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Quantifying the regional source strength of N-trace gases across agricultural and forest ecosystems with process based models

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Abstract

The process-based models DNDC and PnET-N-DNDC were evaluated with regard to their potential to calculate regional inventories of N-trace gas emissions from agricultural and forest soils. To extend the model predictions to regional scale, we linked the models to a detailed GIS-database for Saxony, Germany, which was holding all the spatially and temporally differentiated input information and other model drivers. Total annual N_2O-emissions from agricultural soils in Saxony ranged from 0.5–26.0 kg N_2O-N ha^{-1} yr^{-1} and were calculated to amount to approx. 5475 t N_2O-N yr^{-1} in the year 1995, which compares quite well with previous estimates based on the IPCC approach (4892 t N_2O-N yr^{-1}). Compared to the agricultural soils, N_2O-emissions from forest soils in Saxony (range: 0.04–19.7 kg N_2O-N ha^{-1} yr^{-1}) were much lower and amounted to 1011 t N_2O-N yr^{-1}. In comparison with other sources of N_2O in Saxony our estimates show, that – even in such a highly industrialised region like Saxony – soils contribute more than 50% to the total regional N_2O source strength. Simulated emissions of NO from the agricultural and forest soils were approx. in the same magnitude than for N_2O. The modelled NO-emission rates ranged from 0.4–26.3 kg NO-N ha^{-1} yr^{-1} for the agricultural soils and 0.04–28.3 kg NO-N ha^{-1} yr^{-1} for the forest soils with total emissions of 8868 t NO-N yr^{-1} (agricultural soils) and 4155 t NO-N yr^{-1} (forest soils). Our results indicated that the agricultural and forest soils were a significant source, which contributed 17.9% of the total NO_x emissions from various sources in Saxony. Furthermore, a series of sensitivity tests were carried out, which demonstrated that variations in soil organic carbon content (SOC) and soil texture significantly effect the modelled N-trace gas emissions from agricultural soils at the regional scale, whereas, in addition, for forest soils also the soil pH is within the sensitive factors . Finally, multi-year simulations were conducted for the region with observed meteorological data from 1994–1996. The results demonstrated that the modelled interannual variations, which were obviously induced by only the climate conditions, in the N-gas emissions were as high as 36%. The high interannual variations imply that multi-year (e.g., 5–10 years), instead of single baseline year, simulations would produce more reliable estimates of mean soil N_2O-emissions at regional scale. With respect to the Kyoto protocol this means that the mean N_2O-emissions from soils in the period 1988–1992 should be evaluated instead of focusing on a single year, 1990.

Introduction

With regard to global climate change soils are of significant importance as sources for atmospheric trace gases such as nitrous oxide (N_2O) and nitric oxide (NO). Total emissions of the primarily active greenhouse gas N_2O from all soils are estimated to be in a range of 4.9–15 Tg N yr^{-1}, and, thus, contributing approx. 55–65% to the total global atmospheric N_2O budget (IPCC, 1996). With regard to the sources of the secondarily active greenhouse gas NO, soils are

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with approx. 21 Tg NO-N of similar importance for the global atmospheric NO budget as NO-emissions associated with fossil fuel combustion (Davidson and Kingerlee, 1997).

Production of N_2O or NO in soils is predominantly due to the microbial processes of nitrification and denitrification. Nitrification is an oxidative process during which NH_3/NH_4^+ is oxidised to NO_2^-/NO_3^-. This process obligatory requires the availability of molecular oxygen. In contrast, denitrification is a reductive process, which mainly occurs in oxygen depleted soil zones. Under anaerobic conditions, some microbes can use NO_3^-/NO_2^- as an alternative electron acceptor, thereby reducing NO_3^-/NO_2^- sequentially to NO, N_2O and finally to N_2 (Conrad, 1996). Both processes can simultaneously occur in soils, although the rates of the two processes depend on the soil aeration and the microsite availability of substrates. At low soil pH-values (< 4.0) the physico-chemical process of chemodenitrification has to be considered as an additional process of NO-production in soils (Van Cleemput and Baert, 1984). However, the emission of N-trace gases from soils is the result of simultaneous occurring production and consumption processes (Conrad, 1996), and, hence, an adequate understanding for both production and consumption of N-trace gases in soils is essential for quantifying the gas emissions. With regard to N_2O the only hitherto known consumption process is its further reduction to N_2 by denitrifying bacteria, whereas for NO oxidative and reductive consumption pathways via the microbiological processes nitrification and denitrification have been described (e.g., Dunfield and Knowles, 1997). The rates of N-trace gas consumption in soils are related to the diffusivity of the soil, which influences oxygen availability as well as N-gas residence time. The soil diffusivity is regulated by soil moisture and other soil properties such as texture and SOC-content. This complex pattern of processes involved in N-trace gas production, consumption and emission in/from soils is further controlled by other biotic processes (e.g., mineralisation, plant N-uptake) or by abiotic factors such as soil temperature and moisture, soil pH, N availability, cropping or forest management, soil moisture or N-deposition (e.g., Papen and Butterbach-Bahl, 1999; Kaiser et al., 1996), which do change substantially on spatial as well as on temporal scales (e.g., Davidson et al., 1998; Papen and Butterbach-Bahl, 1999). In view of the complexity of processes underlying the N-trace gas exchange between soils and the atmosphere, it is not astonishing that estimates of the gas source strength of soils on a regional and global scale are highly uncertain. However, quantifying such source strengths is unavoidable for the signatory states to the United Nations Framework of Climate Change (UNFCC), which requires to report annual national inventories of N_2O-emissions from all anthropogenic sources, including soils. Based on the Intergovernmental Panel on Climate Change (IPCC) recommended approach, forest soils are not directly included in the N_2O sources and only accounted for by the term ‘indirect emissions’ (IPCC, 1997). The IPCC approach relies on emission factors, which specify the fraction of N_2O emitted to the atmosphere if N-fertilisers, manure or crop residues are applied to soils. The emission factor for inorganic N-fertilizer applied to soils is 0.0125, i.e., one assumes that 1.25% of total N applied to a field as mineral N-fertilizer is lost in form of N_2O to the atmosphere. Since the emission factors were derived from a limited number of measurements in different countries (IPCC, 1997), the factors themselves still possess large uncertainties. This also applies for national inventories, since the variations in the background conditions such as climate variability, land management, soil properties, etc. are not covered by the IPCC approach (Brown et al., 2001).

Substantial improvements of current estimates of N-trace gas fluxes from soils may only be achieved, if process-based models, which are able to simulate N-trace gas emissions based on the processes involved in N-trace gas production, consumption and emission, are employed in the inventory studies. This paper reports a methodological approach which has been applied to calculate regional inventories of NO- and N_2O emissions across agricultural and forest ecosystems with two process-based models, the DNDC and the PnET-N-DNDC models (Li, 2000; Li et al., 2000; Stange et al., 2000; Butterbach-Bahl et al., 2001) coupled with a geographic information system (GIS) database. The domain area for this study is Saxony, Germany, a region with well documented heterogeneous land use, soil and climate properties. An intensive sensitivity analysis was performed to test the performance of the process based models on the regional scale. Finally, the modelled regional results were compared with the estimates from the IPCC approach.

Material and methods

Model description

Two process-based models, DNDC and PnET-N-DNDC, were utilized for calculating inventories of N-trace gas emissions from agricultural and forest soils, respectively, in Saxony. The two models were developed to integrate the complex interactions among primary drivers (e.g., climate, soil, vegetation, and anthropogenic activity), soil environmental factors (e.g., temperature, moisture, pH, Eh, and substrate concentration gradients), and various biogeochemical reactions, which finally control transformation and transport of C and N in the ecosystems (Li, 2000). Both of the models consist of several sub-models for predicting plant growth, soil climate, decomposition, nitrification and denitrification, respectively. The soil climate sub-module converts daily climate data into soil temperature and moisture profiles for up to 50 horizontal soil layers. It also calculates soil oxygen diffusion within the soil profile (Li et al., 2000). The plant (i.e. crop or forest) growth sub-module simulates crop/forest growth at a daily time step driven by solar radiation, temperature, water stress and N stress, and passes litter production, water and N demands to the soil climate or decomposition sub-modules. The decomposition sub-module tracks turnover of litter (leaves, stem, roots) and other organic matter in the soil, and provides ammonium and dissolved organic carbon (DOC) for the nitrification and/or denitrification sub-modules. The nitrification sub-module predicts growth and death of nitrifiers, the nitrification rate as well as N_2O- and NO-productions from nitrification regulated by soil temperature, moisture, and ammonium and DOC concentrations. The denitrification sub-module simulates denitrification and changes in population size of denitrifiers as a function of soil temperature, moisture, and substrates (e.g., DOC, NO_3^-, NO_2^-, NO and N_2O) concentrations. The denitrification-induced N_2O- and NO-fluxes are calculated based on the dynamics of soil aeration status, substrate limitation and gas diffusion. Furthermore, chemo-denitrification is considered as a source of NO-production in soils. This process is controlled by the availability of nitrite and the soil pH. Since nitrification and denitrification can simultaneously occur in aerobic and anaerobic microsites, a kinetic scheme for anaerobic volumetric fraction (or so-called ‘anaerobic balloon’) was used in both models to calculate the anaerobic fraction of soil in a given soil layer in dependency of O_2-diffusion and the respiratory activity of soil micro-organisms and roots (Li et al., 2000).

