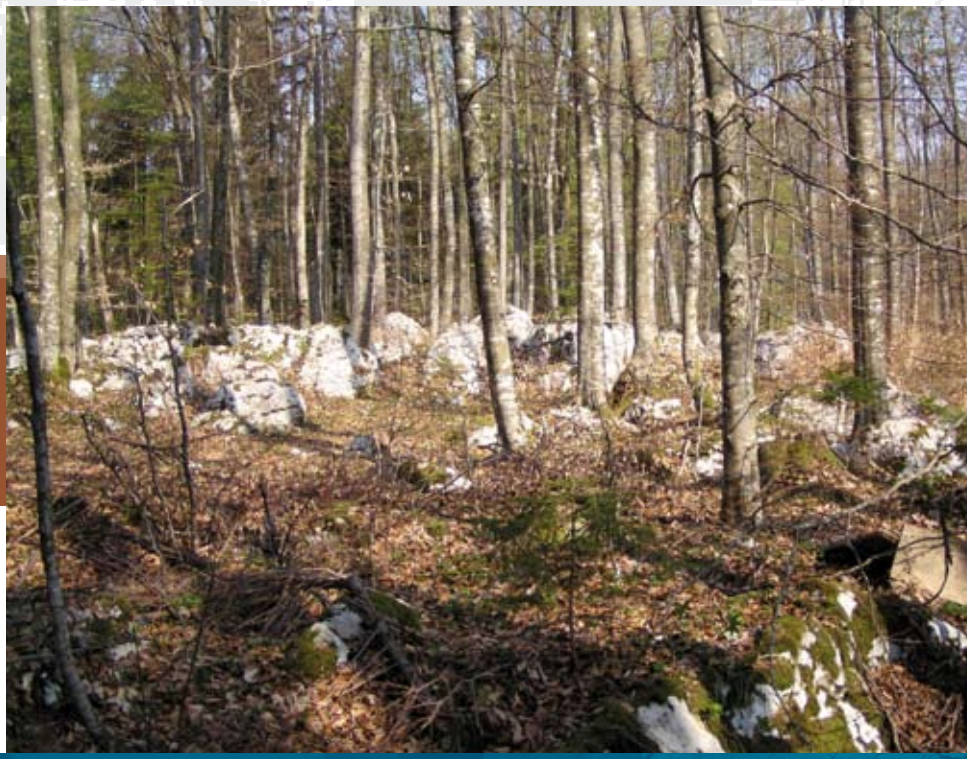
ALTERRA
WAGENINGEN UR

Relationships between nitrous oxide emissions from natural ecosystems and environmental factors

M. Bloemerts
W. de Vries



Alterra-report 1853, ISSN 1566-7197

Relationships between nitrous oxide emissions from natural ecosystems and environmental factors

Commissioned by the KB1 strategic research program “Sustainable spatial development of ecosystems, landscapes, seas and regions" and the European Commission.

Project code [5232419]

Relationships between nitrous oxide emissions from natural ecosystems and environmental factors

Mirjam Bloemerts
Wim de Vries

Alterra-report 1853

Alterra, Wageningen, 2009

ABSTRACT

Bloemerts, M. & W. de Vries, 2009. *Relationships between nitrous oxide emissions from natural ecosystems and environmental factors*. Wageningen, Alterra, Alterra-report 1853. 112 blz.; 13 figs.; 19 tables.; 108 refs.

A literature review on quantitative relationships between environmental factors and nitrous oxide (N_2O) emissions, showed that pH, temperature, water and nitrogen availability were the main controllers of N_2O emissions were. Since the studies were often controlled small-scale experiments with a limited number of influencing environmental variables on a very limited number of plots, this hampered the use of regression models derived from the literature review for regional applications. Consequently, a database was constructed of measured N_2O fluxes from natural ecosystems in temperate and boreal climate, combined with measurements or estimates of influencing variables, i.e. pH, clay content, bulk density, organic carbon content, C/N ratio, mean temperature, mean precipitation, fraction of months with temperatures below zero, N deposition, vegetation class and parent material. All fluxes were natural emissions measured in the field. Manipulation experiments and laboratory studies were not included. The result was a database with 162 records from field measurements in natural soils in the temperate and boreal climate zones. Results of regressions analysis showed that only 15-25% of the variation in measured N_2O emissions was explained by these environmental factors. Depending on the type of data used (only measured environmental factors or also estimated values) N deposition, temperature and vegetation class were among the most influential factors

Keywords: nitrous oxides, forest, green house gas, meta-data analysis, climate, nitrogen deposition, soil properties

ISSN 1566-7197

P.O. Box 47; 6700 AA Wageningen; The Netherlands
Phone: + 31 317 480700; fax: +31 317 419000; e-mail: info.alterra@wur.nl

[Alterra-report 1853/April/2009]

Contents

Preface

This report is the result of an internship Mirjam Bloemerts to finalize her MSc study Environmental Sciences at Wageningen University. We like to acknowledge Drs Andre van Amstel, who was the supervisor from the "leerstoelgroep" Environmental Systems Analysis of Wageningen University, Mr. Jan Cees Voogd for statistical analysis and mr Gert Jan Reinds for making estimates of environmental factors, based on interpolation and modelling approaches, at sites where measurements were lacking.

The authors

Summary

Nitrous oxide (N_2O) is, next to carbon dioxide (CO_2), the main greenhouse gas. Anthropogenic emissions have a large contribution to the total emissions of greenhouse gases. However, natural ecosystems play a role as well. Natural ecosystems provide both sources and sinks for N_2O, and thereby influence the composition of the atmosphere. A commonly used method to estimate N_2O emissions is the IPCC methodology which says that 1 % of the nitrogen deposition is emitted as N_2O. However, research has indicated that N_2O emissions from natural soils will be underestimated when this rule is applied. Several studies showed emissions factors of 2 to 4 %. On the other hand, a factor of 0.2 % was found for N-limited forests (Klemedtsson et al., 1997). These results show that it is useful to update the IPCC method with a relation accounting for local/regional differences. This study was aimed at finding relations between environmental factors and N_2O emissions in order to make proper estimates of N_2O emissions on a European scale.

As a first step, a literature review of published data on the impact of environmental factors on the N_2O emissions was carried out, focusing on quantitative relationships between environmental factors and N_2O emissions. This literature review on the impact of environmental factors gave insight into the mechanisms of N_2O production and it gave an indication which factors were the main influencers of the emissions. It can be concluded that the main controllers of N_2O emissions were: pH, temperature, soil moisture (as %V/V, WFPS, or precipitation), and the availability of nitrogen. The latter can be expressed by several parameters like nitrogen deposition, C/N ratio, and soil NO_3^- concentrations. The influences of all these factors complicate the study of impacts on N_2O emissions. This made it impossible to find one straight-forward relation between the environmental factors and the N_2O emissions. Additionally, the studies on impacts were often controlled small-scale experiments with a limited number of influencing environmental variables on a very limited number of plots. This hampered the use of regression models derived from the literature review for regional applications.

The second step was to find publications on measured N_2O fluxes in the field. These fluxes were used to construct a database of N_2O fluxes from natural ecosystems in temperate and boreal climate. All fluxes were natural emissions measured in the field. Manipulation experiments and laboratory studies were not included. The result was a database with 162 records from field measurements in natural soils in the temperate and boreal climate zones.

The information from the database was used as input for regression analyses of N_2O emissions and the following variables: pH, % clay, bulk density, Organic C, C/N ratio, mean temperature, mean precipitation, fraction of months with temperatures below zero, N deposition, vegetation class and parent material. Regression analyses were applied to three datasets. First, sites for which all variables were measured were

selected for the 'measured' dataset. This regression resulted in the following best model:

Log N_2O = -0.627 + 0.459 * log (N deposition),
R^2_{adj} = 15.2, s.e. = 0.478.

The 'measured' dataset did only contain 25 records since often some of the variables were not measured and consequently, the record had to be deleted from the dataset.

To overcome this problem of lacking data, estimated data were used. Estimates were gathered from several databases and values were assigned based on location. The results of the 'estimated' dataset:
Log N_2O = -1.99 – 1.043 * log (P) + 1.501 * (Fraction T<0) + 0.1464 * (% clay) - 0.410 * (pH) + 0.00711 * (Organic C) + 0.1290 * (C/N ratio) - 7.53 * (parent material: organic) + 0.01082 * (N deposition),
R^2_{adj} = 26.4, s.e. = 0.421.

The 'estimated' dataset did include 98 records which was a large improvement from the 25 records in the 'measured' dataset. However, estimated parameters were deviating largely from measured values.

To compensate, also a dataset 'measured+' was compiled. This dataset included measured data and missing soil properties were added based on published soil classes. The results of the 'measured+' dataset:
Log N_2O = 0.033 – 0.0957 * (Temperature) + 0.349 * log (N deposition) + 0.4006 (vegetation: deciduous) + 0.303 (vegetation: short vegetation),
R^2_{adj} = 22.1, s.e. = 0.457.

The previously mentioned regression analyses did include parent material as a variable. The 'measured+' database was not only run with parent material as a viable, it was also spit into two based on parent material. The dataset of mineral soils did include 82 records and this was the result:
Log N_2O = -0.234 – 0.0744 * (Temperature) + 0.366 * log (N deposition) + 0.334 (vegetation: deciduous) + 0.035 (vegetation: short vegetation),
R^2_{adj} = 17.9, s.e. = 0.439.
The dataset of organic soils did include 19 records and the result had a much higher R^2 value than the other regressions:
Log N_2O = -3.84 – 0.0690 * (% clay) +0.769 * (pH) + 0.00807 * (Organic C),
R^2_{adj} = 57.0, s.e. = 0.386.

The results of the regression analyses show that only a did not result in a perfect description of N_2O emissions based on environmental parameters. Possible reasons for this result were discussed in the discussion. The two main aspects were the high variability of the N_2O emissions over time and space, and the errors in the parameter values. Estimates can be deviating from the study site, and measured data can be local characteristics on a very small scale which do not represent the average conditions of the study site.

1 Introduction

The earth is a greenhouse which provides a living to many organisms. Increasing concentrations of the greenhouse gases cause an enhanced greenhouse effect. Nitrous oxide (N_2O) is, next to carbon dioxide (CO_2), the main greenhouse gas. Anthropogenic emissions have a large contribution to the total emissions of greenhouse gases. However, natural ecosystems play a role as well. Natural ecosystems provide both sources and sinks for N_2O, and thereby influence the composition of the atmosphere. Production and consumption processes in the ecosystems are main drivers of the exchange of gases between the biosphere and the atmosphere (adapted after Conrad, 1996).

Nitrous oxide

Nitrous oxide is a greenhouse gas that contributes to the destruction of ozone in the stratosphere (Cicerone, 1987). Total global N_2O emissions are estimated to be 17.7 Tg N/yr (1 Tg = 10^{12} g) of which 6.6 Tg/yr is emitted by natural soils (IPCC, 2007). Rates of nitrogen processes are important determinants of the N_2O emissions from soils. Nitrification, denitrification and nitrifier denitrification are three main processes that produce nitrous oxide.

Nitrification is the process by which ammonium (NH_4) is formed into nitrate (NO_3) with help of nitrifying bacteria (Smith et al., 2003). This transformation occurs via the formation of nitrite, and during this process oxygen is needed. Nitrification takes place in two steps:

$$NH_4^+ (aq) + O_2 (g) \rightarrow NO_2^- (aq) + H^+ (aq)$$
$$NO_2^- (aq) + O_2 (g) \rightarrow NO_3^- (aq)$$

Oxygen (O_2) is consumed during the process of nitrification. Nitrite can be used as an alternative electron acceptor in case of limited O_2 supply. In this case, the nitrifying bacteria use the NO_2 and reduce it to NO and N_2O, which will be emitted from the soil. The process of nitrification (Smith et al., 2003):

$$\begin{array}{l} \quad\quad NO + N_2O \\ \quad\quad\ \uparrow \\ NH_4^+ \rightarrow NO \rightarrow NO_2^- \rightarrow NO_3^- \end{array}$$

Denitrification converts nitrate (NO_3) into nitrous gas N_2. This process can only take place under anaerobic conditions. During the process of denitrification, nitrate concentrations decrease since nitrate is transformed into nitrite and volatilized into the atmosphere as nitrous gas and nitrous oxide. Emissions of N_2O occur when the transformation of NO_3 into N_2 is not fully completed. This can be the case at lower soil water contents when aerobic processes are favoured. Figure 1.1 shows the steps in the denitrification process (Smith et al., 2003):

$$\begin{array}{l} \quad N_2O \\ \quad \uparrow \\ NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \end{array}$$

The process of nitrifier denitrification is performed by NH_3-oxidisers and starts of as nitrification. However, the oxidisers do continue to transform NO_2 into, finally, NO. The reaction follows these steps:

$$NH_3 \rightarrow NH_2OH \rightarrow NO_2 \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

This process was long thought to be of minor importance for N_2O emissions from soils (Robertson & Tiedje, 1987). Later on, studies have showed a significant contribution of nitrifier denitrification to the total N_2O production. Webster and Hopkins (1996) found a contribution of 30 % in dry sandy soils.

Impact of environmental factors

The three nitrogen processes presented in this chapter are not the only ones. However, they are the main sources of nitrous oxide. Optimum conditions for the three processes are different and, due to this, estimating the N_2O emissions is complicated. Changing conditions are, for example, stimulating one process while reducing the N_2O production by the other two processes. In addition to differences in favouring conditions, there are a number of factors which have a positive or negative effect on one or several of the processes. The influence that the processes have on each other can be explained by the linkages between the three processes (see figure 1.1).

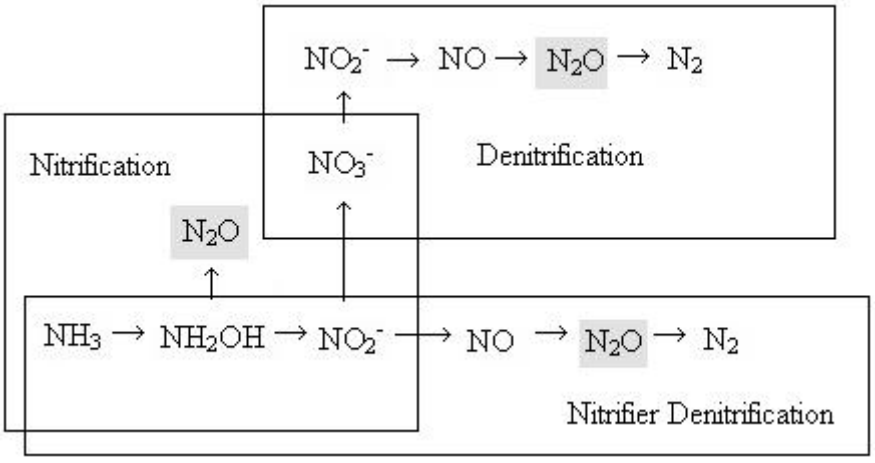


Figure 1.1 The main nitrous oxide producing processes and their linkages (Wrage et al., 2001)

Emission rates of N_2O are very variable in time and space. Environmental variables highly influence the emission rates and thereby cause a large part of the variability. Nitrous oxide emissions are found to be increasing with increasing nitrogen availability (Bowden et al., 1991; Tietema et al., 1991). The increase of N_2O production as a result of increased N availability results in an increase in this

greenhouse gases. Nitrogen availability is not the only factor influencing N_2O emissions. Other variables include temperature, pH, and soil moisture. Knowledge of the relations between emissions and environmental variables will help to upscale the emissions of N_2O.

Purpose of this research

Since emissions from agricultural sites are much higher than from forest soils due to fertilization, there has been a main focus on N_2O emissions from agricultural land. Research by, for example, Stehfest and Bouwman (2006), show the large difference between number of measurements on agricultural sites and number of measurements on natural soils. There is thus a need for more information on the effects of environmental variables and the possibilities to describe these relationships from natural ecosystems. The aim of this study was to assess the N_2O exchange fluxes from natural terrestrial ecosystems on a European scale. Even though these ecosystems have, in general, a lower emission of N_2O than cultivated land and forests in tropical regions (Bouwman, 1990). European natural ecosystems, and specifically forests, are important because they cover a large part of the European continent and thereby their total emissions are of importance.

A commonly used method to estimate N_2O emissions is the IPCC methodology which says that 1 % of the nitrogen deposition is emitted as N_2O. However, research has indicated that N_2O emissions from natural soils will be underestimated when this rule is applied. Several studies showed emissions factors of 2 to 4 % (Machefert et al., 2002; Borken & Beese, 2005; Denier van der Gon & Bleeker, 2005; Pilegaard et al., 2006; Ernfors et al., 2007). On the other hand, a factor of 0.2 % was found for N-limited forests (Klemedtsson et al., 1997). These results show that it is useful to update the IPCC method with a relation accounting for local/regional differences. This study was aimed at finding relations between environmental factors and N_2O emissions in order to make proper estimates of N_2O emissions on a European scale.

