results in the median and mean emission factors shown in table 1.

Using a Kruskal-Wallis ANOVA test, it was determined that the class "redoximorphic soils" is significantly different from the class "well-aerated soils", with a $p\text{-value} < 0.005$. This was true for both the emissions relating only to fertilizer nitrogen input and those relating to both fertilizer and deposition nitrogen input. The "Cold" class was determined to be significantly different from both the "Warm-Wet" and the "Warm-Dry" classes ($p < 0.005$), but the two "Warm" classes are not significantly different from each other. The median values of the emission factors for each class were used in the regionally disaggregated estimations of the N_2O emissions presented in the next paragraph.

To achieve our main objective of estimating the sum of N_2O emissions from agricultural land use and their spatial distribution in Germany, two variants of a calculation model were developed with the ArcGIS ModelBuilder. The variants were:

1. Regionalization based on the soil aeration and climate classifications, using both fertilizer and atmospheric deposition nitrogen input
2. Regionalization based on the soil aeration and climate classifications, using only fertilizer nitrogen input

As a first step common to all variants, all features representing agricultural land use were selected from the CORINE Land Cover dataset. These features were then intersected with the VG250 dataset, which contains the administrative boundaries. In the next step, the nitrogen input per hectare of agricultural land was determined. The quantity of fertilizer used was determined by dividing the total quantity of fertilizer used in individual districts by the area of agricultural land of each district. For the model modification that took the atmospheric nitrogen depositions into account, zonal statistics were applied to determine

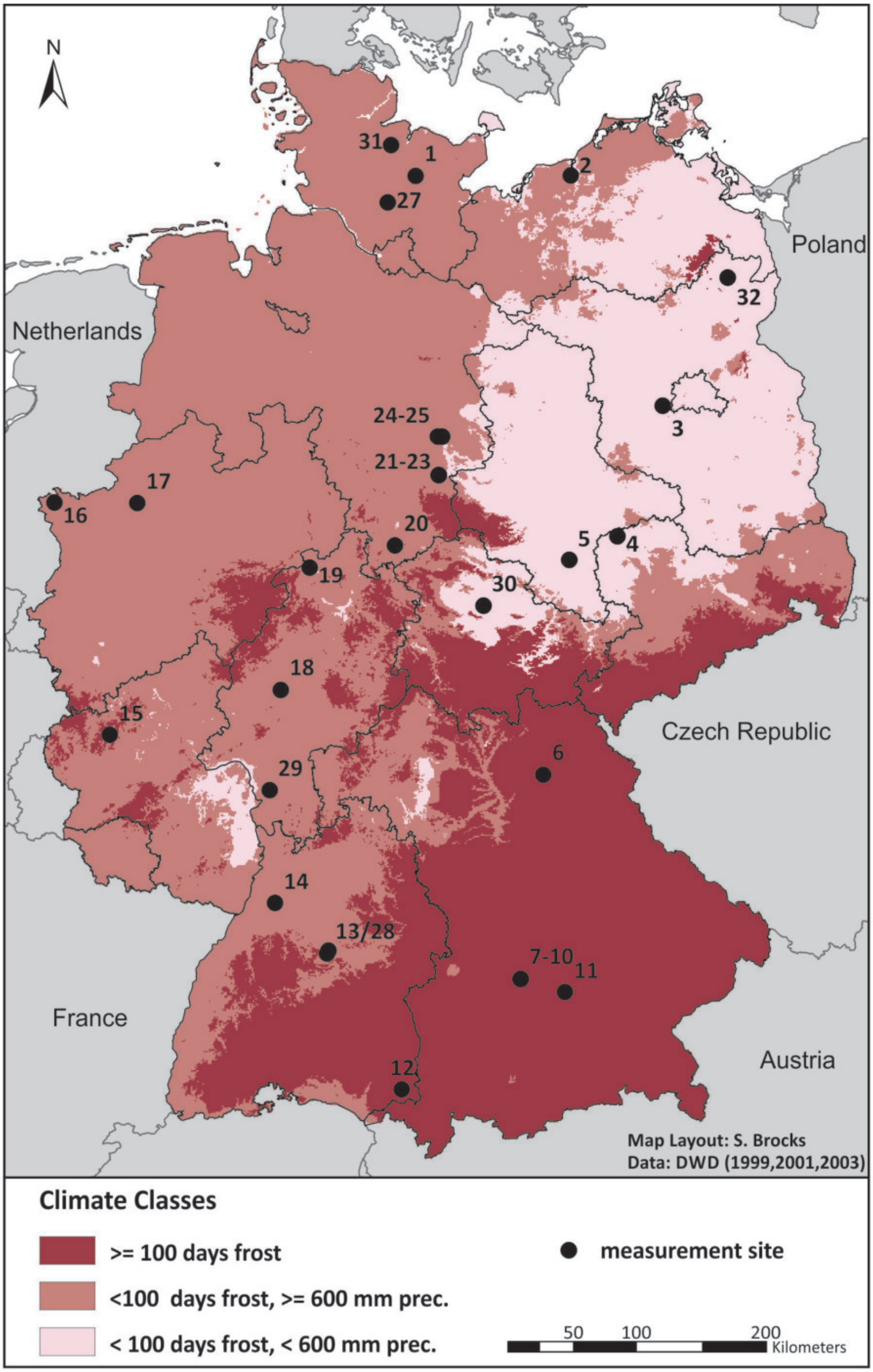

Fig. 3: Climate classes and measurement sites (modified after Jungkunst et al. (2006))

the mean nitrogen deposition per hectare for each district's agricultural land. The quantity of deposited nitrogen was simply added to the quantity of fertilizer used per hectare of agricultural land; this resulted in the total quantity of nitrogen input per hectare of agricultural land for each district in Germany.

