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Effect of temporal resolution on N_2O emission inventories in Dutch fen meadows

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[1] Most countries use a 1-year-resolution emission factor approach (Tier 1 or 2) to estimate terrestrial N_2O emissions as part of their national greenhouse gas inventory. Little attention has so far been paid to the effect of the temporal resolution of the approach (e.g., day, season, and year) on N_2O emission estimates. The effect of lumping temporal variation can be very large because of daily or seasonal variations of processes causing N_2O emissions. Therefore, we compared annual N_2O emissions from a model with daily time steps (DNDC) with those of a model with annual time steps (INITIATOR). Emissions were simulated for two intensively managed grassland plots in the Dutch fen meadow landscape. Annual N_2O emissions from the investigated grasslands were sensitive to rainfall distribution within the year, especially to summer rainfall. We recommend that Tier 2 N_2O emission estimates for intensively managed grasslands on peat soils in the temperate climate zone are adjusted for relative summer rainfall.

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1. Introduction

[2] Terrestrial N_2O emission is an important component of the Dutch anthropogenic greenhouse gas balance. *Brandes et al.* [2007] estimated the contribution of N_2O to the total Dutch greenhouse gas emission for the year 2005 as 8%, from which more than half originates from agricultural soils. These estimates were obtained in compliance with the Kyoto protocol and the UNFCCC guidelines, which imply the use of region-specific emission factors based on total emissions per year [*Brandes et al.*, 2007; *IPCC*, 2006].

[3] It is widely known that N_2O emissions from soils have a large spatial and temporal variability, particularly at the small space-time measurement scales that are often applied [*Flechard et al.*, 2007; *Skiba et al.*, 1996; *Velthof et al.*, 1996b]. Some ecosystems, e.g., needle-leaved forests, have a fairly constant emission throughout the year [*Schulte-Bisping et al.*, 2003]. Other ecosystems have seasonal or event-based emission patterns. In fertilized grasslands, the largest part of the annual N_2O emission occurs as "peak" emissions [e.g., *Calanca et al.*, 2007; *Jones et al.*, 2007; *Velthof et al.*, 1996a]. These peak emissions are caused by events such as fertilizer or manure application [*Bouwman*, 1996], rainfall events [*Ryden*, 1983], or freeze-thaw cycles [*Christensen and Tiedje*, 1990]. A soil-water-filled pore space (WFPS) between 50 and 70% is believed to be optimal for N_2O peaks [*Davidson et al.*, 1991]. At drier conditions (smaller WFPS), N_2O is a by-product of nitrification, and N_2O emission is relatively small. At wetter conditions (larger WFPS), denitrification is the main process, and formation of N_2 is favored over N_2O formation [*Granli and Bøckman*, 1994]. Other major controls on N_2O emission are soil mineral N availability, temperature, and labile organic compounds availability [*Skiba and Smith*, 2000]. Cultivated organic soils are large emitters of N_2O because of large C and N availability.

[4] Besides the well-known issues concerning the choice of spatial scale for measurement, modeling, and reporting N_2O emissions [*Nol et al.*, 2008; *Velthof et al.*, 1996b], also different temporal scales can be distinguished. The IPCC Tier system distinguishes different temporal scales [*IPCC*, 2006]. In the IPCC Tier 1 and Tier 2 methods that most countries use to estimate and report emissions, the annual N_2O soil emission induced by N inputs is calculated as a fraction of the N input. The N_2O emission factor (in %) depends on the type of N input (e.g., N input from grazing animals, animal manure, fertilizers, crop residues, fixation, or deposition). The Tier 1 method is the most basic method and uses default emission factors. Tier 2 is similar, but based on country-specific emission factors and activity data for the most important land uses and activities. The temporal resolution of both the Tier 1 and 2 method is typically a year (annual emission factor), because many activity data are not available at finer temporal resolution. Tier 3 methods make use of process-based models that incorporate relevant factors and processes that affect N_2O emission. The temporal resolution is usually small because daily or hourly soil processes are simulated. Process models which are widely

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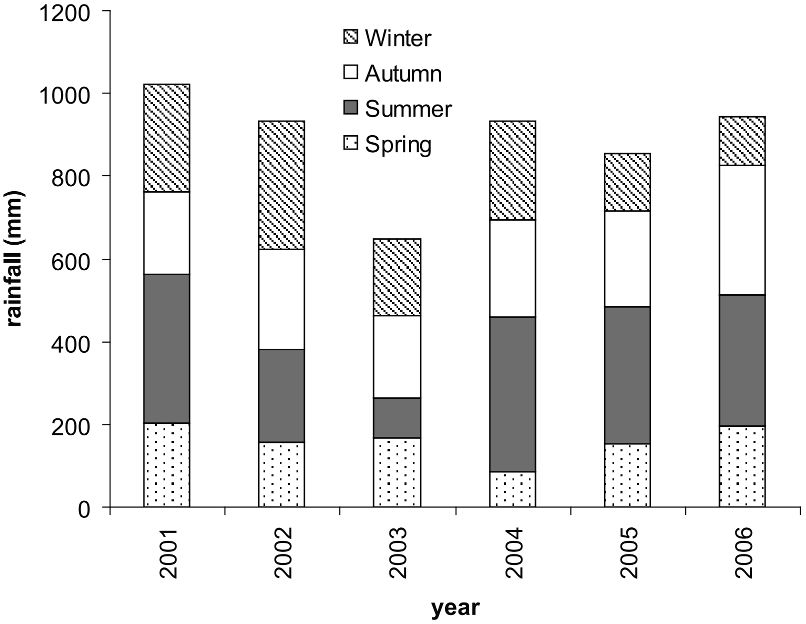

Figure 1. Rainfall distribution (mm) for the simulation years 2001 through 2006.

used to simulate N_2O emissions are the denitrification-decomposition process model (DNDC) [*Li et al.*, 1992], DayCent [*Parton et al.*, 1998], and PaSim [*Riedo et al.*, 1998; *Schmid et al.*, 2001]. N_2O emission factors for Tier 1 and Tier 2 methods are annual averages generally obtained from experimental research, lasting between 1 and 3 years, lumping all small-scale temporal variations. Little attention has so far been paid to the effect of lumping small-scale temporal variability on annual N_2O emission estimates. However, the effect of small-scale temporal variations can be very large because of the strong dynamic nature of causal factors behind N_2O emission and strong nonlinearities in the emission processes. With more information about the temporal variation of the causal factors, one could possibly adjust the emission factor for a specific year and improve the emission estimate of a Tier 2 method, without the need to use data-demanding Tier 3 methods.

[5] The main objective of this paper is to analyze the effect of temporal resolution by comparing annual N_2O emissions from two models with a different temporal resolution. Accordingly, simulated N_2O emissions of a Tier 2 model with a coarse (annual) temporal resolution were compared to results of a Tier 3 model with a fine (daily) temporal resolution. The differences between the models and the effects of these differences on the estimated annual N_2O emissions were studied. For years with large differences in simulated annual N_2O emissions, small-scale processes that could cause these differences were identified. We also estimated emission factors for the simulated years and compared these with emission factors used in the Tier 1 and Dutch Tier 2 methods to analyze whether the factors appropriately average the annual variations in N_2O emissions. As such, the results of this work can contribute to improved identification of emission factors used in Tier 2 based inventories. Identification of the effect of temporal variation on annual N_2O emission may be used to adjust the Tier 2 emission factors for a given year to the specific temporal variation patterns of that year.

2. Materials and Methods

2.1. Research Plots

[6] The N_2O emission was modeled for the years 2001–2006 for two intensively managed grassland plots on peat soils in the Dutch western fen meadow landscape. The research plots are located in polder Zegveld, which is part of the western fen meadow landscape in the Netherlands. Two plots were studied: a "dry" plot (52°8′19″N 4°50′10″E) and a "wet" plot (52°8′12″N 4°50′18″E). The plots are rectangular parcels (approximately 300 by 50 m in size) bordered by ditches and owned by a dairy farmer. The plots are surrounded by other dairy farms. The soil consists of peat originating from wood. The dry plot is representative for most intensively managed grasslands in the western fen meadow landscape. It has a summer groundwater level of about 51 cm below soil surface, whereas the wet plot has a summer groundwater level of about 28 cm below soil surface. For the years 2001 through 2006, the average annual precipitation in the area was 889 mm (Figure 1), and the average annual temperature was 10.9°C. Daily weather data of the Netherlands are available at http://www.knmi.nl.