Research methodology

This study was carried out in three main steps. First, a literature study was carried out on the impacts of environmental factors on the N_2O emissions. This literature review gave insight into the mechanisms of N_2O emissions and it gave an indication which factors were the main influencers of the emissions. The review was conducted by searching peer-reviewed articles.

The second step also involved literature research, finding publications of measured N_2O fluxes in the field. These fluxes were used to construct a database of N_2O fluxes from natural ecosystems in temperate and boreal climate. All fluxes are natural emissions measured in the field. Manipulation experiments and laboratory studies were not included.

Finally, regressions analyses were used to derive empirical relations between nitrous oxide fluxes and environmental variables, such as climatic variables and soil properties. Data were only included if the measurements were done over e period of more than one year. All sites were natural vegetation and measurements were field

fluxes which were not part of a manipulation experiment. Ideally, parameters on the measurement location are measured at the site. However, this is not always the case, and consequently, the database includes many gaps in the data. As an alternative, estimated data based on the coordinates of the measurement were used. The estimates were derived from several databases. The results of the regression analyses will be applied on locations for which all parameters are estimated. Using measured values to perform the analysis would result in an equation which is based on more exact data than the data used for application. This would introduce new uncertainties for the application. However, when all the parameters are estimated based on the coordinates of the location, the uncertainty of the regression analysis will be larger but no additional uncertainties will be introduced with the application.

Purely measured data resulted in a much reduced database. A second version of measured data was compiled by using measured data, if available, and adding soil parameters based on the published soil class. In this case, estimated soil parameters were only added if the soil class was known. The main difference with the purely estimated database is the fact that in this case the soil class was estimated as well. However, the dominant soil class is often different from the local soil class which was published. This was mainly a problem for the organic soils.

Three datasets that were used as input for the regression analyses were thus:
- Estimated data:
  All parameters estimated based on location
- Measured data:
  Purely measured data as published in the articles
- Measured data +:
  Measured data, and missing soil properties were added based on published soil class

Outline of this report

Chapter two describes the findings of the literature review of published data on the impact of environmental factors on the N_2O emissions from natural terrestrial ecosystems. Chapter three explains how a database of measurements is set up and it presents the empirical relations that were derived by regression analyses based on this database. A discussion and conclusions on the work can be found in chapter four. The database and the input to the regression analyses can be found in appendixes.

2 Impacts of environmental factors on nitrous oxide emissions

This chapter discusses the impact of environmental factors on the N_2O exchange from natural (mainly forest) soils and presents relations between environmental factors and N_2O exchange found in literature. An overview is given of the impact of environmental factors as was found in literature. This chapter summarizes literature on relations between environmental factors and N_2O exchange for forests. The rate of N_2O exchange between forest soils and atmosphere is dependent on the local conditions. Section 2.1 gives an overview of the qualitative relations. Next, three main influencing factors are quantitatively described. These factors are temperature, soil moisture, and the availability of nitrogen, and are addressed in section 2.2, 2.3, and 2.4. The fifth section presents regression coefficients and correlations between N_2O emissions and various environmental factors. A final section gives a conclusion on the data presented in this chapter and it discusses the applicability of these kinds of relations for upscaling.

2.1 Qualitative overview

Nitrous oxide is emitted by forest soils through nitrification, denitrification, and nitrifier denitrification. These processes take place under different circumstances and the combination of these processes determines the flux of nitrous oxide. Machefert et al. (2002) presented an overview of the factors favouring nitrification and denitrification (see table 2.1). Information from Wrage et al (2004) on nitrifier denitrification is included in table 2.1. The influence of a variety of factors on the three processes favouring different circumstances complicates the estimation of N_2O emissions from soils. Nitrifier denitrification has not been studied as extensively as nitrification and denitrification. Consequently, the conditions under which nitrifier denitrification occurs are still not clearly defined. However, it has been shown that nitrifier denitrification occurs under conditions of stress (Poth & Focht, 1985) and under dry conditions (Webster & Hopkins, 1996). In summary, the three processes require different conditions. Nevertheless, nitrification, denitrification, and nitrifier denitrification can take place in a soil simultaneously. This is possible due to the large heterogeneity that can be found in soils (Machefert et al., 2002).

Table 2.1 Conditions favoured by N_2O production via nitrification, denitrification, and nitrifier denitrification (adapted after Machefert et al., 2002; Wrage et al., 2004).

	Nitrification	Denitrification	Nitrifier Denitrification
Substrate availability	NH_4^+, urea, amino acids	NO_3^-	NO_2^-
O_2 concentration	High	Low	High
Reduced carbon	No effect	High	Low
Moisture (water filled pore space)	Intermediate 30-70 % WFPS	High 55-100 % WFPS	Low
Soil temperature	High	High	High
pH	> 5	Low (< 5)	-

2.2 The impact of temperature

Temperature is a driver of the process rates of nitrification and denitrification. An increase in temperature will stimulate the process rates under the condition that no limiting or restraining factors, such as the absence of substrate, are present. Winter conditions with freezing and thawing of the soils induce special circumstances under which the nitrous oxide emissions do not respond the same as under conditions of above-zero temperatures. Section 2.1.1 presents literature on the temperature response of N_2O emissions from soils. Winter conditions and its implications for N_2O emissions are described in section 2.1.2.

2.2.1 Temperature response

A commonly used way to express the temperature response of a process is by use of Q_{10}-values. A Q_{10}-value gives the change in process rate for a change in temperature of 10 °C (Ryan, 1991). The function on which the Q10-values are based is (Kirschbaum, 1995):

$$Q_{10} = (K_2/K_1)^{[10 / (T2-T1)]}$$

K_2 and K_1 are process rates at respectively temperature T_2 and T_1, resulting in a change factor for the process rate due to 10 °C temperature change (Kirschbaum, 1995). The temperature response curve as induced by a Q_{10} temperature response is visualised in figure 2.1. Two different curves are shown for N_2O emissions following two different Q_{10}-values.

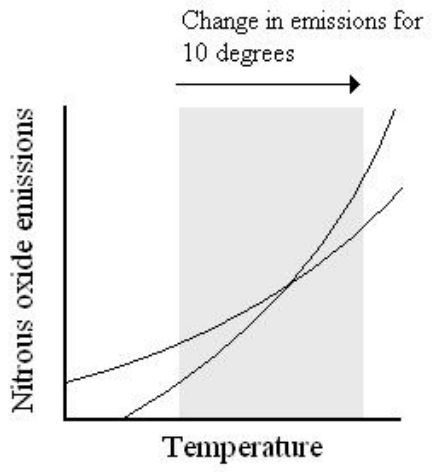


Figure 2.1 An example of two temperature responses of nitrous oxide emissions induced by a Q_{10} temperature response.

Koponen et al. (2006) investigated the temperature response of NO and N_2O emissions from two boreal organic soils in western Finland at 63°56'N, 23°53'E. This area receives a mean annual precipitation of 561 mm and the mean air

temperature is 2.4°C (Koponen et al., 2006). The soils were used for cereal and grass cultivation, but were abandoned 20 and 25-30 years before the study, respectively. The first site has been afforested 17 years ago with birch, and the second site is left uncultivated. The characteristics of the two sites can be found in table 2.2. Soil samples were taken from the two locations in October 2003 and experiments were conducted at various temperatures.

Table 2.2 Soil characteristics of the two soil samples from western Finland studied by Koponen et al. (2006).

Characteristic	Afforested	Abandoned
Soil type (FAO)	Histosol	Histosol
WFPS	44	71
pH	4.7	5.0
C-total (%)	33	19
N-total (%)	2.56	0.98

Temperature response was calculated as Q_{10}-values for the temperature range from 0.4°C to 9.4°C. The afforested soil showed a Q_{10}-value of 1.9 (±0.2) for NO emissions and 6.4 (±2.0) for N_2O emissions. The abandoned site differed mainly in the response of N_2O emissions which had a lower Q_{10}-value of 1.6 (±0.5). The NO emissions were more similar showing a Q_{10}-value of 2.1 (±0.4) (Koponen et al., 2006). The lowest temperature in this experiment was -4.9°C at which the soils were kept for 6 weeks. During these weeks the soils emitted both NO and N_2O, indicating microbial activity at such a low temperature. NO emissions were 1.3 (±0.2) µg NO-N m^{-2} h^{-1} and 1.5 (±0.2) µg NO-N m^{-2} h^{-1} for the afforested and abandoned site, respectively (Koponen et al., 2006). N_2O emissions were significantly higher at the abandoned site with emissions of 5.2 (±1.8) µg NO-N m^{-2} h^{-1} and 20.7 (±2.9) µg NO-N m^{-2} h^{-1} for the afforested and abandoned site, respectively (Koponen et al., 2006).

Temperature and soil water tension as regulating factors of N_2O emissions have been studied by Brumme (1995). N_2O emissions were measured along a gradient from the centre of a gap in the forest into a mature beech stand. The measurements were done in a 146-year-old beech forest in the Solling area in Germany (51°N, 9°E). Information on the study site can be found in appendix 1 (site number 18). The measurements of the N_2O fluxes were accompanied by measurements of soil temperature and soil water tension. The gradient provided different conditions in temperature and soil moisture. The combination of the three measurements showed general trends of increasing emissions with increasing temperature, and decreasing emissions with increasing soil water tension (Brumme, 1995). Q_{10}-values have been calculated based on the measured N_2O fluxes. Table 2.3 presents the Q_{10}-values as found by (Brumme, 1995). Measurements in two forest stands gave a Q_{10}-value of 3.2 for the nitrous oxide emissions (Oura et al., 2001). Oura et al. (2001) measured N_2O fluxes every two weeks from June 1999 to May 2000 in two forests in central Japan: Kannondai and Yasato. The N_2O emission data is combined with simultaneously measured soil temperature at 20 cm depth, and a Q_{10}-value is calculated for these two sites combined. The temperature range of the soil is 5-25°C

and 3-24°C for Kannondai and Yasato, respectively (Oura et al., 2001). More details about the sites can be found in appendix 1 (site number 146 and 147).

Table 2.3 Q_{10}-values for N_2O emissions for the gap and the mature stand, differentiating in temperature and soil water tension classes (Brumme, 1995).

Soil water tension class	Temperature 7-10°C to 10-12°C	Temperature 10-12°C to 12-14°C	Temperature 12-14°C to 14-17°C
Mature stand			
20-855 hPa	-0.9	8.8	6.2
20-200 hPa	-0.9	9.8	6.0
200-400 hPa	-	-	6.1
400-600 hPa	-	3.7	-4.7
Centre of gap			
20-200 hPa	14.4	2.6	4.4

2.2.2 Winter conditions

The importance of winter conditions is shown in the high contribution of winter emissions to the annual budget as found in several studies. In general, 50 to 70 % of the annual N_2O emissions occur during winter (e.g. Flessa et al., 1995; Wagner-Riddle et al., 1997; Kaiser et al., 1998; Rover et al., 1998; Kaiser & Ruser, 2000; Ruser et al., 2001). These findings show that it is important to account for these winter conditions when upscaling annual N_2O emissions and predicting regional emission levels.

Section 2.1.1 presented several studies on the impact of temperature on nitrous oxide emissions. Most of these studies expressed the response with a Q_{10}-value. This form of temperature response would result in negligible emissions during winter since the temperatures are low and processes of N_2O production are at a minimum. However, high emissions of N_2O have been measured during the winter indicating otherwise (e.g. Brumme et al., 1999; Papen & Butterbach-Bahl, 1999; Teepe et al., 2000) Teepe et al. (2000) measured N_2O emissions on a weekly basis during one year in an oak-forest in Germany, and found 50 % of the annual emissions to occur in the months December to March. At the end of January, with a frozen soil and air temperatures of -10°C, N_2O emissions of 16 μg N_2O-N m^{-2} h^{-1} were measured (Teepe et al., 2000). This is supported by findings of Papen and Butterbach-Bahl (1999) and Öquist et al. (2004). Öquist et al. (2004) investigated the formation of N_2O in soils under different temperatures and included soils temperatures below zero. They measured N_2O fluxes from soils at -4.0 °C, 0.5 °C, 5.0 °C, 15.0 °C, and 20.0 °C in combination with soil moisture levels of 15 %, 30 %, 60 %, and 100 % of the soil's water holding capacity. These experiments showed a remarkable increase in emissions, from soils with high soil moisture level, when temperatures dropped below zero. Based on their observations, they propose a conceptual model to describe to relation between temperature and N_2O emissions (see figure 2.2). The increase in N_2O emissions at temperatures below zero is explained by the decrease in diffusion due to freezing. This decrease in diffusion creates micro sites with anoxic conditions, resulting in an increase in N_2O formation. The anomaly at higher temperatures is caused by the enhanced oxygen consumption and the resulting anoxic conditions. This shows that

the oxygen status in the soil is a very important regulator which is indirectly influenced by temperature. This indirect effect of temperature seems to have a stronger impact on N_2O emissions than the direct temperature effect (Tiedje, 1988; Öquist et al., 2004).

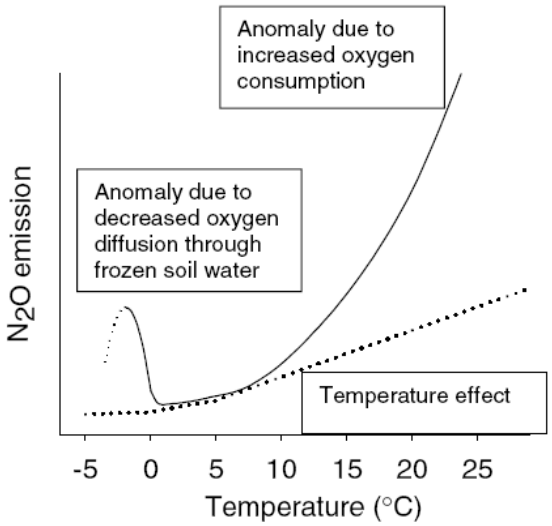


Figure 2.2 The conceptual model of the relation between temperature and N_2O emissions. The dotted line shows the relation when only the direct effect of temperature is included. The solid line includes indirect effects like the increased anoxic conditions (Öquist et al., 2004).

However, this is not the only explanation known for the phenomenon of high emissions during winter (Yu et al., 2007). Micro-organisms die in a frozen soil and become a source of organic carbon which can stimulate N_2O production (Christensen et al., 1990). Another source of nutrient supply in frozen soils can be destroyed roots (Tierney et al., 2001). Groffman (1993) explained the winter emissions by a reduced uptake of N by plants which leaves more N available for N_2O production. Bremner et al. (1980) suggested an accumulation of N_2O under the frozen topsoil which is physically released at thawing. This is supported by Yu et al. (2007) who suggest a lack of oxygen supply in frozen soils. This reduces the oxygen in the subsoil over time and results in anoxic conditions which are favoured by denitrification. Consequently, N_2O production through denitrification is increased (Yu et al., 2007).

Air temperature is often used as a measure for the soil temperature since these two parameters are clearly linked. However, snow cover during winter disturbs the relation between air temperature and soil temperature. The snow functions as an insulator for the soil and, consequently, the soil under a snow pack may be unfrozen while air temperatures are well below zero (Yashiro et al., 2006). Micro-organisms might be able to adapt to these cold, but not yet frozen, conditions and might stay active during the winter while a snow pack prevents to soil from freezing (Yashiro et al., 2006).

2.3 The impact of soil moisture and temperature

Soil moisture is of great importance for the occurrence of anaerobic conditions. Nitrification can take place under aerobic conditions while denitrification requires anaerobic conditions. Oxygen can be excluded from the soil by water. Different parameters can represent the oxygen/moisture status of the soil. Water Filled Pore Space (WFPS) gives the volumetric moisture content relative to the total pore space. Ground water level is another measure which described how large the unsaturated zone of the soil is in which oxygen might be able to penetrate. Input of water to the system by rainfall or throughfall are other measures related to soil. Finally, soil texture affects the soil moisture availability. The literature review showed that most studies that found a dependency on soil moisture, also found a dependency on temperature.

Corre et al. (1999) found N_2O emissions to be most strongly related to WFPS. This finding was based on a 2-year period of measurements on several sites in two forests in Saskatchewan, Canada. This is an area with sandy and clay loam soils (more details in appendix 1; site number 138 and 139). The climate is cold with minimum temperatures in January of -20°C and annual snowfall of more than 100 mm. The relation found between N_2O emissions and WFPS (as ratio of the volumetric moisture content to the total pore space, measured in the upper 15 cm of the soil) could be described by the following function (Corre et al., 1999):

N_2O ($\mu g\ N_2O\text{-}N\ m^{-2}\ day^{-1}$) = 30 WFPS – 9
($R^2 = 0.35$, $p<0.001$)

Studies were conducted in two drained spruce forests on peat soils (Von Arnold et al., 2005b) and two deciduous forests on peat soils (Von Arnold et al., 2005a). All studies were conducted at the Asa Experimental Forest in southern Sweden (site numbers 127, 128, 130, and 13 in appendix 1). Multiple regression analysis was applied for each site separately. An overview of the main site characteristics is given in table 2.4.