Input parameters required by the models include daily climate data, soil properties (e.g., texture, pH, organic matter content, bulk density), vegetation (e.g., crop type/forest type and age), and management (e.g., tillage, fertilisation, manure amendment, planting, harvest etc.). As compared to agricultural soils, many forest soils have a high stone fraction in the uppermost soil layers. Therefore, the PnET-N-DNDC model has been modified to include the stone content, whereas this parameter is not required for the agricultural model DNDC. This new parameter affects hydrological properties and gas diffusion in the soil profile through altering the soil macropore occurrence with increasing stone content. In addition, the stone fraction also affects the soil organic matter content. For further details on the models we refer to Li et al. (1992, 1996, 2000), Li (2000), Stange et al. (2000) and Butterbach-Bahl et al. (2001). Both of the models have been validated extensively against field data sets observed worldwide (e.g., Li et al., 1996; Stange et al., 2000; Butterbach-Bahl et al., 2001; Brown et al., 2001; Smith et al., 2002). The DNDC model has been used in national or regional N-trace gas emission inventories in North America, Europe, Oceania and Asia (Li et al., 1996, 2001; Brown et al., 2001) with robust results based on reasonable input data requirements. The PnET-N-DNDC model developed for predicting soil carbon and nitrogen biogeochemistry in temperate forest ecosystems (Li et al., 2000; Stange et al., 2000) has been used for regional emissions of N_2O and NO from forest soils (Butterbach-Bahl et al., 2001). The model is mainly based on the PnET model (Aber et al., 1996) and the DNDC model (Li et al., 1992), but special emphasis was given in PnET-N-DNDC to improve the process based description of microbial N-turnover processes like e.g. nitrification.

Regional database

The free state of Saxony (18412 km^2), Germany, is characterised by a complex pattern of land uses (Figure 1). The soils under agricultural use cover approx. 56.4% of total area, whereas the share of forest soils is approx. 26.3%. Over a distance of approx. 120 km the study area rises from typical lowland ($<$ 100 m a.s.l.) in the north up to the peaks of the Ore Mountains ($>$ 1000 m a.s.l.) in the south. A GIS database was constructed to hold all of the spatially differentiated information of soil, climate, land cover, and

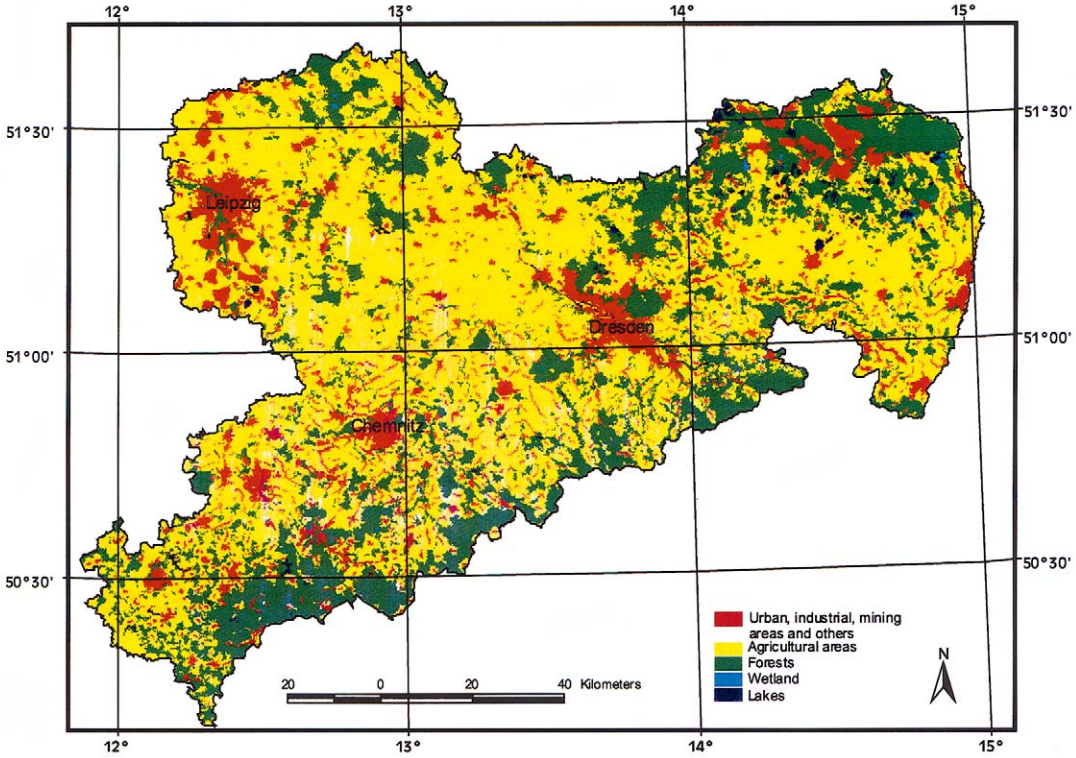


Figure 1. Land use in Saxony, based on information from the CORINE database (Statistisches Bundesamt, 1997).

management for the entire agricultural and forest lands in Saxony.

Soils

The information about soil characteristics utilized in the study were derived from a database provided by the Landesamt für Umwelt und Geologie, Saxony (Rank et al., 1999). This database, based on an intensive soil survey, includes detailed information on soil type, texture, soil pH, SOC, bulk density and stone fraction on a 4 × 4 km grid for all relevant land uses in Saxony (Figure 2). Soil profile samples (sampling depth up to 0.60 m) at each grid point were taken at the sites that were typical for the nearby area. The mean soil pH for agricultural soils was 5.5 and varied in a range of 3.2–8.4. The mean pH value for forest soils was much lower 3.89 for mineral soil and 3.41 for litter layer (range: 2.6–3.9 for mineral soil; range 2.6–7.2 for litter layer). Also with regard to the mean SOC content in the uppermost 10 cm significant differences between agricultural soils (mean: 1.6%, range: 0.1–10.8%) and forest soils do exist (mean: 6.1%, range: 0.5–19.9%). For building up the geometrical foundation of the regional database, only the grid points under either cropland and grassland use (503 cropland/303 grassland) or forest (326) were selected for the simulations with either DNDC (agricultural soils) or PnET-N-DNDC (forest soils). The simulated soil depth was 0.3 m for arable and grassland soils and, depending on the soil type, in a range from 0.2 m (e.g., Rankers) to 0.5 m (e.g., Cambic Podzols) for forest soils.

Climate

Daily rainfall as well as daily values of maximum and minimum temperature for 1994, 1995 and 1996 were obtained from 18 climate stations located within Saxony (Figure 3). The climate data of each station was assigned to the neighbour grid points based on the horizontal and vertical distances between the grid points and the climate stations. That way, the distance between the grid points and climate stations averages to 13.5 km (maximum: 69.8 km), whereas the average deviation in elevation amounts to 30 m (maximum: 157 m).

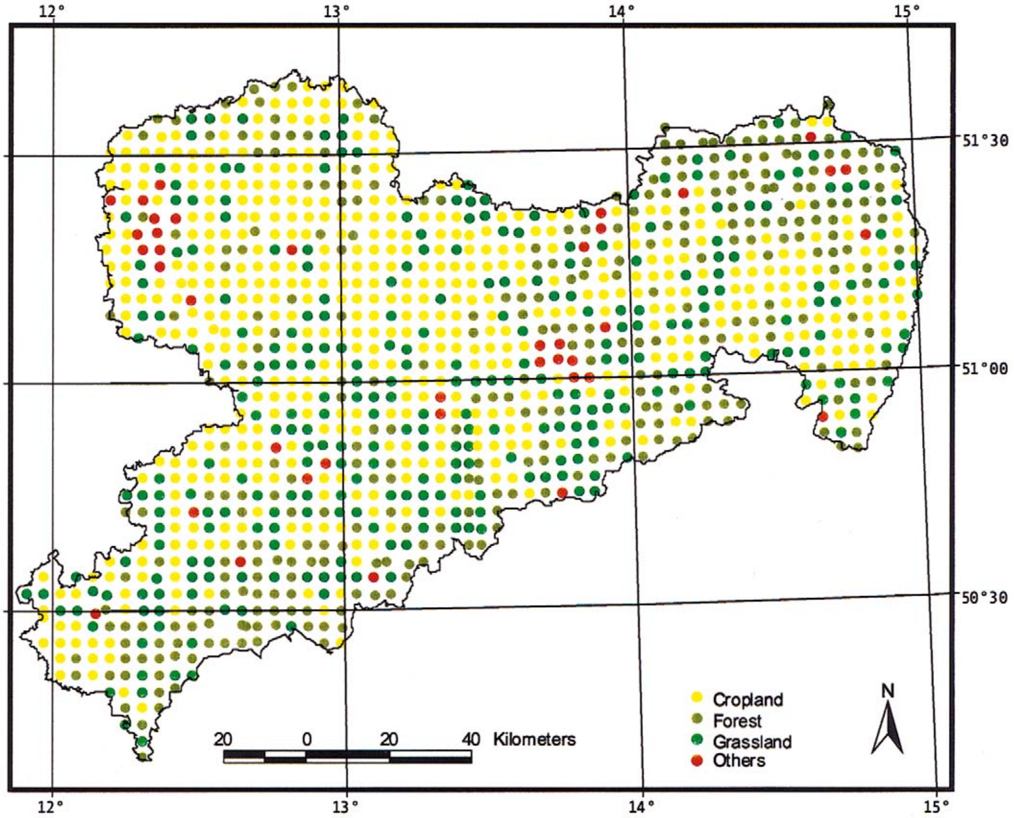


Figure 2. Spatial resolution of soil input data used for model calculations, based on a soil survey by the Landesamt für Umwelt und Geologie, Saxony (Rank et al., 1999).