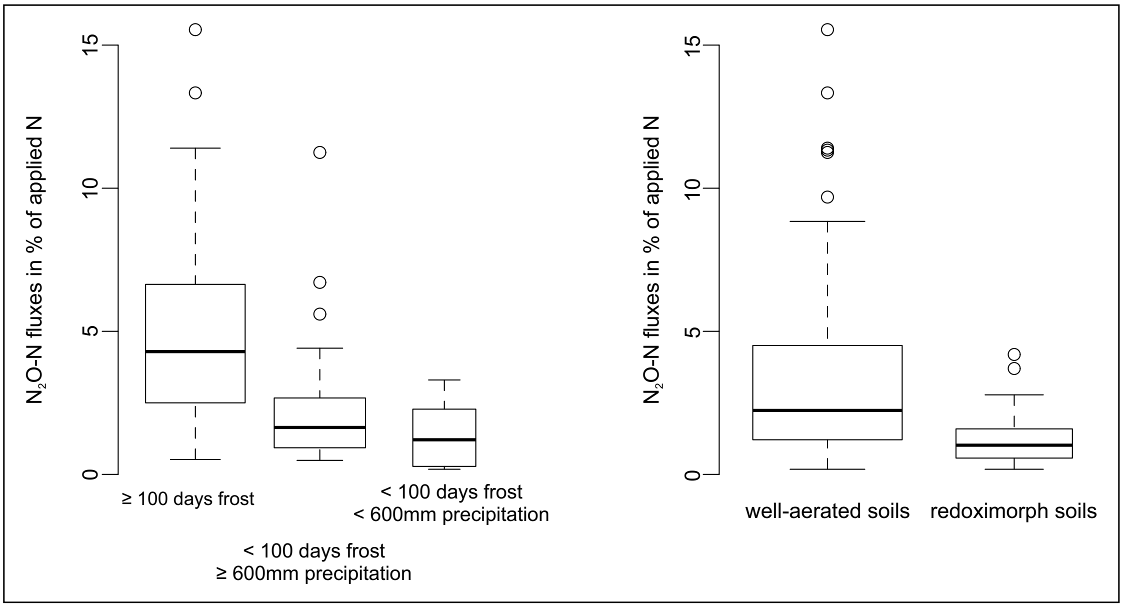

Fig. 4: Distribution of emission factors, ignoring atmospheric deposition

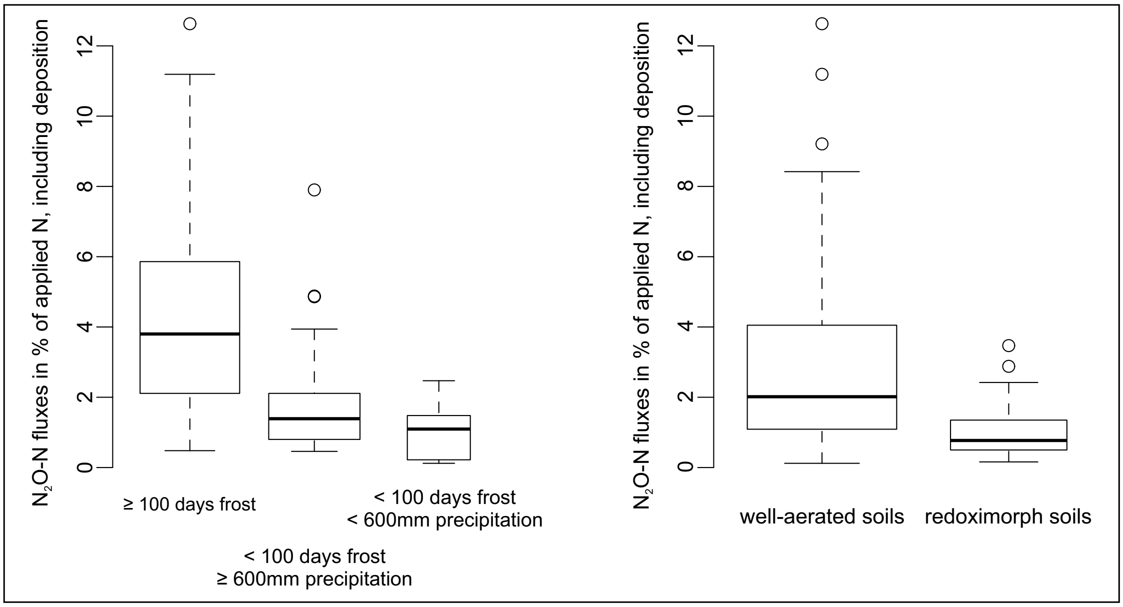

Fig. 5: Distribution of emission factors, considering atmospheric deposition

The emission factors presented in table 1 for soil type, and climate data were used to estimate the N_2O emissions. To obtain the soil type regionalization, the BÜK1000 dataset was intersected with the data. The following 16 of the 71 soil mapping units of the BÜK1000 were classified as redoximorphic: 6: Eutric Histosols, 7: Dystric Histosols, 8,10,11,12 Fluvisols / Gleysols, 9: Gleyic Chernozems, 22,23,43: Stagnic Gleysols, 24: Stagnic Chernozems, 28: Spodo Stagnic Cambisols / Stagnic Podzoluvisols, 47: Eutric Cambisols / Stagnic Gleysols, 48: Stagnic Gleysols / Eutric Cambisols / Haplic Luvisols, 56: Dystric Cambisols / Stagnic Gleysols, 64: Stagnic and Spodic Gleysols. They were chosen because all these soil units feature large areas of soils that are influenced by groundwater or water logging conditions, and therefore exhibit redoximorphic features. The other soil mapping units were classified as well-aerated. For the climate data, a raster data-

