Regional inventory of nitric oxide and nitrous oxide emissions for forest soils of southeast Germany using the biogeochemical model PnET-N-DNDC

Klaus Butterbach-Bahl, Florian Stange,1 and Hans Papen
Fraunhofer Institute for Atmospheric Environmental Research, Garmisch-Partenkirchen, Germany
Changsheng Li
Institute for the Study of Earth, Oceans, and Space, University of New Hampshire
Durham, New Hampshire, USA

Abstract. Though it has been shown recently that forest ecosystems affected by high rates of atmospheric N input are significant sources of N trace gases, reliable regional estimates of the source strength of such forests are missing. In this study, the biogeochemical model Photosynthesis and Evapotranspiration-Nitrification-Denitrification and Decomposition (PnET-N-DNDC), which simulates processes involved in N trace gas production and emission in forest soils on a daily scale, was used to calculate a regional inventory of N trace gas emissions from forest soils in southeast Germany for the year 1997. Prior to its use the model was further validated for climate and site sensitivity using multiyear observations of N trace gas fluxes at the Höglwald Forest site, Germany, and at forest sites in the Netherlands. On a regional scale the model estimates for Bavaria, Germany, that NO and N2O emissions from forest ecosystems in the year 1997 were ~4.21 kt NO-N yr⁻¹ and ~6.64 kt N₂O-N yr⁻¹, respectively. Compared with total annual NOₓ emissions from combustion processes in Bavaria, total emissions of NO from forest soils are of minor importance [4.6%]. However, in summer, NO emissions from forest soils were of significant importance [8.8–22.0%] for the total regional NOₓ burden, since NO emissions showed a strong seasonal pattern with highest emissions during summer. Also, with regard to N₂O, huge seasonal variations were found. Because of high N₂O emissions during periods of freezing and thawing of forest soils, N₂O fluxes in the winter period of 1997 also contributed significantly on the regional scale to total annual N₂O emissions [~38%]. Sensitivity analysis revealed that the accuracy of the N trace gas inventory strongly depended on the quality of regional input data, since the regional estimates of N trace gas fluxes calculated by PnET-N-DNDC were very sensitive to changes in soil texture, soil carbon content, site fertility, and, especially for NO emissions, to changes in soil pH.

1. Introduction

Approximately one third of the Earth's land surface is covered by forests [Potter et al., 1996], which have been shown to be significant sources for the primarily and secondarily active greenhouse gases nitrous oxide [e.g., Goodroad and Keeney, 1984; Papen and Butterbach-Bahl, 1999; Keller et al., 1986; Breuer et al., 2000] and nitric oxide [e.g., Potter et al., 1996; Lee et al., 1997; Gash and Papen, 1999]. The global source strength of forest soils for nitrous oxide was estimated to be in a range of 2.4–5.7 Tg N yr⁻¹ [Houghton et al., 1992], whereas NO emissions from forest soils are ~3.6 Tg N yr⁻¹ [Lee et al., 1997], representing 33% of all NO emissions from soils worldwide [Houghton et al., 1992]. The contribution of temperate forest soils to the global atmospheric budgets of N₂O and NO is still associated with a huge uncertainty. Recent estimates showed that emissions of NO from temperate forests are most likely in a range of 0.04–0.4 Tg NO-N yr⁻¹ but that this value strongly depends on the magnitude of redeposition of NOₓ onto leaf surfaces of the canopy, which is also a source of uncertainty [Yienger and Levy, 1995; Davidson and Kingerlee, 1997]. With regard to N₂O, Houghton et al. [1992] estimated that the source strength of temperate forest soils is in a range of 0.05–2.0 Tg N₂O-N yr⁻¹, whereas estimates by Potter et al. [1996] and Papen and Butterbach-Bahl [1999] were ~0.5 Tg N₂O-N yr⁻¹ and >0.5 Tg N₂O-N yr⁻¹, respectively. The huge uncertainty associated with N trace gas fluxes from temperate forest soils is at least partly due to (1) the limited number of field measurements, (2) the still not sufficiently quantified effects of atmospheric N deposition on NO and N₂O emissions [Papen and Butterbach-Bahl, 1999; Pilegaard et al., 1999; Van Dijk and Duyzer, 1999], and (3) the unconsidered effects of freezing and thawing on the N₂O source strength of temperate forests [e.g., Papen and Butterbach-Bahl, 1999; Teepe et al., 2000]. N trace gas emissions from temperate forest soils are the result of different microbial and physicochemical processes, i.e., mainly of nitrification and denitrification for NO and N₂O.

1Now at Institut für Pflanzenernährung und Bodenkunde, University of Kiel, Kiel, Germany.