Table 1. Rates and amounts of N-fertiliser and manure used for modelling regional N-gas emissions in Saxony, Germany

	Crop (kg N ha^{-1})	N-fertiliser rate (m^3 ha^{-1})	manure rate (ha)	area (t)	total applied N-fertiliser (m^3)	total applied manure
Cropland	Winter wheat	82.5	10.0	167379.7	13808.82	1673.796.66
	Rye	82.5	15.0	72631.5	5992.10	1089.472.08
	Barley	82.5	15.0	130761.6	10787.83	1961.424.15
	Rape	110.0	0.0	95770.4	10534.74	0.00
	Barley	37.5	10.0	58157.2	2180.89	581571.76
	Oats	70.0	10.0	10196.7	713.77	101967.44
	Corn	70.0	15.0	90682.1	6347.74	1360231.01
	Potatoes	90.0	15.0	13103.5	1179.32	196552.61
	Beets	95.0	0.0	25579.3	2430.03	0.00
	Legume hay	87.5	15.0	46735.2	4089.33	701027.74
	Pasture	92.5	10.0	23269.3	2152.41	232693.33
	Vegetables	122.5	0.0	5533.6	677.87	0.00
Grassland	Grassland	65.0	10.0	73120.1	4752.80	731200.61
	Pasture	77.5	10.0	66655.0	5165.76	666549.64
	Non-legume					
	Hay	100.0	15.0	100425.0	10042.50	1506374.77
	Total			980000.0	80855.92	10802861.80

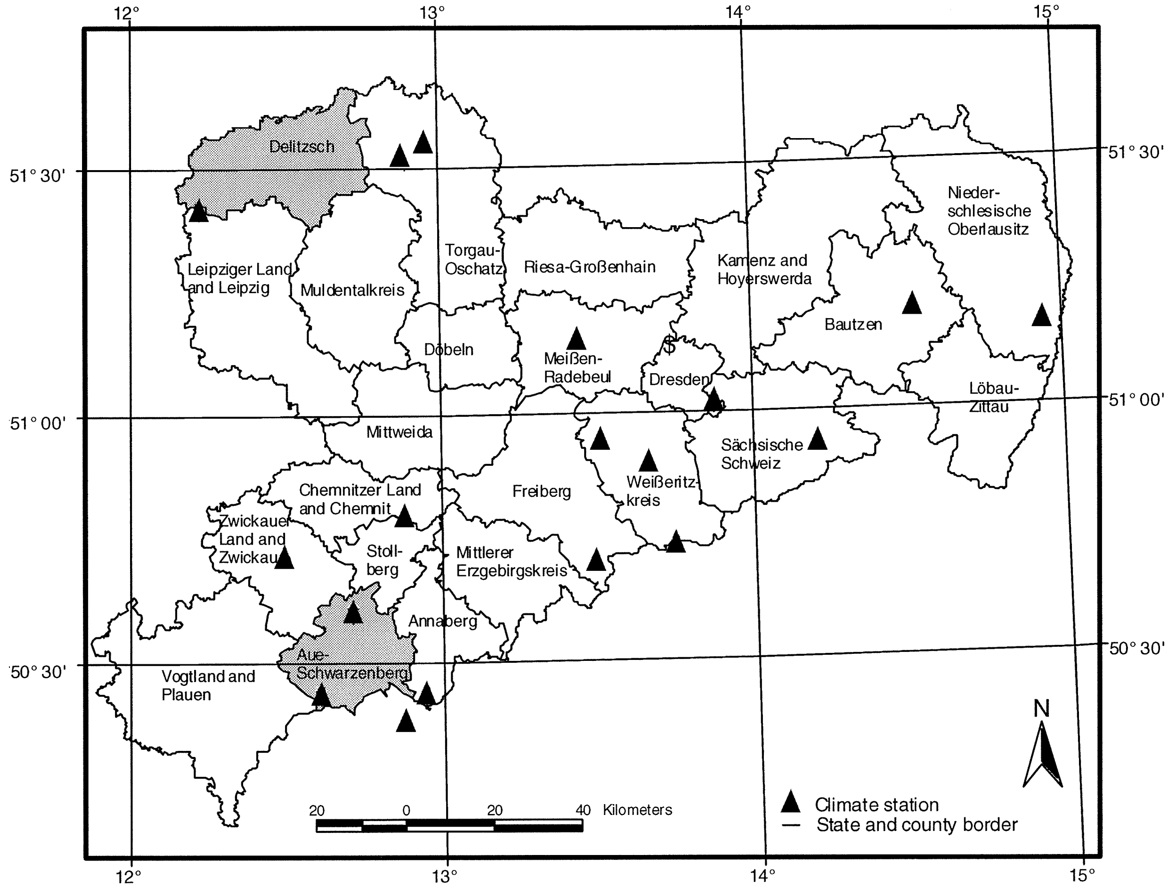


Figure 3. Geographical position of the climate stations and county borders in Saxony, Germany (cities are included in their neighboring rural districts). The counties of Delitzsch and Aue-Scharzenberg were selected for demonstrating daily variations in N-trace gas emissions or for sensitivity analysis on a regional scale, respectively.

Management of arable land

Information on land use was obtained from the CORINE database (Statistisches Bundesamt, 1997). In combination with official statistical data from the Statistischen Ämter des Bundes und der Länder (2000) as well as the official agricultural statistics of the Sächsisches Staatsministerium für Umwelt und Landwirtschaft (2000) the total area of grassland and cropland as well as the share of each crop was asserted for each of the 22 counties in Saxony for the year 1995. To assign the area of grassland in Saxony to the database holding the information on soil properties, the area covered by grassland in each county was equally distributed to all grassland grid points available for this specific region. In the same manner the cropland was distributed to the cropland grid points. Finally, the total cropland area of each county was divided into the major crops based on the official statistics, so that each grid point either represented a certain area of cropland with mixed crop types in the county or sole grassland. Table 1 shows the average rates of N-fertiliser and manure applied to each crop as well as the total amounts of N-fertilisers and manure used in Saxony in the year 1995. The application rates of N-fertiliser were calculated based on the official statistics of N-fertiliser sales in Saxony (Statistisches Bundesamt, 1997), N-demands of the simulated crops (e.g., Ruhr-Stickstoff Aktiengesellschaft, 1980), recommendations for fertiliser use in Saxony (Sächsisches Staatsministerium für Landwirtschaft, Ernährung und Forsten, 1997), as well as on a survey on the use of mineral N-fertilisers in Saxony conducted by Laves and Henk (1997). About 80.8 Mt N fertiliser were applied to the agricultural soils in Saxony in the year 1995. Furthermore, based on the work of Laves and Henk (1997), the

Table 2. Fertiliser type shares of total fertiliser consumption

N-compound	Amount N [t]	Share
Nitrate	2640.2	3.29%
Urea	12888.9	15.66%
Ammoniumnitrate	61942.3	76.83%
Ammoniumphosphate	2652.6	3.31%
Ammoniumsulphate	731.9	0.91%
Total	80855.9	100.00%

chemical composition of the fertiliser was considered in the simulations (Table 2).

The timing for ploughing, planting day, harvest and application of N-fertilisers and manure was set in coordination with the individual needs of the different crops (Sächsisches Staatsministerium für Landwirtschaft, Ernährung und Forsten, 1997; Ruhr-Stickstoff Aktiengesellschaft, 1980; Li et al., 1996) and the actual weather conditions in the year 1995 (Table 3). Based on the actual cropping management in the fields, all of the field visits for the management practices were assigned to the days when there was no or little rainfall on the days and the previous days before. Tillage was simulated on the day before planting.

Total manure production (10.8 M m^3 per year) was derived from the official statistic about life stock in Saxony for the year 1995 (Sächsisches Staatsministerium für Landwirtschaft, Ernährung und Forsten, 1997) and the average manure production per animal (Sächsisches Staatsministerium für Landwirtschaft, Ernährung und Forsten, 1996). Since there was no statistical data to distribute the manure to each individual land cover type, we assumed that the manure was spread in approx. equal amounts to all cropland and grassland (10–15 m^3 ha^{-1}, Table 1).

