Spatial variability of nitrous oxide emissions in an unmanaged old-growth beech forest

Hermann F. Jungkunst1, Anika Bargsten2, Marc Timme3,4, and Stephan Glatzel5*

1 Geocology / Physical Geography, Institute for Environmental Sciences, University of Koblenz-Landau, 76829 Landau, Germany
2 Landscape Ecology, Institute of Geography, University of Göttingen, 37077 Göttingen, Germany
3 Network Dynamics Group, Max Planck Institute for Dynamics & Self-Organization, 37077 Göttingen, Germany
4 Faculty of Physics, University of Göttingen, 37077 Göttingen, Germany
5 Landscape Ecology and Site Evaluation, Faculty of Agricultural and Environmental Sciences, University of Rostock, 18059 Rostock, Germany

Abstract
Nitrous oxide (N\textsubscript{2}O) is a high-impact greenhouse gas. Due to the scarcity of unmanaged forests in Central Europe, its long-term natural background emission level is not entirely clear. We measured soil N\textsubscript{2}O emissions in an unmanaged, old-growth beech forest in the Hainich National Park, Germany, at 15 plots over a 1-year period. The average annual measured N\textsubscript{2}O flux rate was (0.49 ± 0.44) kg N ha\textsuperscript{–1} y\textsuperscript{–1}. The N\textsubscript{2}O emissions showed background-emission patterns with two N\textsubscript{2}O peaks. A correlation analysis shows that the distance between plots (up to 380 m) does not control flux correlations. Comparison of measured data with annual N\textsubscript{2}O flux rates obtained from a standard model (Forest-DNDC) without site-specific recalibration reveals that the model overestimates the actual measured N\textsubscript{2}O flux rates mainly in spring. Temporal variability of measured N\textsubscript{2}O flux was better depicted by the model at plots with high soil organic C (SOC) content. Modeled N\textsubscript{2}O flux rates were increased during freezing only when SOC was > 0.06 kg C kg\textsuperscript{–1}. The results indicate that the natural background of N\textsubscript{2}O emissions may be lower than assumed by most approaches.

Key words: old-growth forest / nitrous oxide / model / spatial variability / background emissions

Accepted May 29, 2012

1 Introduction

The atmospheric abundance of the greenhouse-gas nitrous oxide (N\textsubscript{2}O) has been rising since industrialization and intensification of agriculture and anthropogenic emissions need to be reduced to counteract global warming (Denman et al., 2007). Consequently, anthropogenic emissions need to be separated from natural background emissions for inventories and better scientific understanding. This is not a trivial task. The standard background emission rate of 1.0 kg N\textsubscript{2}O-N ha\textsuperscript{–1} y\textsuperscript{–1} by Bouwman (1996) is only valid for agricultural soils which are in any case highly influenced by man. Therefore, fluxes from forest soils which are less influenced by man should better reflect natural background emissions. Using a third version of PnET-N-DNDC, Kesik et al. (2005) proposed an N\textsubscript{2}O-emission factor for European forests of 0.55 to 0.62 kg N ha\textsuperscript{–1} y\textsuperscript{–1} and for German forests the mean value of 0.72 kg N ha\textsuperscript{–1} y\textsuperscript{–1}. Schulte-Bisping et al. (2003) estimated that the average forest-soil N\textsubscript{2}O-emission rate in Germany is 0.32 kg N ha\textsuperscript{–1} y\textsuperscript{–1}. These estimations are below the background-emission value proposed by Bouwman (1996) for agricultural soils. Most unfertilized agricultural sites are not sites that were never fertilized and like forest site, they are being fertilized by atmospheric depositions. Therefore, natural emissions rates without any anthropogenic impact cannot be measured in Central Europe. To determine realistic natural background-emission rates anyhow joint measure-

Anthropogenic influence is not restricted to N fertilization (Ruser et al., 1998; Fiessler et al., 2002a; Teepe et al., 2004) and plowing (Mosier et al., 1996), and it is unclear after which period of withholding fertilization emission rates return back to their natural background level, if at all. Therefore, heavily biased estimates for natural background emission rates are likely derived from “former” agricultural land due to longer lasting anthropogenic influences. Even soil compaction due to the use of heavy machinery will highly likely have a long-term influence as soil structure controls soil aeration which is a main driver of N\textsubscript{2}O emission.

Actual natural background fluxes may only be determined from undisturbed, unmanaged ecosystems that exhibit vegetation close to the potential natural one. However, such ecosystems have become very rare across the globe (Groombridge and Jenkins, 2000). For the greater part of Central Europe, the potential natural vegetation is beech (Fagus sylvatica L.) forest (Ellenberg and Leuschner, 2010). Hence, natural background emission rates representative for Central
Europe should be recorded in pristine beech forests preferably at contrasting sites, e.g., at different soils and under different climate. However, there are hardly any unmanaged beech forests and there are certainly no pristine beech forests left in Central Europe. Nevertheless, in unmanaged old forest ecosystems anthropogenic influences may be assumed to be low and the N status is not elevated besides the unavoidable atmospheric deposition.

Ecosystems in the core zone of the Hainich National Park (NP) are among the closest to natural that are available in all of Central Europe. Thus, they provide the opportunity to determine the closest estimate to the potential natural background emission in Central Europe.