Table 2.4 An overview of the main site characteristics of the sites studied by Van Arnold et al (2005a; 2005b)

Site nr.	Tree species	Forest age	Depth of peat layer	Organic matter content	pH	C/N ratio	Depth of ground water
127	Spruce	50 yrs	90 cm	92 %	3.2	28	27 cm
128	Spruce	90 yrs	70 cm	86 %	3.3	26	22 cm
130	Beech	60 yrs	82 cm	73 %	3.4	22	15 cm
131	Alder	40 yrs	28 cm	40 %	4.5	16	18 cm

Regressions analyses gave the following equations:

Site 127 (Von Arnold et al., 2005b):
N_2O ($\mu g\ N\ m^{-2}\ h^{-1}$) = 95 – 64 √GWL (cm) – 0.07 * GWL (cm)^2
($R^2_{adj} = 0.26$, $p<0.05$)

Site 128 (Von Arnold et al., 2005b):
N_2O (µg N m^{-2} h^{-1}) = 2 + 0.01 * GWL $(cm)^2$
(R^2_{adj} = 0.19, $p<0.05$)

Site 130 (Von Arnold et al., 2005a):
N_2O (µg N m^{-2} h^{-1}) = 8 + 0.04 * (air temperature) * GWL (cm)
(R^2_{adj} = 0.27, $p<0.05$)

Site 131 (Von Arnold et al., 2005a):

N_2O (µg N m^{-2} h^{-1}) = 43 + 0.3 * $(\text{air temperature})^2$
(R^2_{adj} = 0.07, $p<0.05$)

A calcareous mountain forest was studied by Kitzler et al. (2006b) during the years 2002-2004. This study site, named Achenkirch, is located in the North Tyrolean Alps at an elevation of approximately 900 meter. It is a 127-year-old mixed forest which is dominated by spruce. The loam soil has a pH of 5.8-7.1, and the site receives high loads of precipitation: 1733 mm/yr during the measurement period (Kitzler et al., 2006b). More details on the site characteristics can be found in the database in appendix 1 (site number 51/52). They used a regression model to predict the emissions. This resulted in a dependency on soil moisture and soil temperature. The soil moisture was measured gravimetrically at a depth of 5 cm and soil temperature was measured at 3 cm (Kitzler et al., 2006b). The following equations were found for NO and N_2O emissions (Kitzler et al., 2006b):

N_2O = -12.95 + 0.29 * (soil moisture as cm^{-3} cm^{-3}) + 0.48 * (soil temperature)
(R^2 = 0.89, $p<0.01$)
NO = 1.04 + -0.0034 * (soil moisture as cm^{-3} cm^{-3}) + -0.0308 * (soil temperature)
(R^2 = 0.77, $p<0.05$)

Simultaneously with the study at Achenkirch, two beech forests in Austria were studied. At Schottenwald (site 98 in appendix 1) the beech forest was 142 years old and the silty loam soil had a pH of 4.4 (Kitzler et al., 2006a). The site at Klausenleopoldsdorf (site 91 in appendix 1) was 62 years old and the loamy clay soil had a pH of 4.6. The C/N ratio at both sites was 16. Measurements took place from May 2002 till April 2004. The regression gave the following results for Schottenwald (Kitzler et al., 2006a):

Ln N_2O = 2.9356 + -0.0325 * (soil moisture as cm^{-3} cm^{-3}) + -0.0026 * (soil temperature)
+ 0.0139 (CO_2 flux as mg CO_2-C m^{-2} h^{-1})
(R^2 = 0.53, $p<0.01$)
NO = 3.6122 + -0.0757 * (soil moisture as cm^{-3} cm^{-3}) + 0.2086 * (soil temperature)
(R^2 = 0.95, $p<0.01$)

At Klausenleopoldsdorf the regression gave the following equations (Kitzler et al., 2006a):

Ln N_2O = 6.0238 + -0.1028 * (soil moisture as cm^{-3} cm^{-3}) + 0.0561 * (soil temperature)
+ 0.7427 (CO_2 flux as mg CO_2-C m^{-2} h^{-1})
(R^2 = 0.73, $p<0.05$)

NO = 5.0715 + -0.1015 * (soil moisture as cm^{-3} cm^{-3}) + 0.1978 * (soil temperature)
(R^2 = 0.73, $p<0.05$)

A comparison of the three sites revealed a striking difference in the impact of soil temperature. At Achenkirch and Klausenleopoldsdorf the soil temperature was positively related to N_2O emissions, while at Schottenwald there was a negative relation. The impact of other factors was similar at all three sites with respect to the direction of influence. Magnitudes of the impacts differed. Soil moisture, for example, had a stronger effect at Klausenleopoldsdorf than at Schottenwald.

An oak forest in the Mátra Mountains (site 101 in appendix 1) in Hungary was studied by Rosenkranz et al. (2006). They measured N_2O and NO fluxes during six weeks in the summer of 2004 and three weeks in the autumn of 2004. During these weeks, N_2O was measured every two hours and NO was measured every hour. The site was characterized by a mean annual temperature of 5.7°C and annual precipitation of 780 mm. The soil is a mollic leptosol with 15.8% clay, a ph of 5.4 and a C/N ratio of 22. The N-input by wet deposition was 5.1 kg N ha^{-1} yr^{-1} in 2004 (Rosenkranz et al., 2006). During the measurement campaigns, emissions of NO and N_2O were measures as well as WFPS (%) and soil temperature. WFPS was determined gravimetrically by drying for 24 hours at 105°C. Multiple polynomial equations were used to describe the emissions of NO and N_2O (Rosenkranz et al., 2006):

N_2O (µg N m^{-2} h^{-1}) = 13.2187 + 0.3412 * (soil temperature) – 0.8069 * (WFPS) – 0.0171 * (soil temperature)^2 + 0.0124 * (WFPS)^2
(R^2 = 0.73)

Ln NO = -10.858 + 0.2876 * (soil temperature) + 0.4393 * (WFPS) – 0.0103 * (soil temperature)^2 – 0.0042 * (WFPS)^2
(R^2=0.69)

A different dependency was found by Skiba et al. (1994). They measured NO and N_2O fluxes from agricultural and natural soils. Data from fourteen measurement locations, both natural and agricultural, in South East Scotland were used for linear regression, and NO and N_2O were both found to be dependent on NO_3 in the soil. In addition, N_2O emissions were found to be dependent on soil moisture (Skiba et al., 1994). Soil moisture was measured by oven drying and was expressed as % of the soils dry weight:
Log N_2O (ng N m^{-2} s^{-1}) = -6.26 + 1.45 log (mg NO_3-N kg $soil^{-1}$)

+ 3.61 * log (soil moisture)
(R^2 =0.33)

Log NO (ng N m^{-2} s^{-1}) = -3.23 + 1.01 * log (mg NO_3-N kg $soil^{-1}$)
+ 0.165 * (soil temperature)
(R^2 = 0.61)

Measurements of N_2O fluxes from 22 sites of woodlands, grassland, and agricultural sites in Scotland were analyzed by Skiba et al. (1998). The pH of the sites ranged from 3.1 to 5.6 and the N-input ranged from 10 kg N ha^{-1} yr^{-1} as background deposition to 235 kg N ha^{-1} yr^{-1} for agricultural fields due to fertilisation and excretion. More details of the non-agricultural sites can be found in the database in appendix 1 (site numbers 73, 74, 74, 76, and 107). Multiple regression analysis of all the sites combined gave the following relationship (Skiba et al., 1998):

Log N_2O (µg N m^{-2} h^{-1}) = -1.04 + 0.403 * log N input (kg N ha^{-1} yr^{-1}) + 0.165 * soil temperature (°C at 5 cm depth) - 0.015 * soil water content (% dry weight)
(R^2 = 0.48)

Temperature and precipitation are the main characteristics of climate. These factors have an indirect effect on NO and N_2O emissions via, for example, the process rates and soil moisture. Zechmeister-Boltenstern et al. (2002) have linked the emissions directly to temperature and precipitation. The stepwise multiple regressions analysis was based on measurements of N_2O fluxes in a 140-year-old beech forest in Austria (site 82 in appendix 1). This forest is located on a silty loam soil with a pH of 4.3, and a C/N ratio of 15.7. The area has an average annual temperature of 10.0°C and an annual precipitation of 970 mm (Zechmeister-Boltenstern et al., 2002). Soil fluxes were linked to temperature and precipitation, and the following relationship was found (Zechmeister-Boltenstern et al., 2002):

N_2O (µg N m^{-2} h^{-1}) = -24.3 + 5.4 * temperature (°C) + 0.6 * precipitation (mm)
(R^2 = 0.63, $p<0.0001$)

Borken and Beese (2005) found a relationship between annual throughfall, which is a measure of precipitation, and N_2O emissions in a spruce, beech, and pine forest in Germany. Information on the sites can be found in the database in appendix 1 (sites number 8-13). The relation is based on measurements during the years 1998 and 1999. Water input is measured as mm throughfall in the forest. NO correlation between N input via throughfall and N_2O fluxes was found. The relation is as follows (Borken & Beese, 2005):

N_2O (kg N ha^{-1} yr^{-1}) = 0.001 * throughfall (mm yr^{-1}) – 0.26
(R^2_{adj} = 0.64, p = 0.001)

A relationship between N_2O emissions and the clay and silt content in the upper 20 cm of the soil is described by Borken and Beese (2005). Their research includes 2 years of measurements in 6 forest stands: spruce, beech, and pine forests on two

locations in Germany (site 8, 9, 10, 11, 12, and 13 in appendix 1). The forests were, on average, 100 years old and grew on soils classified as cambisols (Borken & Beese, 2005). The percentage of silt and clay in the soil was found to be a good descriptor of the cumulative N_2O emissions (Borken & Beese, 2005):

N_2O (kg N ha^{-1}) = 0.012 * (clay and silt (%)) + 0.99
(R^2_{adj} = 0.87, p = 0.004)

2.4 The impact of N availability

The availability of both nitrate and ammonium has an influence on the potential for N_2O emissions. Atmospheric nitrogen deposition is a main input source of nitrogen to natural ecosystems and is thereby a regulating factor for the N_2O emissions. In general, an increase in nitrogen availability results in an increase in N_2O emissions. However, this is not the case when other factors are limiting the production of N_2O. Nitrogen deposition can be measured as dry deposition or wet deposition; it can be either NO_3 or NH_4, or both; it can be measured as deposition or in the throughfall. These different possibilities on how to express nitrogen availability complicate a quantitative comparison of different studies.

Several researchers have published relations between nitrogen availability and N_2O emissions. However, not all studies do support the presence of a relation between N availability and N_2O emissions. Borken et al. (2002) did not find any effect on the N_2O emissions after a treatment of reduced nitrogen deposition during seven years. They investigated a 70-year-old spruce plantation on a loamy silt soil in Germany (51°31'N, 9°34'E) during seven years. Three different plots were used. One plot was roofed and the rainwater was collected, cleaned by ion exchange and sprayed on the plot. Another plot was used as control. This plot was roofed and the rainwater was collected after which it was sprayed to the plot without any treatment. The third plot was without any artificial influence and the rain could fall on the plot without any interruptions. N_2O emissions were measured for one year before the treatment period, and during one year at the end of the treatment period. No significant difference was found between the plots and between the years (Borken et al., 2002).

Butterbach-Bahl et al. (1998) have derived relations between NH_4^+ input by wet deposition and the emissions of NO and N_2O. The dependencies are based on continuous measurements at Höglwald during 1994. Höglwald is a spruce forest with a minimal age of 90 years and has a soil texture of 41 % sand, 36 % silt, and 23 % clay (Butterbach-Bahl et al., 1998). Continuous measurements of N_2O and NO were made from 5 chambers for a period of one year. Based on these measurements, the following dependencies have been derived (Butterbach-Bahl et al., 1998):

NO (µg NO-N m^{-2} h^{-1}) = 14.1 + 16.7 [NH_4^+ input by wet deposition (mmol m^{-2})]
(R^2 = 0.657, p<0.001)

N_2O (µg NO-N m^{-2} h^{-1}) = 4.7 + 1.4 [NH_4^+ input by wet deposition (mmol m^{-2})]
(R^2 = 0.384, p<0.001)

Denier van der Gon and Bleeker (2005) evaluated 22 peer-reviewed articles on N_2O emissions from coniferous and deciduous forests. Based on the emissions of N_2O and the nitrogen deposition (NH_4^+ and NO_x), two functions have been derived. One function for coniferous forests (Denier van der Gon & Bleeker, 2005):

N_2O (kg N ha^{-1} yr^{-1}) = 0.014 * N deposition (kg N ha^{-1} yr^{-1}) + 0.11
(R^2 = 0.28)

The other function describes the N_2O emissions from deciduous forests (Denier van der Gon & Bleeker, 2005):

N_2O (kg N ha^{-1} yr^{-1}) = 0.063 * N deposition (kg N ha^{-1} yr^{-1})
(R^2 = 0.2)

The C/N ratio is a parameter which is influenced by the availability of nitrogen. C/N ratios have been used by Klemedtsson et al. (2005) to describe N_2O emissions. They used 12 sites in forests on drained peat lands and histosols for which N_2O emissions are measured during a period of at least one year. A C/N ratio of 25 was found to be a threshold above which N_2O emissions were neglectable (Klemedtsson et al., 2005). Additionally, they described N_2O emissions as a function of C/N ratios. The formula used is as follows (Klemedtsson et al., 2005):

Mean annual N_2O emissions = a*$e^{(-b*\text{C/N ratio})}$

Regression analysis gave values for a and b in this formula. When all the 12 sites, which are in Sweden, Finland, and Germany, are included, the following values were found: a = 481 and b = 0.39, with an R^2_{adj} of 0.96 (Klemedtsson et al., 2005). One outliner in the dataset was excluded which changed the values to a = 20, b = 0.19, and R^2_{adj} = 0.92 (Klemedtsson et al., 2005). Limiting the analysis to sites in Sweden to have more homogenous climatic conditions, resulted in a = 527, b = 0.40, and R^2_{adj} = 0.99 (Klemedtsson et al., 2005). The strong relation between C/N ratios and N_2O emissions found in this study can be explained by the relative homogeneity of the soils in this study which only includes histosols. This relative homogeneity reduced the importance of other variables in this study and strengthens the relation between C/N ratios and N_2O emissions (Klemedtsson et al., 2005).

Soil NH_4^+ concentrations have been linked to N_2O emissions by MacDonald et al. (1997). They investigated three sites in Scotland of which two were coniferous forest and one was upland moor land (Site 122, 123, and 124 in appendix 1). The pH in the sites was ranging from 3.1 to 3.3 and N deposition ranged 6.4-46.2 kg N ha^{-1} yr^{-1}. N_2O fluxes were measured on these three sites in the year 1994. A relationship was found between N_2O emissions and NH_4^+ in the soil (MacDonald et al., 1997):

N_2O (ng N m^{-2} s^{-1}) = -1.15 + 0.08 * soil NH_4^+ (µg N g^{-1} dry soil)
(R^2 = 0.24, $p<0.05$)

Nitric oxide and nitrous oxide emissions have been measured in fifteen European forest sites in the NOFRETETE project. Pilegaard et al. (2006) found several significant relationships between the emissions and the environmental factors on the sites. Nitrogen deposition was only found to be significantly related to NO emissions and not to the emissions of N_2O (Pilegaard et al., 2006). C/N ratios, as a measure of N availability, were found to be significantly related to the N_2O emissions. Nitrogen deposition was measured as NH_4^+ and NO_3^- in throughfall. The following relations were found to be significant (Pilegaard et al., 2006):

NO ($\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$) = -3.29 + 19.45 * N deposition ($g\ N\ m^{-2}\ yr^{-1}$)
– 22.45 (type: deciduous)
($R^2 = 0.71$, N deposition: $p<0.01$, Type: $p<0.1$)

N_2O ($\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$) = 26.49 – 0.69 * C/N – 0.07 * age (yr)
($R^2 = 0.67$, C/N: $p<0.001$, Age: $p<0.05$)

Ln (N_2O ($\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$)) = 4.82 – 0.14 * C/N – 0.01 * age (yr)
($R^2 = 0.87$, C/N: $p<0.001$, Age: $p<0.05$)

NO + N_2O ($\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$) = -6.33 = 2.06 * N deposition ($g\ N\ m^{-2}\ yr^{-1}$)
($R^2 = 0.53$, N deposition: $p<0.01$)

NO/N_2O ($\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$) = -2.23 = 7.82 * N deposition – 0.10 * age
($R^2 = 0.73$, N deposition: $p < 0.001$, Age: $p<0.1$)

Butterbach-Bahl et al. (2002a) have measured N_2O fluxes from five pine forests in Germany during the period 1995-1998. Linear regression was applied to find relationships between N-input and N_2O and NO emissions. Two sites were excluded from the regression since these sites were only measured during two measuring campaigns. The other three sites, Wildbahn, Hubertusstock, and Kienhorst are located on sandy loam soils in north-eastern Germany. Nitrogen input as NO_3^- and NH_4^+ via throughfall ranges from approximately 15 to 20 kg N $ha^{-1}\ yr^{-1}$. The sites can be found in the database of appendix 1 as site number 37, 38, and 39. The relationships found by Butterbach-Bahl et al. (2002a):

N_2O ($\mu g\ N\ m^{-1}\ h^{-1}$) = -16.0 + 1.6 * N-input ($kg\ N\ ha^{-1}\ yr^{-1}$)
($r^2 = 0.839$)

NO ($\mu g\ N\ m^{-1}\ h^{-1}$) = -83.2 + 6.1 * N-input ($kg\ N\ ha^{-1}\ yr^{-1}$)
($r^2 = 0.993$)

The study by Kitzler et al. (2006b) in Achenkirch (site 51/52 in appendix 1) was mentioned in section 2.2 on the impact of soil moisture and temperature. Their regression model also found dependencies on nitrogen deposition which describes the N_2O emissions as a function of NO_3^- and NH_4^+ in the throughfall (Kitzler et al., 2006b):

$N_2O = 2.00 – 0.41*$ (NO_3^- and NH_4^+ in throughfall)
($R^2 = 0.83$)

2.5 Regression coefficients and correlations between nitrous oxide emissions and various environmental factors

Relationships describe the dependency of one factor on one or more other factors. The previous sections presented Q_{10}-values and equations describing relationships of N_2O and NO emissions on one hand and several environmental factors on the other hand. However, there are other ways to describe relationships. An often used example is the correlation coefficient. This section presents several correlation analyses.