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and chemodenitrification at soil pH values of <5.0 for NO, occurring simultaneously in the soil [e.g., Firestone and Davidson, 1989; Bremer, 1997]. The magnitude of processes involved in N trace gas production is strongly controlled by other biotic processes (e.g., mineralization or plant N uptake) or by abiotic factors like temperature, soil moisture, or N deposition [e.g., Brumme and Beese, 1992; Sitaula and Bakken, 1993; Rennenberg et al., 1998], which do change substantially on spatial and temporal scales [e.g., Williams et al., 1992; Davidson et al., 1998; Butterbach-Bahl et al., 2001a]. Therefore significant improvements of current estimates of N trace gas fluxes from temperate forest ecosystems may only be achieved if mechanistic models are developed and used that are able to predict N trace gas emissions based on the processes involved in N trace gas production/consumption and emission. For temperate forest ecosystems such a model was recently developed [Li et al., 2000] and validated for its predicting capability of NO and N$_2$O fluxes from forest soils for a wide range of deciduous and coniferous forest ecosystems in Europe and the United States [Stange et al., 2000].

This model, the Photosynthesis and Evapotranspiration-Nitrification-Denitrification and Decomposition (PnET-N-DNDC) model, was used in this study to derive estimates of regional fluxes of NO and N$_2$O in southeast Germany and to answer the following questions: (1) What are the magnitudes of N$_2$O fluxes from forest soils on a regional scale, and how important are N$_2$O fluxes during winter time? (2) What is the magnitude of NO fluxes from forest soils on a regional scale, and how important are such fluxes in relation to other sources of NO, especially during summer times? (3) What are the strengths and weaknesses of such a modeling approach?

2. Methods

2.1. PnET-N-DNDC Model

PnET-N-DNDC was recently developed to predict soil carbon and nitrogen biogeochemistry in temperate forest ecosystems and to simulate the emissions of NO and N$_2$O from forest soils. 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 improving the mechanistic description of nitrification [Stange, 2000]. PnET is a forest physiology model used for predicting forest photosynthesis, respiration, organic carbon production and allocation, and litter production. This model has already been used in regional studies in order to predict the sensitivity of forest production on climate variability and site quality [e.g., Goodale et al., 1998]. DNDC is a soil biogeochemistry model used for predicting soil organic matter decomposition and nitrogen turnover in agricultural soils. Also, this model has been used recently to predict regional N$_2$O emissions, e.g., from croplands in the United States and China (C. Li et al., Modeled cropland N$_2$O emissions for the United States and China, submitted to the Journal of Geophysical Research, 2001).

PnET-N-DNDC consists of five submodels for predicting forest growth, soil climate, decomposition, nitrification, and denitrification, respectively (Figure 1). The soil climate submodel converts daily climate data into soil temperature and moisture profiles and calculates soil oxygen diffusion in the forest soil profile. The forest growth submodel simulates forest growth driven by solar radiation, temperature, water stress, and N stress and passes litter production and water and N demands to the soil climate or decomposition submodels (Figure 1). The decomposition submodel tracks turnover of the litter and other organic matter in the soil and passes ammonium, nitrate, and dissolved organic carbon (DOC) to the nitrification or denitrification submodels. The nitrification submodel predicts growth and death of nitrifiers, with the nitrification rate as well as NO and N$_2$O productions from nitrification depending on soil temperature, moisture, ammonium, and DOC concentration. The denitrification submodel simulates denitrification and changes in population size of denitrifiers as a function of soil temperature, moisture, and substrate concentrations (DOC, NO$_3^-$, NO$_2^-$, NO, and N$_2$O). The denitrification-induced NO and N$_2$O fluxes are calculated based on the dynamics of soil aeration status, substrate limitation, and gas diffusion. As a further source of NO emissions from soils, chemodenitrification, i.e., chemical decomposition of NO$_2^-$ to NO, was considered, which occurs only when soil pH is <5.0 [Li et al., 2000]. It was assumed that the main source of nitrite in soils is nitrification, since rates of nitrification in forest soils (200–1000 kg N ha$^{-1}$ yr$^{-1}$) are usually higher than rates of denitrification (<50 kg N ha$^{-1}$ yr$^{-1}$) [e.g., Zak et al., 1990; Stark and Hart, 1997; Barton et al., 1999]. Therefore chemodenitrification rates in PnET-N-DNDC depend on pH, temperature, and nitrification rates in the soil. Since nitrification and denitrification can simultaneously occur in aerobic and anaerobic microsites, the conceptual model of an “anaerobic balloon” was used to calculate the anaerobic fraction of soil in a given soil layer in dependency of O$_2$ diffusion and magnitude of soil and root respiration [Li et al., 2000].