Forests

The PnET-N-DNDC model requires forest type and forest age as initial conditions for simulation. This information was provided by the Landesanstalt für Forsten, Saxony, on a base of 48 forest districts. These data, supplemented with other information on land use, climate and soil properties as provided by the databases described above, allowed us to determine the spatial distribution of forest types and age classes in Saxony. The total forested area in Saxony is 4267 km^2. The dominating forest type is spruce (1827 km^2), followed by pine (1204 km^2) and oak (135 km^2) (Table 4).

The above listed information was incorporated into a GIS database, which was further linked to DNDC or PnET-N-DNDC to support the regional simulation runs. Figure 4 summarises the approach adopted in the study for calculating regional inventories of soil N-trace gas emission in Saxony.

Sensitivity tests

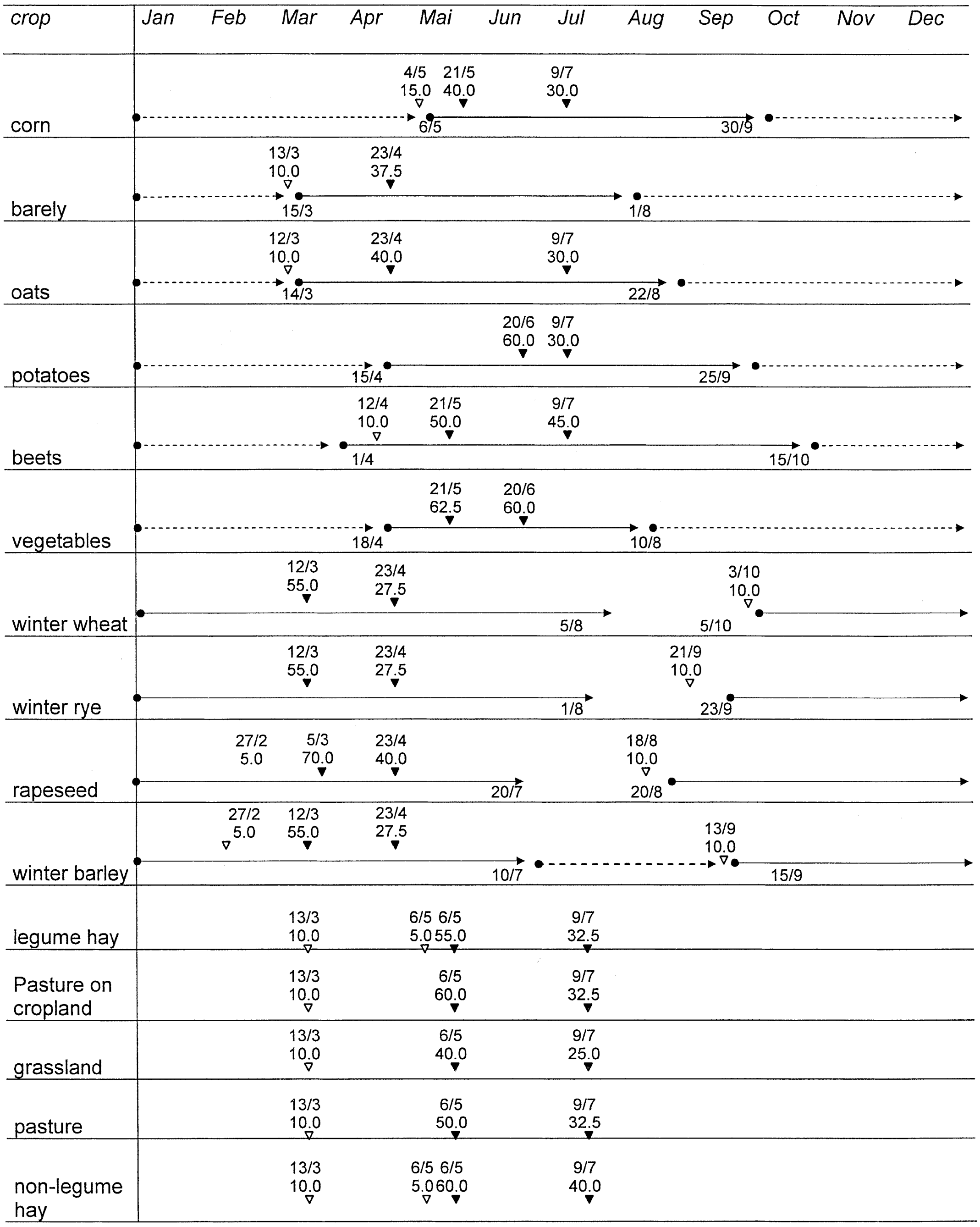
Since the data used in the GIS database are generalised (e.g., soil type) and aggregated (e.g., administrative borders, forest districts, soil), uncertainty will be inherently produced during the upscaling processes. In order to identify the impacts of individual factors such as land management practices (e.g., fertilisation, crop type, forest type), soil properties (e.g., soil organic matter content, texture or soil pH) or climate on the modelled regional emissions of N-trace gases we conducted a series of sensitivity tests for a selected county (Aue-Schwarzenberg). In these tests, more than 30 different scenarios were composed for representing the expected variations in soil properties, crop types, or fertilisation rates. The baseline scenario was constructed based on the actual land use and land management in Aue-Schwarzenberg in the year 1995. Furthermore, to investigate the impacts of interannual variations in the meteorological conditions on the N-trace gas emissions from soils in Saxony, we conducted multi-year simulations for the years 1994–1996 with the observed meteorological data, but without changing land cover and land use.

Results

Estimates of N_2O-emissions from soils in Saxony

The simulation of N_2O- and NO-emissions from agricultural and forest soils in Saxony, required approx. 10000 simulation runs for one year, covering 806 different agricultural and 326 forest sites. The emissions of N_2O from soils varied greatly in space and time depending on the type of land use, soil texture and management practice. The emission rates for agricultural sites ranged from 0.5–26.0 kg N_2O-N ha^{-1} yr^{-1}, with an average value of 5.6±3.4 kg N_2O-N ha^{-1} yr^{-1}. Among all the simulated crops (e.g., winter and summer wheat, barley, rape, maize, sugar beets), the highest loss rates of N_2O were

Table 3. Scheme for cropping practices and grassland management



crop	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sep	Oct	Nov	Dec
corn	●				4/5 15.0 ▽ 6/5 ● 21/5 40.0 ▼		9/7 30.0 ▼		30/9 ▶ ●			▶
barely	●		13/3 10.0 ▽ 15/3 ●	23/4 37.5 ▼				1/8 ▶ ●				▶
oats	●		12/3 10.0 ▽ 14/3 ●	23/4 40.0 ▼			9/7 30.0 ▼	22/8 ▶ ●				▶
potatoes	●			15/4 ●		20/6 60.0 ▼	9/7 30.0 ▼		25/9 ▶ ●			▶
beets	●			1/4 ● 12/4 10.0 ▽	21/5 50.0 ▼		9/7 45.0 ▼			15/10 ▶ ●		▶
vegetables	●			18/4 ●	21/5 62.5 ▼	20/6 60.0 ▼		10/8 ▶ ●				▶
winter wheat	●		12/3 55.0 ▼	23/4 27.5 ▼				5/8 ▶		3/10 10.0 ▽ 5/10 ●		▶
winter rye	●		12/3 55.0 ▼	23/4 27.5 ▼				1/8 ▶	21/9 10.0 ▽ 23/9 ●			▶
rapeseed	●	27/2 5.0	5/3 70.0 ▼	23/4 40.0 ▼			20/7 ▶	18/8 10.0 ▽ 20/8 ●				▶
winter barley	●	27/2 5.0 ▽	12/3 55.0 ▼	23/4 27.5 ▼			10/7 ▶ ●		13/9 10.0 ▽ 15/9 ●			▶
legume hay			13/3 10.0 ▽		6/5 5.0 ▽ 6/5 55.0 ▼		9/7 32.5 ▼					
Pasture on cropland			13/3 10.0 ▽		6/5 60.0 ▼		9/7 32.5 ▼					
grassland			13/3 10.0 ▽		6/5 40.0 ▼		9/7 25.0 ▼					
pasture			13/3 10.0 ▽		6/5 50.0 ▼		9/7 32.5 ▼					
non-legume hay			13/3 10.0 ▽		6/5 5.0 ▽ 6/5 60.0 ▼		9/7 40.0 ▼					

main crop ●——————▶
planting day harvest day

intercrop (legume hay): ●- - - - - - - - - -▶

N-fertilizer application date, amount [kg N ha^{-1}] 9/7 32.5 ▼
manure application date, amount [m^3 ha^{-1}] 13/3 10.0 ▽

Table 4. Forest type, age and acreage in Saxony

	Forest Area km^2	Forest Age % 1–40 years	40–100 years	> 100 years
Total	4267			
Spruce	1827	30	57	13
Pine	1204	31	53	16
Others	994			
Oak	135	26	47	27
Hardwoods	11	50	32	18
Birch	86	10	88	2
Beech	10	8	35	57

simulated for vegetables. This type of crop received the highest input of mineral N-fertilizer (123 kg N ha^{-1} yr^{-1}). High rates of N_2O losses were also simulated for some meadow sites with high SOC content (> 4.0%) and application of mineral fertiliser (100 kg N ha^{-1} yr^{-1}) and/ or manure (30 kg N ha^{-1} yr^{-1}).