Furthermore, if N\textsubscript{2}O release can be redrawn by a biogeochemical model without local recalibration, the model can be used for determining to a certain degree “near-natural N\textsubscript{2}O fluxes” for similar ecoregions in Central Europe. By using a publicly accessible model without site-specific recalibration, this assessment would be applicable to these areas. In any case, the outcome of a measurement and modeling approach of a “long-term” unmanaged beech forest will add to the understanding of N\textsubscript{2}O fluxes from natural ecosystems. A well-known phenomenon associated with gas-flux measurement from soils is the high spatial and temporal variability (Folunso and Rolston, 1984; Huang et al., 2011). An issue that needs to be considered in this respect is the question of spatial autocorrelation (Jurasinski et al., 2012). What is the optimal distance between flux-measurement chambers to avoid autocorrelation (e.g., pseudoreplication)?

The objectives of this study were: (1) to determine N\textsubscript{2}O fluxes within an unmanaged beech forest site in the Hainich National Park at 15 plots during a 1-year period; (2) to calculate if distance between the plots matters to avoid autocorrelation; (3) to test if the set of 15 individually varying soil parameters helps to explain the spatial variation of the N\textsubscript{2}O fluxes; (4) to evaluate if a model (Forest-DNDC) without recalibration, as needed for any regionalization, individually run with the set of 15 soil input parameters, can account for N\textsubscript{2}O emissions of this near-natural ecosystem. Thereby the relevance of spatial variability for the assessment of N\textsubscript{2}O fluxes in unmanaged temperate forests will be elucidated.

2 Materials and methods

2.1 Study site

Our research site is located within the Hainich National Park (NP) (51°04′46″ N, 10°27′08″ E, 440 m asl) in Thuringia, Germany. The Hainich NP was established in 1997 to protect one of the largest beech forests in Central Europe. Due to a unique history as a military base for more than 60 years prior to 1997, a large part of the forest has been taken out of management and developed with little disturbance. In the centuries before, the forest at the Hainich research site was used by the local village population as a coppice with standard systems and therefore has not been exposed to clearcut (Gleixner et al., 2009). As a consequence, the trees cover a wide range of age classes with a maximum up to 250 y. The forest is dominated by beech (65%). The aboveground stem C pool is ≈ 130 t C ha\textsuperscript{-1} (Gleixner et al., 2009). Maximum tree height varies between 30 and 35 m with a maximum leaf-area index (LAI) of 5.0 m\textsuperscript{2} m\textsuperscript{-2}. The long-term mean annual air temperature is 7.5°C–8°C, and the mean annual precipitation is 750–800 mm. The latest estimates for wet and dry deposition for the Hainich area are 25 kg N ha\textsuperscript{-1} for 2007 (Builtjes et al., 2010) and show no strong trend over more than a decade.

Within the same area, an intensive soil survey was undertaken for detail soil-C analyses (Sch rampf et al., 2011). The soils are rather shallow and very clayey Eutric Cambisols related to Vertisols. The clay contents in the deeper horizons (20–60 cm) are well > 60% and in the topsoil ≈ 50% (Sch rampf, personal communication). The litter layers usually are gone by the end of summer, and by the onset of spring shallow Oi and Oe horizons appear. The mean C stocks for the top 20 cm are 6.92 kg C m\textsuperscript{-2} and 4.97 kg C m\textsuperscript{-2} for 20 to 60 cm (Sch rampf et al., 2011).

2.2 Field measurements and N\textsubscript{2}O-flux analysis

Measurements of N\textsubscript{2}O fluxes were carried out using a closed-chamber technique employing 15 cylindrical polyvinyl chloride (PVC) frames (30 cm in diameter and 15 cm tall). The collars were randomly distributed throughout the footprint of an eddy covariance tower (run by the Max Planck Institute for Biogeochemistry, MPI, Jena) as well as in a small valley just outside this fetch. The frames had been set up in the top-soil 2 weeks before starting the gas sampling. The location of each frame was selected stratified randomly.

N\textsubscript{2}O exchange was measured 34 times within the period from November 2005 to November 2006 by placing a PVC lid (30 cm in diameter and 30 cm tall) at each frame and taking five gas samples from the chamber headspace using gas-tight syringes (60 mL) after 0, 5, 10, 15, and 20 minutes of closure. N\textsubscript{2}O concentration was analyzed in the laboratory using an automated gas-chromatograph (GC) system (GC-14B, Shimadzu, Germany) equipped with flame ionization and an electron-capture detector. A detailed description of the GC system is given by Loftfield et al. (1997). For calibration, three certified standards were used (303 ppb, 1000 ppb, 1998 ppb). As no saturation effects were found, fluxes were calculated from the linear slope of the concentration change over time taking into account the headspace temperature and the coefficient of determination for each regression.

During all N\textsubscript{2}O measurements at the GC, we regularly performed measurements of the standard gases. Forty replicate measurements of the 303 ppb N\textsubscript{2}O standard gas were used to calculate the analytical uncertainty range of the N\textsubscript{2}O measurements of 1%. Annual flux rates were calculated by summing up the assumed steady fluxes (1) until the next measurement and (2) since the last measurement, and applying the arithmetic means of both values following Jungkunst et al. (2004).
2.3 Soil and model input parameters

Meteorological data, in this case daily minimum and maximum air temperature as well as daily precipitation, were observed 2 m above ground at a station located outside the forest installed by the MPI.