2.2. Modeling the Effect of Freezing and Thawing on N$_2$O Emissions

Recently it has been shown that winter fluxes of N$_2$O are of crucial importance for estimates of annual N$_2$O losses from temperate forest soils [Papen and Butterbach-Bahl, 1999; Teepe et al., 2000; Butterbach-Bahl et al., 2001a], since N$_2$O fluxes during such periods contributed up to 73% of the total annual N$_2$O loss [Papen and Butterbach-Bahl, 1999]. Because of the importance of winter fluxes for global and regional estimates of N$_2$O emissions from temperate forest soils we implemented four different mechanisms in PnET-N-DNDC that have been hypothesized to explain the observation of high fluxes of N$_2$O during freezing and thawing events [e.g., Christensen and Tiedje, 1990; Flessa et al., 1995; Papen and Butterbach-Bahl, 1999]. These mechanisms are (1) death of microorganisms due to frost and consequent increase in substrate availability for microbial N turnover, (2) concentration effect of water during freezing on substrate availability, (3) tight coupling of nitrification and denitrification in the water-saturated organic layer, and (4) decrease of soil porosity due to the volumetric extension of water during the phase transition from water to ice (approximately +10%) and thus reduction of O$_2$ diffusion into the soil with consequences for the size of anaerobic sites within the soil and the accumulation of N$_2$O in the different soil layers [Stange, 2000].

2.3. Climate Sensitivity of PnET-N-DNDC

Continuous measurements of N trace gas fluxes at the Högwald Forest sites have revealed a huge interannual variability of soil NO and N$_2$O emissions [Butterbach-Bahl et al., 2001b], which was driven for N$_2$O mainly by freezing and thawing events and with regard to NO by differences in temperature and precipitation. We used this unique data set of field N trace gas measurements to further test and validate the climate sensitivity of PnET-N-DNDC by running the model for the 3-year period 1995–1997 and by comparing model simula-
tion and field measurements on a daily timescale. Because of the limited number of long-term NO flux measurements from temperate forests, predictions of NO emissions by PnET-N-DNDC have up to now only been validated for the spruce and beech site at the Högwald Forest, Bavaria, and for an oak stand in the United States [Stange et al., 2000]. In this paper, we used an additional data set of NO measurements in a Douglas fir and a beech stand in the Netherlands in the years 1996 and 1997, provided by Van Dijk and Duyzer [1999], to further validate the model for predictions of NO emissions from temperate forest soils.

2.4. Regional Model Drivers

The study area is located in southeast Germany (106,000 km², or ~30% of the area of Germany) and covered all of Bavaria (70,500 km²) (Figure 2). Approximately 34% of the study area is covered by forests.

2.4.1. Climate. Daily rainfall and temperature data for 1997 were obtained from 30 climate stations located within the area of investigation (see Plate 1). Data were provided either by the Bayerische Landesanstalt für Forst- und Holzwirtschaft, Munich, Germany (available at http://www.lwf.uni-muenchen.de), or were downloaded from the National Climatic Data Center, Asheville, USA (available at http://www.ncdc.noaa.gov/ncdc.html). The data were spatially interpolated for each polygon based on the nearest weather station (Plate 1), using the Thiessen polygon approach in ArcView (Environmental Systems Research Institute, Inc., Redlands, California). In using 30 climate stations for the study area, this method does not allow us to consider small-scale effects (less than ~50 km) of geomorphology on the distribution of rainfall and temperature (e.g., decrease of temperature with increasing altitude). However, if the small band of foothills region of the Alps in the southernmost part of the study area (~20–40 km in depth) is neglected, the differences in geomorphology and also in the distribution and amount of rainfall over the entire study area are rather small (mean annual temperature for all polygons: 7.8 ± 1.2°C; mean annual precipitation for all polygons: 644.9 ± 63.5 mm). For the foothill region, increased amounts in annual precipitation and lower values of mean annual temperature can be observed (e.g., climate station Berchtesgaden, mean annual rainfall: 1871 mm; mean annual temperature: 5.2°C). Further information on differences in regional climate is given by Müller-Westermeier et al. [1999].

2.4.2. Soils. Information on soil properties was obtained from the soil map of Germany as provided in digital format by the Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany (Plate 1) [Hartwich et al., 1995]. This map
contains information about soil texture, soil pH, and soil organic carbon content (SOC) for selected soil profiles. Since SOC contents provided with the soil map were mainly attributed to soils under agricultural use, we calculated SOC for the uppermost mineral forest soils from stand age, forest type, and litter input [Stange, 2000]. Comparison of calculated and measured SOC contents for nine different sites with different stand characteristics in central Europe did not reveal significant differences between the two approaches (measured: 5.0 ± 1.5% SOC; simulated: 4.7 ± 1.5% SOC).