2.2. Data Collection

[7] Management, soil, and hydrological parameters were measured on the plots for the years 2001 through 2006 (Table 1). Overall, the management for both research plots is comparable. Both plots were grazed by cattle. A time series of N_2O measurements was also available for model verification [*Jacobs et al.*, 2003]. On 27 dates between 15 May 2001 and 28 June 2002, N_2O emissions were measured at ten randomly selected locations in each plot. The mea-

Table 1. Management Data From Both Research Plots From 2001 Through 2006

Year and Plot	Manure Application[a] (kg C ha^{-1} a^{-1})	Removal by Mowing[a] (kg C ha^{-1} a^{-1})	Excretion During Grazing[a,b] (kg DM (ha^{-1} a^{-1}))	Manure Application[a] (kg N ha^{-1} a^{-1})	Removal by Mowing[c] (kg N ha^{-1} a^{-1})	Fertilizer Use[a] (kg N ha^{-1} a^{-1})	Excretion During Grazing[d] (kg N ha^{-1} a^{-1})	Grazing Days[a] Sheep (Heads ha^{-1})	Grazing Days[a] Cows (Heads ha^{-1})
2001									
Dry plot	1293	2822	1539	46	176	133	45	272	61
Wet plot	1854	2454	3760	68	153	132	129	0	251
2002									
Dry plot	905	1421	6605	46	89	129	226	1024	338
Wet plot	1688	2495	5856	77	156	137	200	0	391
2003									
Dry plot	1574	2112	6080	85	132	120	194	657	268
Wet plot	1557	1659	6175	85	104	122	232	450	417
2004									
Dry plot	0	6388	1500	0	399	71	15	300	0
Wet plot	0	5496	0	0	344	68	0	0	0
2005									
Dry plot	1673	2517	12250	89	157	149	148	0	289
Wet plot	1586	3946	7500	85	247	149	82	0	159
2006									
Dry plot	824	3207	8001	38	200	140	197	300	298
Wet plot	1285	2434	7750	60	152	122	103	30	190
Average									
Dry plot	1045	3078	5996	51	192	124	138	426	209
Wet plot	1328	3081	5714	63	193	122	124	80	235

[a] Information from the farmer (K. Van Houwelingen, personal communication, 2008).

[b] The C content is about 35% of the dry matter content [*Martinez*, 2002]; the models use the dry matter content as input.

[c] Estimated using information from the farmer (K. Van Houwelingen, personal communication, 2008) and C:N ratio grass yield [*Lantinga*, 1984].

[d] Estimated using information from the farmer (K. Van Houwelingen, personal communication, 2008), animal numbers, grazing days, C excretion, and N excretion numbers [*Bussink*, 1994].

surement frequency was between once a month during winter and twice a week during the growing season. Ten static flux chambers were used to carry out the measurements.

2.3. Models for N_2O Estimations

[8] Emissions of N_2O were simulated for both plots for the years 2001 through 2006 with the models INITIATOR and DNDC. INITIATOR [*de Vries et al.*, 2003a] has a yearly temporal resolution, and DNDC [*Li*, 2007] has a daily temporal resolution.

2.3.1. INITIATOR

[9] The model INITIATOR [*de Vries et al.*, 2003b] has been developed to quantify the leaching and runoff of N to groundwater and surface water and of emissions of ammonia and nitrous oxides to the air in response to N inputs. It includes all N inputs and outputs, including gains and losses within and from housing systems, soil, groundwater, and surface water. The model uses a simple approach to maintain transparency and to be able to apply the model in data-poor circumstances. In this study, the animal housing, manure production, and the surface water part of the model were not considered. The INITIATOR application was limited to only the soil part of the model. The total input at the soil surface is calculated by adding the input by animal manure, fertilizer, atmospheric deposition, and biological N fixation. The fate of N in the terrestrial system is calculated as a sequence of occurrences: ammonia emissions, followed by N uptake, N mineralization and immobilization, nitrification, and denitrification in the soil. All N transformation processes are linearly related to the inflow of N. The linear transformation constants are a function of type of manure, land use, soil type, and/or hydrological regime. Emissions of NO_x and N_2O are calculated as a fraction of nitrification and denitrification in the soil, with nitrification and denitrification being equal to a fraction of the net N input to the soil. The net N input is defined as the sum of all N inputs minus NH_3 emission, N uptake, and N immobilization. Table 2 gives a summary of the characteristics of INITIATOR that are relevant for comparison with DNDC.

2.3.2. DNDC

[10] The model DNDC was selected because it has been calibrated and validated for many sites around the world [*Brown et al.*, 2002; *Butterbach-Bahl et al.*, 2001; *Cai et al.*, 2003; *Grant et al.*, 2004; *Jagadeesh Babu et al.*, 2006; *Kesik et al.*, 2005; *Kiese et al.*, 2005; *Pathak et al.*, 2005; *Saggar et al.*, 2004; *Xu-Ri et al.*, 2003; *Zhang et al.*, 2006] and can simulate drained organic soils. Version 9.1 of DNDC was used. DNDC is based on biogeochemical concepts [*Li*, 2007]. The core of the model is a combination of the Nernst [*Stumm and Morgan*, 1996] and Michaelis-Menten [*Paul and Clark*, 1989] equations to track microbial activities at hourly and daily time steps. These two equations are coupled via a so-called "anaerobic balloon." The size of the "balloon" is defined by the modeled redox potential from the Nernst equation. The soil substrates are allocated on the basis of the calculated aerobic and anaerobic parts of the soil. With the Michaelis-Menten equation, redox reactions can be calculated on the basis of the calculated substrate concentrations. This gives again a new redox potential.

Table 2. Overview of Model Characteristics of INITIATOR and DNDC Relevant for Comparison

Aspect	INITIATOR [*de Vries et al.*, 2003b]	DNDC Version 9.1 [*Li*, 2007]
	General Characteristics	
Domain	Agricultural and natural soils	Agricultural and natural soils
Compounds	N, C (Organic matter)	N, C (Organic matter)
Inputs to the soil	Animal manure application, fertilizer application, grazing, deposition, and biological N fixation	animal manure application, fertilizer application, grazing, deposition, and biological N fixation
Outputs	NH_3, NO_x and N_2O emissions from soil	NH_3, NO_x and N_2O emissions from soil
Soil layers	Two layers: rooting zone and saturated zone	One soil layer, typically 50 cm, divided into sub layers of 5 cm
Dynamics and time step	Steady state; yearly balance	Dynamic, with a time step of 1 h to 1 day.
Hydrology	Yearly water balance based on a separate hydrological model	One-dimensional soil heat flux and moisture flow model to calculate daily soil temperature and soil moisture. Driven by daily precipitation and temperature
	Processes	
N fixation	Model input	Dependent on N demand by crops
NH_3 emission	Emission fractions for manure application, dependent on application technique, fertilizer application, grazing	Emission fractions for manure application, fertilizer application, grazing
N uptake by vegetation	Growth function dependent on crop type, soil type, soil moisture and N availability	Growth function dependent on light, N availability, moisture and temperature
N Mineralization	Fraction of the field N input in the field corrected for both N emission and N uptake. In peat soils, net nitrogen mineralization is calculated as a function of soil wetness class (drainage) and land use.	First-order kinetics related to three biologically active nitrogen pools (microbial biomass, active humus and passive humus) with decomposition rates regulated by clay content, N availability, soil temperature, and soil moisture.
(De)nitrification	Fraction of net N input (N input minus NH_3 emission, uptake and immobilization) as a function of soil type and soil wetness class	Process-oriented modeling of nitrification and denitrification sequence ($NO_3 \rightarrow NO_2 \rightarrow N_2O \rightarrow N_2$) Process depends on moisture content, oxygen content, ammonium content, nitrate content, soil temperature and pH. Details are given by *Li* [2007].
N_2O and NO_x emission	Emission fractions due to nitrification and denitrification	See above on (de)nitrification

[11] DNDC includes two parts. The first part predicts soil temperature, moisture, pH, redox potential, and substrate (NH_4+, NO_3- and DOC) concentrations. This part is driven by the input parameters about climate, soil, and management. The second part predicts N_2O, NO, N_2, NH_3, and CH_4 fluxes. These emissions are calculated using nitrification, denitrification, and fermentation submodels with input parameters estimated in the first part of the model. The model has a site mode and regional mode. Because in this research N_2O fluxes were simulated on plot scale, the site mode of the model was used.