Tab. 1: Emission factor medians and means of soil and climate classes

Class	EF[1]		EF deposition[2]	
	Median	Mean	Median	Mean
Redoximorphic Soils (n=34)	1.02	1.21	0.77	1.02
Well-aerated Soils (n=56)	2.24	3.59	2.02	3.02
Well-aerated and Cold (n=25)	4.29	5.39	3.80	4.53
Well-aerated and Warm-Dry (n=10)	1.21	1.37	1.10	1.06
Well-aerated and Warm-Wet (n=21)	1.64	2.50	1.39	2.03

[1] emission factor relating to fertilizer nitrogen input

[2] emission factor relating to fertilizer and deposition nitrogen input

set representing the three climate classes was generated. This was achieved by combining the datasets of the 30-year average precipitation and the frost days using a nested map algebra script. This script determines the climate class to which each raster cell belongs by checking the frost days and precipitation values against the thresholds defined by the class definition:

> Con("% frost %" >= 1000 ,1 ,Con("% prec%" >= 600 ,2 ,3))

To combine this raster dataset with the previously generated vector dataset containing land use, administrative borders and nitrogen input, it had to be converted into a vector dataset and then intersected with the data. At this point, all the data that was necessary to estimate the N_2O emissions in the intended regionally disaggregated manner had been collected.

Next, a hierarchy of emission factors had to be developed. Based on the results showing the independence of soil aeration on climatic conditions, soil aeration had been chosen as the primary factor for determining which emission factor to choose: If the soil type is redoximorphic, the emission factor for the class "Redoximorphic Soils" was used. Otherwise, the emission factor of the respective climate class was used to calculate the emissions.

In a final step, the area of each feature was multiplied with the N_2O emissions per hectare (calculated in the previous step) to determine each feature's estimated N_2O emissions per year. This is necessary in order to estimate the total N_2O emissions from agricultural land use in Germany.

In order to be able to compare our data to the national greenhouse gas inventories published by the member parties to the United Nations Framework Convention on Climate Change (UNITED NATIONS 1992), the annual direct N_2O-N emissions produced by managed soils were also estimated. This was achieved by regionally disaggregating the respective part of the Tier 1 guidelines to determine N_2O emissions from managed soils (IPCC 2007). According to these guidelines, nitrogen inputs from the following sources had to be considered for direct N_2O emissions:

- synthetic nitrogen fertilizers
- organic N applied as fertilizer
- urine and dung N deposited by grazing animals on pasture, range and paddock
- N in crop residues
- N mineralization associated with loss of soil organic matter
- drainage/management of organic soils

To facilitate a comparison with the climate and soil-aeration based approach and for reasons of data availability, only the first two and the last of these nitrogen sources where considered in this comparatively simple approach. For Germany, only two emission factors are relevant: EF_1 for N_2O emissions from nitrogen inputs to soils, with a value of 0.01, and EF_2 for drained or managed organic soils. For EF_2, the value of 5.8 kg N_2O-N/ha that was suggested by COUWENBERG (2009) was used instead of the default value from IPCC (2007), which is 8 kg N_2O-N/ha. To allow this calculation, the features representing agricultural land use were again intersected with the VG250 dataset and the BÜK1000 dataset, and then combined with the fertilizer use dataset. In a second step, the quantity of nitrogen used per hectare was calculated. This estimate accounts for direct N_2O emissions by both organic and mineral soils, by multiplying the nitrogen input due to fertilizer use per hectare (for non-organic soils) and the area (for organic soils) by the respective emission factor. Indirect N_2O emissions were not considered by this approach because the IPCC guidelines attribute indirect N_2O emissions from deposited nitrogen to the location where the nitrogen was originally volatilized, a process for which no data is readily available.

3 Results

Figures 6 and 7 show a visualization of the results of the regionally disaggregated estimation of N_2O emissions using the main variants of the two presented approaches. Figure 6 shows a clear similarity to figure 1. This can be explained by the fact that, apart from the specific emission factor for organic soils, the estimated emissions are proportional to the district-level fertilizer use: For each district, a distinct emission-per-hectare value can be seen. In figure 7, more information was used to estimate the emissions. The highest emissions are found in the south of Germany, in the region covered by the "Cold" climate class. Another notable feature that is visible on the map is the lower emissions in the regions covered by redoximorphic soils, mainly visible in eastern and southern Germany. This is a result of the lower emission factor for the class "Redoximorphic Soils" when compared with the other classes, cf. table 1. The strong difference in estimated N_2O emissions between Schleswig-Holstein and Mecklenburg-West Pomerania can be explained by the fact that the quantity of nitrogen fertilizer applied to the soils differs drastically between the two regions, as can be seen in figure 1: There is a difference of 50–100 kg N/ha between the federal states of Schleswig-Holstein and Mecklenburg-West Pomerania.

Table 2 shows the aggregate N_2O emissions for all of the variants developed in this contribution and the N_2O emissions due to managed organic soils and fertilizer use that were reported in the national greenhouse gas inventory in 2011. Uncertainties for the estimates made in this contribution are also shown: These are the upper and lower boundaries of the calculated emission values, and are based on using the upper and lower boundary of the 0.95 confidence interval of the different climate and soil-aeration class emission factors. These uncertainties should provide some rough guidance on the estimated values; however, the uncertainties of the input data such as land use, soil classification etc. cannot be quantified correctly.