Corre et al. (1999) measured N_2O emissions on two forest sites in Canada. Both sites are Aspen forest stands, and one is located on a sandy soil while the other is located on a clay loam soil. More details on the measurement sites can be found in the database in appendix 1 (site number 138 and 139). The correlation analysis tested the significance of correlation coefficients between N_2O and WFPS, NH_4^+, NO_3^- & NO_2^-, soluble organic C, rainfall and maximum air temperature. The forest on sandy soil was only found to be significantly correlated with rainfall (0.40, $\alpha = 0.10$) (Corre et al., 1999). The forest on the clay loam soil on the other hand, was found to be significantly correlated with 5 out of 6 factors (table 2.5).

Table 2.5 Pearson correlation coefficients between N_2O emissions and environmental factors at a forest site on clay loam (adapted after Corre et al., 1999).

N_2O vs.	Correlation coefficient	Level of significance (α)
WFPS	0.59	0.05
NH_4^+ in soil (Mg ha^{-1})	0.64	0.20
NO_3^- & NO_2^- in soil (Mg ha^{-1})	0.73	0.10
Rainfall (mm)	0.56	0.01
Maximum air temperature (°C)	0.62	0.01

Härtel et al. (2002) measured N_2O and CO_2 fluxes in a forest site in the Tyrolean Alps (site 47 in appendix 1). This forest received a nitrogen input of 18 kg N ha^{-1} yr^{-1} and stands on a soil with pH ranging 5.8-7.0. The site was investigated from May 1998 to October 1999. A Spearman correlation analysis tested the correlation of N_2O emissions with 5 other parameters (see table 2.6). A spruce and an oak forest in Hungary were investigated by Horvath et al. (2006). They measured NO and N_2O fluxes from October 2002 till September 2003. The forests are located on sandy loam soil with a pH of 4. More details on the study site can be found in appendix 1 as site number 100 and 101. Measurements took place twice per month. In addition to N_2O and NO fluxes, soil temperature and soil moisture were measured at several depths. Correlation analysis (see table 2.7) showed significant correlations between soil temperature and N_2O and NO fluxes, while soil moisture was only significantly correlated in a few cases (Horvath et al., 2006).

Table 2.6 Spearman correlation coefficients between N_2O emissions and environmental factors at a forest site in the Tyrolean Alps (adapted after Härtel et al., 2002).

N_2O vs.	Correlation coefficient	Level of significance (p)
NO_3^- (mg m^{-2} d^{-1})	0.73	<0.01
Air temperature (°C)	0.57	<0.05
Soil temperature at 3 cm (°C)	0.65	<0.01
Soil temperature at 10 cm (°C)	0.59	<0.05
CO_2 flux (mg m^{-2} h^{-1})	0.91	<0.01

Table 2.7 Correlation coefficients between N_2O and NO emissions and soil temperature and soil water content. Significant at p = 0.05 (adapted after Horvath et al., 2006).

		N_2O emissions		NO emissions	
		Spruce	Oak	Spruce	Oak
Soil temperature (°C)	5 cm	0.45	0.66	0.38	0.53
	10 cm	0.67	0.64	0.26	0.49
	20 cm	0.67	0.72	0.25	0.48
Soil water content (V/V)	5 cm		-0.63		NS
	10 cm		-0.68		NS
	20 cm	NS	-0.67	-0.29	NS

A study by Regina et al. (1996) was conducted in 1991 and 1992 on 19 peat soils in central and eastern Finland. The sites were both virgin and drained peat lands. All sites were acid, with pH ranging from 3.8 to 5.0 (Regina et al., 1996). The fluxes of N_2O were expressed in microgram per cubic meter per day, and a correlation analysis showed relations between the emissions and site characteristics (see table 2.8).

Table 2.8 Pearson correlation coefficients between N_2O fluxes and characteristics in virgin and drained peat lands in central and eastern Finland (Regina et al., 1996).

	N_2O (µg N_2O m^{-2} d^{-1}) in 1991 [1]	N_2O (µg N_2O m^{-2} d^{-1}) in 1992 [1]
N_2O (µg N_2O m^{-2} d^{-1}) in 1992	0.83 ***	
Number of NO_2 oxidizers [2]	0.85 ***	0.81 ***
Nitrification potential at pH 4 [3]	0.57 **	0.51 *
Nitrification potential at pH 6 [3]	0.55 *	
Depth of water table in 1991 (cm)	-0.58 ***	-0.69 ***
Depth of water table in 1992 (cm)	-0.37 **	-0.51 ***
Total N content [4] (µg cm^{-3})	0.79 ***	0.79 ***
Total P content [4] (µg cm^{-3})	0.54 ***	0.53 **
Total K content [4] (µg cm^{-3})	-0.24 **	
Total Ca content [4] (µg cm^{-3})	0.78 ***	0.85 ***
pH	0.63 ***	0.50 **

[1] Correlation coefficients and two-tailed significances: * p<0.05, ** p<0.01, *** p<0.001.
[2] Measured in the three upper layers of the soil.
[3] Measured in one-week incubation for the upper three layers of the soil.
[4] Measured in the 0-20 cm layer of the soil.

The high correlations between phosphor (P) content in the soil and the N_2O emissions can be explained by the high correlation between phosphor and nitrogen (N) in the soil (0.92, p<0.001). Potassium (K) and calcium (Ca) are both correlated to

nitrogen and phosphor which might explain the relations between N_2O emissions and both potassium and calcium.

Hackl et al. (2004) studied 12 other sites in Austria. The sites comprised six forest types and two forest stands of each type. N_2O production was measured in soil cores and linked to environmental characteristics at the sites (see table 2.9 and 2.10).

Table 2.9 Site characteristics of 10 Austrian sites (adapted after Hackl et al., 2004).

	Soil type	pH	C/N
Oak-Hornbeam 1	Dystric Planosol	4.2	23.4
Oak-Hornbeam 2	Calcaric Planosol	5.2	21.0
Woodruff-beech 1	Dystric Planosol	4.6	22.5
Woodruff-beech 2	Dystric Cambisol	4.0	13.1
Acidophilous beech 1	Dystric Cambisol	4.6	26.9
Acidophilous beech 2	Dystric Cambisol	3.2	23.5
Spruce-fir-beech 1	Chromic Cambisol	5.3	17.1
Spruce-fir-beech 2	Stagnic Luvisol	3.8	16.9
Floodplain 1	Calcaric Fluvisol	6.9	11.7
Floodplain 2	Calcaric Fluvisol	7.0	17.2
Austrian pine 1	Rendzic Leptosol	7.2	28.0
Austrian pine 2	Rendzic Leptosol	7.2	37.0

For seven of the sites, N_2O emissions showed a strong correlation with soil moisture. However, for the remaining five sites, there was no significant correlation between soil moisture and N_2O emissions. The correlations that were found to be significant were all in the range 0.55-0.81 (Hackl et al., 2004). The correlation between pH and N_2O emissions were more confusing, since they were negatively correlated at two sites while a positive correlation was found at two other sites. NO_3-N and CO_2 were mostly positively correlated, but for both factors a significant negative correlation was found at one site. This resulted in a wide spread in the correlation coefficients. It should be noted that the spruce-fir-beech sites both had a low mean annual temperature and a high precipitation load compared to the other sites. The floodplains were warmest and driest. However, this difference was not as large as for the spruce-fir-beech sites. In sum, soil moisture seemed to have the most constant correlation over all sites in this study.

2.6 Discussions and conclusion

This chapter presented results of research on the impact of environmental factors on N_2O and NO emissions. The relations found by different authors show large differences. For some of the factors it is not even clear whether the relationship is positive or negative, as is the case for soil moisture content. This is probably due to the non-linear curve of the impact of moisture on N_2O production which finds it origin in the fact that different processes steer the production of N_2O. The different findings are related to the spatial and temporal variability of N_2O and NO emissions. Some of the factors, like nitrogen deposition, are important on the long-term scale while soil moisture changes have an indirect effect and are important for the local short-term conditions under which N_2O and NO emissions occur.

Table 2.10 Site characteristics of 10 Austrian sites, and the Spearman correlation coefficients between N_2O emissions and significant environmental factors (adapted after Hackl et al., 2004).

	Correlation coefficients: N_2O(µg N_2O-N m^{-2} h^{-1}) vs.			
	Soil moisture	pH	NO_3-N (µg g^{-1} dry weight)	CO_2 production
Oak-Hornbeam 1	0.784 ****		0.580 ***	
Oak-Hornbeam 2	0.765 ****		0.476 **	
Woodruff-beech 1	0.806 ****		0.388 *	
Woodruff-beech 2	0.637 ****			
Acidophilous beech 1				0.652 ****
Acidophilous beech 2		0.809 ****	-0.472 **	0.688 ****
Spruce-fir-beech 1		-0.345 *		0.447 **
Spruce-fir-beech 2				
Floodplain 1	0.569 ***			
Floodplain 2	0.567 ***		0.352 *	0.389 *
Austrian pine 1		0.375 *		-0.390 *
Austrian pine 2	0.666 ****	-0.637 ****	0.483 **	0.683 ****

Interdependencies between various environmental factors complicate the situation and contribute to the low R^2 values found in most of the studies that were presented in this chapter. Higher R^2 values were often found in studies at one site while including measurements from several sites often resulted in a lower R^2 value. It is difficult to state a general conclusion as results showed large differences. It seems that on average, N input showed higher R_2 values as predictor of N_2O fluxes than soil moisture.

The aim of this study was to upscale N_2O emissions and to be able to predict emissions with help of derived relations. Consequently, the daily fluctuations in emissions were not the main focus. Ideally, an equation should be derived to predict annual N_2O and NO emissions on a regional scale. The challenge was to find a way in which the information on impacts as presented in this chapter could be used to derive empirical relations. Table 2.11 gives an overview of all the relations presented in this chapter and their regional applicability. This applicability was based on four criteria:

- Type of research
- Length of measurement period
- Number of plots
- Ecosystem type

A study met the criteria when:
- It were field measurements
- Measurements lasted longer than 6 months
- There were more than 10 plots
- It were measurements in a natural (mainly forest) ecosystem

The type of research is important since field measurements are representative of natural conditions while manipulation and laboratory studies usually include extreme conditions. Measurements over a short period are not reliable as annual fluxes. Consequently, measurements over a longer period were preferred. The criterion was arbitrairily set at 6 months. A study that included only one site gives a site specific results which can not be extrapolated to a larger scale. The number of 10 plots as a criterion was set arbitrarily.

When a study met all the four criteria, the regional applicability was labelled as 'high'. Meeting three of the four criteria was labelled as 'moderate', meeting two was labelled as 'low', and meeting one of none of the criteria was labelled as 'very low'. Additionally, if only one plot was included in the study, the study could be labelled as 'low' at the best. This resulted in 2 times a 'high' regional applicability, 3 times 'moderate', 15 times 'low', and 2 times 'very low'. This overview shows that most relations presented in this chapter can not be used for the purpose of regional modelling. Exceptions are the studies by Klemedtson et al (2005) and Pilegaard et al (2006). However, the study by Klemedtsson et al (2005) was limited to organic soils and the sites were all in Sweden, Norway, Denmark and Germany. The sites studied by Pilegaard et al (2006) were more spreaded However, in both cases, the number of plots remains low to very low for a European wide application.

Table 2.11 Overview of the studies included in this chapter and their characteristic related to the relevance of the study.

Environmental factors	Ecosystem	Type of research	Time period: months	Nr of plots	Author	Regional applicability
Temperature:	Forest	Laboratory	3	1	(Öquist et al., 2004)	Very low
	Forest	Laboratory	2	2	(Koponen et al., 2006)	Very low
	Forest	Field	5	1	(Brumme, 1995)	Low
	Forest	Field	12	2	(Oura et al., 2001)	Low
	Forest	Field	24	1	(Von Arnold et al., 2005a)	Low
Soil moisture:	Forest	Field	24	2	(Corre et al., 1999)	Low
	Forest	Field	24	1	(Von Arnold et al., 2005b)	Low
	Forest	Field	24	6	(Borken & Beese, 2005)	Moderate
N availability:	Forest	Field	18	2	(Butterbach-Bahl et al., 1998)	Low
	Forest	Field + manipulation	various	22	(Denier van der Gon & Bleeker, 2005)	Moderate
	Forest; peat	Field	12	12	(Klemedtsson et al., 2005)	High
	Forest + moorland	Field	18	3	(MacDonald et al., 1997)	Low
	Forest	Field	12	15	(Pilegaard et al., 2006)	High
	Forest	Field	28-36	3	(Butterbach-Bahl et al., 2002a)	Moderate
	Forest	Field	24	1	(Kitzler et al., 2006b)	Low
Soil moisture + temperature:	Forest	Field	24	1	(Von Arnold et al., 2005a)	Low
	Forest	Field	24	1	(Kitzler et al., 2006b)	Low
	Forest	Field	24	1	(Kitzler et al., 2006a)	Low
	Forest	Field	2	1	(Rosenkranz et al., 2006)	Low
	Forest	Field	28	1	(Zechmeister-Boltenstern et al., 2002)	Low
Soil moisture + N availability:	Forest + agriculture	Manipulation	<2	14	(Skiba et al., 1994)	Low
Soil moisture + temperature + N availability:	Forest + grass + agriculture	Field + manipulation	1-12	22	(Skiba et al., 1998)	Low

3 Relations between environmental factors and nitrous oxide emissions

The previous chapter presented a literature study on the impact of environmental factors on N_2O emissions. It was concluded that most of these relations can not simply be used, because they were based on manipulations, were measured less than six months or did only include a limited number of plots. This chapter describes the work to derive relations between environmental factors and N_2O emissions based on field measurements during more than one year from a large number of plots. These relations can be used to estimate annual N_2O emissions on a large regional scale. These estimates are now often performed by the IPCC method which tells that 1% of the nitrogen deposition is emitted as N_2O.

First of all, a literature study was conducted to construct a database of measured N_2O emissions from natural ecosystems. Collecting and selecting of data is described in section 3.1 as well as the set up of the database. Section 3.2 describes how the input files for the regressions are made and what information included in each of the input files. Next, the procedure of the regression analyses is explained. Results from chapter two were not applied to the dataset. However, information from chapter two is used as background knowledge and helped to determine which variables to be included in the regression analyses. Results of the regression analyses are presented in section 3.3, and section 3.4 gives a comparison of the results for the different datasets

3.1 Set-up of the database

First, the general approach for the set up of the database is described in section 3.1.1. Section 3.1.2 presents the site characteristic of the database and section 3.1.3 describes the soil characteristics. Database parameters related to N_2O and NO measurements are described in section 3.1.4.

3.1.1 General approach

Literature was studied to find data on N_2O fluxes measured in temperate and boreal natural ecosystems. On part of the measurement sites, NO was measured simultaneously with N_2O. These NO fluxes were included in the database as extra information. There were a limited number of NO fluxes available and therefore no regression analyses were done for NO emissions. The regressions of the N_2O emissions are described from section 3.2 onwards.