N_2O-emissions from forest soils were in a range of 0.04–19.7 kg N_2O-N ha^{-1} yr^{-1}, with a mean value of 2.4 kg N_2O-N ha^{-1} yr^{-1}. The highest emissions of N_2O were simulated for drained organic soils, whereas the lowest emissions were simulated for some shallow, sandy soils with high stone content in the Ore Mountains.

Total N_2O-emissions from agricultural soils in Saxony in the year 1995 were estimated to be approx. 5475 t N_2O-N yr^{-1}, which is equivalent to 41.1% of all sources for N_2O in Saxony (Table 5). Forest soils were a weaker but still significant source for N_2O in Saxony, contributing approx. 7.6% or 1011 t N_2O-N yr^{-1} to the total regional source strength for atmospheric N_2O. Total simulated emissions of N_2O from agricultural and forested soils in Saxony in 1995 were 6486 t N_2O-N yr^{-1}. This figure demonstrates that even in such a highly industrialised region like Saxony the soils still contribute almost 50% to the total N_2O source strength.

The regional distribution of simulated N_2O-emissions from soils is shown in Figure 5. The figure shows that highest emissions have been predicted for agricultural soils. However, for some forest soils located at the foot of the ore mountains, which stretch from west to east in the most southern parts of Saxony, the modelled annual N_2O-emissions are still higher than 4 kg N_2O-N ha^{-1} yr^{-1}. Most soils in this latter region have a relatively high clay content (> 15%) and are deep and therefore predominantly used for intensive agriculture. Much lower emissions were simulated for the 'Muckower Heathland', an area with predominantly sandy soils, located in the most North-Eastern region of Saxony (Figure 5).

Estimates of NO-emissions from soils in Saxony

The simulated emissions of NO from agricultural and forest soils were approx. in the same magnitude than for N_2O. The range of emissions was 0.4–26.3 kg NO-N ha^{-1} yr^{-1} for agricultural soils and 0.04–28.3 kg NO-N ha^{-1} yr^{-1} for forest soils. The modelled mean emission rate of NO from the agricultural soils was 8.4 ± 4.2 kg NO-N and thus approx. 3 kg higher than the mean emission rate of N_2O from the same soils. Even higher average emissions of NO were predicted for forest soils in Saxony (9.7 kg NO-N ha^{-1} yr^{-1}). The modelled high NO-emissions were related to the low soil pH values, which are common for most forest soils in Saxony (forest floor pH, range: 2.6–7.6, average 3.4±0.01; mineral soil pH, range: 2.6–7.7, average: 3.9±0.01). For pH values < 4.0 an exponential increase in NO-production by chemo-denitrification was realised in the PnET-N-DNDC model, so that low soil pH values will result in high emissions of NO from forest soils.

The modelled total soil NO-emission in Saxony in the year 1995 was 13023 t NO-N yr^{-1}, including 8868 t NO-N yr^{-1} from agricultural soils and 4155 t NO-N yr^{-1} from forest soils (Table 6). This figure only reflects the flux of NO from the soils excluding possible canopy absorption or other effects. However, in comparison with other NO_x sources in Saxony (Table 6), the soil source accounted for 17.9% of the total NO_x emissions from the region. In addition, the strong seasonality of the soil NO emissions

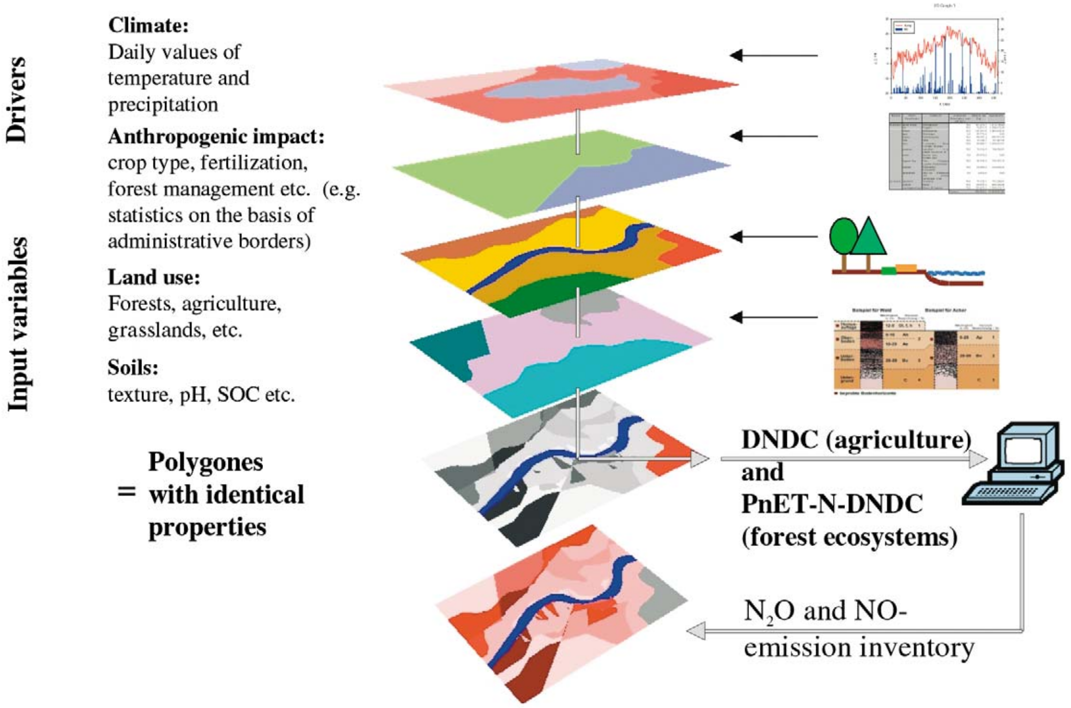


Figure 4. Schematic drawing of the approach used to calculate regional inventories of soil borne N-trace gas emissions in Saxony by linking mechanistic models to a GIS database.

significantly elevated the soil contributions in summer (up to 25–30%).

Compared to N_2O-emissions the soil NO-emissions were relatively uniform in space. This is mainly due to the much lower effect of land use (forest or agriculture) on the NO-emissions. However, as it was already described for N_2O-emissions, the North-Eastern regions of Saxony with prevailing sandy soils had lower NO-emissions as compared to other regions in Saxony (Figure 6).

Sensitivity analysis

In order to test the sensitivity of the model output to variations in the input values on a regional scale, we chose the county of Aue-Schwarzenberg and changed the value of single input parameters such as land use, land management, atmospheric N deposit or soil properties. Figures 7 and 8 summarise the results of this sensitivity study for cropland, whereas Table 7 summarises the results for the forested areas of the county.

At the regional scale, SOC content was the most sensitive parameter for the DNDC-modelled N_2O-emissions from agricultural soils. Changes in SOC by ±20% resulted in an increase/decrease of N_2O-emissions by +31% or −26%, respectively (Figure 7). With regard to NO fluxes the SOC content and soil texture were the most sensitive parameters. However, varying soil texture between its neighbour classes or SOC content by ±20% could only change the NO fluxes by less than 20%. The modelled NO fluxes were also robust to changes in crop type, fertilisation rate, timing of fertiliser application, or timing of crop planting (Figure 8). Replacement of winter wheat or rye with fallow (scenario 1 applied for approx. 6% of total farmland in Aue-Schwarzenberg) reduced N_2O- and NO-emissions by about 10%. However, this reduction was mainly due to the reduced N-fertiliser use during the fallow seasons.

Comparable results were also obtained for the sensitivity of regional predictions of N-trace gas emissions from forest soils in the county of Aue-Schwarzenberg. It is obvious from Table 7 that besides the SOC content also the soil pH has a significant effect on the predicted N_2O-as well as on NO-emissions. This is due to the fact that in the PnET-N-DNDC model chemo-denitrification is explicitly implemented as a source for NO-production in soils in such a way that the activity of this process increases exponentially

Table 5. Sources of N_2O in Saxony, Germany (year 1995)

Emission source	N_2O-emission source strength (t N_2O-N yr^{-1})
Industry[a]	889 (6.7%)
Huge combustion plants[a]	3238 (24.3%)
Other combustion plants[a]	127 (1.0%)
Small consumer[a]	41 (0.3%)
Domestic fuel[a]	58 (0.4%)
Road traffic[a]	2119 (15.9%)
Waste water treatment[a]	139 (1.0%)
Composting[a]	81 (0.6%)
Diesel engines in the agriculture	134 (1.0%)
Agricultural soils (*IPCC-approach*[a]) /	
Agricultural soils (DNDC)	4892 / 5475 (41.1%)
Forest soils (PnET-N-DNDC)	1011 (7,6%)
Sum	13312 (100%)

[a] Data from the Landesamt für Umwelt und Geologie, Saxony (2000)