The estimated emission sums from the disaggregated IPCC methodology only differ by 7.2% from the sums reported in the national greenhouse gas inventory. This small discrepancy can be explained by the following facts:

Mineral fertilizer data: the official inventory uses the current data on the quantity of mineral fertilizer sold in Germany provided by the Federal Statistical Office (not available in a spatially disaggregated format) and also considers nitrogen losses due to NH^-_3 and NO emissions (UMWELTBUNDESAMT 2013, 458)

Organic fertilizer data: the official inventory calculates the quantity of organic fertilizer based on the number of livestock kept by farmers (UMWELTBUNDESAMT 2013, 458)

Different emission factors used in the national greenhouse gas inventory (the inventory uses the value of 0.0125 (IPCC 1997) for EF_1, the emission factor for nitrogen input, and the value 8 for EF_2, the factor for managed organic soils (IPCC 2007); in this paper, the values of 0.01 from IPCC (2007) for EF_1 and 5.8 for EF_2 from COUWENBERG (2009) are used)

Table 3 shows the aggregate sums and average emission fluxes for Germany's states when estimating the N_2O emissions using the variant that classifies by climate class and soil aeration and takes both fertilizer and deposition nitrogen input into account. The uncertainty shown is again the upper and lower boundary of the emissions when calculating using the upper and lower boundary of the 0.95 confidence interval of the respective class of emissions factors, instead of the median emission factor.

4 Discussion and conclusion

The basic approach of this study, i.e. without any assumptions as to soil and climate impact, estimates the total emissions for Germany to be 35 Gg N_2O-N per year, which is comparable to the results of the national inventory, i.e. 40.66 Gg (UMWELTBUNDESAMT 2013, 469). As explained above, the discrepancy is because some sources of reactive nitrogen were not included in this study. Therefore, we are basically dealing with the same database, and as a result the scenarios of climate and soil impact are directly comparable. The variation of regionally specific results provide the basis for general discussions within the scientific communities on how realistic they may be. Such an analysis, i.e. comparing different scenarios allows elucidation of potential additional mitigation options, which may then be implemented by political decisions. Additionally, regions in which additional measurement would be most effective to improve both the inventory and process understanding can be identified. The emission values for the soil- and climate-based regionalization are significantly higher (i.e., by a factor of roughly 1.7) than the compiled results of the regionally disaggregated IPCC methodology. This can be explained by the fact that the emission

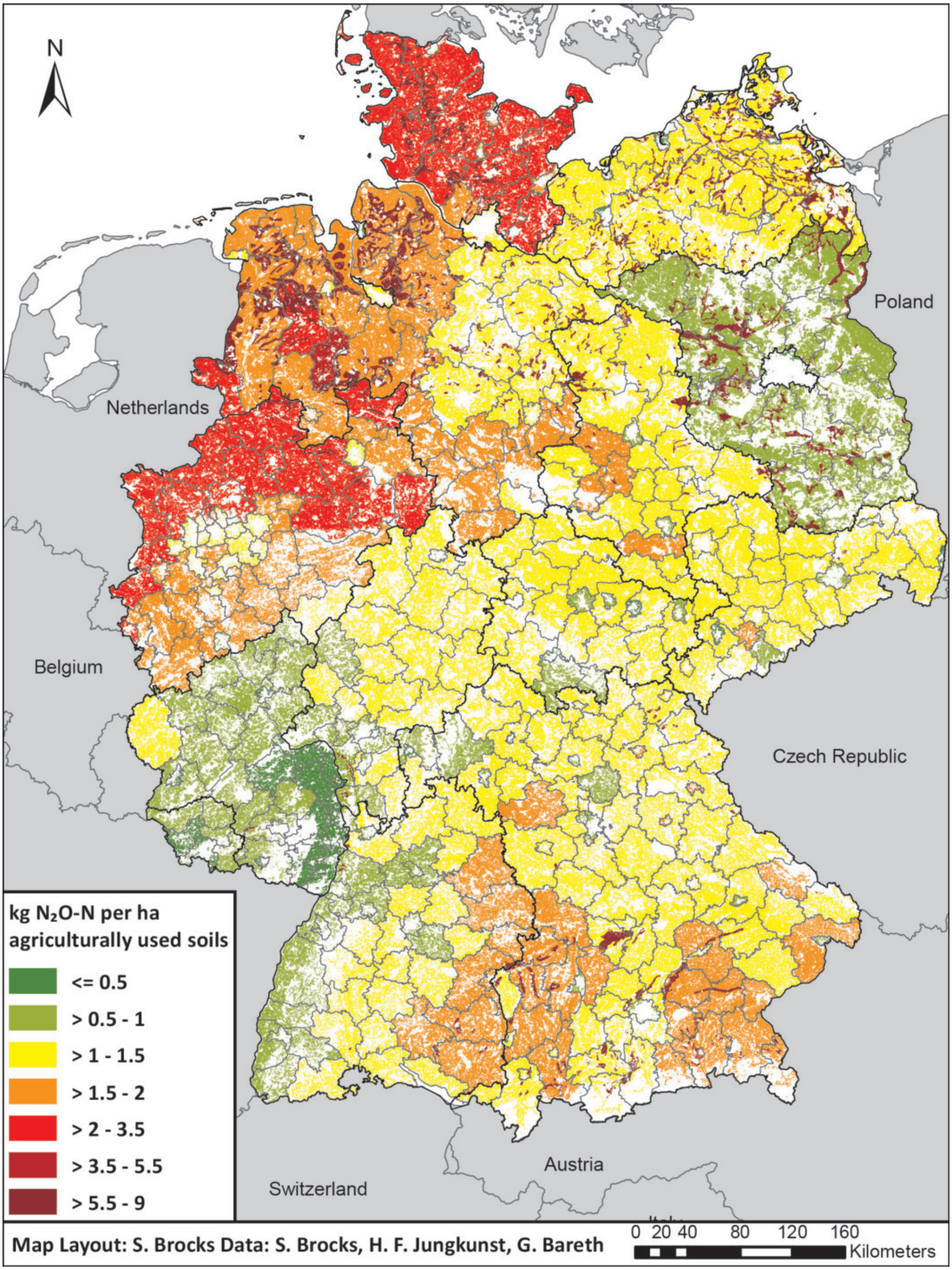

Fig. 6: Regionally disaggregated estimation of N_2O emissions using the IPCC method

factor suggested by the IPCC is lower than all of the calculated emission factors except for the emission factor for the “Redoximorphic Soils” class.