The data was gathered in a database which can be found in appendix 1. The database is build up of four components. First of all, data from the NOFRETETE project (Kesik et al., 2006; Pilegaard et al., 2006) was included. Within this project, fifteen European field sites were studied. Additionally, the database of NO and N_2O emissions from Stehfest and Bouwman (2006) was used and the relevant non-

agricultural sites were selected. Relevant sites were characterized as 'natural' and located in the temperate, boreal and arid climate zones. An important criterion was that the sites should not be fertilized. The database of Denier van der Gon and Bleeker (2005) was another source of information to this research. Relevant sites of natural, unfertilized sites were selected and included in the database.

In addition to the information from these three existing databases, a literature review was carried out to find additional publications on measured NO and N_2O emissions from natural ecosystems in temperate and boreal ecosystems. The criteria for the selection of measurement sites were threefold: it should be a natural ecosystem, it should have a temperate or boreal climate, and the site should not be fertilized. The literature review was based on articles from peer-reviewed journals. All measurements were made in soils of natural ecosystems in boreal and temperate climates. Laboratory studies were not included in the database since the local conditions in the field are important determinants of the emissions rates and these can not be mimics in a laboratory. Consequently, studies on soil samples and soil cores were excluded.

The measurements can vary in duration and in frequency. The results of this study were used in modelling annual emissions and, consequently, it was important that the measured values were a representation of annual fluxes. Selection criteria that were set for the duration and frequency of the measurements are:

- Measurements should be done over a period of at least one year;
- Measurements should be done at least once every two weeks;
- Measurements done less than once every two weeks but at least once per month were included when the measurement period was at least two years.

Information from the three databases and the literature review were combined into one database. The sites were ordered in three groups. Forests form one group, the second group is other vegetation which includes grasslands, prairies and steppe, and the third group are the organic soils.

A total of 151 records were included in the final database. The numbers of the records are in the range 1-162 since the database did previously contain 162 records. A selection procedure did eliminated 11 records from the database since they did not meet the criteria of minimum length of the measurement period and minimum measurement frequency. The final 151 records are located over the northern hemisphere with an emphasis on Europe. Only 22 measurements from outside Europe can be found in the database. The dominant land use is forest as 130 forest sites are included and 21 non-forest sites. Mineral soils outnumber organic soils by 128 to 23. Both N_2O and NO fluxes are included. However, NO fluxes were only measured in 29 cases while 146 records include measured N_2O fluxes.

The database does not only include emission data from the measurement sites. From each location also site characteristics, soil characteristics, as well as information on the measurements was included. Not all variables were known for each location but the aim was to collect as much information as possible since these data were needed

to derive the empirical relations which were the goal of the formation of this database. In the following sections, more information is given on site characteristics (3.1.2), soil characteristics (3.1.3) and measurements (3.1.4).

3.1.2 Site characteristics

Ten site characteristics were included:
- Coordinates (latitude and longitude)
- Annual temperature (°C)
- Annual precipitation (mm)
- Vegetation type (dominant)
- Depth to groundwater (cm)
- N-input (kg N ha^{-1} yr^{-1})
- Humus type
- Parent material; mineral or organic soil
- Soil class
- Soil texture

These site characteristics are a measure of the environmental factors influencing N_2O emissions. The three main factors, as identified in chapter 2, are temperature, N availability and soil moisture. The annual temperature is, obviously, related to temperature. N-input is related to nitrogen availability. Soil moisture is expressed by annual precipitation, depth to groundwater, parent material, soil class, and soil texture.

3.1.3 Soil characteristics

A series of soil characteristics that affect N_2O emissions were included:
- Depth of organic layer (cm)
- Clay (%)
    - 0-10 cm
    - 0-20 cm
- pH
    - Organic layer
    - 0-10 cm
    - 0-20 cm
- Organic C
    - Organic layer
    - 0-10 cm (g C kg^{-1})
    - 0-20 cm (g C kg^{-1})
- C/N ratio
    - Organic layer
    - 0-10 cm
    - 0-20 cm
- Soil temperature (°C)
- Soil water content (%)
- WFPS (%)

The C/N ratio is a measure for the nitrogen availability, and soil temperature is a measure for temperature. Several characteristics are related to soil moisture: clay %, soil water content, and WFPS. The soil characteristics give a more detailed description of the soil in which N_2O is produced and consumed. These characteristics are obtained from soil sampling and soil analysis. For some of the characteristics, two or even three layers are identified: 0-10 cm, 0-20 cm, and the organic layer. Soil properties change with depth, and the top layer is usually most active. The layer 0-20 cm was used for the regression analyses since this is the layer in which most of the nitrogen transformations occur. However, some studies indicate that this might not be the part of the soil which is of main interest for N_2O emissions. Christensen et al. (1996), for example, argued that the soil layer at approximately 1 meter depth is the main producer of N_2O. Their case might be an exception, but it is a finding to keep in mind. The organic layer was added since some publication reported it separately and it is additional information that explains the situation on the site.

3.1.4 Nitrous oxide and nitrous oxide measurements

Two sets of parameters were included: one for N_2O measurements and one for NO measurements. For N_2O, the following parameters were included:
- Period of measurements
- Measuring method
- Measuring frequency
- Number of measuring devices
- Number of replicates
- Mean N_2O emission (kg N ha^{-1} yr^{-1})

For NO the same data was included:
- Period of measurements
- Measuring method
- Measuring frequency
- Number of measuring devices
- Number of replicates
- Mean NO emission (kg N ha^{-1} yr^{-1})

The description of the measurements of N_2O and NO are meant to give an impression of the quality of the emission data. Different measuring methods can be used to determine N_2O and NO fluxes. In most cases a closed chamber was used to measure N_2O fluxes and a dynamic chamber was used for NO fluxes. The pictures in figure 3.1 show examples of these commonly used measurement devices for N_2O and NO fluxes.

Articles included many different descriptions of measuring devices. These descriptions have been grouped into 6 measuring methods:
- PVC column
- Closed chamber

- Dynamic chamber
- Open chamber
- Tree chamber
- Gas sampler

Figure 3.1 Chambers used as measurement devices for N_2O and NO fluxes at location Speuld, The Netherlands. These chambers are used as closed chambers for N_2O and as dynamic flow chambers to measure NO (Left picture: Janet Mol; right picture: NBV).

3.2 Input to regression analyses

Three input data files were made based on the database in appendix 1. This section explains how measurements were selected for the input files and describes the differences between the three input files. Sections 3.2.1 to 3.2.3 describe the preparation and construction of the three input files. All input files can be found in appendix 2.

Ideally, parameters on the measurement location were measured at the site. However, this was not always the case, and consequently, the database included many gaps in the data. As an alternative, estimated data based on the coordinates of the measurement were used. The estimated were derived from several databases. When all the parameters are estimated based on the coordinates of the location, the uncertainty of the regression analysis will be larger but no additional uncertainties will be introduced with the application. Using measured values to perform the analysis results in an equation which is based on more exact data than the data used for application. This introduces new uncertainties for the application.

Purely measured data resulted in a much reduced database. A second version of measured data was compiled by using measured data, if available, and adding soil parameters based on the published soil class. In this case, estimated soil parameters were only added if the soil class was known. The main difference with the purely estimated database was that for these data the soil class was estimated as well. However, the dominant soil class was often different from the local soil class which was published. This was mainly a problem for the organic soils. The estimated database only contained one location with an organic soil while there were 20 sites with organic soils according to the publications. When a mistake was made in

estimating the soil class, the soil parameters were assigned to the soil classes and the error was prolonged.

The three options that thus were used:
- Estimated data:
  All parameters estimated based on location
- Measured data:
  Purely measured data as published in the article
- Measured data +:
  Measured data, and missing soil properties are added based on published soil class

Sites from outside Europe were excluded since estimated values were used for some of the regressions and estimates were only available for Europe. Site without a proper description of the location were excluded for the same reason, since it was impossible to find estimated values if it was not possible to derive coordinates for the measurement location. Another reason for exclusion was absence of parameter values. This latter reason of exclusion mainly reduced the size of the input files of measured data. Each of the categories will be described separately in the following three sub sections. For estimated parameters values, it is also described how the estimates are derived.

3.2.1 Estimated data

This section describes the work for the regression analysis on factors influencing the N_2O and NO emissions based on estimated parameters. This means that location and measured fluxes are used in combination with estimated site and soil characteristics.

Locations and soil classes
The database, as described in section 3.1, was used as the basis for the regression analysis. The location of all plots at which N_2O fluxes were measured was overlaid with the FAO 1:1000000 soil map of Europe to assess the soil characteristics. Since a soil map of Europe is used, only measurements within Europe could be included. Part of the articles published coordinates of the measurement location while others described the location in varying levels of detail. Coordinates were used to locate the measurements on the European soil map. In case of missing coordinates, it was attempted to find the coordinates by means of searching with the Google Earth application. For locations with sufficient information on the location, it was possible to find the coordinates with a relative high accuracy. However, several measurement locations were described in very general terms and in these cases it was often impossible to locate the sites on the map. Consequently, these locations were excluded from this exercise.

The locations were assigned to Soil Mapping Units (SMU's). Within each SMU, several Soil Typological Units (STU's) can be present. For this exercise, the dominant STU within each SMU is assigned to the measurement location. Marieke Maree

developed a database in which STU's are linked to soil parameters. A summary of her work is given her. More information can be found in her unpublished paper (Maree, 2007). She based her work on two databases of soil profiles, namely the WISE-database[1] version 1.1 and the SPADE-database[2]. Using the program MS Access, the locations with their related SMU were linked to the data from WISE and SPADE. This was done in several steps. First of all, the SMU was linked to the STU's present in the SMU. Next, the dominant STU in each SMU was selected and this STU was used in the next steps. The dominant STU was linked to a soil class according to the FAO 1974 soil classification. However, soil classes were grouped to form 33 soil clusters which were used for this exercise. The clustering is based on four characteristics of the soil: texture, pH class, gley, and organic matter content. STU's have information on several soil layers. The information was included for five layers of the soil: A, B, C (+R), E, and O (+H/L/F) horizon. However, not all horizons were present for each STU.

Two situations required special attention. Location number 40 (Darmstadt, Germany) was assigned SMU number 1. This was due to the location in the middle of the city while the measurements were done in a deciduous forest near Darmstadt. Possible SMU's were defined and three soil clusters were found around Darmstadt: calcareous loam, dystric loam, and eutric loam. Calcareous loam could be excluded due to the low pH at the location. Eutric loam was more abundant in the area than dystric loam and, based on this, the location was assigned to the soil cluster of eutric loam. Location 109 (Lelystad, The Netherlands) belonged to soil cluster number 4: unknown wet calcareous. However, no soil profiles were found for this soil cluster in either the WISE-database or the SPADE-database. Therefore, it was not possible to identify soil parameters of this soil cluster and no estimated soil parameters were available for location 109. Consequently, this location was excluded for the regression analysis based on estimated soil parameters.

Soil parameters

As described above, soil clusters were associated with data from the WISE and SPDAE databases and soil parameters were related to each site. Each soil cluster had information on seven estimated soil parameters: thickness of the soil layer (cm), organic carbon content (%), nitrogen content (%), pH, bulk density, sand (%), and clay (%) in the soil. The soil parameters were present per soil horizon. However, the depth of the horizons differs per soil and therefore it was decided to rearrange the soil parameters from horizons to layers. The layers of 0-10 cm and 0-20 cm were calculated based on the depth of the horizon and the bulk density. For all soils, the horizons were included in the following order: O-A-E-B-C. Figure 3.2 shows the

[1] WISE = World Inventory of Soil Emission potentials. It was developed by ISRIC (International Soil Reference and Information Centre) in The Netherlands. WISE is a database with information on 19 parameters of thousands of soil profiles worldwide (source: *website ISRIC*).

[2] SPADE = Soil Profile Analytical Database for Europe. It was developed through the European Soil Bureau Network. The database was developed to define the Soil Typological Units. Soil properties are included for use of modeling Hollis, J.M., R.J.A. Jones, C.J. Marshall, A. Holden, J.R. Van de Veen & L. Montanarella, 2006. *SPADE-2: The soil profile analytical database for Europe, version 1.0*. Luxembourg, Office for Official Publications of the European Communities. European Soil Bureau Research Report No.19 EUR 22127 EN..

locations of the measurements and illustrated the spread over the European continent. It is clear, form the picture, that the measurements were not evenly spread over Europe. Several areas showed a higher density of sampling sites than other. In general, Central Europe was well represented while southern Europe was missing in the picture.

Figure 3.2 The European locations at which N_2O fluxes were measured and which could be related to the soil database to find associated soil parameters.

Nitrogen deposition

EMEP data on nitrogen deposition was collected for the years of measurements for all European locations. EMEP provides annual deposition as kg ha^{-1} yr^{-1}. The locations of measurements were related to the EMEP data with a spatial resolution of 50 km by 50 km. The average yearly deposition was calculated for the years of measurements. There was no specification into monthly deposition. Consequently, all years that were (partly) included in the measurement period were used to calculate the average. For example: measurements were from May 1993 to May 1994, thus deposition was the average of the years 1993 and 1994. Two publications did not mention the year of measurement. To be able to link it to N deposition, four years prior to the year of publication was used for N deposition. This might not be correct, but it will differentiate between high and low N input locations. This was the case for measurements 49, 50, 80, and 81.

Climate data

The CRU database, available through IPCC, was used to collect climate data for the locations. The dataset comprised series of monthly meteorological data on a 0.5° * 0.5° grid basis (New et al., 1999). Monthly temperature and precipitation were collected. Average temperature and mean monthly precipitation over the measurement period were calculated as well as the fraction of the months in the measurement period with a minimum temperature below zero. The latter parameter was calculated as a measure for the winter conditions. Conditions of freezing and thawing do interfere with the usual temperature response of nitrogen processes in the soil as described in section 2.1.2. Measurements cover the years 1980 to 2004. However, the data available in the CRU database only covered the years 1980 to 2000. For measurements after the year 2000, an average of the period 1991-2000 was taken as an approximation of the years after 2000. A 10-year average was taken instead of only the year 2000 since climate is very variable from year to year. In case of measurements starting in or before the year 2000 and continuing afterwards, a part of the period was not covered by the CRU data. Also in these cases, the average of the years 1991-2000 was used.

3.2.2 Measured data

Measured data was collected from articles. In most cases, all data came from the article in which the N_2O fluxes are published. However, there were a few cases in which the author referred to other articles for a more specific site description. These articles, mentioned in the publication, were used to enlarge the amount of data. Nevertheless, even when including these data, there were only 25 sites for which all the parameters of the regression analysis were present. Consequently, all that was done for setting up the measured dataset was taking the database, selecting the needed parameters and deleting all sites with missing values.

3.2.3 Measured data +

This dataset is used as an alternative for the measured dataset which only contained 25 sites. To enlarge the dataset of measured data, measured data were used and estimated data were added to fill in the gaps in the database. To prevent too much of uncertainty, limitations were used. This imposed the exclusion of sites for which the soil type was not known. When the soil type was known, it could be transferred to a soil cluster as used for the estimated parameters. Based on these soil clusters, soil properties could be assigned to the location in case of missing values. Estimated data was only available for Europe and therefore this regression was limited to Europe.

3.2.4 Input variables of the regression analyses

The N_2O emissions (kg N_2O-N ha^{-1} yr^{-1}) were transformed to a logarithmic scale, and the following variables included in the regression analysis:

5 soil variables

- Clay (%)

- pH
- Organic Carbon (g/kg soil)
- C/N ratio
- Bulk density (kg m^{-3})

3 climate variables
- Mean temperature (°C)
- Mean monthly precipitation (mm)
- Fraction of months with minimum T<0°C

1 deposition variable
- Nitrogen deposition (kg N ha^{-1} yr^{-1})

2 classes
- Vegetation type
- Parent material

Soil variables were included in two forms: for the top soil as 0-10 cm, and for a thicker layer as 0-20 cm. These two were included in separate regression analyses. The climate variables were specifically for the measurement period. The same was the case for nitrogen deposition. Two variables were included as a category-variable. The classes for these variables were:

Vegetation type:
- Deciduous forest (dec)
- Coniferous forest (con)
- Mixed forest (mix)
- Short vegetation (e.g. grass, heath) (sv)

Parent material:
- Mineral soil (m)
- Organic soil (o)

3.2.5 Procedure for the Regression analyses

The statistical program GenStat (release 7.1) was used for the regression analyses. The best subset of predictor variables in the regression analyses were selected by the module RSELECT. The best subset was selected based on adjusted R^2:

$$R^2_{adj} = 100 * (1 - (n - 1) * RSS / (SSY * (n - p)))$$

RSS = residual of sum of squares for the subset at hand
SSY = sum of squares about the mean of the response variate
n = number of records
p = number of fitted parameters

Using adjusted R^2 as selection criteria, adding an extra variable introduces a penalty. This selecting procedure is used to select the best subset of predictor variables with a preference for a low number of predictor variables. The adjusted R^2 does improve

when the F-ratio[3] is larger than one when an extra variable is added. Another selection criterion is the significance of the parameter. Parameters with a significance of more than 0.055 were excluded. Parameters were considered to be significant when the level was between 0.015 and 0.055. Levels below 0.015 were regarded as highly significant.