2.4.3. Atmospheric N input. Values for atmospheric N deposition in the year 1997 for 23 forest sites within the area of investigation were obtained from the Bayerische Landesanstalt für Forst- und Holzwirtschaft, Munich, Germany. The magnitude of N deposition at the different sites for bulk precipitation and throughfall was in a range of 7–16 kg N ha⁻¹ yr⁻¹ (mean value: 10.7 ± 2.5 kg N ha⁻¹ yr⁻¹) and 11–32 kg N ha⁻¹ yr⁻¹ (mean value: 15.5 ± 5.0 kg N ha⁻¹ yr⁻¹), respectively. These data were spatially interpolated for each polygon based on the nearest measurement site.

2.4.4. Soil fertility. In PnET-N-DNDC the soil fertility parameter represents the long-term effects of land use history and atmospheric N input on the fertility of soils [Li et al., 2000]. Since information on land use history was scarce and not available on a regional scale, we used a simple empirical equation, which is based on the concentration of N in precipitation (data from the Bayerische Landesanstalt für Forst- und Holzwirtschaft), to calculate the input parameter soil fertility. This equation was derived by comparing concentrations of N in the rainfall and information about site fertility for nine forest sites within central Europe and the United States (Figure 3). The site fertility was estimated from the literature describing the different sites (e.g., Harvard Forest, United States: Bowden et al. [1991], Aber et al. [1993], and Magill et al. [1997]; Kopenhagen, Denmark: Ambus and Christensen [1995]; Schottenwald, Austria: Jandl et al. [1997]) and was based on nutrient availability in the soils (e.g., Harvard Forest, United States: poor; Kopenhagen, Denmark: moderate; Schottenwald, Austria: rich). More detailed information for the sites used for the estimation of the equation is given by Stange et al. [2000] and Stange [2000]. The soil fertility variable has a direct effect on the magnitude of nutrient dynamics within the stand [Stange et al., 2000], that is, high soil fertility will support increased turnover rates of, for example, mineralization and nitrification.

2.4.5. Forest cover. Information on forest cover was obtained from the coordination of information on the envi-

Figure 2. Location of the study area in southeast Germany.
environment (CORINE) database as provided by the Statistisches Bundesamt, Wiesbaden, Germany (available at http://www.destatis.de). Within this database, areas covered with deciduous forests, coniferous forests, or mixed forests are differentiated (Plate 1). Since PnET-N-DNDC has already been parameterized for, for example, spruce, pine, beech, oak, and birch [Li et al., 2000], we run different scenarios (see section 2.4.7) in order to estimate the effect of different forest types on N trace gas emissions at the regional scale.

Figure 3. Relation between N concentration in the rainfall and soil fertility as used in PnET-N-DNDC. For more details about the different forest sites see Stange et al. [2000] and Stange [2000].

Figure 4. (a) Precipitation (top line) and air temperature (bottom line) and measured and simulated (b) \( \text{N}_2\text{O} \) and (c) NO emission rates from soil of the spruce stand at the Högwald Forest (Germany) for the years 1995–1997. Field data represent daily means of \( \text{N}_2\text{O} \) and NO emission rates [Papen and Butterbach-Bahl, 1999; Gasche and Papen, 1999; Gasche and Papen, 2001; Butterbach-Bahl et al., 2001a]. Figures 4b and 4c show measured (symbols) and simulated (lines) data.
2.4.6. Humus type. PnET-N-DNDC differentiates three different humus types, i.e., raw humus, moder, and mull. We assumed that the humus type of coniferous or mixed forest is either a raw humus or a moder and that the humus type of a deciduous forest is either a moder or a mull (see also section 2.4.7) [Beyer, 1998].

2.4.7. Scenarios tested. In view of the variability/uncertainty of different parameters used as model input parameters on a regional scale (e.g., forest type and age, soil texture, and soil pH), different scenarios were tested in order to calculate ranges of uncertainties of N trace gas emissions. As a baseline scenario we assumed that the forested areas are covered with 80-year-old plantations with either spruce (coniferous forests), beech (deciduous forests), or a 50/50 mixture of beech and spruce (mixed forests). Also, average values of soil properties were used within the baseline scenario, i.e., average values of pH, SOC, soil texture, and soil fertility. Thereafter several scenarios were tested, where either the forest type (e.g., from spruce to pine or from beech to oak), the forest age (±30 years), the humus type (e.g., shift from raw humus to moder or from moder to mull), the pH (maximum and minimum values for each polygon), the soil texture (plus or minus one soil class), or the SOC content and the soil fertility (both ±50%) was changed.