The differences between the estimate when regionalizing by soil aeration and climate classification and the estimate resulting from the disag-

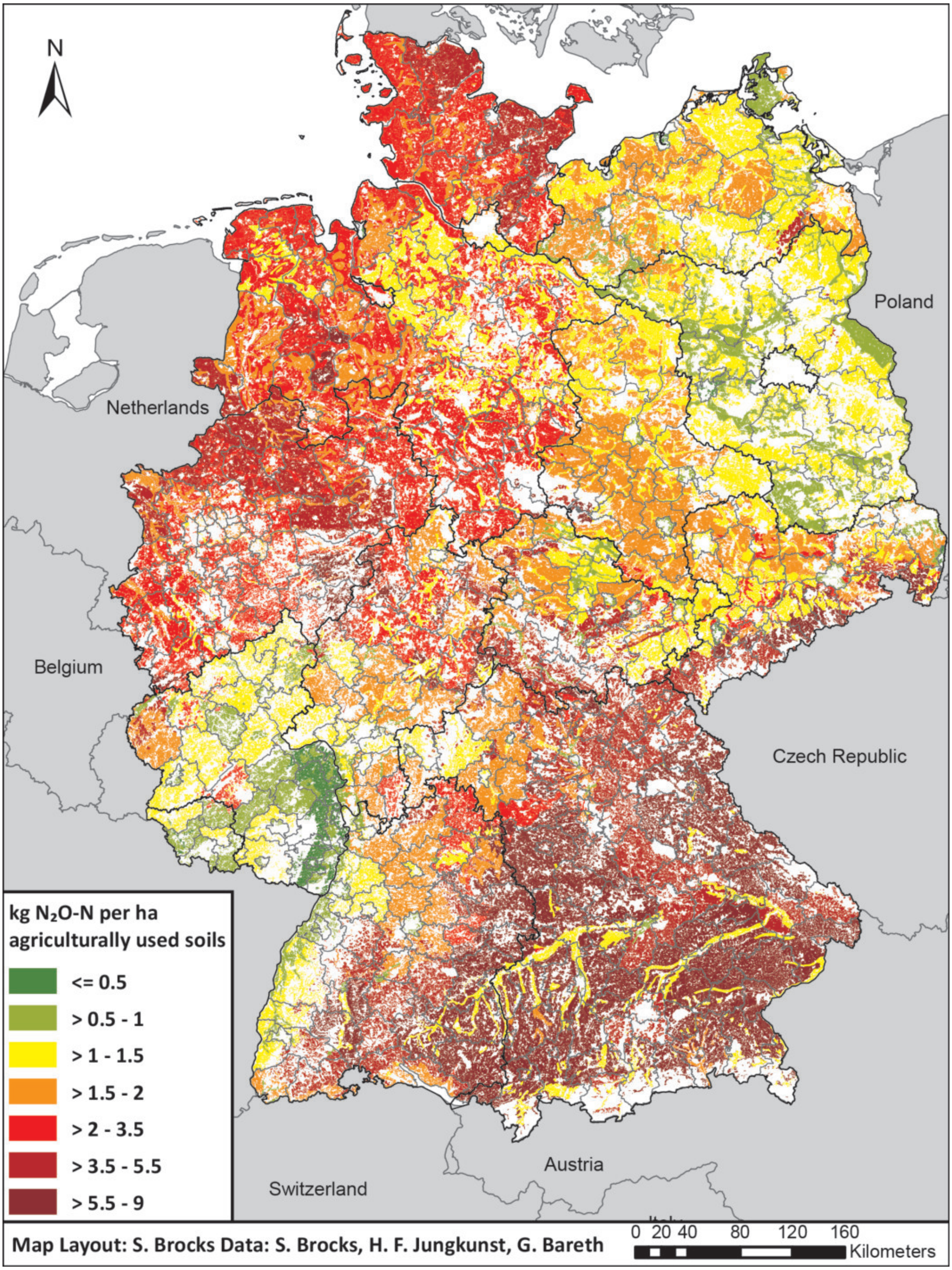

Fig. 7: Regionally disaggregated estimation of N_2O emissions based on climate classes and soil aeration

gregated IPCC methodology can be derived from figure 8 by showing the regionalized IPCC methodology (bottom) and the climate and soil-aeration based estimations (top) side-by-side for the eastern German region of Saxony. This clearly shows how the IPCC methodology only considers nitrogen

Tab. 2: Estimated aggregate N_2O emissions from agricultural land use in Germany

Estimation	Gg N_2O-N emissions per year	(uncertainty)
IPCC 2006	35.70	
Climate classes and soil aeration[1]	59.63	(49.90 – 98.19)
Climate classes and soil aeration[2]	60.30	(51.15 – 109.42)
UMWELTBUNDESAMT (2013, 469)[3]	40.66	