Additionally, we determined soil temperature and soil moisture at each plot at the time of gas sampling. Soil temperature was measured using a mobile temperature sensor (Testo 110, Testo, Germany), and soil moisture was determined gravimetrically from the top 10 cm of soil following removal of litter by oven-drying at 105°C for 36 h. To compare the gravimetric soil water content with the soil moisture displayed by the Forest-DNDC model (see subsection 2.4) we calculated the water-filled pore space (WFPS) according to Parton et al. (2001) by

$$WFPS = B/D \cdot \frac{BD}{1 - BD/PD}$$

where $B/D$ is the gravimetric soil water content, $BD$ is the bulk density, $WD$ is the density of water, and $PD$ is the particle density of the average soil material (quartz) with a value of 2.65 g cm$^{-3}$.

Bulk density, soil organic C (SOC), and soil pH ($\text{H}_2\text{O}$) were determined at the beginning of the measurement period in November 2005. To determine soil bulk density, undisturbed soil samples from 0 to 5 cm depth were taken using stainless-steel soil cores of known volume (100 cm$^3$). Then the samples were oven-dried at 105°C for 24 h. Concentration of SOC was determined by the mean difference of 5 g (air-dried) of the soil sample and 5 g dried at 430°C in a muffle furnace (until constant weight was achieved). For the determination of soil pH, the soil was homogenized and afterwards measured in a soil-to-water suspension (1:2.5) using a glass electrode.

2.4 Forest-DNDC

For all 15 plots, we simulated the N$_2$O fluxes for the Hainich research site using the model Forest-DNDC (http://www.dndc.sr.unh.edu/). Forest-DNDC simulates C and N dynamics in soil as well as trace-gas exchange (N$_2$O, CH$_4$, N$_2$, NO, and NH$_3$) between soil and atmosphere from wetland steel soil cores of known volume (100 cm$^3$). Then the samples of soil were taken using stainless steel samples from 0 to 5 cm depth were taken using stainless-steel soil cores of known volume (100 cm$^3$). Then the samples were oven-dried at 105°C for 24 h. Concentration of SOC was determined by the mean difference of 5 g (air-dried) of the soil sample and 5 g dried at 430°C in a muffle furnace (until constant weight was achieved). For the determination of soil pH, the soil was homogenized and afterwards measured in a soil-to-water suspension (1:2.5) using a glass electrode.

Further, we tested whether correlations between N$_2$O flux rates at different plots depend on spatial distance between the plots. We first extracted the spatial coordinates of all 15 plots and computed their mutual distances $d(i, j)$ for all distinct pairs $d(i, j)$, where i, j are chosen from {1, 2, ..., 15}, yielding 15 x 14/2 = 105 distances. For each of the 105 possible pairs of plots, we also computed the cross-correlation coefficient $C_{flux}(i, j)$ of their flux time series (34 time points each). The resulting correlation between the distances and flux correlations was tested for significance using a bootstrap permutation. We repeatedly associated the flux values to randomly chosen plots, again computed the cross-correlation coefficient $C_{rand}(i, j)$, and generated a histogram of 20 000 such randomly occurring correlations obtained from random association of actual fluxes to actual plot locations.

An analogous bootstrap analysis (based on 20 000 random permutations) was performed for accessing the significance of correlations between soil parameters (pH value, SOC content, clay content, and bulk density) and N$_2$O flux rates.

2.5 Statistical analyses

Further, we tested whether correlations between N$_2$O flux rates at different plots depend on spatial distance between the plots. We first extracted the spatial coordinates of all 15 plots and computed their mutual distances $d(i, j)$ for all distinct pairs $d(i, j)$, where i, j are chosen from {1, 2, ..., 15}, yielding 15 x 14/2 = 105 distances. For each of the 105 possible pairs of plots, we also computed the cross-correlation coefficient $C_{flux}(i, j)$ of their flux time series (34 time points each). The resulting correlation between the distances and flux correlations was tested for significance using a bootstrap permutation. We repeatedly associated the flux values to randomly chosen plots, again computed the cross-correlation coefficient $C_{rand}(i, j)$, and generated a histogram of 20 000 such randomly occurring correlations obtained from random association of actual fluxes to actual plot locations.

An analogous bootstrap analysis (based on 20 000 random permutations) was performed for accessing the significance of correlations between soil parameters (pH value, SOC content, clay content, and bulk density) and N$_2$O flux rates.

3 Results

3.1 Physical and chemical soil parameters

Physical and chemical soil parameters (BD, soil pH, SOC, clay content) at the 15 plots are summarized in Tab. 2. Although forest structure and land-use history in the research area are homogeneous (Jurasisinski et al., 2012), soil parameters are less so. Bulk density ranged from 0.79 g cm$^{-3}$ (plot 2) to 0.92 g cm$^{-3}$ (plot 4). Soil pH showed the lowest value at plot 2 (4.8) and the highest soil pH at plot 4 (6.7). The clay content and the soil organic carbon showed even larger variability. The clay content varied from 30.8% to 51%, and the SOC ranged from 0.032 to 0.087 kg C (kg soil)$^{-1}$.