3. Results and Discussion

3.1. Multiyear Validation of PnET-N-DNDC

In order to test the climate sensitivity of PnET-N-DNDC, we run the model for the spruce stand of the Högwald Forest for the 3-year period 1995–1997 (Figure 4). Figure 4 shows that PnET-N-DNDC can replicate the seasonal and interannual variability of both the NO and the N₂O emissions with a high degree of accuracy. Average N₂O emissions over this period of time were $3.76 \pm 0.25$ g N ha⁻¹ day⁻¹ (field measurements) and $2.65 \pm 0.11$ g N ha⁻¹ day⁻¹ (simulation by PnET-N-DNDC). The correlation coefficients for measured versus modeled fluxes were $r^2 = 0.331$ (NO) and $r^2 = 0.538$ (N₂O), respectively.

In order to further validate predictions of NO emissions by PnET-N-DNDC, we simulated NO emissions for 35-year-old stands of Douglas fir and beech on a loamy sand in the Netherlands (for site details see Van Dijk and Duyzer [1999]). Figures 5b and 5c show measured (symbols) and simulated (lines) data.
Plate 1. Regional maps of (left) soil texture (with permission of the Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, February 10, 1999, Germany) [Hartwich et al., 1995] and (right) forest cover (data from Statistisches Bundesamt, Wiesbaden, Germany) of southeast Germany. White dots represent locations of 30 climate stations from which the model drivers rainfall and precipitation were obtained.
NO emissions at both sites with a reasonable accuracy (model efficiency: douglas fir site, $r^2 = 0.557$; beech site, $r^2 = 0.258$). However, NO fluxes at the douglas fir site were, at least in the year 1996, underestimated by PnET-N-DNDC (mean of field measurements: douglas fir site, 36.0 $\pm$ 3.8 g NO-N ha$^{-1}$ day$^{-1}$; beech site, 22.5 $\pm$ 3.5 g NO-N ha$^{-1}$ day$^{-1}$; mean of model predictions for days of field observation: douglas fir site, 24.1 $\pm$ 1.7 g NO-N ha$^{-1}$ day$^{-1}$ ($\sim$32%); beech site, 20.5 $\pm$ 1.5 g NO-N ha$^{-1}$ day$^{-1}$ (8.9%)). From the results of this study and the study already published by Stange et al. [2000] we concluded that for a regional inventory of N trace gas emissions from forest soils the climate and site sensitivity of PnET-N-DNDC is sufficient.

3.2. Rates of NO Emissions From Forest Soils in Southeast Germany

Using the baseline scenario, Plate 2 gives an overview of the regional distribution of NO emissions in southeast Germany. Total annual NO emissions were 5.40 kt NO-N for the entire study area and 4.21 kt NO-N for Bavaria (Table 1). Highest emissions of NO ($\geq$6.0 kg NO-N ha$^{-1}$ yr$^{-1}$) were found for predominantly coniferous ecosystems in areas with relatively...
Table 1. Compilation of Seasonal and Annual Emissions of NO and N₂O From Forest Soils for the Entire Study Area and Bavaria and Comparison to NOₓ Emissions From Nonsoil Sources

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<tr>
<th></th>
<th>Annual N2O Emissions From Soil Sources, kt N2O-N</th>
<th>Winterb</th>
<th>Summerc</th>
<th>Summer dayd</th>
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<td>Bavaria</td>
<td>9.26</td>
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<td>0.53</td>
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<tr>
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<td>4.21</td>
<td>0.53</td>
<td>2.01</td>
<td>0.055</td>
</tr>
<tr>
<td>Entire study area</td>
<td>2.71</td>
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<tr>
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<tr>
<td>Transportation</td>
<td>70</td>
<td>17.3</td>
<td>17.5</td>
<td>0.192</td>
</tr>
<tr>
<td>Industry</td>
<td>13.7</td>
<td>3.3</td>
<td>3.4</td>
<td>0.057</td>
</tr>
<tr>
<td>Domestic fuels</td>
<td>7.6</td>
<td>1.18</td>
<td>1.9</td>
<td>0.021</td>
</tr>
<tr>
<td>Total</td>
<td>91.3</td>
<td>22.4</td>
<td>22.8</td>
<td>0.250</td>
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<tr>
<td>Forest soil</td>
<td>1.6</td>
<td>2.4</td>
<td>8.8</td>
<td>22.0</td>
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<tr>
<th></th>
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<tr>
<td>Bavaria</td>
<td>6.64</td>
<td>2.71</td>
<td>1.94</td>
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<tr>
<td>Entire study area</td>
<td>2.01</td>
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Data are from Bayerisches Usweltamt (Dr. K. Stepper, personal communication, 2000).

Sum of N gas emissions in the period from January 1, 1997, through March 31, 1997.

Sum of N gas emissions in the period from June 1, 1997, through August 31, 1997.