[1] relating to fertilizer and deposition nitrogen input
[2] relating to fertilizer nitrogen input
[3] emissions due to fertilization and managed organic soils

inputs (which are only available at a district level, explaining the different emission levels shown per district) and whether or not the soil is classified as organic soil (visible through the high-emission areas in Brandenburg). In contrast, the climate and soil-aeration based estimate exhibits a higher degree of regionalization, especially in areas such as the one shown in the figure, in which the borders of the different climate classes meet. The most apparent discrepancies resulted from the relevantly higher emission factor for the "Cold" class in the regionalization. At least since the publication by FREIBAUER and KALTSCHMITT (2003), the core region around the state of Bavaria and adjacent regions of other states are "suspected" to exhibit higher emissions than the rest of Germany. This repeating pattern is not that surprising since the studies of KAISER and RUSER (2000), JUNGKUNST et al. (2006) and DECHOW and FREIBAUER (2011) rely on numerous identical studies, which are additionally clustered at the Scheyern site (FLESSA et al. 1995; DÖRSCH 1999; RUSER et al. 2001; SEHY et al. 2003). Even though each additional measurement site confirmed the high emission values for this "Cold" region, we highly recommend more dispersed measurements in this region. Actually, most of these sites did not emit a higher proportion of its annual emissions during the winter than sites in the other regions do. Therefore, more intensive frost-thaw events are unlikely to be the only causative factor. Apparently, the summer emissions are also higher for that region. If this pattern was to be repeatedly confirmed, we may clearly concentrate with elaborating mitigation options potential for Germany in this "Cold" region.

Tab. 3: Estimated total N_2O emissions per state in Germany when classifying by climate characteristics and soil aeration, accounting for deposition and fertilizer nitrogen input

State	Mg N_2O-N per year (uncertainty)		Average N_2O-N flux in kg/ha (uncertainty)	
Baden-Württemberg	7063	(6086 – 11186)	3.82	(3.29 – 6.05)
Bavaria	20334	(17590 – 31205)	5.12	(4.43 – 7.86)
Berlin	3	(2 – 5)	0.55	(0.27 – 0.80)
Brandenburg	1656	(1092 – 2563)	1.04	(0.68 – 1.60)
Bremen	25	(21 – 45)	1.74	(1.47 – 3.19)
Hamburg	31	(28 – 56)	1.38	(1.23 – 2.47)
Hesse	2308	(1952 – 4008)	2.22	(1.88 – 3.86)
Lower Saxony	7363	(6354 – 13279)	2.24	(1.93 – 4.04)
Mecklenburg-West Pomm.	2273	(1698 – 3771)	1.43	(1.07 – 2.38)
North Rhine-Westphalia	6320	(5331 – 11476)	3.11	(2.63 – 5.66)
Rhineland-Palatinate	1111	(911 – 1954)	1.11	(0.91 – 1.95)
Saarland	125	(103 – 230)	0.99	(0.82 – 1.83)
Saxony	2675	(2241 – 4289)	2.41	(2.02 – 3.87)
Saxony-Anhalt	2160	(1401 – 3311)	1.53	(0.99 – 2.35)
Schleswig-Holstein	3953	(3293 – 7309)	3.23	(2.69 – 5.98)
Thuringia	2223	(1798 – 3506)	2.33	(1.89 – 3.68)
overall	59625	(49902 – 98194)	2.81	(2.35 – 4.63)