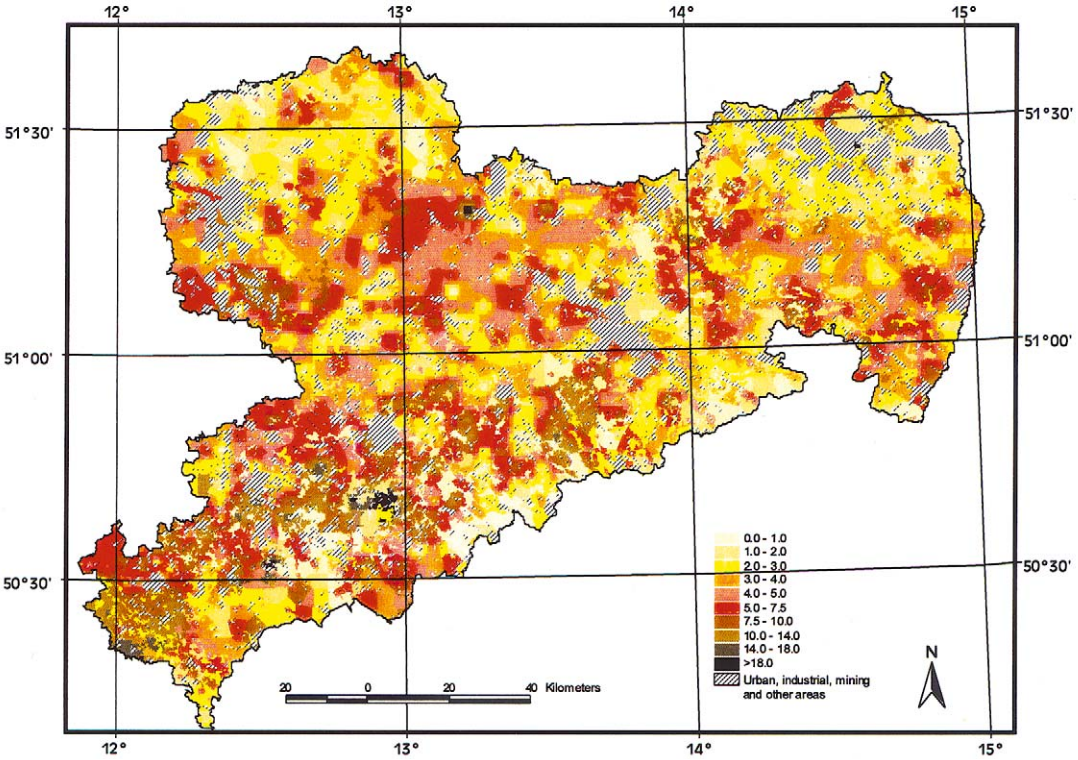


Figure 5. Regional maps of N_2O-emissions (kg N_2O-N ha^{-1} yr^{-1}) from agricultural and forest soils in Saxony, Germany, in the year 1995.

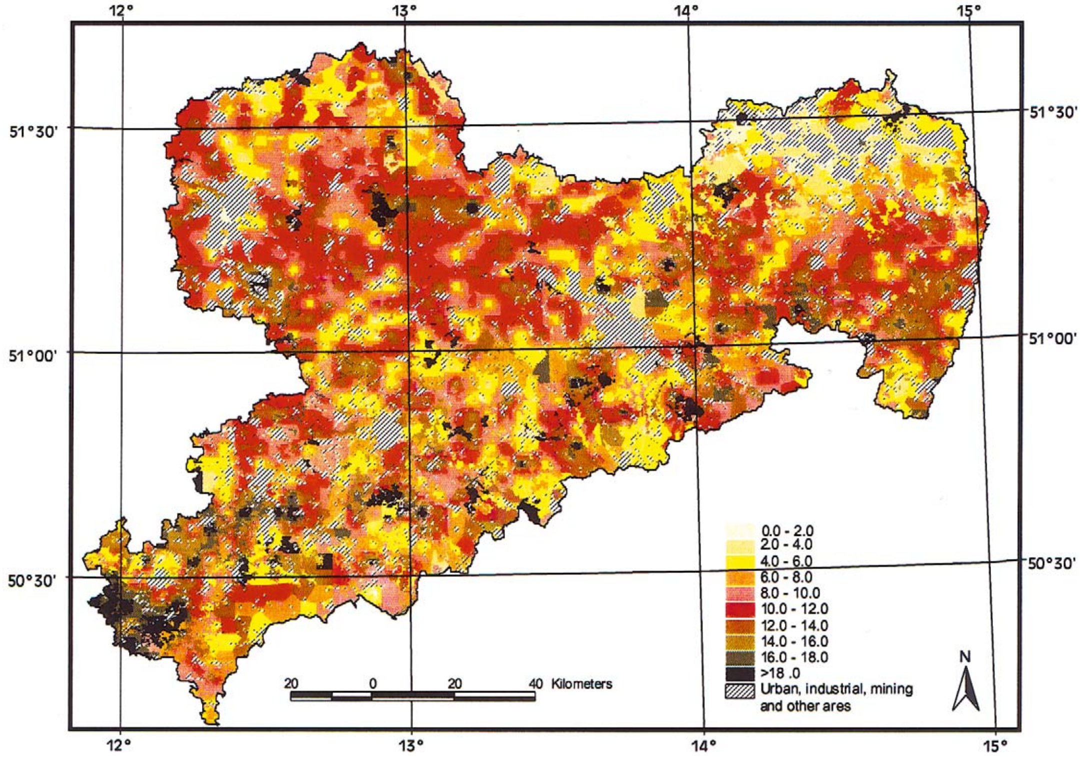


Figure 6. Regional maps of NO emissions (kg NO-N ha^{-1} yr^{-1}) from agricultural and forest soils in Saxony, Germany, in the year 1995.

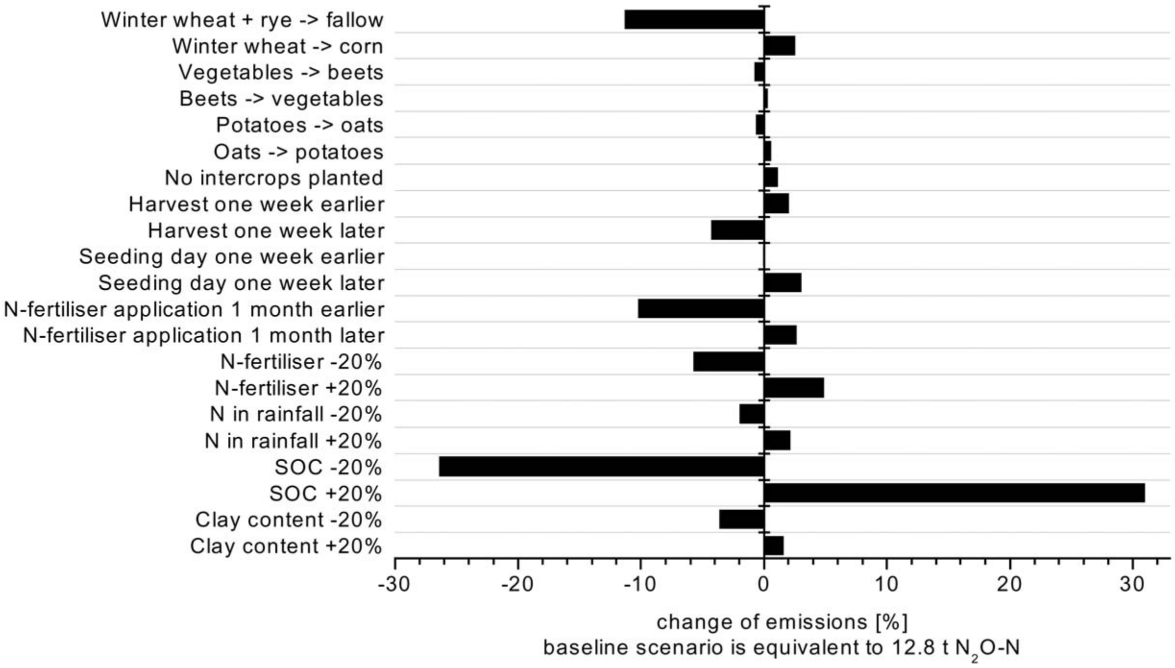


Figure 7. Sensitivity of regional predictions of N_2O-emissions from agricultural soils in the county Aue-Schwarzenberg, Saxony, to changes in input parameters.