Mean maximum NO emission in summer.

low soil pH values in the forest floor (≤4.0) and with a loamy or sandy loam texture of the mineral soil. The pronounced pH effect on NO emissions (Table 2, see section 3.4) is mainly due to increased NO production via chemodenitrification at low pH values [Li et al., 2000; Stange et al., 2000]. The magnitude of predicted NO emissions are within the range of observed NO emissions from different forest soils in central Europe. Gasche and Papen [1999, 2001] and Butterbach-Bahl et al. [2001b] reported annual loss rates of NO from the beech and the spruce sites at the Hölzgod Forest in the range of 0.8–3.5 kg NO-N ha⁻¹ yr⁻¹ and 6.4–9.1 kg NO-N ha⁻¹ yr⁻¹, respectively. For pine forest ecosystems of the northeastern German lowlands, Butterbach-Bahl et al. [2001c] reported NO loss rates of 0.3–3.4 kg NO-N ha⁻¹ yr⁻¹. Comparable magnitudes of NO fluxes were also reported for N-affected forest sites in (1) the Netherlands, with emissions of ~10 kg NO-N ha⁻¹ yr⁻¹ from soils of a Douglas fir plantation and of ~6.8 kg NO-N ha⁻¹ yr⁻¹ from a nearby beech plantation [van Dijk and Duyzer, 1999], and (2) Denmark, with annual emissions of 3.1 kg NO-N ha⁻¹ yr⁻¹ from a Norway spruce plantation [Pilegaard et al., 1999].

Compared to total regional NO emissions from nonsoil sources, i.e., transportation, industry, and domestic fuels, total NO emissions from forest soils are on average for Bavaria, only ~5% of total emissions (Table 1). Furthermore, this figure does not include a canopy reduction factor, which was suggested to reduce soil NO emissions due to red deposition of NOₓ within the canopy by a factor of ~50% for temperate forests [Yienger and Levy, 1995; Lee et al., 1997]. Consideration of such a canopy reduction factor, which is still highly uncertain, would reduce the contribution of forest soils as sources of atmospheric NOₓ in Bavaria to <3%. However, if the annual figure for NO emissions from forest soils is not used, but only NO emissions during summer times when emissions are highest (mean average sum for the period June–August 1997: 650 g NO-N ha⁻¹; Plate 2b) are considered [see also Gasche and Papen, 1999; Van Dijk and Duyzer, 1999], the importance of forest soils as sources for atmospheric NOₓ strongly increases (Table 1). Compared to the winter period, NO emissions during the summer period (June–August) are approximately three-fold higher and contribute ~50% of the total annual NO emissions from forest soils in Bavaria (Plate 2d). Furthermore, if the regional inventory was evaluated for daily maximum NO emissions in summer, a mean maximum daily NO emission rate of 20.1 g NO-N ha⁻¹ day⁻¹ (range: 0.65–135.8 g NO-N ha⁻¹ day⁻¹) was found (Plate 2c). This means, applied to Bavaria, that 22% of NOₓ emissions during an “optimal” summer day are originating from forest soils. If we assume that NOₓ emissions from agricultural soils in summer are at least on the same order of magnitude as from forest soils, but are most likely much higher [e.g., Slemr and Seiler, 1984; Davidson and Kingerlee, 1997; Thornton and Valente, 1996], soil NO emissions in southeast Germany turn out to be a nonnegligible source for the atmospheric NOₓ burden in summer, at least in the more rural areas. This finding is in good agreement with the results and conclusions of other groups who estimated/calculated NO emissions inventories from soils (e.g., Lee et al. [1997] for the global estimate, Simpson et al. [1995, 1999] for the European Union, and Davidson et al. [1998] for the southeastern United States).