2.4. Model Parameterization and Verification

[12] For DNDC, the use of default values for all model parameters resulted in unrealistic hydrological dynamics and crop uptake. DNDC was therefore parameterized with measured data and coefficients valid for the Dutch situation. INITIATOR was specifically developed and, in its standard configuration, already parameterized for the Dutch situation [*de Vries et al.*, 2003a]. Calibration of both models toward the N_2O measurements was not done because it would make valid comparison with the measurements and between models impossible. Verification with independent measurements was done for both models to determine whether modeled N_2O emissions were realistic.

2.4.1. Parameterization of DNDC

[13] For both research plots, simulation with default DNDC parameters gave unrealistic results of groundwater level and water-filled pore space (WFPS), which seriously affected N_2O emissions. Input parameters driving the simulation of the groundwater level and WFPS in DNDC are the mean highest groundwater level (MHW, m), WFPS at wilting point, WFPS at field capacity, and hydraulic conductivity (m h^{-1}). Both plots have an MHW of 0 m, because in winter the groundwater level can reach surface level for days, and the plots often become nearly flooded [*Velthof et al.*, 1996a]. The essential difference between the plots is the mean lowest groundwater level (MLW, m). Unfortunately, DNDC does not use MLW as an input parameter. Using measured values of WFPS at wilting point, WFPS at field capacity, hydraulic conductivity, and 0 for the MHW, the model simulated a continuously saturated soil and a groundwater level permanently at the surface. Therefore the MHW for both plots was parameterized with a simulated WFPS for 27 dates between 15 May 2001 and 28 June 2002 [*Jacobs et al.*, 2003], using the detailed hydrological model SWAP [*Van Dam*, 2000]. The MHW input parameter of DNDC was parameterized by searching for the smallest residual error between WFPS values simulated with DNDC and WFPS values simulated with SWAP. After the parameterization, the best fitted MHWs were 0.60 m for the dry plot and 0.49 m for the wet plot. *Velthof and Oenema* [1995] measured WFPS on the same plots on 34 dates for the year 1992. The best fitted MHWs were used to simulate the WFPS for 1992 and compared with the measured WFPS. The model also adequately simulated WFPS for this year; the root-mean-squared error decreased by 24% for the dry plot and 50% for the wet plot compared to the default model run (data not shown).

Table 3. Adaptations to the Crop Parameters in DNDC

Adapted Parameter	Default DNDC	Adapted for Dutch Fen Meadow	Source
Maximum grain production (kg dry matter ha^{-1})	200	245	*Barrett et al.* [2004] and *Elgersma et al.* [1998]
Water requirement (kg water for producing 1 kg dry matter)	350	354	*Smid et al.* [1998]
Maximum LAI	3	5	*Lantinga* [1984]
Accumulative degree days of maturity or TDD (°C)	2500	1650	Calculated for simulated years (±165 days × 10°C)

[14] After parameterization of WFPS, the grass died at the end of every simulation year. This problem was solved by changing the default crop parameters of DNDC. Four default crop parameters for perennial grass differ from measured parameters in Dutch grasslands: maximum grain production (kg dry matter ha^{-1}), water requirement (kg water for producing 1 kg dry matter), maximum leaf area index (LAI), and accumulative degree days of maturity (TDD, °C). The default values for these crop parameters were adapted to more realistic values (Table 3). Other default crop parameters, such as the root-shoot distribution, were close to measured values.

[15] The default C:N ratio for the aboveground biomass of perennial grass in DNDC, i.e., 35, is larger than C:N ratios measured in Dutch grasslands, which are generally around 16 [*Lantinga*, 1984]. However, using smaller C:N ratios caused the grass to completely disappear at the end of every simulation year, even when nitrogen inputs were very large. Apparently, DNDC assumes that grasslands are less efficient in N use than Dutch grasslands. With a C:N ratio of 16, the nitrogen demand for the first half of every year increased to more than 600 kg N ha^{-1}. DNDC was originally developed for simulating arable crops. Apparently, the root turnover in DNDC is too fast for perennial grasslands. The default (fixed) C:N ratio of 35 for leaf and stem biomass was therefore used, which means a corresponding C yield of 4.1 ton C ha^{-1} a^{-1} (117 kg N from grass cut × 35) for the dry plot and 4.4 ton C ha^{-1} a^{-1} (125 kg N from grass cut × 35) for the wet plot. As DNDC calculates with a constant C content of 40%, this corresponds with a yield of about 10.5 ton dry weight grass ha^{-1} a^{-1}, which is realistic for Dutch grasslands [*Elgersma et al.*, 1998; *Oenema et al.*, 2005].

2.4.2. Model Verification

[16] Upscaling of the N_2O emission measurements to yearly emission estimates of the entire plot was needed in order to compare the measurements with the model outputs. The target scale (the daily and annual emission from an entire plot) is larger than the measurement scale. The duration of a measurement was 1 h, and the surface area covered by the flux chamber was approximately 0.5 m^2. For spatial upscaling, the plot emission was estimated as the arithmetic mean of the N_2O emissions from the ten locations. The measured emissions were compared with the emissions simulated with DNDC on a daily scale. Measured and modeled trends and peaks in emissions were compared, and deviations between the minimum and maximum emissions were calculated. To verify annual N_2O emissions, the measurements also had to be scaled up in time. Previous research [*Velthof et al.*, 1996a] showed that N_2O emissions in the growing season are significantly larger than N_2O emissions outside the growing season. Therefore the data set was split into "growing season" and "off-season." The growing season for grasslands is defined as the period between 1 March and 1 October [*Van Dijk et al.*, 2005]. As defined by *de Gruijter et al.* [2006], the average N_2O emission was computed as

$$\hat{\mu} = \frac{O_G}{O_G + O_O} \times \hat{\mu}_G + \frac{O_O}{O_G + O_O} \times \hat{\mu}_O \qquad (1)$$

where $\hat{\mu}$ is the estimate of the annual average N_2O emission, O_G is the number of days in the growing season, O_O is the number of days in the off-season, and $\hat{\mu}_G$ and $\hat{\mu}_O$ are the estimates of the average N_2O emission in the growing season and off-season, respectively. The variance of the estimation error was computed as

$$Var(\hat{\mu} - \mu) = \left(\frac{O_G}{O_G + O_O}\right)^2 \times \frac{S_G^2}{n_G} + \left(\frac{O_O}{O_G + O_O}\right)^2 \times \frac{S_O^2}{n_O} \qquad (2)$$

where $Var(\hat{\mu} - \mu)$ is the variance of the estimation error of the annual N_2O emission, S_G^2 is the sample variance of N_2O emissions in the growing season, n_G is the number of measurement dates in the growing season, S_O^2 is the sample variance of N_2O emissions in the off-season, and n_O is the number of measurement dates in the off-season. The standard error was computed as the square root of equation (2), and for each plot it was verified if the simulated annual N_2O emissions from DNDC and INITIATOR were within the confidence intervals of the measured annual N_2O emissions.