3.2 Soil climate

Figure 1 presents the daily soil temperature and soil moisture simulated with Forest-DNDC and the mean measured soil temperature and soil moisture measured at the time of gas sampling from plot 1. All other plots showed a similar pattern (Tab. 2). The modeled soil temperature matched well with the measured soil temperature except for soil temperature near freezing. The modeled soil water content shows good agreement in the period from October 2005 to June 2006, but in the period from July to October 2006 the Forest-DNDC model overestimates the soil water content (Fig. 1).
Table 2: Plot-specific soil parameters (soil pH, soil organic carbon [SOC], clay content, bulk density [BD], and measured and modeled N₂O fluxes) of all 15 plots of the Hainich research site.

<table>
<thead>
<tr>
<th>Plot</th>
<th>pH</th>
<th>SOC / kg C (kg soil)^{-1}</th>
<th>Clay / %</th>
<th>BD / g cm^{-3}</th>
<th>N₂O / μg N m^{-2} h^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>measured</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>average SD</td>
</tr>
<tr>
<td>1</td>
<td>4.9</td>
<td>0.033</td>
<td>36.2</td>
<td>0.9</td>
<td>1.44 21.88</td>
</tr>
<tr>
<td>2</td>
<td>4.8</td>
<td>0.032</td>
<td>30.8</td>
<td>0.86</td>
<td>-0.49 10.25</td>
</tr>
<tr>
<td>3</td>
<td>5.3</td>
<td>0.05</td>
<td>45.3</td>
<td>0.92</td>
<td>12.68 22.05</td>
</tr>
<tr>
<td>4</td>
<td>6.7</td>
<td>0.087</td>
<td>50.5</td>
<td>0.88</td>
<td>0.22 15.26</td>
</tr>
<tr>
<td>5</td>
<td>5.8</td>
<td>0.04</td>
<td>42.0</td>
<td>0.84</td>
<td>3.85 16.33</td>
</tr>
<tr>
<td>6</td>
<td>5.4</td>
<td>0.036</td>
<td>39.3</td>
<td>0.86</td>
<td>2.95 17.33</td>
</tr>
<tr>
<td>7</td>
<td>5.3</td>
<td>0.041</td>
<td>36.4</td>
<td>0.87</td>
<td>7.95 18.86</td>
</tr>
<tr>
<td>8</td>
<td>6.2</td>
<td>0.047</td>
<td>41.2</td>
<td>0.86</td>
<td>10.47 23.28</td>
</tr>
<tr>
<td>9</td>
<td>6.0</td>
<td>0.064</td>
<td>51.0</td>
<td>0.89</td>
<td>13.38 19.42</td>
</tr>
<tr>
<td>10</td>
<td>6.6</td>
<td>0.062</td>
<td>48.6</td>
<td>0.79</td>
<td>6.53 11.03</td>
</tr>
<tr>
<td>11</td>
<td>5.7</td>
<td>0.052</td>
<td>44.2</td>
<td>0.79</td>
<td>5.98 13.41</td>
</tr>
<tr>
<td>12</td>
<td>5.3</td>
<td>0.054</td>
<td>35.0</td>
<td>0.81</td>
<td>5.03 16.75</td>
</tr>
<tr>
<td>13</td>
<td>6.4</td>
<td>0.05</td>
<td>44.5</td>
<td>0.86</td>
<td>3.54 22.33</td>
</tr>
<tr>
<td>14</td>
<td>6.1</td>
<td>0.041</td>
<td>38.7</td>
<td>0.87</td>
<td>2.81 17.20</td>
</tr>
<tr>
<td>15</td>
<td>6.2</td>
<td>0.046</td>
<td>40.2</td>
<td>0.91</td>
<td>-1.61 20.30</td>
</tr>
<tr>
<td>Average</td>
<td>6.1</td>
<td>0.049</td>
<td>41.6</td>
<td>0.86</td>
<td>4.98 (n = 510) 16.93 (n = 510)</td>
</tr>
<tr>
<td>SD</td>
<td>0.6</td>
<td>0.014</td>
<td>5.8</td>
<td>0.04</td>
<td>18.42 33.41</td>
</tr>
</tbody>
</table>

Figure 1: (a) Daily soil temperature (0–12 cm depth) from plot 1 simulated by Forest-DNDC. Solid circles represent the soil temperature (integral between 0 and 12 cm) measured at the time of gas-flux sampling at plot 1. (b) Daily soil WFPS (0–12 cm depth) from plot 1 simulated by Forest-DNDC. Solid circles represent the WFPS calculated with the gravimetric soil water content (0–10 cm) measured at the time of gas-flux sampling at plot 1.
soil water content showed no values below 0.57 WFPS. In contrast, the measured soil water content ranged between 0.28 and 0.71 WFPS.