3.3. Rates of N₂O Emissions From Forest Soils in Southeast Germany

Plate 3 gives an overview of the magnitude of simulated N₂O emissions in southeast Germany in the year 1997. Total N₂O emissions from forest soils for the entire study area and Bavaria were 9.26 kt N₂O-N and 6.64 kt N₂O-N, respectively, and thus were ~50% higher than total NO emissions (Table 1). Maximum annual N₂O emissions of 10–15 kg N₂O-N ha⁻¹ yr⁻¹ were predicted for the Fichtelgebirge region in northeast Bavaria (Plate 3a), a region with silty loam textured soils for which very high rates of atmospheric N input of up to 32 kg N per ha⁻¹ yr⁻¹ were also reported (Bayerische Landesanstalt für Forst- und Holzwirtschaft, Munich, Germany). The mean annual N₂O emission rate from forest soils in Bavaria in the year 1997 was 2.3 kg N₂O-N ha⁻¹ yr⁻¹ (range: 0.14–4.6 kg N₂O-N ha⁻¹ yr⁻¹). In our simulation, deciduous forests showed, on average, higher N₂O emissions (mean: 3.1 kg N₂O-N ha⁻¹ yr⁻¹) than did coniferous forests (2.1 kg N₂O-N ha⁻¹ yr⁻¹). This prediction is in accordance with observations by others who also found higher N₂O fluxes under beech as compared to spruce forests for different sites in Germany [Butterbach-Bahl et al., 1997; Borken and Brumme, 1997; Papen...
and Butterbach-Bahl, 1999]. Also, the magnitude of calculated N$_2$O fluxes for southeast Germany is in accordance with observations of N$_2$O fluxes in other temperate forest ecosystems in Europe that are affected by atmospheric N deposition [e.g., Tietema et al., 1991; Brumme and Beese, 1992; Ambus and Christensen, 1995; Papen and Butterbach-Bahl, 1999]. However, most of these studies have not considered the importance of winter N$_2$O fluxes for estimating annual N$_2$O fluxes from temperate forests. Since the improved version of PnET-N-DNDC allows the estimation of N$_2$O fluxes during freezing and thawing with a remarkable accuracy (see Figure 4), we used PnET-N-DNDC to differentiate between winter (Plate 3b) and summer (Plate 3c) N$_2$O fluxes and also to calculate the relative contribution of winter fluxes to the annual N$_2$O losses (Plate 3d) on a regional scale. The simulations show that (1) accumulated fluxes of N$_2$O during the winter period from January 1, 1997, through March 31, 1997 (mean: 761 g N$_2$O-N ha$^{-1}$), were approximately identical in magnitude to the accumulated N$_2$O fluxes for the summer period from June 1, 1997, through August 31, 1997 (mean: 786 g N$_2$O-N ha$^{-1}$) and (2) strong regional differences did occur. On a regional scale, high fluxes of N$_2$O were predicted if the clay content of the soils was

Plate 3. Regional maps of N$_2$O emissions from forest soils in southeast Germany. (a) Mean annual N$_2$O emission rate (kg N$_2$O-N ha$^{-1}$ yr$^{-1}$). (b) Sum of N$_2$O emissions during the period from January 1, 1997 through March 31, 1997 (g N$_2$O-N ha$^{-1}$). (c) Sum of N$_2$O emissions during the period from June 1, 1997 through August 31, 1997 (g N$_2$O-N ha$^{-1}$). (d) Relative contribution of winter N$_2$O fluxes to total annual N$_2$O fluxes (percent).
Table 2. Sensitivity of Regional Predictions of N Trace Gas Fluxes in Southeast Germany From Variations in Model Input Parameters Using a Baseline Scenario of 9.26 kt N2O-N Emission and 5.40 kt NO-N Emission*

<table>
<thead>
<tr>
<th>Soil Parameter</th>
<th>N2O Emission</th>
<th>NO Emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce versus pine beech versus oak</td>
<td>−9.1</td>
<td>+9.2</td>
</tr>
<tr>
<td>Forest age</td>
<td></td>
<td></td>
</tr>
<tr>
<td>−30 years</td>
<td>−1.5</td>
<td>−14</td>
</tr>
<tr>
<td>−30 years</td>
<td>−17</td>
<td>−0.8</td>
</tr>
<tr>
<td>Raw humus versus moder; moder versus mull</td>
<td>+20</td>
<td>+5.6</td>
</tr>
<tr>
<td>PH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>−7.2</td>
<td>+6.9</td>
</tr>
<tr>
<td>Maximum</td>
<td>+4.9</td>
<td>−51.4</td>
</tr>
<tr>
<td>Soil texture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>−1 texture class</td>
<td>−11.1</td>
<td>−25.0</td>
</tr>
<tr>
<td>+1 texture class</td>
<td>+45.5</td>
<td>+25.0</td>
</tr>
<tr>
<td>Soil organic carbon and soil fertility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>−50%</td>
<td>−3.6</td>
<td>−33.1</td>
</tr>
<tr>
<td>+50%</td>
<td>+42.4</td>
<td>+8.1</td>
</tr>
</tbody>
</table>

*Emissions show percent of variation from baseline scenario.

>15%, the soil moisture content at the beginning of soil freezing was high, and the length of the freezing period was sufficient to allow the penetration of frost into deeper soil layers. On average, winter N2O fluxes contributed 38% to the annual N2O losses from forest ecosystems in Bavaria (Plate 3d).