2.5. Analysis of Temporal Resolution Effects

[17] For 2001 through 2006, differences between the simulated annual N_2O emissions from DNDC and INITIATOR were compared, and the years with the largest difference in simulated N_2O emissions were selected for further analysis. For these years, we analyzed which inputs with high temporal variation caused the differences. Next, a three-step analysis was used to trace the effect of high-resolution temporal variation of these inputs on the annual N_2O emission using DNDC. This high-resolution temporal variation cannot be included in INITIATOR because of its annual temporal resolution.

2.5.1. Step 1: Identification of High-Resolution Variables and Their Interactions

[18] All input variables that require input at a high temporal resolution in DNDC, e.g., daily temperature, were selected for further analysis. Interactions of these variables that, on the basis of literature, can have a combined effect

on N_2O emission (e.g., the combination of rainfall and fertilizer N input) were selected as well.

2.5.2. Step 2: Selection of Key Variables and Variable Interactions

[19] Many variables (e.g., manure application) not only affect N_2O emissions on the day itself, but have a prolonged effect and may influence daily N_2O emissions for periods of weeks or months after the actual event. Therefore, N_2O emissions are often more strongly correlated with the aggregate value of such a variable over the previous period than with the variable value at the day of N_2O measurement. To identify the period over which the variable values need to be aggregated, correlations between daily N_2O emission and values of variables aggregated over varying periods were explored. For each variable and variable interaction, identified in step 1, the optimum aggregation period with the largest correlation coefficient was determined for use in further analysis.

[20] The temporal variation in variable values over the different years was analyzed by comparing the values of the variables among the different years. The analysis was done for four seasons separately. For instance, if in the year 2002 relatively more grazing occurred in spring as compared to other years the variable "grazing" in spring 2002 was classified as "high." For the year with the lowest value of the same parameter a classification "low" was assigned. A similar analysis was made for the variable interactions on the basis of a multiplication of the variable values.

[21] The variables and variable interactions classified "high" of "low" for the years with the largest differences in annual N_2O emission simulated by DNDC compared to INITIATOR were identified as "key" variables and variable interactions. These "key" variables and variable interactions can be the main cause of differences in simulated N_2O emission between the two models and consequently show the effect of difference in temporal resolution of the models.

2.5.3. Step 3: Analysis of the Effects of Temporal Variation in Key Variables on N_2O Emission

[22] To identify the influence of the identified key variables and variable interactions on the differences in annual N_2O emission between DNDC and INITIATOR and analyze the effect of the within-year temporal variation in variable values temporal distribution of the key variables and interactions was manipulated.

[23] Two different methods were used to manipulate the temporal variation in key variables. In the first method, a key variable for a season which was classified as "high" was substituted for the same variable from a year with a "low" classification for that season. The advantage of this "switch" method is that the key variables keep a natural variation, but the disadvantage is that annual totals of the variables could also change. If that was the case, INITIATOR was run as well with the new annual total value of the variable for comparison. In the second method, the within-year distribution of key variables was changed while keeping the annual totals equal. This was done by increasing a variable in a specific season while proportionally decreasing this variable in the other seasons or vice versa. Key variable interactions were manipulated as well by changing the distribution of the variables over the year and thereby influencing the variable interactions.

2.6. Comparison of Simulated Annual Average Emission Factors With the IPCC Default Values (Tier 1) and Dutch Values (Tier 2)

[24] Using the simulated annual N_2O emissions, emission factors were computed, following the IPCC Tier 1 (default values) and Tier 2 (national values) approaches. N_2O emission factors based on DNDC and INITIATOR results for the six simulation years were estimated using the available management and climate data. The N_2O emission factor, EF_{ij}, for model i and year j was calculated as:

$$EF_{ij} = \frac{N_2O_{ij} - \mathrm{BackgroundN_2O}}{\mathrm{Ninput}_j} \tag{3}$$

where N_2O_{ij} is the N_2O emission (kg N_2O-N ha^{-1} a^{-1}) for model i and year j, BackgroundN$_2$O is the measured background emission (kg N_2O-N ha^{-1} a^{-1}), and Ninput$_j$ (kg N ha^{-1} a^{-1}) is the nitrogen input by fertilization, manure application, and manure due to grazing in year j. The N input by deposition was not included, in line with common practice when calculating N_2O emission factors from measurements [*IPCC*, 2006]. A similar approach was used by *de Vries et al.* [2005] to estimate emission factors with INITIATOR on the basis of national N_2O emission estimates. In this research no unfertilized plots were considered, but *Velthof et al.* [1996a] measured the background emissions for an unfertilized wet and an unfertilized dry plot from the same farm during 2 years, yielding a measured background emission of 8.6 kg N ha^{-1} a^{-1} for the dry plot and 2.0 kg N ha^{-1} a^{-1} for the wet plot.

3. Results

3.1. Verification

[25] Figure 2 shows daily N_2O emissions modeled with DNDC and the N_2O measurements for both plots. Box plots indicate the error caused by spatial variation of ten N_2O measurements. While for the dry plot only 58% of the modeled emissions on the measurement dates falls between the minimum and maximum measured emission, the trend of the simulations is similar to the trend in measured emissions. DNDC in general overestimated the fluxes of N_2O compared to the measurements. For the wet plot, the model fit was satisfactory for spring and summer, while the autumn fit was poor. DNDC modeled larger emissions in autumn than measured.

[26] In Figure 3, yearly totals, estimated from 1 July 2001 through 30 June 2002, of the N_2O emissions are shown. For both plots, the estimates from INITIATOR and DNDC are within the confidence intervals of the measurement estimates and therefore not statistically significantly different from the measurements. Verification does not reject either of the two models and neither does it show that one of the two is more accurate than the other.

3.2. Analysis of Temporal Resolution Effect

[27] For the dry plot, the largest difference of modeled annual N_2O emissions between DNDC and INITIATOR was found for 2003 with a higher estimate from INITIA-