A run with GenStat did include the following steps:
- Running multiple regressions with only one parameter at a time: each parameter is one regression;
- Running multiple regressions with groups of two parameter, groups of three parameters, groups of four parameters, etc;
- Each regression had an adjusted R^2. The regression with the highest adjusted R^2 was selected as best model. Since adjusted R squares were compared, adding variables introduced a penalty;
- The result: the best model with the combination of lowest number of variables and best performance.

The N_2O fluxes were included as logarithmic values. The option of logarithmic variables was considered for each variable individually. Without performing a regression analysis, four variables were selected as being possibly better to be described as logarithmic variables. These four were the most skewed variables. These variables were nitrogen deposition, C/N ratio, Organic C, and precipitation. In order to investigate the effect of log-transformations, there was a stepwise chain in which more variables were log-transformed. All possible combinations with the four selected variables were tested, while the other variables were still included but were not log-transformed. Each of the three databases was analysed separately since they contained different kind of data. The results of this analysis are presented in table 3.1.

Table 3.1 The log-transformed parameters of the three databases for the regression analyses: 'estimated', 'measured', and 'measured+'.

	N_2O flux as:	Logarithmic variables:	Number of records
Estimated data	Log(N_2O)	Precipitation	98
Measured data	Log(N_2O)	N deposition	25
Measured data +	Log(N_2O)	N deposition	101

3.3 Results of regression analyses

The final results of the regression analyses are presented in this section. All results are for the soil layer of 0-20 cm. The results of the dataset of estimated data can be found in section 3.3.1. Section 3.3.2 presents the results of the regression analysis for measured data and 3.3.3 presents the relation found with the regression analysis for

[3] The F-ratio is the variance of one group divided by the variance of another group. In this case, the new regression with the extra variable is accepted if the variance of the new regression is less than the variance of the previous regression.

the measured+ data. Set in which measured data are completed with estimated parameters.

The R^2-value is use as an indication of the performance of the relation. A higher value is not a better relation pre see. It might also be the spread of the values which is larger, and this might reduce the relative error of the errors in the dataset. Standard error as additional information gives in indication of the absolute error range in the calculations.

3.3.1 Empirical relation for estimated data

The dataset of estimated values did included 98 records. The regression of the estimated dataset used log-transformed N_2O fluxes and log-transformed precipitation. The best model did include eight out of eleven variables as significant predictor variables:

Log N_2O = -1.99 – 1.043 * log (P) + 1.501 * (Fraction T<0) + 0.1464 * (% clay)
- 0.410 * (pH) + 0.00711 * (Organic C) + 0.1290 * (C/N ratio)
- 7.53 * (parent material: o) + 0.01082 * (N deposition)
R^2_{adj} = 26.4, s.e. = 0.421

The fraction of months with a temperature below zero was the parameter which was most significant and nitrogen deposition was the least significant of the eight parameters included in the best model (see table 3.2). Parameter 'parent material' was included even though the category was estimated. None of the actual organic soils were estimated to be organic, and one mineral soil was estimated to be organic. Nevertheless, the parameter was found to be a significant predictor of N_2O fluxes. Consequently, this parameter must be a measure for something else than parent material. It is unknown what it does represent.

Table 3.2 Estimates of the parameters and their standard error and probability for the regression analysis.

Variable:	Estimate:	Standard error:	Level of significance:
Constant	-1.55	1.67	*
Log(P)	-1.043	0.433	0.018
Fraction T<0	1.501	0.350	0.000
% clay	0.1464	0.0496	0.004
pH	-0.410	0.169	0.017
Organic C	0.00711	0.00281	0.013
C/N ratio	0.1290	0.0477	0.008
Parent material: o	-7.53	2.19	0.001
N deposition	0.01082	0.00550	0.052

A few of the observations were overestimated by the regression equation. However, most of the observations were underestimated (see figure 3.3). The regression included a log-transformed N_2O flux. On a logarithmic scale, the underestimation would not seem as large as they do now. However, the actual performance does not

change by plotting the results on a different scale. One measurement had an annual net uptake of N_2O. The model was not able to reproduce this negative flux.

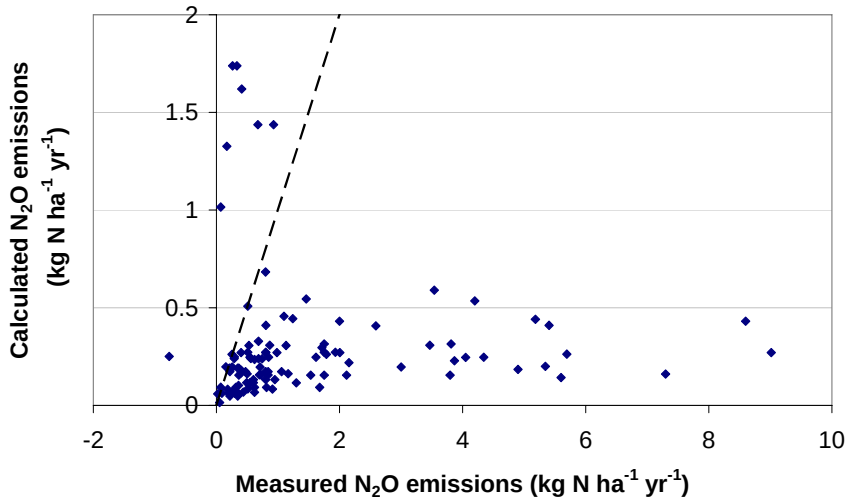


Figure 3.3 Plot of the measured and calculated N_2O emissions for the dataset of estimated parameters.

3.3.2 Empirical relation for measured data

The database of measured data contained 25 records. Bulk density and the fraction of months with a temperature below zero were excluded as parameters since none of the records included these data. For the regressions of the 'measured+'-database, two log transformations were done for N_2O emissions and for N deposition. Only nitrogen deposition was included as significant parameter in the best model:

$\text{Log } N_2O = -0.187 + 0.459 * (\text{N deposition})$
$R^2_{adj} = 15.2$, s.e. = 0.478

The low R^2 value was a disappointment since the dataset of measurements was expected to have the best results. After all, the measured data were expected to be the best representation of the situation on the measurement locations. However, this was not the case. The database did only include 25 records which might have been a bad representation of the overall situation and thereby it might have disturbed a smooth fit for the regression analysis. A look into the input revealed that the sites were spread over Europe, only two sites were organic, and the nitrogen deposition was low with a mean value of 15 kg N ha^{-1} yr^{-1}. The standard errors of the constant and parameter in the relation are given in table 3.3. Compared to the other results, the level of significance is low and the standard errors were high. This was not surprising since the R^2 is low and the number of observations is low.

Table 3.3 Estimates of the parameters and their standard error and level of significance for the regression analysis.

Variable:	Estimate:	Standard error:	Level of significance:
Constant	-0.187	0.225	*
N deposition	0.459	0.200	0.031

Figure 3.4 shows the plot of the measured N_2O fluxes versus the calculated N_2O fluxes. It is remarkable that all measured N_2O fluxes below 2 kg N ha^{-1} yr^{-1} were overestimated while all the emissions higher than 2 kg N ha^{-1} yr^{-1} were underestimated.

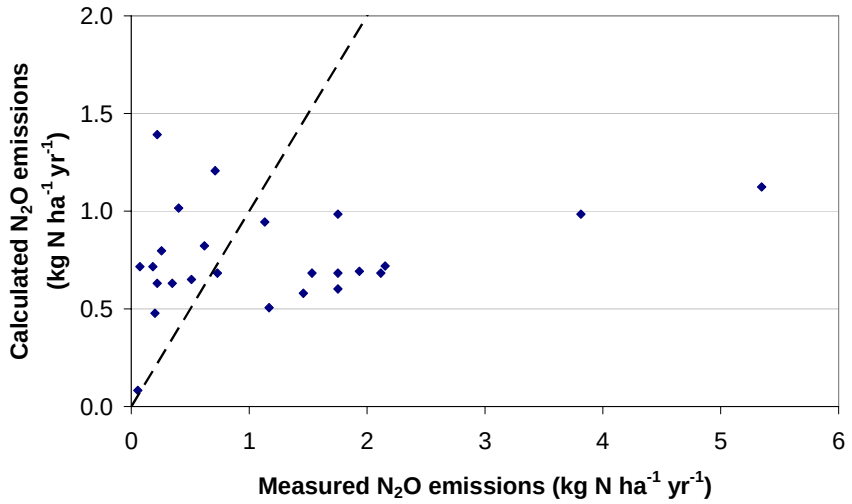


Figure 3.4 Plot of the measured and calculated N_2O emissions for the dataset of measured parameters.

3.3.3 Empirical relation for measured data +

For the regressions of the 'measured+'-database, two log transformations were done for N_2O emissions and for N deposition. Soil classes in this database were based on the soil profile descriptions at the plot. As a consequence, the division between organic soils and mineral soils was consistent with the situation at the location of the N_2O flux measurements. For this database parent material was not only included as a variable in the regression analyses. The whole database was split in two and separate regression analyses were performed for each group of soils. This resulted in one empirical relation for the total database, one for mineral soils, and one for organic soils.

All soils combined

The overall database consisted of the 82 mineral records and the 19 organic records. The best model for this dataset of 101 records was:

Log N_2O = 0.473 – 0.0957 * (Temperature) + 0.349 * log (N deposition)
+ 0.4006 (veg: dec) + 0.303 (veg: sv)
R^2_{adj} = 22.1, s.e. = 0.457

Parent material as a parameter did offer the possibility to differentiate between the two types of parent material. However, this parameter was not found to be included as a significant predictor in the best model. More detailed information about the parameters of the combined dataset can be found in table 3.4.

Table 3.4 Estimates of the parameters and their standard error and probability for the regression analysis.

Variable:	Estimate:	Standard error:	Level of significance:
Constant	0.473	0.215	*
Temperature	-0.0957	0.0240	0.000
Log(N deposition)	0.349	0.133	0.010
Vegetation: dec	0.4006	0.0980	0.000
Vegetation: sv	0.303	0.179	0.000

The plot of the measured versus the calculated N_2O fluxes shows that a group of high flux measurements is underestimated (see figure 3.5). The sites for which high N_2O fluxes (more than 10 kg ha^{-1} yr^{-1}) were located in Germany and Austria, and a few organic sites were in Finland, Sweden and The Netherlands. High emissions were generally underestimated while low emissions often were overestimated.

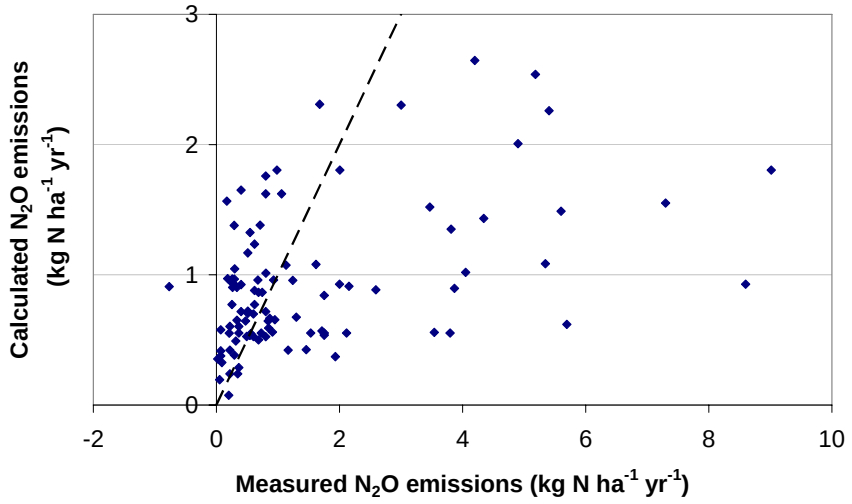


Figure 3.5 Plot of the measured and calculated N_2O emissions from all soils combined.

Mineral soils

A total of 82 records were included in the group of mineral soils. Of these, four sites have short vegetation, 38 are coniferous forests, and 37 are deciduous forests. The best model was found by including mean temperature, N deposition and vegetation in the model as parameters. Separating mineral soils from the total dataset did not result in a better regression of the N_2O fluxes. The regression for the mineral soils:

Log N_2O = 0.274 – 0.0744 * (Temperature) + 0.366 * log (N deposition)
+ 0.334 (veg: dec) + 0.035 (veg: sv)

R^2_{adj} = 17.9, s.e. = 0.439

Characteristics of the parameter values can be found in table 3.5. Temperature was significant at a level p<0.01. Nitrogen deposition and vegetation had a slightly higher level of significance. For vegetation only one level of significance was given for the group. The standard error of the parameters showed that deciduous forests are significantly different from coniferous forests. However, short vegetation did not show a significant difference from the reference level which was set by coniferous forests.

Table 3.5 Estimates of the parameters and their standard error and probability for the regression analysis of mineral soils.

Variable:	Estimate:	Standard error:	Level of significance:
Constant	0.274	0.271	*
Temperature	-0.0744	0.0276	0.009
Log(N deposition)	0.366	0.143	0.012
Vegetation: dec	0.334	0.109	0.011
Vegetation: sv	0.035	0.264	0.011

The performance of the relation is plotted in figure 3.6. High values of measured N_2O emissions are underestimated by the calculations. The ten highest measured N_2O emissions are all located in Austria and Germany. Of these ten sites, eight are deciduous forests while for the total dataset only 50 % of the locations are deciduous forest. The mean N deposition on these locations is 25.8 kg N ha^{-1} yr^{-1} while the average for the total database is 23 kg N ha^{-1} yr^{-1}. The group of underestimated N_2O emissions is consequently not very different in nitrogen input compared to the total dataset, neither was there a large difference in any of the other variables.

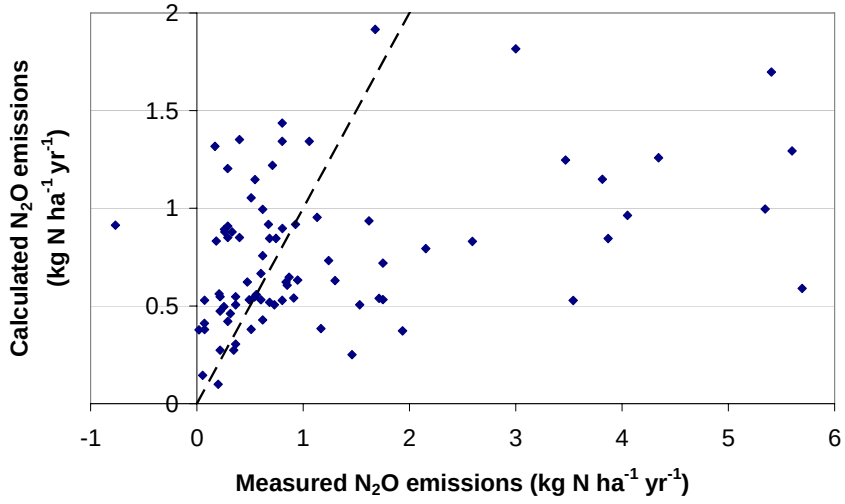


Figure 3.6 Plot of the measured and calculated N_2O emissions from mineral soils.

Organic soils

The group of organic soils included only 19 records. This small database included six measurements in Sweden, five in Germany, three in England, two in Finland and The Netherlands, and one in Denmark. This distribution was not a full representation of Europe, but it included the main regions with organic soils in Europe. Regression analysis of this group did result in an empirical relation for N_2O with the variables '% clay', 'pH', and 'Organic C':

Log N_2O = -3.40 – 0.0690 * (% clay) +0.769 * (pH) + 0.00807 * (Organic C)
R^2_{adj} = 57.0, s.e. = 0.386

The standard error for the organic soils is smaller than for the mineral soils. This means that even with a database which is much smaller in size, it was possible to give a more precise calculation of the N_2O emissions. The standard errors of the individual parameters in the relation are given in table 3.6.

Table 3.6 Estimates of the parameters and their standard error and probability for the regression analysis of organic soils.