3.3 Measured N₂O flux rates

Figure 2 presents an overview of air temperature, precipitation, and both the average measured and modeled N₂O flux rates obtained from 15 plots distributed over the Hainich research site for the years 2005 and 2006. The mean measured N₂O flux rates were obtained from averaging flux rates of all 15 plots. A seasonal pattern of measured N₂O exchange was lacking. Average measured N₂O-N flux rates (November 2005 to November 2006) exhibited small amplitudes between –4.54 and 40.5 μg m⁻² h⁻¹, but most average measured N₂O flux rates do not significantly differ from zero (t-test, p = 0.05) (see Fig. 1). A portion of 38% of all (n = 510) observed N₂O flux rates shows negative values. The highest measured N₂O flux rates occurred between January and February 2006. During this time, there was an extended frost period with soil temperature below –0.5°C. This period contributes 40% to the annual measured N₂O flux rate. A second period with mean measured N₂O flux rates significantly different from zero started at the end of June 2006 (June 21–28, 2006) and contributes 15% to the annual measured N₂O flux rate. During this period, the air temperature strongly increased (see Fig. 1). The annual measured N₂O flux rate for the Hainich research site for the 1-year measuring period (November 2005 to November 2006) was (0.49 ± 0.44) kg N ha⁻¹ y⁻¹. The 15 individual plots showed measured N₂O flux rates between –87.6 and 121.6 μg N m⁻² h⁻¹. During periods with higher mean N₂O emissions, only small negative fluxes occurred (see Fig. 3) and these fluxes are within the uncertainty range. During the frost period, nearly all plots exhibited positive measured N₂O flux rates. Also the spatial variability showed high values in this period (range: –17.5 to 94.6 μg N m⁻² h⁻¹, mean: 27.5 μg N m⁻² h⁻¹). In the second period (end of June) with N₂O flux rates that were significantly different from zero, the spatial variability was also high (range: –18.0 to 121.6 μg N m⁻² h⁻¹, mean: 30.1 μg m⁻² h⁻¹). During the periods with a background emission pattern (Brumme et al., 1999), both negative and positive N₂O fluxes occurred at similar ratio (range: –54.3 to 88.6 μg N m⁻² h⁻¹, mean: 3.4 μg N m⁻² h⁻¹).

3.4 Spatial correlation of measured N₂O flux rates between different plots

There is a weak positive correlation (correlation coefficient 0.085) suggesting that flux correlations between plots tend to be larger at the more distant plots (Fig. 4a). However, flux correlations are broadly distributed in the range between –0.3 and +0.77 and the best linear fit (least square regression) shows only a low average increase of flux correlations with distance at 0.17 km⁻¹. Together with the small correlation coefficient, this suggests that the correlation between the

Figure 2: (a) Daily mean air temperature for 2005 and 2006 recorded 2 m above the ground and (b) daily precipitation for 2005 and 2006. (c) The black dots are the mean field N₂O flux rates with (n = 15) for the Hainich research site, the gray squares are the mean modeled N₂O flux rates (n = 15), and the gray line shows the mean daily modeled N₂O flux rates. The error bars on each individual data point are the standard deviation.

© 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim www.plant-soil.com
N\(_2\)O flux rates at any two plots is almost independent of the distance between them. Indeed, a randomized (bootstrap) sampling of the given data (see section 2) yields some insight into whether this slightly positive correlation might be significant. We therefore created 20,000 random permutation samples by randomly associating plots with flux time series, obtaining the distribution shown in Fig. 4b. We observe that 25.7% of the correlations between N\(_2\)O flux correlations and randomized plot locations are larger than the observed value of 0.084%, and 74.3% are lower. This strongly indicates that there is no significant correlation between the actual interplot distances and the actual interplot N\(_2\)O flux correlations at spatial distances < 400 m.

3.5 Modeled N\(_2\)O flux rates

The modeled N\(_2\)O flux rates of the 15 individual plots showed no negative values. They ranged between 0.0 and 255.7 µg N m\(^{-2}\) h\(^{-1}\) (see inset in Fig. 3). The 15 individual plots exhibited the highest variability in modeled N\(_2\)O flux rates from each other (high standard deviation) on May 23, 2006 (Fig. 3). Plot 4, and, to a lesser degree, plot 9 and plot 10, with high N\(_2\)O fluxes, drive this high standard deviation (Tab. 2).

Mean modeled N\(_2\)O-N flux rates (2.54 to 81.72 µg m\(^{-2}\) h\(^{-1}\)) were typically higher than the actual measured N\(_2\)O-N flux rates (−4.54 to 40.5 µg m\(^{-2}\) h\(^{-1}\)). During this period, modeled...
N$_2$O flux rates (1.40–133.09 µg N m$^{-2}$ h$^{-1}$) were up to three times larger than the measured N$_2$O flux rates. Mean modeled N$_2$O flux rates showed lowest values from November 2005 to March 2006 and from September to November 2006. Highest values occurred at the end of April 2006 (see Fig. 1). Furthermore, the daily modeled N$_2$O flux rates showed a weak seasonal pattern. The model does not account for N$_2$O uptake. The annual modeled N$_2$O flux rate at measurement intervals and the annual modeled N$_2$O flux in daily resolution for the Hainich research site for the 1-year measuring period (November 2005 to November 2006) were (1.77 ± 1.82) and (1.56 ± 0.006) kg N ha$^{-1}$ y$^{-1}$, respectively.