3.4. Reliability of N Trace Gas Emission Inventory

The magnitude and range of N trace gas fluxes predicted for forest ecosystems in southeast Germany is in general accordance with field observations in central Europe [e.g., Brumme and Beese, 1992; Papen and Butterbach-Bahl, 1999; Gasche and Papen, 1999; Van Dijk and Duyzer, 1999]. Also, the prediction of high N2O emissions for the winter period in 1997 is in agreement with results of continuous measurements of N2O emissions at the spruce and beech sites of the Hgwild Forest, Bavaria [Butterbach-Bahl et al., 2001a]. However, the regional study has shown that model predictions by PnET-N-DNDC will strongly rely on the quality of regional input data. Table 2 shows the sensitivity of regional predictions of N trace gas fluxes for different model input parameters. It is obvious from Table 2 that with regard to the N2O emission inventory, the estimate is most sensitive to the reliability of information about soil texture and soil carbon content and site fertility. The latter factors have both been estimated for the study area by empirical equations, but regional data sets are not available at present. With regard to the NO emission inventory, the most sensitive parameters are pH values of the mineral soil and of the forest floor, soil organic carbon content, and site fertility and soil texture. It is not surprising that NO emissions are very sensitive to changes in soil pH, especially since chemodenitrification will increase in importance at lower pH values [Stange et al., 2000; Li et al., 2000]. Therefore, in order to improve the NO estimates, a regional map of soil pH values, especially for forest soils, is strongly required.

In conclusion, we are confident that our regional estimate of N trace gas emissions from forest soils of southeast Germany is close to reality and is accurate within a factor of 1.5. Because of the interannual variability of meteorological parameters used as model drivers, which is the reason for the huge range of interannual changes in N trace gas fluxes from forest soils [Butterbach-Bahl et al., 2001b], and in view of rapid changes in land use, use of process-oriented models may be the only promising approach for more reliable estimates of rates of exchange of N trace gases between soils and the atmosphere on a regional or even global scale.

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References


Borken, W., and R. Brumme, Liming practice in temperate forest ecosystems and the effects on CO2, N2O and CH4 fluxes, Soil Use Manage., 13, 251–257, 1997.


Firestone, M. K., and E. A. Davidson, Microbiological basis of NO and N2O production and consumption in soil, in Exchange of Trace Gases
Between Terrestrial Ecosystems and the Atmosphere, edited by M. O.
Flesa, H., P. Dorsch, and F. Beese, Seasonal variation of N₂O and
CH₄ fluxes in differently managed arable soils in southern Germany,
Gasche, R., and H. Papen. A 3-year continuous record of nitrogen
gas trace gas fluxes from untreated and limed soil of a N-saturated
spruce and beech forest ecosystem in Germany, 2, NO and NO₂
Gasche, R., and H. Papen. Spatial variability of NO and NO₂ fluxes
from soil of spruce and beech forest ecosystems, Plant Soil, in press,
Goodale, C. L., J. D. Aber, and E. P. Farrell. Predicting the relative
sensitivity of forest production in Ireland to site quality and climate
Goodroad, L. L., and D. R. Keeney. Nitrous oxide emission from
spruce and beech forest ecosystem in Germany, 2, NO and NO₂
emissions from fertilized and unfertilized soils, J. Geophys. Chem., 2, 1–24,
1995.
Hartwich, R., D. Krug, and W. Eckelmann. Bodennutzungskarte der
Bundesrepublik Deutschland, map, 1:100000, Bundesanstalt fu
der Bodenforschung, Hannover, Germany, 1995.
Houghton, J. T., B. A. Callander, and S. K. Varney (Eds.), Climate
Change 1992, The Supplementary Report to the IPCC Assessment
Jandl, R., H. Kopezki, and G. Glatzel. Effect of a dense Allium ursinum
(L.) ground cover on nitrogen dynamics and mesofauna of
Keller, M., W. A. Kaplan, and S. C. Wofsy. Emissions of N₂O, CH₄,
and CO₂ from tropical forest soils, J. Geophys. Res., 91, 11,791–
11,802, 1986.
Lee, D. S., T. Köhler, E. Grobler, F. Rohrer, R. Sausen, L. Gallardo-
Estimations of global NOₓ-emissions and their uncertainties, Atmos.
Li, C., S. Frolking, and T. A. Frolking. A model of nitrous oxide
emission from soil driven by rainfall events, 1. Model structure and
Li, C., J. Aber, F. Stange, K. Butterbach-Bahl, and H. Papen. A
process-oriented model of N₂O and NO emissions from forest soils,
Magill, A. H., J. D. Aber, J. J. Hendricks, and R. D. Bowden. Biogeo-
chemical response of forest ecosystems to simulated chronic nitrogen
Bundesrepublik Deutschland, Deutscher Wetterdienst, Offenbach
am Main, Germany, 1999.
Papen, H., and K. Butterbach-Bahl. A 3-year continuous record of
nitrogen trace gas fluxes from untreated and limed soil of a N-
saturated spruce and beech forest ecosystem in Germany, 1, N₂O
Pilegaard, K., P. Hummelshøj, and N. O. Jensen. Nitric oxide emission
from a Norway spruce forest floor, J. Geophys. Res., 104, 3433–3445,
1999.
Process modeling of controls on nitrogen trace gas emissions from