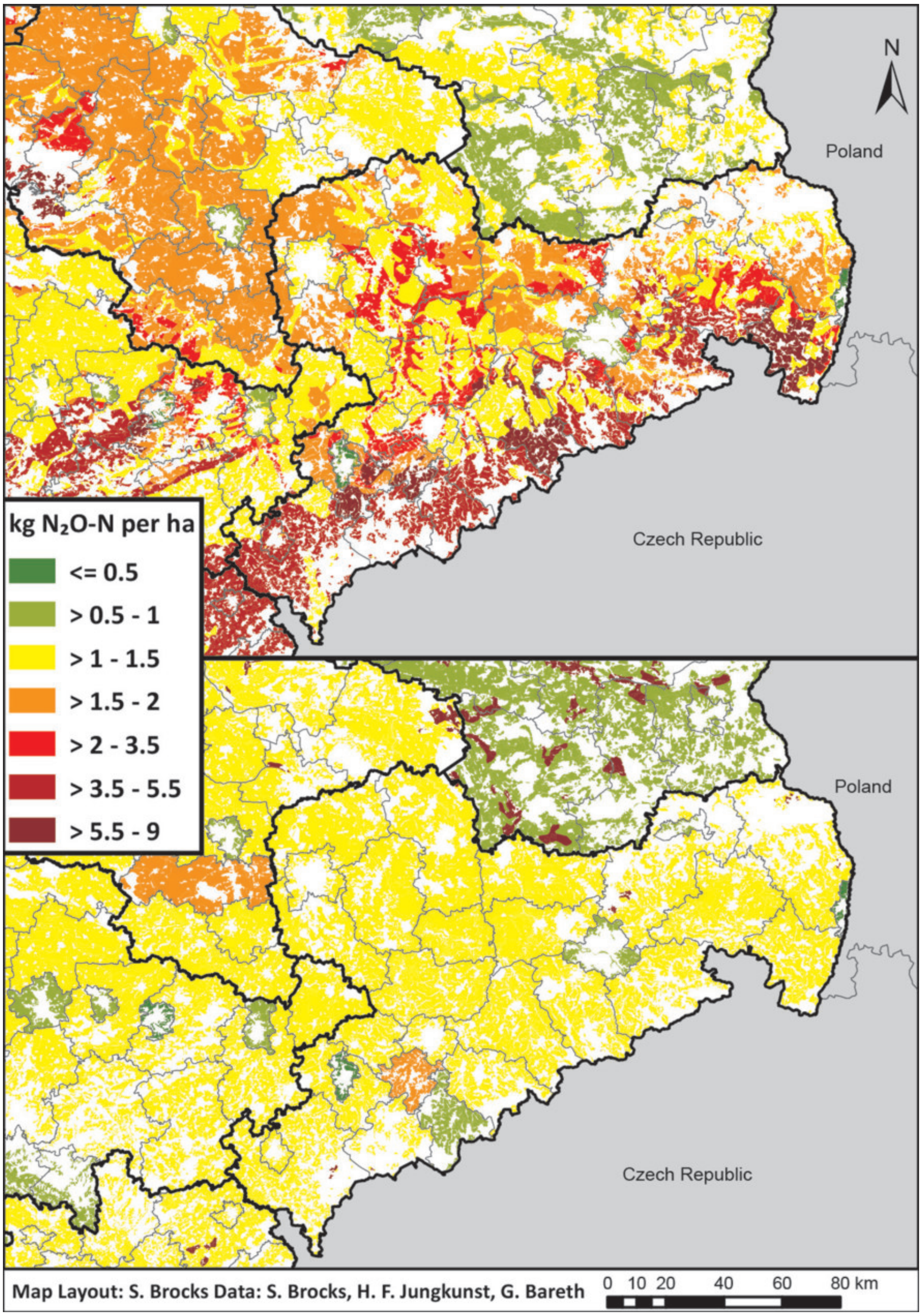

Fig. 8: Comparison of N_2O emission estimation between estimation using climate classes and soil aeration (top) and the disaggregated IPCC emission estimation (bottom)

The other apparent discrepancy is the result of different emission factors that were applied for managed organic soils, which is most visible by the well-delineated areas with emissions > 5 kg N_2O-N per hectare in northern Germany. The IPCC methodology ignores nitrogen input and assumes a fixed emission value for such soils. Whether or not one emission factor really fits to all organic soils should be further investigated. At least it would fit to the result of this study found for the redoximorphic soils, which are related to the organic soils. It is logical that highly water saturated soils do not exhibit a high dependency to climate conditions in Germany. However, it is surprising that organic soils are defined as high emitting sites, whereas redoximorphic ones exhibited the opposite. This is another important issue that was identified here, and we again highly recommend studies on N_2O emission dynamics under changing high water saturation by comparing mineral and organic water logged soils under agricultural use. The underlying processes should be identified in more detail.

In the future, results could be improved with better input data. This could be, e.g., better soil data such as the upcoming German-wide BÜK200 with a scale of 1:200 000 or a land-use dataset with a higher precision. Furthermore, increasing the sample size of the emission measurements would result in emission factors that are more representative.

The comparison with process-based models as EFEM-DNDC by NEUFELDT et al. (2006) yielded general agreement: NEUFELDT et al. (2006) provided modeled direct N_2O emissions from agricultural soils for the state of Baden-Württemberg of 3.08 kg N_2O-N per hectare, which is 20% lower than the emissions estimated for Baden-Württemberg in this work. HAAS et al. (2013) calculated N_2O emissions of 2693 Mg N_2O-N for the year 2000 and the state Saxony, which is within 1% of the estimate made in this paper. The difference can be explained by the fact that LandscapeDNDC not only accounts for direct N_2O emissions from agricultural soils due to fertilization and deposition of nitrogen, but also accounts for indirect emissions from grazing and residues (HAAS et al. 2013, 626). However, the spatial distribution of their results only partially matches that seen for our results, as shown in the top part of figure 8: Hotspots exhibiting high emission rates are found in areas with high soil organic carbon content according to the BÜK1000. Within the area covered by the "Warm-Dry" climate class, these high-SOC areas match the areas classified as well-aerated in this work, where a higher-emission factor is used. In contrast, the areas of highest emissions in the estimate made in this work are the areas in the south of Saxony that lie within the "Cold" climate class, and these do not match any emission hotspots in the paper by HAAS et al. (2013). MANDER et al. (2010) employed an approach that is similar to the one presented in this work. They calculated median emission values per hectare for different land-uses and soil types using data from 950 study sites/experiments, and estimated N_2O and CH_4 emissions for Estonia using GIS map algebra. However, they did not take differences in nitrogen input and climate characteristics into account, but only used the soil type and land use. Their median rate of N_2O-N emissions of 1.4 kg per hectare of arable land is significantly lower than the overall average of N_2O-N emissions of 2.81 kg N_2O-N estimated in this paper. However, if one considers the more maritime climate of Estonia, it could be mostly related to the northwest of Germany, and the emission rate there was lower than the national average, 2.24 kg N_2O-N per hectare for Lower Saxony. Beyond that, it should be noted that MANDER et al. (2010) did not consider any differentiation in the amount of fertilizer applied which highly limits comparison with results presented in this paper.

The results of DECHOW and FREIBAUER (2011) also suggest that emissions on agricultural soils are strongly influenced by climate and soil properties. Their mean annual emission level from agricultural lands is 40 Gg N_2O-N. For croplands, their results show high N_2O emission rates in the southern part of Germany, comparable to the high-emission "Cold" region of this contribution. However, their results suggest differentiation between emissions from grasslands and croplands, a distinction we do not explicitly make in this contribution, because grasslands and redoximorphic soils are linked in this dataset. More data on redoximorphic croplands and well-aerated grasslands would be advantageous. At the very least, we have to find out if it is grass that reduces N_2O emission or the redoximorphic processes in the soils.

Generally, emissions should not only be related to area, but also to agricultural yield, i.e. how many kg N_2O per J of food has to be discussed. This would better facilitate interstate comparisons of emissions (Tab. 3). However, data availability is a limiting factor in this context. Preliminary calculations, which we made using the data that are available from STATISTISCHES BUNDESAMT (2013), suggest that drastically different outcomes in a comparison of states based on emissions per crop yield should not be expected.

Like process-based models, the presented approach offers the opportunity to estimate emissions from different scenarios, by substituting the measured climate or land-use data with projected data. But compared to process-based models the advantage of our approach is that less input data are required, since many (especially spatial) data are often not available. Hence, alternative scenarios for land-use change and climate-change can be computed more easily. The analysis of the results and the comparison to other, more process-based projections will push the scientific discussions and policy decisions forward.