4 Discussion

4.1 Comparison with other studies

Except for the recent study by Guckland et al. (2010), all previously published studies focusing on N$_2$O exchange from soils in beech-forest ecosystems were performed in managed forest ecosystems (references in Tab. 3). Still our results agree well with the results of Brumme et al. (1999) and Brumme and Borken (2009) for forests dominated by the background-emission type. They found that soils in beech forests with a mull organic horizon usually show background emissions sometimes interrupted by event emissions like frost and thaw. The annual N$_2$O flux rates ([0.49 ± 0.44] kg N ha$^{-1}$ y$^{-1}$) were within the lower range of values reported for temperate beech-forest soils (see Tab. 3).

Contrasting to the other studies, the core zone of the Hainich NP is a close to natural deciduous forest which is unique in Central Europe. This could be a reason why most N$_2$O fluxes did not significantly differ from zero. It may also well be that N is immobilized as a part of rising soil organic-matter stocks (Gleixner et al., 2009). In any case, it clearly supports the notion that most natural ecosystems do not emit significant amounts of N$_2$O and natural background emissions are somewhat lower than the simulated average value with PnET-N-DNDC for forests in Germany (Kesik et al., 2005). Guckland et al. (2010) found even lower emission rates of N$_2$O ranging from –31.4 to 167.8 µg N m$^{-2}$ h$^{-1}$ at a site covered to 59% with beech also located in the Hainich NP. These measurements were performed on loess soils (Luvisols) with lower clay content than in this study resulting in an annual N$_2$O flux rate of (0.19 ± 0.16) kg N ha$^{-1}$ y$^{-1}$. The N$_2$O fluxes measured by Guckland et al. (2010) during freezing and thawing amounted to 94% of the emissions of the first year. Our values of 38% are closer to the values observed by Papen and Butterbach-Bahl (1999) who estimated a contribution up to 39% to the total annual N$_2$O emission caused by freezing and thawing at a 96-y-old beech plantation in the Höglwald (S Germany). Therefore, the bulk of N$_2$O emissions at the Hainich site is related to frost. Similar results were also observed by Butterbach-Bahl et al. (2002), Papen and Butterbach-Bahl et al. (2002).

Table 3: Compilation of published annual N$_2$O flux rates from soils of temperate beech forests.

<table>
<thead>
<tr>
<th>Site</th>
<th>Annual N$_2$O flux / kg N ha$^{-1}$ y$^{-1}$</th>
<th>Observation period</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hainicha, Germany</td>
<td>0.49 ± 0.44</td>
<td>2005–2006</td>
<td>this study</td>
</tr>
<tr>
<td>Hainichb, Germany</td>
<td>0.11 ± 0.11</td>
<td>2005–2007</td>
<td>Guckland et al. (2010)</td>
</tr>
<tr>
<td>Solling, Germany</td>
<td>1.93 ± 0.63</td>
<td>1990–2000</td>
<td>Brumme and Borken (2009)</td>
</tr>
<tr>
<td>Solling, Germany</td>
<td>0.54 ± 0.14</td>
<td>2000–2001</td>
<td>Borken and Beese (2006)</td>
</tr>
<tr>
<td>Göttinger Wald, Germany</td>
<td>0.17 ± 0.03</td>
<td>1993–1995</td>
<td>Brumme et al. (1999)</td>
</tr>
<tr>
<td>Zierenberg, Germany</td>
<td>0.41 ± 0.12</td>
<td>1991–1992</td>
<td>Brumme et al. (1999)</td>
</tr>
<tr>
<td>Klausenleopoldsdorf, Austria</td>
<td>6.82 ± 0.5</td>
<td>2002–2003</td>
<td>Kitzler et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>7.63 ± 0.5</td>
<td>2003–2004</td>
<td>Kitzler et al. (2006)</td>
</tr>
<tr>
<td>Schottenwald, Austria</td>
<td>10.42 ± 0.6</td>
<td>2003–2004</td>
<td>Kitzler et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>10.15 ± 0.4</td>
<td>2003–2004</td>
<td>Kitzler et al. (2006)</td>
</tr>
<tr>
<td>Tuttilingen, Germany</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SW exposed, control</td>
<td>0.07</td>
<td>2003–2004</td>
<td>Dannemann et al. (2006)</td>
</tr>
<tr>
<td>SW exposed, thinned</td>
<td>0.05</td>
<td>2003–2004</td>
<td>Dannemann et al. (2006)</td>
</tr>
<tr>
<td>NE exposed, control</td>
<td>0.05</td>
<td>2003–2004</td>
<td>Dannemann et al. (2006)</td>
</tr>
<tr>
<td>NE exposed, thinned</td>
<td>0.04</td>
<td>2003–2004</td>
<td>Dannemann et al. (2006)</td>
</tr>
<tr>
<td>NW exposed, control</td>
<td>0.22</td>
<td>2003–2004</td>
<td>Dannemann et al. (2006)</td>
</tr>
<tr>
<td>NW exposed, thinned</td>
<td>0.86</td>
<td>2003–2004</td>
<td>Dannemann et al. (2006)</td>
</tr>
<tr>
<td>Börnhőved Lake region, Germany</td>
<td>0.4</td>
<td>1993</td>
<td>Mogge et al. (1998)</td>
</tr>
<tr>
<td>Soroe, Denmark</td>
<td>0.5</td>
<td>1997</td>
<td>Beier et al. (2001)</td>
</tr>
</tbody>
</table>