Variable:	Estimate:	Standard error:	Level of significance:
Constant	-3.40	1.13	*
% clay	-0.0690	0.0252	0.015
pH	0.769	0.158	0.000
Organic C	0.00807	0.00160	0.000

The R^2 is much higher for this relation for organic soils than the one for the relation for mineral soils. Separating organic soils from the mineral soils showed to be very useful for the organic soils. Organic soils differentiate from mineral soils in two main aspects: a higher organic carbon content in the soil and, at least in this dataset, a higher clay content. These two characteristics of organic soils were included as significant variables in the empirical relation for organic soils while these variables were not included in the relation for mineral soils. This is another indication of the advantage for organic soils to have a separate relation. Figure 3.7 shows a plot of the measured and calculated N_2O fluxes. This figure is very different from the previous ones and the underestimation of the higher emissions is not as large as for the other regressions.

3.4 Comparing the results of the three datasets

Five different regression analyses were performed. One regression was performed for the 'estimated' dataset, one for the 'measured' dataset and three for the 'measured+' dataset. The latter was analysed as a whole and as two separate subsets; namely mineral soils and organic soils. Best results were expected for the measured dataset since these parameters are actually measured in the field while the estimated are upscaled or modelled data for grid cells of varying spatial scales. Surprisingly, the 'estimated' dataset did have the best result and the 'measured' data had the worst fit (see table 3.7).

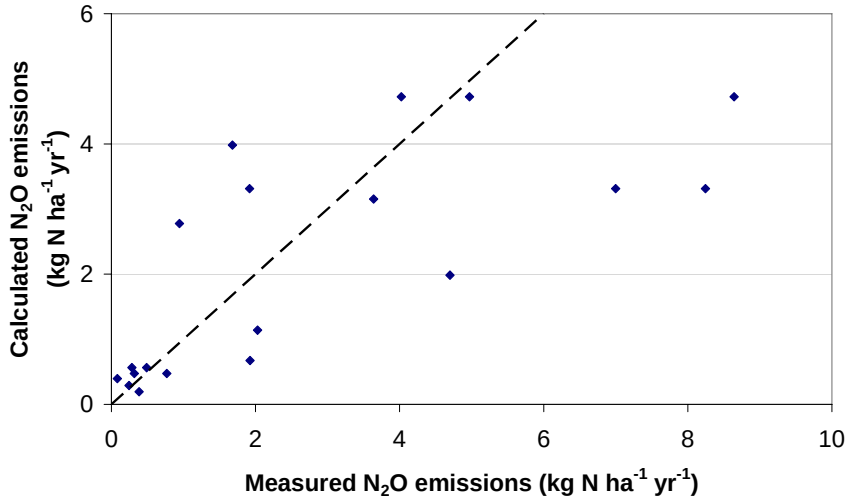


Figure 3.7 Plot of the measured and calculated N_2O emissions from organic soils.

A possible explanation can be that estimated values might not be the precise values at the field, but at least the parameters were all derived by the same method for all locations. This was not the case for the measured data since the researchers each did their work in their own way. Consequently, the measurement errors and inconsistencies in the measured data might be larger than the errors in the estimated values.

Table 3.7 Summary of the percentage variance accounted for of the regression analyses for the five regression analyses. 'Estimated', "measured+', and 'measured' are the three datasets that were used for the regressions.

	'Estimated'	'Measured+'	'Measured'
Mineral soils	-	17.9	-
Organic Soils	-	57.0	-
All soils	26.4	22.1	15.2

The 'measured+' dataset was split up into mineral soils and organic soils. The result of the regression for the organic soils was a positive outliner in the results. The R^2 was much higher than for the other regressions. A possible reason for this result is the lower number of sites with variables which are more equal than for the mineral soils. Additionally, the organic soils were centred inn the northern part of Europe which probably excluded part of the regional differences.

Differences in environmental variables in the three datasets

The differences between the regressions were, of course, caused by differences in input. Both the number of observations differed and the parameter values were different. But how different were the datasets? Did the estimated values differ largely with the measured data? Were the values different for the individual locations or were they only different in mean values? Table 3.8 shows the mean parameter values for each dataset. It shows that the 'measured' dataset included, on average, sites with

a lower N_2O flux than the 'estimated' dataset. It also shows that the estimated amounts of nitrogen deposition are much higher than the measured values.

Table 3.8 Average values for the input parameters of the different datasets relative to the 'estimated'-dataset. The parameter values of the 'estimated'-database are set at 100 and the parameter values of the other dataset are given relative to the 'estimated'-dataset.

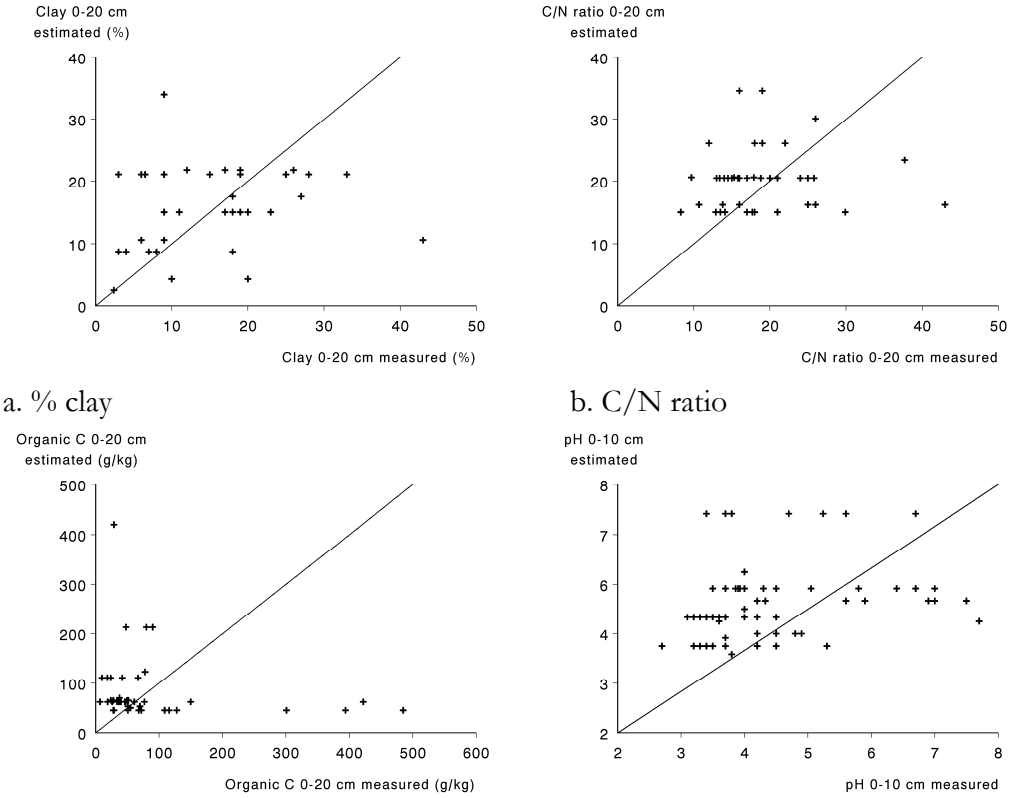
Variable:	'Estimated'	'Measured'	'Measured+'	'Measured+' Organic soils	'Measured+' Mineral soils
Temperature	100	103	94	80	96
Precipitation	100	114	107	99	109
N deposition	100	57	94	86	96
% clay	100	97	120	201	102
pH	100	94	90	78	92
Organic C	100	94	144	487	71
C/N ratio	100	100	102	122	98
N_2O flux	100	88	100	199	79

The literature study, as presented in chapter 2, showed that the results of this study are in the range of what could have been expected. It is not possible to obtain perfect descriptions of N_2O emissions due to large variability in both time and space. This is most clearly the case when a diverse dataset is used as was done in this study. Different studies were included from different research groups, at different time intervals, over different periods, at many different locations.

Differences in measurements and estimates of environmental variables

The differences in input were discussed and these differences are caused by different sites which were included in the dataset and the differences between estimates and measurements. The estimates are used as an alternative for the measured data. The estimated parameter values were plotted against the measured values to find out how accurately the estimates were defined. Figure 3.8 shows the plots of the soil characteristics. Estimated values for clay percentage, C/N ratios, organic C content, and pH were completely different from measured values and no general pattern could be recognized. Organic soils are usually not the dominant soil class, and consequently, organic soils are often estimated to be mineral soils. The other parameters are shown in figure 3.9. These estimates are much better than for the soil parameters. Temperature estimates are most precise and gave the closest representation of the measured values.

The plots show that the estimates for the soil characteristics were not able to reproduce the measured data. This is a major problem for the plans to use estimated values instead of measured values. Nevertheless, using precipitation, temperature, and nitrogen deposition as estimated values in model application is not likely to cause problems since these parameters gave the most accurate estimated values. The use of estimated soil parameters does not seem to be an option based on the plots shown in figure 3.8.



a. % clay b. C/N ratio

c. Organic C d. pH

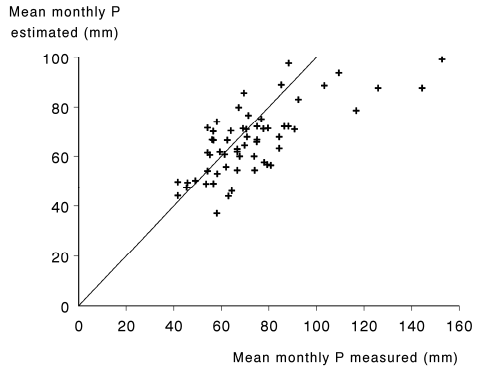
Figure 3.8 Plots of estimated versus measured parameter values of soil characteristics: a) % clay, b) C/N ratio, c) Organic C, and d) pH.

Impact of nitrogen deposition

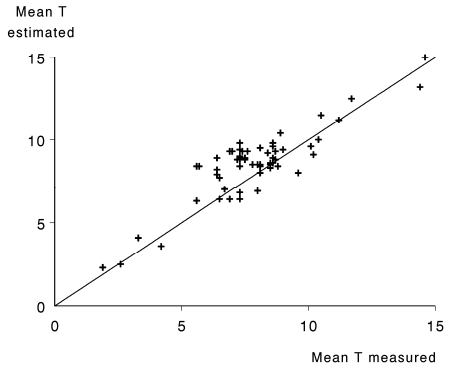
Local conditions have an impact on the emissions of N_2O. Most of the variables that have an influence on the emission rates are natural conditions. Consequently, humans can not steer the emissions from natural soils. However, nitrogen deposition partly originates from anthropogenic sources, and consequently, humans can reduce the emissions of the greenhouse gas N_2O by reducing the nitrogen deposition. The impact of nitrogen deposition on the N_2O emissions differs between the three datasets. Nitrogen deposition in natural areas is often in the range of 10 to 40 kg N ha^{-1} yr^{-1}.

Figure 3.10 shows the impact of nitrogen deposition in the N_2O emissions for the three datasets. The curves were derived by taking the average parameter values of the dataset for all the variables except nitrogen deposition. Deposition values of 0 to 100 kg N ha^{-1} yr^{-1} were used. A comparison of the three curves shows that reducing nitrogen deposition from 40 to 10 kg N ha^{-1} yr^{-1} results in the largest reduction of N_2O emissions for the measured dataset. The estimated dataset is least sensitive to changes in nitrogen deposition in the range from 10 to 14 kg N ha^{-1} yr^{-1}. An additional conclusion that can be drawn based on this graph is related to the highest N_2O fluxes. In a situation with average soils and site parameters, nitrogen deposition

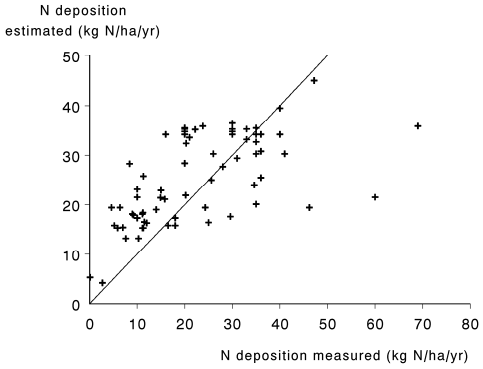
can increase to 100 kg N ha^{-1} yr^{-1} but still the N_2O fluxes do not exceed 2 kg N ha^{-1} yr^{-1}. Consequently, it is a combination of factors that cause the highest N_2O fluxes.



a. Mean monthly precipitation



b. Mean temperature



c. N deposition

Figure 3.9 Plots of estimated versus measured parameter values for a) mean monthly precipitation, b) mean temperature, and c) nitrogen deposition.

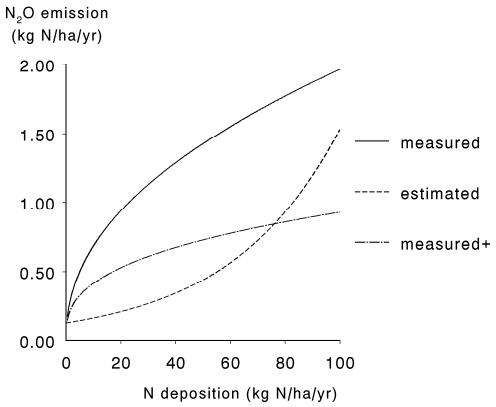


Figure 3.10 The impact of nitrogen deposition on the N_2O emissions based on the equations derived from the three datasets: 'estimated', 'measured', and 'measured+' dataset.

4 Discussion and conclusion

The previous two chapters presented a summary of the literature review and results of the regression analyses. Results are always subject to discussion in one way or another. This chapter discusses the value of the results from the perspective of the validity and applicability of the derived relations. This discussion is followed by the conclusion of the research as presented in this report.

4.1 Discussion

It might seem a simple exercise to derive relations between different parameters. However, many aspects of concern are included in relation to the validity and applicability of the derived relations.

Variability of N_2O emissions

First of all, it is important to keep in mind that N_2O emissions are highly variable over time and space. Coefficients of variation up to almost 500 % have been reported (van den Pol-van Dasselaar et al., 1998). A large part of the spatial variability is related to local soil parameters (Velthof et al., 2000). Spatial patterns found in the field are not significantly affected by diurnal variability and the same spatial patterns were found to be maintained for a period ranging from days to months (Velthof et al., 2000). However, these stable spatial patterns can show large changes in magnitude while preserving the same pattern. Variability in time is found on the diurnal scale as well as the seasonal and annual scale. Many different seasonal patterns have been found. Conditions as soil type and climate have a strong influence on the seasonal pattern (van Groenigen et al., 2005). All these variabilities in the fluxes do raise the question whether the measured fluxes are a good representation of the actual N_2O emissions. Velthof et al. (1996) studied inter-annual variation in fluxes and concluded that one year of flux measurements can be used to estimate N_2O fluxes in other years. However, it can still be questioned whether this one year of measurements provides a good annual flux since spatial and temporal variations influence the compiled annual flux. Flechard et al. (2007) found an uncertainty up to 50 % for annual estimates based on flux chamber measurements. The uncertainty becomes larges as fewer measurements are made in time and space. The selection criteria, as presented in section 3.1, on the length and frequency of the measurements were meant to set a minimum quality for the annual fluxes at the measurement locations used for the regression analyses.

The temporal variation of N_2O emissions can have many causes. Precipitation is, for example, a major determiner of the moisture conditions, and thereby influences the N_2O emissions. Temperature influences the productivity of soils and has an impact on N_2O emissions. A different type of influencer is for example the change in N_2O flux due to the eruption of the Mt. Pinatubo in the year 1991. The Pinatubo emitted aerosols into the air and caused a global cooling (Dutton & Christy, 1992). And cooling causes a lower N_2O production in the soil. These kinds of events are external

influencers of the N_2O emissions. The measurements used for this study did include a few observations from the year 1992. Consequently, these measurements were influenced by the global cooling caused by the Mt. Pinatubo. This introduced errors, since this was not accounted for in the regressions.

Impact of research group

The definition used by the different researchers is a second topic of discussion. N_2O fluxes were related to environmental factors. These factors should all be described and measured in the same way in order to have the best possible relation with the fluxes. Nitrogen deposition is a good example of this problem. There are many possibilities of what nitrogen deposition may include. There is wet deposition, dry deposition, and throughfall. Nitrogen deposition can include different forms: the main compartments are NO_3, NH_4, and NO_x. The measured data in the database consisted of different definitions for nitrogen deposition and it was therefore difficult to compare the different locations. This also complicated the situation for the regression analyses. Estimated data were all based on the same EMEP database, and the nitrogen deposition was therefore consistent in definition over the whole dataset. This may (partly) explain the higher R^2 values for the regression of the 'estimated' dataset compared to the 'measured' dataset.

An extra exercise was done to investigate the impact of the researcher by clustering the records of the database. The regression is not of use for the application. However, it might give an understanding about the influence of the research group on their measurements. The records were grouped into five groups based on first author:

- "Borken"
- "Brumme"
- "Butterbach"
- "NOFRETETE" included data from the data file from the NOFRETETE-project, received from Butterbach-Bahl (2007).
- "Others" included the remaining measurements which had not yet been assigned to group A to D.