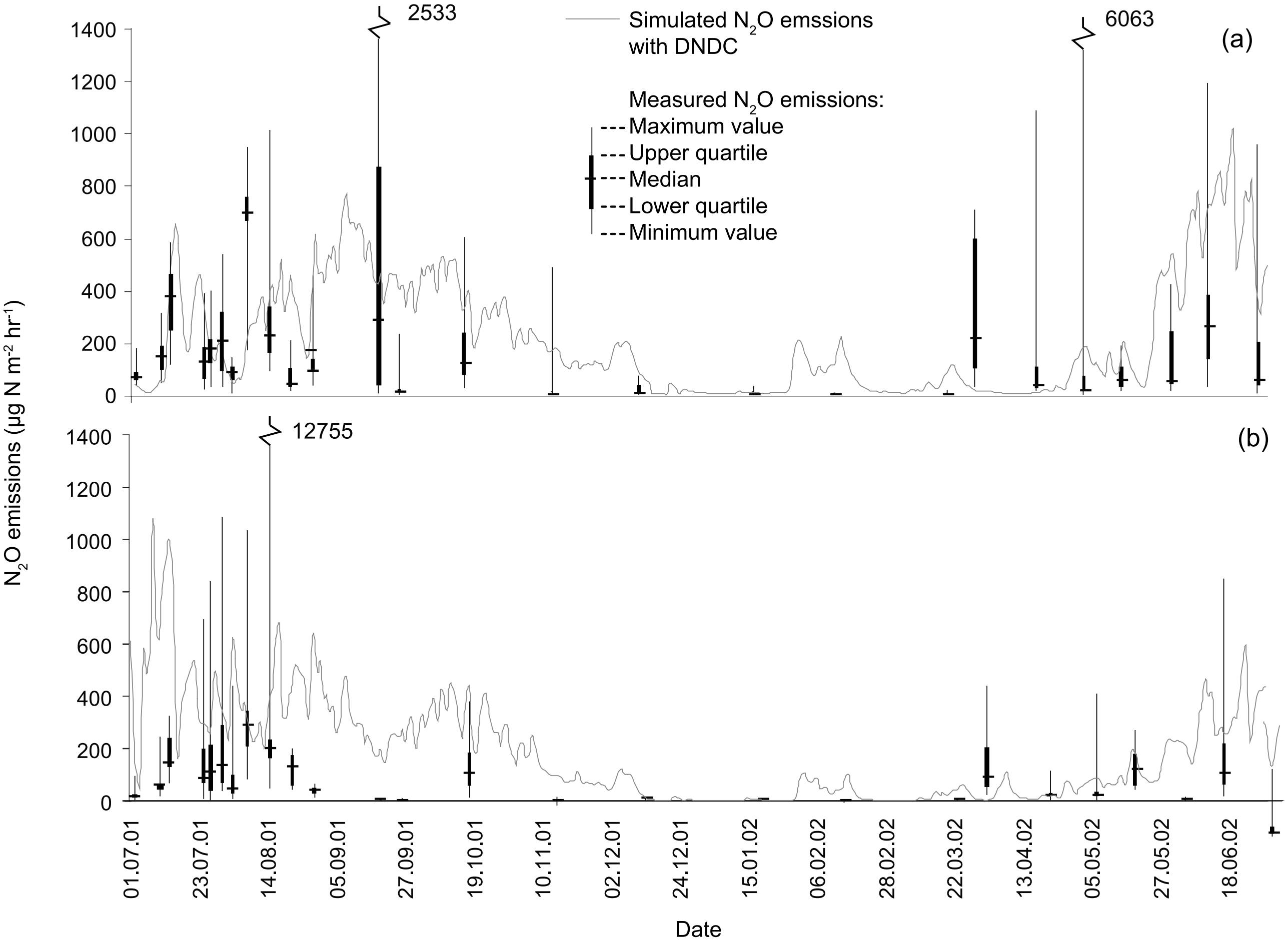

Figure 2. Measured and modeled N_2O emissions for the (a) dry and (b) wet plots from 1 July 2001 through 30 June 2002. The values between the lower and upper quartile represent the 50% confidence interval.

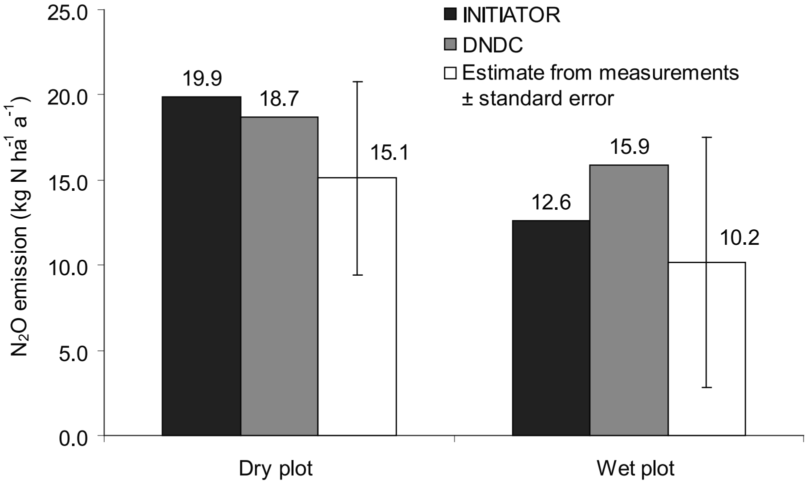

Figure 3. Total annual N_2O emission for the period 1 July 2001 through 30 June 2002 estimated with INITIATOR, DNDC, and estimates based on measurements.

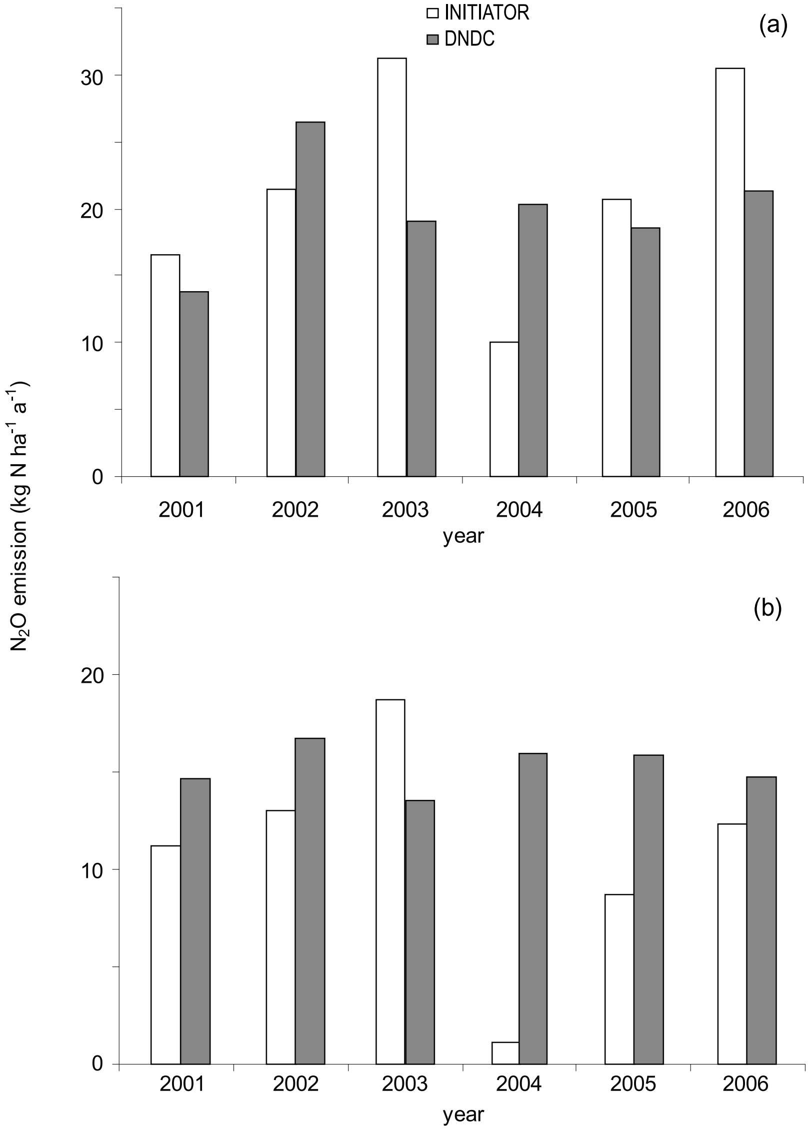

Figure 4. Annual N_2O emissions estimated with INITIATOR and DNDC for 2001 through 2006 for the (a) dry and (b) wet plots.

TOR than from DNDC (Figure 4a). On the contrary, in 2004 the emission estimated with DNDC was much larger than the emission estimated by INITIATOR. For the wet plot (Figure 4b), for only 1 of the 6 simulation years (2003) the estimated N_2O emission of INITIATOR was larger than the estimated N_2O emission of DNDC. The trends of the differences between DNDC and INITIATOR were the same as for the dry plot. Because the years 2003 and 2004 showed the largest differences between the modeled N_2O emissions for both plots, these years were important in the subsequent analysis of the temporal resolution effect.

3.2.1. Step 1: Identification of High-Resolution Variables and Their Interactions

[28] The variables with high temporal resolution in DNDC are rainfall, temperature, N removal due to mowing, N input due to fertilization, N input due to manure application, and N input due to grazing. All interactions of rainfall and N inputs (rainfall and fertilization, rainfall and manure application, rainfall and grazing) were selected for analysis in the second step, because the interaction of rainfall and N application is known to trigger N_2O emissions [*Flechard et al.*, 2007; *Jones et al.*, 2007; *Smith et al.*, 2003]. Because both grass residues are a source of enhanced emissions, the interaction between rainfall and mowing was also used in the second step [*Velthof et al.*, 1996a]. Finally, interaction between rainfall and temperature was selected as well, because high temperature in combination with rainfall can cause N_2O emission peaks [*Skiba and Smith*, 2000].