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Appendix: N_2O emission measurements and emission factors

Site	Year	N fert.	N dep.	N_2O flux	EF[1]	EF dep.[2]
			kg N/ha/a		% of applied N	
1	1993	78	30	1.5	1.92	1.39
1	1993	79	30	5.3	6.71	4.88
1	1993	319	30	2.1	0.66	0.60
2	1996–1998	81	21	0.6	0.74	0.59
2	1996–1998	193	21	1.1	0.57	0.52
2	1996–1998	77	21	0.8	1.04	0.82
2	1996–1998	106	21	1.1	1.04	0.87
3	1999–2004	75	16	1.3	1.73	1.43
3	1999–2004	150	16	2.1	1.40	1.26
4	1997–1999	80	17	2.4	3.00	2.47
5	2002–2003	40	18	0.1	0.18	0.12
5	2002–2003	80	18	0.2	0.28	0.22
5	2002–2003	120	18	0.3	0.21	0.18
6	1998–1999	75	14	10.0	13.33	11.19
7	1992–1993	83	19	9.4	11.33	9.21
7	1992–1993	83	19	12.9	15.54	12.63
7	1992–1993	190	19	9.6	5.05	4.59
7	1992–1993	190	19	16.8	8.84	8.03
8	1992–1994	127	19	6.5	5.12	4.45
8	1992–1994	127	19	12.3	9.69	8.42
8	1992–1994	125	19	8.3	6.64	5.76
9	1995–1997	50	19	5.7	11.40	8.28
9	1995–1997	150	19	6.9	4.60	4.09
9	1995–1997	90	19	2.7	3.00	2.48
9	1995–1997	180	19	3.6	2.00	1.81
9	1995–1997	65	19	1.3	2.00	1.55
9	1995–1997	130	19	2.4	1.85	1.61
10	1999–2000	210	17	1.1	0.52	0.48
10	1999–2000	200	17	8.7	4.35	4.01
10	1999–2000	227	17	7.2	3.17	2.95
10	1999–2000	202	17	6.4	3.17	2.92
10	1999–2000	175	17	3.1	1.77	1.62
10	1999–2000	200	17	3.9	1.95	1.80
10	1999–2000	202	17	5.7	2.82	2.60
10	1999–2000	92	17	2.3	2.50	2.11
10	1999–2000	92	17	3.3	3.59	3.03
11	1995–1996	170	22	7.3	4.29	3.80
11	1995–1996	270	22	17.1	6.33	5.86
12	1996–1998	170	20	0.3	0.18	0.16
13	1994–1995	100	15	5.6	5.60	4.86
14	1993–1994	145	17	6.4	4.41	3.94
14	1993–1994	165	17	5.1	3.09	2.80
15	1995–1998	120	17	0.5	0.42	0.36
15	1995–1998	240	17	0.8	0.33	0.31
15	1995–1998	360	17	2.4	0.67	0.64
16	1995–1998	120	59	0.9	0.75	0.50
16	1995–1998	240	59	0.9	0.38	0.30

Site	Year	N fert.	N dep.	N_2O flux	EF[1]	EF dep.[2]
			kg N/ha/a		% of applied N	
17	1995–1998	120	41	0.8	0.67	0.50
17	1995–1998	240	41	1.2	0.50	0.43
18	1996–1997	40	16	0.8	2.00	1.43
18	1996–1997	80	16	1.0	1.25	1.04
18	1996–1997	120	16	1.3	1.08	0.96
18	1996–1997	240	16	2.8	1.17	1.09
18	1996–1997	400	16	4.2	1.05	1.01
18	1996–1997	40	16	0.4	1.00	0.72
19	1996–1997	195	18	2.3	1.18	1.08
20	1995–1997	76	18	1.1	1.45	1.17
20	1995–1997	153	18	1.1	0.72	0.64
21	1995–1996	115	17	3.2	2.78	2.42
21	1995–1996	115	17	2.0	1.74	1.52
21	1995–1996	212	17	0.9	0.42	0.39
22	1995–1996	220	17	3.5	1.59	1.48
23	1992–1996	40	17	4.5	11.25	7.90
23	1992–1996	60	17	1.6	2.67	2.08
23	1992–1996	108	17	1.0	0.93	0.80
23	1992–1996	175	17	1.5	0.86	0.78
23	1992–1996	350	17	1.7	0.49	0.46
24	1992–1996	110	17	1.8	1.64	1.41
24	1992–1996	210	17	2.5	1.19	1.10
25	1994–1996	130	18	1.6	1.23	1.08
25	1994–1996	260	18	2.7	1.04	0.97
27	2001–2002	74	33	3.1	4.19	2.88
27	2001–2002	100	33	1.8	1.80	1.35
27	2001–2002	174	33	3.6	2.07	1.74
28	2007	319	15	5.7	1.79	1.71
28	2007	401	15	8.8	2.19	2.11
28	2007	528	15	10.6	2.01	1.95
29	2007	100	14	0.7	0.72	0.63
29	2007	60	14	0.8	1.35	1.10
29	2007	100	14	0.7	0.74	0.65
30	2006	31	14	1.0	3.30	2.28
30	2007	371	15	1.1	0.29	0.27
30	2008	156	15	1.6	1.02	0.93
30	2009	27	15	0.6	2.28	1.48
31	2006–2008	360	23	13.3	3.70	3.47
31	2006–2008	360	23	8.7	2.43	2.28
32	2011	160	14	0.5	0.31	0.29
32	2011	160	14	0.8	0.5	0.46
32	2011	160	14	1	0.63	0.58
32	2011	160	14	1.1	0.69	0.63

[1] emission factor relating to fertilizer nitrogen input

[2] emission factor relating to fertilizer and deposition nitrogen input