a main soil texture: clay; b main soil texture: silt (loess)
Significantly higher annual N$_2$O flux rates usually derive from sites showing a clear seasonal pattern with low N$_2$O fluxes during the winter months and high N$_2$O fluxes during the summer. Seasonal emission patterns like the one observed by Zechmeister-Boltenstern et al. (2002) for a 140-y-old beech stand located at Schottenwald (Austria) report (3.6 ± 1.0) kg N ha$^{-1}$ y$^{-1}$ in 1996, (4.2 ± 1.3) kg N ha$^{-1}$ y$^{-1}$ in 1997, and (4.3 ± 1.8) kg N ha$^{-1}$ y$^{-1}$ in 1998. Kitzler et al. (2006) found N$_2$O flux rates ranging between −6.3 and 75.4 μg N m$^{-2}$ h$^{-1}$ for a site with a 142-y-old beech stand at Schottenwald (Austria) and between −1.0 and 82.8 μg N m$^{-2}$ h$^{-1}$ in a 62-y-old beech forest at Klausenleopoldsdorf (Austria) in 2002. The seasonal variations in N$_2$O emissions at these sites followed mainly forest management and the annual changes in soil temperature, soil moisture, and the availability of N in the soil.

### 4.2 Measured vs. modeled N$_2$O exchange

Our results reveal that measured and modeled soil temperatures fit well except for the period with soil temperature near the freezing point. The soil cooled down slower and warmed up faster than the model simulation.

Similar results were found by Szyska et al. (2008) who applied the original version of DNDC designed for agricultural ecosystems and not Forest-DNDC. In contrast, measured soil moisture differed significantly from modeled soil moisture, which does not fall to WFPS values < 0.57. The reason for this is the model settings, particularly the wilting point, for the default soil texture "clay loam". However, both parameters significantly affect the N$_2$O exchange and Forest-DNDC was designed with a strong soil-moisture control on N$_2$O emissions (Lamers et al., 2007; Zhang et al., 2002). Only a few studies report about the match between measured and Forest-DNDC-simulated soil water contents. Kröbel et al. (2010) found an overestimation of the soil water content by DNDC (version DNDC89). At a site in Scotland on a glacial till with very low hydraulic conductivity in the subsoil which makes drainage very slow, Froliking et al. (1998) reported DNDC to underestimate soil moisture. Beheytal et al. (2007) also mentioned an underestimation of WFPS for different investigated sites in their study using the DNDC version 8.3P. Saggar et al. (2004) reported a poor match between measured and simulated WFPS for a silt-loam soil in New Zealand using NZ-DNDC. However, a successful simulation of soil temperature and soil water conditions is necessary for a successful simulation of N$_2$O flux rates (Saggar et al., 2004).

The annual N$_2$O flux rate of the Forest-DNDC simulation overestimated the annual measured N$_2$O flux rate. Forest-DNDC also fails to correctly simulate the actual fluctuations of measured N$_2$O flux rates except for the plot with the highest SOC content (plot 4), which reflected a part of the fluctuations. Forest-DNDC failed to show the N$_2$O emissions during frost expect for plot 4, plot 9, and plot 10. These plots showed higher N$_2$O emissions during frost. This suggests that the ground was not frozen deeply and that the measured N$_2$O release is related to processes typically related to frost–thaw cycles as a sudden increase of bioavailable C and N (Röver et al., 1998) or spontaneous release of previously produced N$_2$O (Goodroad and Keeney, 1984). These small-scale differences can be triggered by differences in soil C content and the model seems to be very sensitive to the parameter setting for SOC, because all three plots exhibit SOC contents > 0.06 kg C (kg soil)$^{-1}$. At the plots with < 0.06 kg C (kg soil)$^{-1}$ SOC, no increasing N$_2$O emissions during frost took place. The model produced thaw-induced elevated N$_2$O flux rates at the end of April. This event contributes to a great part to the annual N$_2$O flux rate. However, we did not observe a thawing peak in the field, but due to the short duration of such peaks, this is not surprising. Consequently, this is in line with Stange et al. (2000), who also reported disagreements between modeled and measured N$_2$O flux rates especially during freezing and thawing. The second N$_2$O peak in summer 2006 did not appear in the simulated data. This confirms the findings by Saggar et al. (2004), who remarked that the DNDC model had limited success in predicting the size and timing of very high emissions. Abdalla et al. (2009) also found that DNDC poorly described those fluxes from zero-fertilizer treatments.

As it is impossible to provide the data needed for calibration of large and insufficiently examined areas, N$_2$O fluxes for these cannot be achieved by parameter-intensive models. As these input parameters can only be derived by referring to ubiquitously available proxies as digital elevation models (Glatzel and Bareth, 2006), it is unlikely to achieve realistic mechanistic upscales in the near future. This does not apply to the simulation of natural N$_2$O fluxes from clean-air ecosystems that do not exist anymore in Central Europe as the prediction of reactions of the ecosystem reaction to external (climatic) and internal (soil) may very well be simulated best by calibrated models.