3.2.2. Step 2: Selection of Key Variables and Variable Interactions

[29] All variables identified in step 1, except temperature, were severely skewed and were therefore log-transformed prior to further analysis. The N_2O emission was also log-transformed. The temporal aggregation results are shown in Table 4 for the dry plot. Management variables (fertilization, manure, grazing, and mowing) have a larger prolonged

Table 4. Number of Days Over Which Variable Values are Aggregated as Day Itself Plus Previous Days to Obtain the Largest Correlation Coefficients, r^2, With Daily N_2O Emission With DNDC, Dry Plot

Variable	Optimal Number of Days	Variable	Optimal Number of Days	r^2
Variables				
Rainfall	10			0.15
Temperature	27			0.48
Manure	115			0.14
Fertilization	160			0.31
Grazing	41			0.21
Mowing	85			0.38
Interactions Between Variables (Variable × Variable)				
Rainfall	12	Temperature	10	0.65
Rainfall	9	Manure	121	0.22
Rainfall	10	Fertilization	162	0.44
Rainfall	10	Grazing	48	0.28
Rainfall	10	Mowing	102	0.52

effect on N_2O emissions than meteorological variables (temperature and rainfall). The highest correlation coefficient ($r^2 = 0.65$) was found between daily N_2O emission and the interaction between rainfall summed over 12 prior days and temperature summed over 10 prior days.

[30] In Table 5, the results of the analysis of the seasonal variable values between the years are presented. Table 5 shows that "high" and "low" variable values correspond to large differences in simulated yearly N_2O emission for summer rainfall, winter temperature, autumn grazing, interaction between rainfall and temperature, and interaction between rainfall and mowing. These variables were therefore identified as key variables in explaining the effects of temporal variation on simulated N_2O emissions.

[31] The same analysis was also performed for the wet plot (data not shown). The identified key variables for the wet plot were summer rainfall, spring fertilization, and autumn mowing. The key variable interactions were rainfall and temperature and rainfall and mowing.

3.2.3. Step 3: Analysis of the Effects of Temporal Variation in Key Variables on N_2O Emission

[32] The results of this analysis are given in Tables 6a and 6b. Switching the variable distributions between years hardly affected the INITIATOR results because of the small differences in change in yearly total variable values. DNDC however strongly reacted to switching the variable distributions between years. Exchanging summer rainfall for the years 2003 and 2004 caused for both plots a large increase of N_2O emission in 2003 and a large decrease of N_2O emission in 2004. For the other substituted variables the effect was less pronounced.

[33] For 2003, which originally had a dry summer, making the summer wetter and the other seasons drier increased the emission for the dry plot by 27% and for the wet plot by 23%. For 2004, which originally had a wet summer, making the summer drier and the other seasons wetter decreased the emission for the dry plot by 11% and for the wet plot by 3%.

[34] Increasing the interaction of rainfall and temperature in 2003 led to a dramatic increase in N_2O emissions (more than three times the original emission for the dry plot, see Tables 6a and 6b). The effect of decreasing the interaction rainfall and temperature in 2004 was a large decrease in N_2O emissions for both plots. Manipulation of the key variables and variable interactions in 2003 or 2004 sometimes also affected the emissions in 2005 and 2006 because of differences in N content of the soil which is passed on to the next year (Tables 6a and 6b).

4. Discussion

4.1. Parameterization and Verification

[35] Default parameters of DNDC yielded unrealistic results, particularly for the soil hydrology. Problems with the parameterization of field capacity and wilting point for

Table 5. Relative Value of Variables in Different Years by Season[a]

Dry Plot	2001	2002	2003	2004	2005	2006
Seasonal Contribution of Variable: Rainfall						
Spring	high	medium	high	low	high	high
Summer	high	medium	**low**	**high**	high	medium
Autumn	low	low	medium	low	low	high
Winter	high	high	high	high	medium	low
Seasonal Contribution of Variable: Temperature						
Spring	low	high	high	medium	medium	low
Summer	medium	low	high	medium	low	medium
Autumn	high	low	low	low	medium	high
Winter	medium	high	**low**	**high**	medium	low
Seasonal Contribution of Variable: Manure						
Spring	medium	medium	medium	low	medium	high
Summer	low	high	medium	low	medium	medium
Autumn	high	medium	medium	low	high	low
Winter	high	low	high	low	medium	medium
Seasonal Contribution of Variable: Fertilization						
Spring	medium	low	medium	high	medium	medium
Summer	low	high	high	high	medium	high
Autumn	high	high	medium	Low	high	high
Winter	high	high	medium	Medium	low	low
Seasonal Contribution of Variable: Grazing						
Spring	low	high	medium	Low	medium	medium
Summer	high	high	medium	Low	high	high
Autumn	low	low	**low**	**high**	low	low
Winter	low	low	high	Medium	low	low
Seasonal Contribution of Variable: Mowing						
Spring	low	low	high	Medium	high	low
Summer	high	medium	medium	low	medium	low
Autumn	low	medium	low	medium	low	high
Winter	low	low	low	low	low	high
Variable Combinations						
Rainfall and Temperature	high	high	**low**	**high**	high	high
Rainfall and Manure	high	high	high	low	high	medium
Rainfall and Fertilization	high	medium	medium	low	high	high
Rainfall and Grazing	low	high	high	low	high	high
Rainfall and Mowing	low	low	**low**	**high**	medium	high

[a] "High" indicates relatively high variable values as compared to other years, and "low" indicates relatively low values as compared to 2001–2006 average. Bold cases represent key variables and key interactions.

Table 6a. Change in Emissions Calculated by DNDC as Result of Within-Year Temporal Distribution Manipulation Experiments for a Number of Key Variables and Interactions for the Dry Plot[a]

Dry Plot	2001	2002	2003	2004	2005	2006
Switch Method: Variables Substituted Between 2003 and 2004						
Rain in summer	-	-	+62%	−37%	−2%	+1%
Temperature in winter	-	-	+3%	−6%	0%	+2%
Grazing in autumn	-	-	0%	+1%	−2%	−1%
Changing Intra-Annual Distribution While Keeping Annual Totals Equal						
More rain in summer 2003	-	-	+27%	+1%	0%	+2%
Less rain in summer 2004	-	-	-	−11%	−2%	+1%
Temperature and rain larger in 2003	-	-	+330%	+12%	+4%	+3%
Temperature and rain smaller in 2004	-	-	-	−83%	−3%	0%

[a] No entry indicates not applicable (nothing was changed compared to the original run).

DNDC have also been observed by *Beheydt et al.* [2007]. However, accurate simulation of soil moisture is a key requirement for reliable simulation of N_2O emissions [*Frolking et al.*, 1998]. Therefore, parameterization is essential. After parameterization, the WFPS corresponded to the measured WFPS in 1992, 2001 and 2002, which were all average in terms of summer rainfall. We assume that the model also performed well for years with wet and dry summers. *Jagadeesh Babu et al.* [2006] indicate the use of default crop parameters in DNDC as a potential source of errors, but could not adjust these because of lack of data. *Tonitto et al.* [2007] adjusted the crop parameters for their research in Illinois in the same way as in this research.

[36] Although not every simulated daily emission fell between the minimum and maximum measured value for the dry plot, the patterns were similar (Figure 3). The annual modeled fluxes were within the borders of the confidence intervals of the measured fluxes (Figure 4).

[37] The simulated nitrogen inputs and outputs to soil were compared with measurements on nitrogen inputs and outputs at other sites in the Dutch fen meadow landscape to analyze differences between modeled and measured nitrogen flows (Table 7). For both DNDC and INITIATOR, measured N inputs of fertilizer and manure were used. The N deposition used by INITIATOR was based on estimates by an emission deposition model, whereas DNDC used the measured N concentration in rain (mg N l^{-1}). Mineralization and accompanied subsidence of the surface layer has been observed in both plots [*Beuving and Van den Akker*, 1996]. *Kuikman et al.* [2005] estimated that the mineralization is about 363 kg N ha^{-1} a^{-1} for the dry and about 136 kg N ha^{-1} a^{-1} for the wet plot. For the dry plot, both models estimated a smaller mineralization, although INITIATOR is closer to the estimate of *Kuikman et al.* [2005] and DNDC largely underestimates the mineralization. For the wet plot the modeled mineralization rates are closer to the estimate of *Kuikman et al.* [2005]. INITIATOR represents differences between mineralization rates of the dry and the wet plot better than DNDC.