Table 6. Sources of NO in Saxony, Germany (year 1995)

Emission source	NO_x-emission source strength (t NO_x-N yr^{-1})
Industry[a]	2100 (2.9%)
Huge combustion plants[a]	26781 (36.8%)
Other combustion plants[a]	867 (1.2%)
Small consumer[a]	960 (1.3%)
Domestic fuel[a]	1516 (2.1%)
Road traffic[a]	27066 (37.2%)
Diesel engines in the agriculture[a]	386 (0.5%)
Agricultural soils (DNDC-Simulation)	8868 (12.2%)
Forest soils (PnET-N-DNDC)	4155 (5.7%)
Sum	72699 (100%)

[a] Data from the Landesamt für Umwelt und Geologie, Saxony (2000)

Table 7. Sensitivity of modelled N trace gas fluxes from forest soils in County Aue-Schwarzenberg, Saxony, to changes in input parameters. Values in parenthesis are deviation in % from baseline scenario

Scenarios	N_2O-emissions		NO-emissions	
	t N_2O-N a^{-1}	kg N_2O-N ha^{-1} a^{-1}	t NO-N a^{-1}	kg NO-N ha^{-1} a^{-1}
Baseline-scenario	74 (100%)	2.3	373 (100%)	10.5
Spruce→beech	86 (+16%)	2.7	243 (−35%)	7.6
Spruce→pine	91 (+23%)	2.8	326 (−13%)	10.2
pH + 20%	192 (+159%)	6.0	132 (−64%)	4.1
pH − 20%	24 (−68%)	0.7	607 (+63%)	18.9
SOC + 20%	112 (+51%)	3.5	375 (+1%)	11.7
SOC − 20%	54 (−27%)	2.7	337 (−10%)	10.5

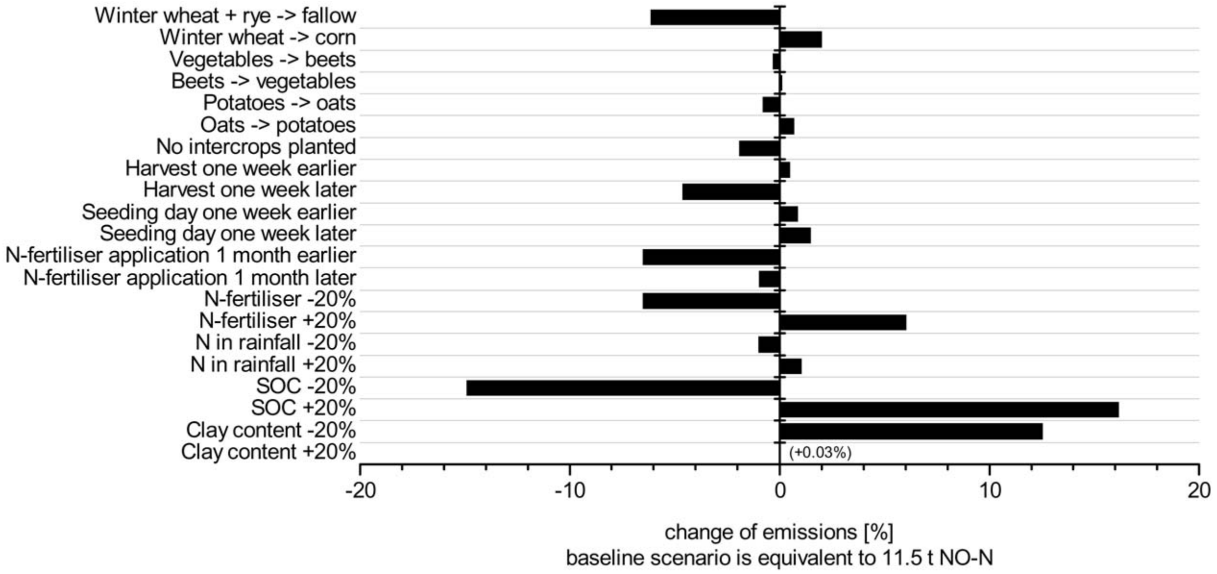


Figure 8. Sensitivity of regional predictions of NO-emissions from agricultural soils in the county Aue-Schwarzenberg, Saxony, to changes in input parameters.

Table 8. Comparison of simulated and measured N_2O-emissions from differently managed agricultural fields. Values for the DNDC simulation are mean values for Saxony, i.e. integrated for different soil properties and climate stations. For the field measurements the N fertiliser rate, the measured N_2O-emissions, the time of measurements, the field crop and the relevant reference are given.

	DNDC-simulation (1995)		Field measurements				
	N-fertiliser [kg N ha^{-1}]	N_2O-emissions [kg N_2O-N ha^{-1} yr^{-1}]	N-fertiliser [kg N ha^{-1}]	N_2O-emissions [kg N_2O-N ha^{-1} yr^{-1}]	Period of time	Field crop	References
Non-legume hay	100.0	12.6	0-96	7-20	11/93-11/94	Meadow	Flessa et al., 1998
			70-120	1.9-18.4	1989-1998	Ryegrass	Dobbie et al., 1999
			40-240	0.8-2.7	08/96-10/97	Meadow	Kammann et al., 1998
Rape	110.0	6.5	172	4.0	1996	Winter rape	Kaiser et al., 1998a
Wheat	82.5	6.2	195-210	1.1-1.2	04/92-09/92		Kaiser et al., 1996
			60	0.9	04/93-09/93		Kaiser et al., 1996
			130	3.5	1996	Wheat	Kaiser et al., 1998a
			90	1.8-3.6	1.8-3.6		Ruser et al., 2001
Winter rye	82.5	5.4	0	55	11/1993-11/1994	Rye/Meadow	Flessa et al., 1998
Grassland	65.0	4.9	350	1.8-2.4	1994/1995		Kaiser et al., 1998b
			215	6.6	Apr.-Sep. 1992	Grassland	Kaiser et al., 1996
			120-360	2.24	1992-1995		Smith, K. et al., 1998
Summer barley	37.5	4.5	40	3.3-6.1	1996		Kaiser et al., 1998b
			60	1.0-1.2	04/92-09/92		Kaiser et al., 1996
			90-144	0.5-0.9	04/92-09/93	Summer barley	Kaiser et al., 1996
			160	16.8	07/92-08/93		Flessa et al., 1995
Winter barley	82.5	4.4	60	1.7	04/93-09/93	Winter barley	Kaiser et al., 1996
			146	3.7	1996		Kaiser et al., 1998a
Maize	70.0	4.4	150	2.3	04/94-09/93		Kaiser et al., 1996
			275	12.5	11/93-11/94	Maize	Flessa et al., 1998
			65-130	1.3-2.4	03/96-02/97		Ruser et al., 2001
Pasture	81.4	3.8	-	1.9	07/93-10/93		
			250	3.2	02/96-02/97	Pasture	Flessa et al., 1996
			85	1.4-6.5	04/93-11/94		Williams et al., 1999
Potatoes	90.0	3.3	140	1.2	1994		Smith, K. et al., 1998
			170	3.1-3.2	1996/1997	Potatoe	Smith, K. et al., 1998
			50-150	5.3-6.2	03/95-02/96		Ruser et al., 2001
Beets	95.0	2.3	110	3.6	1995	Beets	Kaiser et al., 1998a
			70	2,9	1996		Kaiser et al., 1998a
Legume hay	87.5	1.2	175	1.3-1.6	1994/1995		
			0	1.4–1.5	1994/1995	clover	Kaiser et al., 1998b

at soil pH < 4.0 (Li et al., 2000). Furthermore, the activity of nitrification and denitrification as well as loss rates of N_2O and NO during both processes are directly affected by changes in soil pH (Li et al., 2000). In contrast to the DNDC model the PnET-N-DNDC model is rather sensitive to changes in stand properties. Changing all forests in Aue-Schwarzenberg from spruce to beech resulted in an increase of N_2O-emissions by 16% but in a decrease of NO-emissions by 35% (Table 9). This is mainly due to the effect of forest type on soil hydrology, since the soil moisture at beech sites is increased in winter and spring due to strongly reduced interception losses as compared to spruce sites. This and the improved quality of beech litter (narrower C/N ratio of beech litter as compared to spruce litter) favours denitrification activities in beech soils, thereby increasing N_2O losses, but decreasing NO-emissions due to increased NO consumption by denitrification in the soil.

The sensitivity of predictions of N-trace gas emissions from soils in Saxony by the DNDC and PnET-N-DNDC models to interannual changes in climate is shown in Figure 9. For the three years period of 1994–1996 the highest N_2O-emissions from forested as well as agricultural soils were predicted for the year 1995 with a total emission of 6487 t N_2O-N, which is 1991 t N_2O-N higher than that in 1996. A comparable trend of the interannual variability of emissions was also predicted with regard to NO-emissions from soils, i.e. highest emissions in 1995 and lowest in 1996 (Figure 9). Evaluation of the climate data of the three years shows that the year 1995 was the wettest in the period 1994–1996, whereas the year 1996 was the coldest and driest of the three years investigated (Figure 9). The results suggest that the modelled cropland N gas emissions are more sensitive to changes in meteorological drivers than the modelled forest N gas emissions. However, the interannual variations need more studies to distinguish the impacts of climate or management.

Discussion

N_2O-emissions

Estimates of regional N-trace gas emissions from soils can currently not be validated per se. This problem can not be thoroughly solved by the comparisons with field measurements, since most field observations do not cover either the entire years or the entire domain regions with diverse land-use and management. The spatial variability of N_2O-emissions can be a severe problem (Williams et al., 1999), since the studies employing chambers for measurement may not be able to obtain precise fluxes for a mean N_2O-emission at even a field scale. However, in Table 8 results of field measurements of N_2O-emissions from differently managed agricultural fields, most of them carried out in Central Europe, are compared to the results obtained with the DNDC model for Saxony. It is obvious from the table that the simulated N_2O-emissions are well within the span of reported N_2O-emissions. The result is encouraging since the model used for the study is a general version of DNDC without any specific calibrations or validations done for the Saxony region in advance. We assume the reasonable results should attribute to incorporation of the fundamental biogeochemical processes in DNDC that enables the model to be applicable across climate zones, soil types, and management regimes. In addition, the extensive validations done during the past decade have elevated the reliability of the model (Li et al., 1996; Stange et al., 2000; Butterbach-Bahl et al., 2001; Brown et al., 2001, Smith et al., 2002).