As the parameter settings for denitrification in versions of Forest-DNDC without site-specific calibration do not permit N$_2$O uptake, all modeled N$_2$O fluxes had a positive sign. 38% of the measured N$_2$O flux rates were negative and also other studies observed negative N$_2$O flux rates (Kitzler et al., 2006; Chapuis-Lardy et al., 2007; Guckland et al., 2010). However, the measured N$_2$O flux rates are usually small and the standard errors of these fluxes are high. Although the PnET-N-DNDC version presented by Stange (2001) did simulate N$_2$O uptake, the small involved amounts are a challenge to modeling N$_2$O field fluxes.

### 4.3 Spatial variability of N$_2$O flux rates

The spatial variability in N$_2$O emissions is naturally large (Folorunso and Rolston, 1984; Mathieu et al., 2006; Turner et al., 2008) but so are underlying soil variables. This applies to measurements derived from low spatial representation
(small chambers or taken from small soil augers) and was confirmed by our data. Our measured N₂O flux rates observed at the 15 individual plots show their highest spatial variability when high N₂O flux rates occur. However, also in periods with low mean N₂O flux rates the variability was pronounced. The modeled N₂O flux rates simulated with individual soil parameters from the 15 plots also exhibited a high spatial variability. This is due to the differences in the parameter settings for SOC. N₂O fluxes at plots with low (0.032–0.054 kg C [kg soil]⁻¹) SOC content fluctuated less than plots with high (0.062–0.087 kg C [kg soil]⁻¹) SOC concentrations. The measured N₂O flux rates did not display this effect. Therefore, the differences in SOC do not explain differences found in N₂O as model results frequently suggest. Nevertheless, also the modeled N₂O flux rates showed their highest variability when high N₂O flux rates occur.

4.4 Spatial correlation of N₂O fluxes

One may assume that N₂O fluxes from nearby sites are more strongly correlated than N₂O fluxes from more distant sites, but we are not aware of any studies on this issue. We observed no autocorrelation of N₂O flux rates at the Hainich research site. This confirms the results of Jurasinski et al. (2012), who found soil CO₂ efflux to lack autocorrelation except for summertime fluxes with dominant modeled ash fine-root biomass at the same site as the one examined in this contribution. For N₂O studies about spatial variability usually focus on differences of emissions caused by differences in soil properties (Ambus and Christensen, 1995; Röver et al., 1999). For our 15 different plots at the Hainich research site, we found no relationships between individual soil parameters and N₂O flux rates.

A potential reason for lacking autocorrelation between the plots could be that the minimum distance is not short enough. However, in our opinion it is more likely that driving parameters as C : N ratio (Klemmedtsson et al., 2005), N input (Ambus and Robertson, 2006), and soil water status (Jungkunst et al., 2008) vary in a short range as much as in longer distances. The latter two are very well determined by the heterogeneity of interception which hardly ever is determined. Also, Don et al. (2012) discovered that small-scale heterogeneity of SOC (a major prerequisite for N₂O emissions) was so high that paired sampling did not significantly reduce the number of required samples. Therefore, there are no indications given that “realistic” mean values for one ecosystem type are best derived by wide and randomly spread measurements. Several chambers in close proximity to each other are more pragmatic for a measurement team and most likely produce a similar variability as more distant chamber measurements. Unfortunately, the spatial variability of driving factors does not really explain spatial variability of N₂O fluxes. The reason for that should be investigated in more detail. For the moment, mean ecosystem values better explain mean fluxes for which Forest-DNDC and others have been designed anyhow. Still, Forest-DNDC without site-specific recalibration could not account for N₂O emissions of this near-natural ecosystem. This is mainly due to the inability of Forest-DNDC to account for event-based peaks.

5 Conclusions

Like other forest ecosystems that lack strong seasonal patterns and show few event-induced occasions of N₂O release, the beech forest examined in this study displayed annual N₂O flux rates < 0.5 kg N ha⁻¹ y⁻¹. The core area of the Hainich NP is the closest approximation of a natural ecosystem in Central Europe. Therefore, we propose a maximum background emission factor of 0.5 kg ha⁻¹ N y⁻¹. Our study also indicates that Forest-DNDC without recalibration is not appropriate for simulating annual fluxes of N₂O for zero-fertilizer treatments. Therefore, a Forest-DNDC-based regionalization of N₂O fluxes without a wealth of site-specific recalibration parameters is inappropriate. A broader validation of the model seems to be necessary especially for sites with low SOC values.

The absence of spatial correlations of N₂O fluxes indicates that within one site the distance between each chamber is secondary. This is valuable for designing measurement plots because larger distances between individual chambers are not required. The latter of course needs to be further verified by additional studies. It remains a challenge for future measurements and modeling to satisfactorily reproduce the spatial variability between sites and within sites of natural N₂O emissions.

Acknowledgments

Our work was funded by the Deutsche Forschungsgemeinschaft (DFG) (GI 308/5-1 and 5-2). We acknowledge the help of Petr Holy in collecting gas samples and the Max Planck Institute of Biogeochemistry for providing us the climate data.

References