[38] The nitrogen outputs by DNDC are generally too small, particularly for the net crop removal and denitrification (total emissions of N_2, N_2O, and NO_2). The latter value was influenced by underestimation of mineralization in the dry plot. Furthermore, DNDC simulates a strong N accumulation in the soil, which seems unrealistic in view of the underestimated mineralization. The nitrogen outputs by INITIATOR are more in line with the measurements; only N leaching is significantly underestimated. DNDC simulates N_2O emissions quite independently from the estimated N uptake and N leaching. A crucial difference between both models is the much smaller N_2O/N_2 ratio estimated by INITIATOR because of the much larger estimated denitrification. Measurements by *Van Beek et al.* [2004b] are between the DNDC estimate and the INITIATOR estimate for denitrification. Denitrification measurements by *de Klein and Van Logtestijn* [1994] (4–16 kg N ha^{-1} a^{-1}) from grassland on peat soil are close to the DNDC estimate, although these measurements were only limited to the topsoil (<20 cm). These findings show that analysis of the nitrogen balance provides valuable information about mea-

Table 6b. Change in Emissions Calculated by DNDC as Result of Within-Year Temporal Distribution Manipulation Experiments for a Number of Key Variables and Interactions for the Wet Plot[a]

Wet plot	2001	2002	2003	2004	2005	2006
Switch Method: Variables Substituted Between 2003 and 2004						
Rain in summer	-	-	+39%	−25%	−3%	−1%
Fertilization in spring	-	-	−2%	0%	0%	0%
Mowing in spring	-	-	+1%	−9%	−3%	+1%
Changing Intra-Annual Distribution While Keeping Annual Totals Equal						
More rain in summer 2003	-	-	+23%	+2%	+2%	+2%
Less rain in summer 2004	-	-	-	−3%	−3%	−2%
Temperature and rain larger in 2003	-	-	+78%	+7%	+5%	+5%
Temperature and rain smaller in 2004	-	-	-	−74%	−5%	−3%

[a] No entry indicates not applicable (nothing was changed compared to the original run).

Table 7. Nitrogen Balance Annual Averages for the Validation Period From 1 July 2001 to 30 June 2002[a]

	Dry Plot			Wet Plot		
	DNDC	INITIATOR	Measurements	DNDC	INITIATOR	Measurements
		Nitrogen Inputs to Soil				
Fertilizer	104	104	104[b]	110	110	110[b]
Manure (applied and grazing)	187	187	187[b]	264	263	263[b]
Deposition	39	39		39	39	
N fixation	21	25		3	25	
N mineralization	178	298	363[c]	136	93	136[c]
Total	529	654		484	530	
		Nitrogen Outputs to Soil				
NH_3 volatilization	27	27	39[d]	36	37	66[d]
Grass loss (cut and grazed)	83	240	221[b]	174	248	424[b]
N leaching	55	6	38[e]	12	4	38[e]
Denitrification, of which:	22	381	126–213[f]	19	242	
N_2O emissions[g]	19	20		16	13	
NO emissions[g]	2	6		2	4	
N_2 emissions[g]	2	358		1	227	
Total	209	652		240	531	
Nitrogen change in soil	+320	+2		+311	−1	

[a] Comparison of simulated and measured nitrogen inputs and outputs to the soil. Units are kg N ha^{-1} a^{-1}.
[b] Information from farmer (K. Van Houwelingen, personal communication, 2008).
[c] *Kuikman et al.* [2005].
[d] *Sonneveld et al.* [2008].
[e] *Van Beek et al.* [2004a].
[f] *Van Beek et al.* [2004b].
[g] Not taken into account for the calculation of the "total" to prevent double counting.

sured and modeled nitrogen flows for both plots. For the objectives of this study, however, the balance was only used to show differences between modeled and measured nitrogen flows.

4.2. Analysis of Temporal Resolution Effect

[39] In three steps, the effect of high-resolution temporal variation on N_2O emissions was analyzed. For the variables manure, fertilization, and mowing the largest correlation with daily N_2O emission was found using the sum of the variable over a period of more than 2 months (Table 4). For the estimation of the annual N_2O emission it is, therefore, not necessary to know the exact dates of these events. The effect of these events on N_2O emission is prolonged and nitrogen levels in the soil are enhanced for several months; thus knowing the months in which the events occur is sufficient to estimate the annual N_2O emission. Rainfall gave the best correlation when using the sum of the prior 10 days for the dry plot. Apparently, it takes about 10 days for the hydrology in the field to return to the initial situation and the effect of rainfall on N_2O emission is noticeable for more than a week.

[40] The analysis of the temporal resolution effects showed for both plots that changes in the rainfall data set have the largest effect on annual N_2O emission. The dry plot is more sensitive to summer rainfall than the wet plot. Apparently, the high water levels in the ditches surrounding the wet plot cause the plot to keep a certain wetness even in dry summers. Note that the summer in 2003 was dry and the summer of 2004 was wet (Figure 1). Climatological studies indicate that the frequency of these extreme wet and dry years will increase [*Koninklijk Nederlands Meteorologisch Instituut* (*KNMI*), 2006]. This study showed that the estimation of the annual N_2O emission is very sensitive to seasonal changes in rainfall. Especially the amount of rainfall in summer affects annual N_2O emissions. Temperatures are high in summer and nitrogen is applied in spring or summer. Nitrogen application in spring also causes high nitrogen levels in summer because of the prolonged effect. These conditions are needed for N_2O emission peaks, together with a certain wetness of the soil. Because for the research plots the conditions for temperature and nitrogen application are always met in summer, the amount of rainfall is probably the decisive condition for N_2O emission. Large summer rainfall amounts causes large summer N_2O emissions and a large annual N_2O emission, and vice versa. *Jones et al.* [2007] also found large N_2O emissions due to large rainfall amounts in the growing season. *Flechard et al.* [2007] observed N_2O emission factors, which were consequently smaller for dry years than for other years. For boreal sub humid climates, *Grant et al.* [2006] already advised to decrease emission factors for dry years.

4.3. Inclusion of Finer Temporal Resolution Into Low Temporal Resolution Models

[41] Ideally, countries would use Tier 3 methods to accurately simulate their N_2O emissions, but limited data availability makes this difficult. However, we could use information from Tier 3 methods at small spatial extents (parcels) to improve Tier 2 methods. For instance, the proportion of summer rainfall is not considered in the low temporal resolution model INITIATOR. The analysis of the temporal resolution effects shows that the proportion of summer rainfall can potentially have a large effect on annual N_2O emission. Therefore, the INITIATOR model can be improved by adjusting the N_2O emissions for years with a