With regard to the PnET-N-DNDC model, which was used for the simulation of N_2O-emissions from forest soils, simulated N_2O-emissions are within the wide range of published N_2O-emissions from soils of different forest ecosystems in Central Europe (0.1–20.0 kg N_2O-N ha^{-1}, see compilation of results in Papen and Butterbach-Bahl, 1999). However, the calculated mean value of 2.4 kg N_2O-N ha^{-1} is rather high, in view of results by Brumme et al. (1999) for 11 different forest sites in Germany and Butterbach-Bahl et al. (2002) for 5 pine forest sites in the North-Eastern German lowlands. For most of their sites these authors found annual N_2O-emission rates < 2 kg N ha^{-1} yr^{-1}. Explanation for the difference between the modelled and observed N_2O-emission rates remains unclear although there are some assumptions. For example, the modelled high N_2O fluxes could be related to the high clay contents and reasonably high SOC-contents ($>$ 4%) in the forest soils. To verify our estimates for these areas, more field measurements would be needed. This highlights that model testing and application as well as field and laboratory experiments should go hand in hand to further improve our understanding of N-trace gas emissions from soils.

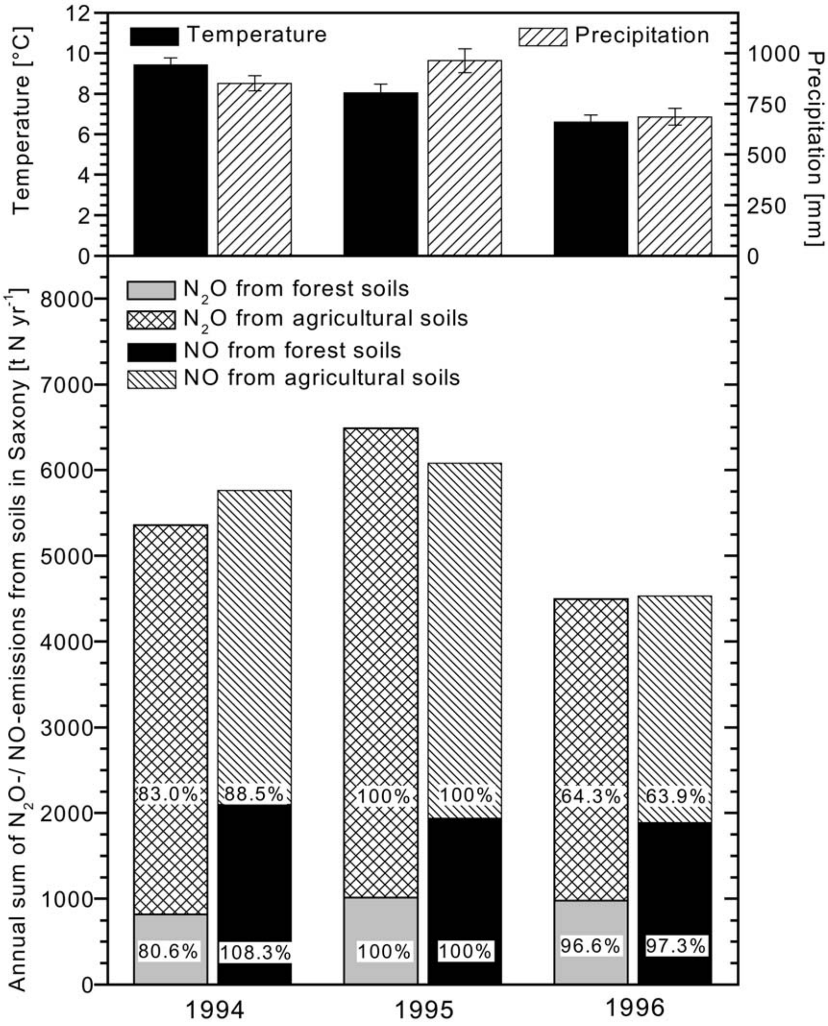


Figure 9. Interannual variability of mean annual temperature (±SD), mean annual sum of precipitation (±SD) and simulated N_2O- and NO-emissions from soils in Saxony. As bases for the calculation of the mean annual temperature and mean annual sum of precipitation data from 18 meteorological stations were used. Percent values in the individual columns indicate changes in the magnitude of N-trace gas emissions as compared to the base year 1995.

NO-emissions

Estimated NO-emissions from agricultural soils in Saxony are 0.4–26.3 kg NO-N ha^{-1} yr^{-1} and thus within the range of NO-emissions reported previously in the literature (e.g., Skiba et al., 1997; Jambert et al., 1997), which ranged from 1.1–52 kg NO-N ha^{-1} yr^{-1} for different maize fields in North-America and UK. Several publications have shown, that the NO-emissions substantially increased after fertilisation of arable land (e.g., Slemr and Seiler, 1984; Ludwig et al., 2001) and that highest rates of NO-emissions ($>$ 21 kg N ha^{-1} yr^{-1}) were mostly observed during summer. However, since the reports about measured NO-emissions from agricultural soils are still sparse and mostly restricted to short time intervals, the uncertainty for observed NO-emission estimates is substantial. This fact is highlighted by an extensive literature review by Ludwig et al. (2001). This is also partly true for estimates of NO-emissions from forest soils. However, in the recent past Gasche and Papen (1999), Van Dijk and Duyzer (1999), Pilegaard et al. (1999) and Butterbach-Bahl et al. (2002) published estimates for NO-emissions from different forest ecosystems in Central Europe based on the extensive, multi-year measurements covering all seasons. The results from these measurements show that

NO-emissions from forest soils are in a range of < 1 to > 7 kg N ha^{-1} yr^{-1}. The observations confirm our finding in this study that forest soils are a significant source of atmospheric NO in Saxony. In comparison with the observed NO-emissions, our estimated mean NO-emission (9.7 kg NO-N ha^{-1} yr^{-1}) from the forest soils appears to be rather high. The overestimation of NO-emissions from forest soils in Saxony is most likely related to the way how chemo-denitrification is described in the PnET-N-DNDC model. Based on the work of Blackmer and Cerrato (1986) we used in the PnET-N-DNDC model an exponential relationship to describe the effect of soil pH on NO-production via chemo-denitrification if the soil pH is < 4.0 (Li et al., 2000). Though this factor is further modified by temperature and the rate of nitrification, we always simulate extremely high values of NO-production via chemo-denitrification in forest soils with pH values < 3.2. Since many forest soils in Saxony have such low pH values, our estimates may be biased by the overestimation of chemo-denitrification. There is no doubt, that this is a weak point of the model. However, we would like to emphasize that more field measurements and laboratory experiments will be needed to further improve the model behaviours.

Comparison with IPCC estimate

Our estimate of regional N_2O-emission from agricultural soils in Saxony for the year 1995 with 5475 t N_2O-N is only 10% higher than the estimate from the IPCC approach for the same year (Landesamt für Umwelt und Geologie, Saxony, 2000). Our modelled mean value of N_2O-emissions for the arable land in Saxony (1995: 5.6 ± 3.4 kg N_2O-N ha^{-1} yr^{-1}) is very close to the results for direct N_2O-emissions from cultivated lands in Germany done by Boeckx and Van Cleemput (2001) with the IPCC approach (7.4 kg N ha^{-1} yr^{-1}). The consistency between the DNDC-modelled and IPCC approach-estimated N-gas inventories has been also reported by Brown et al. (2001) and Li et al. (2001) for the U.K. and China, respectively. This shows that detailed process-based models can be utilized for large scales and produce reasonable estimates in agreement with the observation-based factor approaches for direct N_2O-emissions from agricultural soils such as the IPCC methods. However, the advantages of using process-based models for calculating N-trace gas emission inventories or for developing mitigation strategies are obvious. The modes of calculation with detailed underlying biogeochemical processes, allow to identify and to assess the specific effects of any single model driver or model input parameter on N-trace gas emissions, including climate, soil properties, and field management practices (e.g., crop type and rotation, tillage, fertilization, manure amendment, irrigation, weeding, grazing, etc.). This implies that the process-based models can be used for policy making analysis by comparing alternative management scenarios for their effects on ecosystem production, soil fertiliy, C sequestration, and greenhouse gas emissions at regional or national scale. The models can be also utilized for predicting the feedback of future climate changes on trace gas emissions. Furthermore, the predictive power of process-based models and its sensitivity to meteorological input parameters is especially important with regard to the reporting commitments of annex I states in the framework of the Kyoto-protocol. Our results from this study show that N-gas emissions can vary significantly from year to year only due to the differences in climate. This result clearly demonstrates that the definition of the base year, which is required by the framework of the Kyoto-protocol for calculating greenhouse gas emissions, will need to be further clarified due to the non-negligible interannual variations in the climate conditions. A time span longer than 5 years would be more reliable to quantify soil average trace gas emissions at national scale.

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