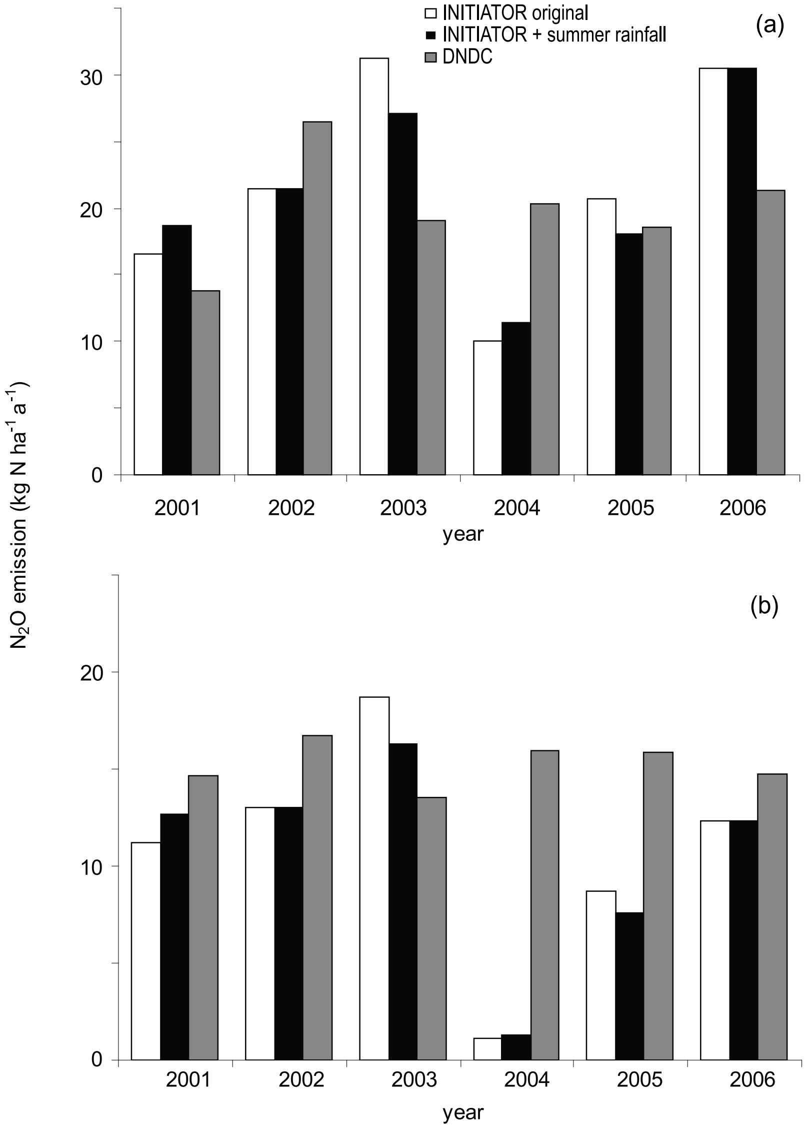

Figure 5. Annual N_2O emissions estimated with INITIATOR and DNDC for 2001 through 2006 for the (a) dry and (b) wet plots (see also Figure 4) compared with updated INITIATOR estimates, which take into account the effect of relatively low or high amounts of summer rainfall.

relatively low or high summer rainfall (Table 5). For years with "medium" summer rainfall (Table 5) the emissions were not adjusted, but for years with "low" or "high" summer rainfall, a linear adjustment was made proportional to the deviation from the normal summer rainfall (i.e., 25% of annual rainfall, according to daily weather data of the Netherlands, available at http://www.knmi.nl). For both plots, this temporal resolution effect was estimated to be 12.9% (±4.5%). For instance, the annual emission increases by 12.9% when the summer rainfall has a share of 26% of the annual rainfall and decreases by 12.9% when the share is 24% of the annual rainfall. The adjusted N_2O emissions are given in Figure 5. The annual estimated emissions slightly improved; the root-mean-squared error between DNDC and INITIATOR decreased by 13% for the dry parcel and by 2% for the wet parcel, but differences in results between the models still remain (Figure 5). INITIATOR estimated on average larger N_2O emissions for the dry plot and DNDC estimated on average larger N_2O emissions for the wet plot. This is probably because INITIATOR puts more emphasis on N_2O emission due to mineralization from the dry plot, while DNDC puts more emphasis on N_2O emission due to denitrification caused by the high WFPS from the wet plot. Accordingly, differences in modeled annual N_2O emissions are not only caused by differences in temporal resolution, but also by differences in model concepts.

4.4. Comparison of Simulated Annual Average Emission Factors With the IPCC Default Values (Tier 1) and Dutch Values (Tier 2)

[42] Table 8 shows that the emission factors for DNDC and INITIATOR for the dry plot over the six simulation years are very similar. These emission factors were derived

Table 8. Nitrogen Inputs and Estimated Annual N_2O Emission Factors Derived From the Simulated N_2O Emissions of DNDC and INITIATOR

	2001	2002	2003	2004	2005	2006
Dry Plot						
N input due to manure and fertilizer (kg N ha^{-1} a^{-1})	224	401	399	86	386	376
DNDC N_2O emission factor	2.3%	4.4%	2.6%	13.6%	2.6%	3.4%
INITIATOR N_2O emission factor (%)	4.5%	3.8%	6.6%	3.0%	3.7%	6.7%
Wet Plot						
N input due to manure and fertilizer (kg N ha^{-1} a^{-1})	328	414	438	68	315	285
DNDC N_2O emission factor (%)	3.9%	3.5%	2.6%	20.6%	4.4%	4.5%
INITIATOR N_2O emission factor (%)	3.2%	3.0%	4.5%	−1.1%	2.6%	4.3%

assuming a constant background emission. The emission in 2004 simulated by INITIATOR was smaller than the background emission, causing a negative emission factor. The large emission factors for DNDC in 2004 are caused by the large summer rainfall.

[43] The default Tier 1 value for the N_2O emission factor according to the updated IPCC Guidelines [*IPCC*, 2006] is 1% for the application of manure and fertilizer on both mineral and organic soils, on the basis of results of a global N_2O emission inventory of *Bouwman et al.* [2002]. The emission percentages used in the Dutch Tier 2 approach are also 1% for mineral soils but 2% for organic soils. This value is mainly based on measurements during a 2 year experimental study by *Velthof and Oenema* [1995], who measured N_2O emissions from managed grassland in the Netherlands on two mineral soils (sand and clay) and two peat soils (similar to this study, a dry and a wet plot). These authors calculated N_2O emission factors near 1% for the mineral soils but near 2% and 4% for the "wet" and "dry" peat soils, respectively. The larger values were caused by the larger C and N turnover rates and shallower groundwater levels in peat soils, leading to larger denitrification rates. It is clear that the DNDC and INITIATOR estimates are closer to the national value than the IPCC default value. Note, however, that the differences between the DNDC and INITIATOR estimates and the national value are still substantial.

5. Conclusions

[44] Comparison of predictions obtained with the high temporal resolution model DNDC and the low temporal resolution model INITIATOR enabled an assessment of the effect of temporal resolution on annual N_2O emission. However, differences between modeled N_2O emission are also influenced by differences in model concepts and these differences are hard to separate from those caused by differences in temporal resolution. The results point to the important role of distribution of rainfall within a year for estimating annual N_2O emissions from intensively managed grasslands in the fen meadow landscape. In years with a relatively large summer rainfall, N_2O emission estimated with DNDC was larger than estimated with INITIATOR. In years with a relatively small summer rainfall, the opposite occurred. One important conclusion from this work is therefore that low temporal resolution inventory models such as INITIATOR (and other Tier 2 methods) may be improved for intensively managed grasslands on peat soils by adjusting N_2O emission estimates for years with relatively dry summers and wet summers. More research is needed to analyze to what degree these conclusions may be extrapolated to other ecosystems.

[45] The analysis used to identify key variables and variable interactions showed that not the daily values of these variables are important for predicting daily and annual N_2O emissions, but the average of the variables over weeks or even months. Aggregates over longer periods showed the largest correlation with daily N_2O emissions. Especially for management variables, the largest correlations were found using the average of months or even longer. Because of this prolonged effect, the exact dates of nitrogen application are not important for estimating annual N_2O emissions for intensively managed grasslands on peat soils. It is sufficient to know in which month the application took place. This will greatly simplify upscaling efforts of N_2O emissions.

[46] The emission factors estimated from DNDC and INITIATOR varied largely between the models and between years. It is therefore recommended to estimate emission factors over a large time period (decades) and to be cautious with years with very large of very small summer rainfall.

[47] **Acknowledgments.** This work was funded by the Dutch project "Climate Changes Spatial Planning" (KvR ME1). We thank Cor Jacobs and Peter Kuikman from Alterra for supplying measurements from the two research plots. We thank Jan-Cees Voogd for valuable assistance with the use of INITIATOR and Changsheng Li and Egbert Lantinga for help with DNDC. We thank ROC Zegveld, especially Karel van Houwelingen, for providing the management data of the research plots. We also thank the anonymous reviewers for their valuable comments.

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