Regression analysis, based on the 'measured+'-database showed that 'group' was a significant explaining variable for the N_2O emissions. The variable 'group' did indirectly include other variables since a group is usually related to a specific site or specific region. Consequently, variables like nitrogen deposition were different for the different groups. However, the overall variance accounted for did increase for the regression when including the groups. This was in indication that the group of researchers did have some impact on the measurements. This is something which is not something to account for during application of empirical relations. However, it is knowledge to keep in mind when applying relations.

Large differences in R^2 values for published regression analyses

The literature review revealed large differences in R^2 values for different studies. This study resulted in R^2 values ranging from less than 20 up to almost 60. Pilegaard et al (2006) published an article on the NOFRETETE-project with good results on the

regression analyses. The data of the NOFRETETE-project were analysed in the hope to find some indications why results can be very different in R^2. A data file of the project was provided by Klaus Butterbach-Bahl (2007). Regression analyses of these data did by far not represent the results as published by Pilegaard et al. (2006). Consequently, the data file was compared to data in the publication and the data file appeared to contain more sites. The supplementary sites were excluded, but still the results were not as successful as published. A comparison of the data revealed differences in the data of the data file and the published data. The data as published was put into GenStat and R^2 values of 85 were found. This is comparable with the published results. The difference in data between the publication and the received data-file was explained by the fact that the data used by Pilegaard et al. (2006) was only for one specific year while the data-file included the measurements for all years. This small change from the data of Pilegaard, which is one specific year and all data was collect in a similar way, to the data file which comprises all data from the NOFRETETE project, did result in a large difference in the regression analyses for these two sets of data. This small change which results in such a large difference, illustrates the sensitivity and complexity of the system.

Upscaling

The regression analyses resulted in equations to be used for calculating N_2O emissions. These equations can now be applied on a European scale to estimated annual fluxes. Upscaling is required and there are two main types: upscaling in time and upscaling in space.

Upscaling in time requires temporal interpolation. The most common method is linear interpolation (Pennock et al., 2006). This assumes that the measurements are a good representative of a longer period. The quality of this interpolation depends on the measuring frequency and on the temporal variations present at the site. Three types of variations have been defined by Brumme et al. (1999). First of all, there is a background emission pattern which is not influenced by climate or site conditions. Secondly, a seasonal pattern can often be found which is related to the temperature pattern over the year. Finally, the third pattern is event based and can be related to precipitation events or freezing and thawing (Brumme et al., 1999). The method of linear interpolation can not fully represent all these types of variability and introduces errors in the computed values. The second main method for temporal interpolation uses correlations between measured fluxes and controlling factors (Pennock et al., 2006). This approach is far more complex and more difficult to apply at a large scale.

Published data were presented as mean fluxes per hour, per day or per year. Especially the published annual fluxes were subject to temporal interpolation since the authors must have applied interpolation. Most likely this was done by linear interpolation. Many of the long term measuring campaigns only measured once every two weeks. Interpolation based on these data was not free of errors, but it was the best option available since there was a lack of more precise data.

Next to upscaling in time, there is upscaling in space. This requires spatial interpolation. Schimel and Potter (1995) described a measure and multiply approach.

For this approach, the region is divided into several classes which represent areas that are expected to have a more or less similar N_2O flux. Then, the measured flux for a certain class is multiplied by the area that this class covers (Schimel & Potter, 1995). For the measurements included in this study, there was often no spatial interpolation. There was either only one location or the fluxes of the different chambers were simple averaged. The local conditions were assumed to be equal since this were small-scale measurements and the chambers were located close to each other.

Organic soils and mineral soils

Results of the regressions for mineral and organic soils were very different. The regression for organic soils had a higher R^2. This is in line with Klemedtsson et al. (2005). They argued that variables, like soil moisture and organic C, are much more stable over time for organic soils than for mineral soils. As a result, organic soils have a more evenly distributed N_2O flux with fewer hotspots than mineral soils. Additionally, large amount of organic matter are present which is liberated by high mineralization rates (Klemedtsson et al., 2005). This is a large source of nitrogen. Consequently, they found C/N ratios to be the main descriptor of N_2O emissions from organic soils. However, with smaller C/N ratios nitrogen was no longer the rate-limiting factor and the influence of other variables became more important (Klemedtsson et al., 2005). This aspect of many rate-limiting factors interfering with each others complicates the calculation of N_2O emissions. Organic soils are good examples of soils in which many conditions are often optimal or at least not limiting for N_2O production.

The regression of the mineral soils of the 'measured+' database did result in a regression with the same variables as for the total dataset, but different values. However, the regression of the organic soils gave a completely different regression (see section 3.3.3). This can be explained by the fact that mineral soils were the dominant parent material in the overall dataset. And, in agreement with Klemedtsson et al. (2005), different variables were important for N_2O emissions from organic soils since conditions like soils moisture and temperature were not rate-limiting for these soils.

Measured and estimated data

Regression analyses were performed for both estimated parameters and for measured parameters. Measured values are very site specific. A soil sample is taken at one location and this sample is analysed for a series of parameters. Estimated values, on the other hand, are approximations for a larger region. Depending on the parameter, an estimate is based on a grid of a certain dimension. Consequently, estimated data was already subject to a certain degree of upscaling while measured data was not.

A comparison of the measured and estimated values revealed that the temperature and nitrogen deposition estimates showed the same general pattern as the measured data even though the values were not exactly the same. However, for some sites the estimations were completely wrong, if the measured data were assumed to be the right values. For precipitation data, a vague pattern could be recognized between

estimate and measurements, but it was not as clear as for temperature and nitrogen deposition. Estimated values for C/N ratios, organic C content, clay percentage, and pH were completely different from measured values and no general pattern could be recognized. Organic soils are usually not the dominant soil class, and consequently, organic soils are often estimated to be mineral soils.

It is debatable which value is 'wrong'. Measured data were actually measured in the field or in soil samples from the field. However, local conditions can vary over short distances and the measured value might represent an extreme situation. Consequently, a measured value cannot be wrong, but it might not be a good representation of the measurement site. An estimate usually is an upscaled value. Climate parameters, for example, do not come from the nearby meteorological station as is the case for most of the measured climate parameters. Estimated climate parameters are based on several meteorological stations and values are interpolated over distance and area. In this sense, neither measured nor estimated values are wrong.

The answer on which of the values is wrong depends on the question. If one needs site specific conditions then usually the measured data are more precise. If one needs to estimate regional values, then estimated values are probably more useful. In the case of upscaling N_2O emissions on a European scale, the application is on the level of estimated values. The values used for the 'estimated' dataset are the same kind of values as will be used for applying the relations. Based on this, it can be argued that it is most useful to use estimated values. These values included the uncertainties of upscaling and the relations based on these values can be easily applied. However, the N_2O fluxes that were used were measured values which were very site specific. From this perspective, measured parameters are favoured. For the regressions in this study it was chosen to compare both types of values. Estimated values because these will be used in the application, and measured values to find out whether this would result in a better regression. The results showed the best result for the estimated values. A possible explanation is that estimated values might not be the precise values at the field, but at least the parameters were all derived by the same method for all locations. This was not the case for the measured data since the researchers each did their work in their own way.

4.2 Conclusion

From the literature review on the impacts of environmental factors on N_2O emissions. It can be concluded that the main controllers of N_2O emissions are: pH, temperature, soil moisture (as %V/V, WFPS, or precipitation), and the availability of nitrogen. The latter can be expressed by several parameters like nitrogen deposition, C/N ratio, and soil NO_3^- concentrations. The influences of all these different factors complicate the study of impacts on N_2O emissions.. This made it impossible to find one straight-forward relation between the environmental factors and the N_2O emissions. Consequently, the literature review revealed the main controlling variables but it did not give quantitative information for the regression analyses. Additionally, the studies on impacts were often controlled small-scale experiments with a limited

number of influencing variables on a very limited number of plots. This hampered the use of regression models derived from the literature review for regional applications.

The results of the regression analyses generally had a low R^2, implying that annual N_2O emissions have a large variability in that can not only partly be captured by the environmental factors used in ths study. It has to be noted that the study included different studies from different research groups, at different time intervals, over different periods, and at many different locations. The regression for the organic soils showed a much higher percentage of variance accounted for. This is probably due to the fact the conditions in organic soils are more stable over time.

Based on the results, it can be concluded that the dataset of estimated values did perform best, and the relation found for this dataset was more significant than for the measured dataset. However, it was shown that the estimates for precipitation, temperature, and nitrogen deposition were comparable with measured data, but this was not the case for the soil properties. This implies that relationships with estimated data including soil properties are ambiguous.

Literature

Ambus, P. & S. Christensen, 1995. *Spatial and Seasonal Nitrous-Oxide and Methane Fluxes in Danish Forest-Ecosystems, Grassland-Ecosystems, and Agroecosystems.* Journal of Environmental Quality 24 (5), 993-1001.

Beier, C., L. Rasmussen, K. Pilegaard, P. Ambus, T. Mikkelsen, N.O. Jensen, A. Kjoller, A. Priemé & U.L. Ladekarl, 2001. *Fluxes of NO_3^- , NH_4^+, NO, NO_2, AND N_2O in an old Danish beech forest.* Water Air and Soil Pollution: Focus 1, 187-195.

Borken, W., F. Beese, R. Brumme & N. Lamersdorf, 2002. *Long-term reduction in nitrogen and proton inputs did not affect atmospheric methane uptake and nitrous oxide emission from a German spruce forest soil.* Soil Biology & Biochemistry 34 (11), 1815-1819.

Borken, W. & F. Beese, 2005. *Control of nitrous oxide emissions in European beech, Norway spruce and Scots pine forests.* Biogeochemistry 76 (1), 141-159.

Borken, W. & F. Beese, 2006. *Methane and nitrous oxide fluxes of soils in pure and mixed stands of European beech and Norway spruce.* European Journal of Soil Science 57 (5), 617-625.

Bouwman, A., 1990. *Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere.* In: Bouwman, A. (Ed). Soils and the Greenhouse Effect. Chichester, John Wiley and Sons Ltd, pp. 61-127.

Bowden, R.D., P.A. Steudler, J.M. Melillo & J.D. Aber, 1990. *Annual Nitrous-Oxide Fluxes from Temperate Forest Soils in the Northeastern United-States.* Journal of Geophysical Research-Atmospheres 95 (D9), 13997-14005.

Bowden, R.D., J.M. Melillo, P.A. Steudler & J.D. Aber, 1991. *Effects of Nitrogen Additions on Annual Nitrous-Oxide Fluxes from Temperate Forest Soils in the Northeastern United-States.* Journal of Geophysical Research-Atmospheres 96 (D5), 9321-9328.

Bowden, R.D., G. Rullo, G.R. Stevens & P.A. Steudler, 2000. *Soil fluxes of carbon dioxide, nitrous oxide, and methane at a productive temperate deciduous forest.* Journal of Environmental Quality 29 (1), 268-276.

Bremner, J.M., S.G. Robbins & A.M. Blackmer, 1980. *Seasonal Variability in Emission of Nitrous-Oxide from Soil.* Geophysical Research Letters 7 (9), 641-644.

Brumme, R. & F. Beese, 1992. *Effects of Liming and Nitrogen-Fertilization on Emissions of CO_2 and N_2O from a Temporate Forest.* Journal of Geophysical Research-Atmospheres 97 (D12), 12851-12858.

Brumme, R., 1995. *Mechanisms of Carbon and Nutrient Release and Retention in Beech Forest Gaps .3. Environmental-Regulation of Soil Respiration and Nitrous-Oxide Emissions Along a Microclimatic Gradient.* Plant and Soil 169, 593-600.

Brumme, R., W. Borken & S. Finke, 1999. *Hierarchical control on nitrous oxide emission in forest ecosystems.* Global Biogeochemical Cycles 13 (4), 1137-1148.

Butterbach-Bahl, K., R. Gasche, C.H. Huber, K. Kreutzer & H. Papen, 1998. *Impact of N-input by wet deposition on N-trace gas fluxes and CH_4-oxidation in spruce forest ecosystems of the temperate zone in Europe.* Atmospheric Environment 32 (3), 559-564.

Butterbach-Bahl, K., L. Breuer, R. Gasche, G. Willibald & H. Papen, 2002a. *Exchange of trace gases between soils and the atmosphere in Scots pine forest ecosystems of the northeastern German lowlands 1. Fluxes of N_2O, NO/NO_2 and CH_4 at forest sites with different N-deposition.* Forest Ecology and Management 167 (1-3), 123-134.

Butterbach-Bahl, K., A. Rothe & H. Papen, 2002b. *Effect of tree distance on N_2O and CH_4-fluxes from soils in temperate forest ecosystems.* Plant and Soil 240 (1), 91-103.

Butterbach-Bahl, K., 2007. *NOFRETETE data file.* personal communication.

Castro, M.S., P.A. Steudler, J.M. Melillo, J.D. Aber & S. Millham, 1993. *Exchange of N_2O and CH_4 between the Atmosphere and Soils in Spruce-Fir Forests in the Northeastern United-States.* Biogeochemistry 18 (3), 119-135.

Christensen, S., S. Simkins & J.M. Tiedje, 1990. *Spatial Variation in Denitrification - Dependency of Activity Centers on the Soil Environment.* Soil Science Society of America Journal 54 (6), 1608-1613.

Christensen, S., P. Ambus, J.R.M. Arah, H. Clayton, B. Galle, D.W.T. Griffith, K.J. Hargreaves, L. Klemedtsson, A.M. Lind, M. Maag, A. Scott, U. Skiba, K.A. Smith, M. Welling & F.G. Wienhold, 1996. *Nitrous oxide emissions from an agricultural field: comparison between measurements by flux chamber and micrometerological techniques.* Atmospheric Environment 30, 4183-4190.

Cicerone, R.J., 1987. *Changes in Stratospheric Ozone.* Science 237 (4810), 35-42.

Conrad, R., 1996. *Soil microorganisms as controllers of atmospheric trace gases (H-2, CO, CH_4, OCS, N_2O, and NO).* Microbiological Reviews 60 (4), 609-&.

Corre, M.D., D.J. Pennock, C. Van Kessel & D.K. Elliott, 1999. *Estimation of annual nitrous oxide emissions from a transitional grassland-forest region in Saskatchewan, Canada.* Biogeochemistry 44 (1), 29-49.

Denier van der Gon, H. & A. Bleeker, 2005. *Indirect N_2O emission due to atmospheric N deposition for the Netherlands.* Atmospheric Environment 39 (32), 5827-5838.

Dong, Y., D. Scharffe, J.M. Lobert, P.J. Crutzen & E. Sanhueza, 1998. *Fluxes of CO_2, CH_4 and N_2O from a temperate forest soil: the effects of leaves and humus layers.* Tellus Series B-Chemical and Physical Meteorology 50 (3), 243-252.

Du, R., D.R. Lu & G.C. Wang, 2006. *Diurnal, seasonal, and inter-annual variations of N_2O fluxes from native semi-arid grassland soils of inner Mongolia.* Soil Biology & Biochemistry 38 (12), 3474-3482.

Dutton, E.G. & J.R. Christy, 1992. *Solar radiative forcing at selected locations and evidence for global lower tropospheric cooling following the eruptions of El Chicón and Pinatubo.* Geophysical Research Letters 19, 2313-2316.

Duxbury, J.M., D.R. Bouldin, R.E. Terry & R.L. Tate, 1982. *Emissions of Nitrous-Oxide from Soils.* Nature 298 (5873), 462-464.

Ernfors, M., K. Von Arnold, J. Stendahl, M. Olsson & L. Klemedtsson, 2007. *Nitrous oxide emissions from drained organic forest soils - an up-scaling based on C:N ratios.* Biogeochemistry 84, 219-231.

Flechard, C.R., P. Ambus, U. Skiba, R.M. Rees, A. Hensen, A. van Amstel, A.V. Pol-van Dasselaar, J.F. Soussana, M. Jones, J. Clifton-Brown, A. Raschi, L. Horvath, A. Neftel, M. Jocher, C. Ammann, J. Leifeld, J. Fuhrer, P. Calanca, E. Thalman, K. Pilegaard, C. Di Marco, C. Campbell, E. Nemitz, K.J. Hargreaves, P.E. Levy, B.C. Ball, S.K. Jones, W.C.M. van de Bulk, T. Groot, M. Blom, R. Domingues, G. Kasper, V. Allard, E. Ceschia, P. Cellier, P. Laville, C. Henault, F. Bizouard, M. Abdalla, M. Williams, S. Baronti, F. Berretti & B. Grosz, 2007. *Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe.* Agriculture Ecosystems & Environment 121 (1-2), 135-152.

Flessa, H., P. Dorsch & F. Beese, 1995. *Seasonal-Variation of N2o and Ch4 Fluxes in Differently Managed Arable Soils in Southern Germany.* Journal of Geophysical Research-Atmospheres 100 (D11), 23115-23124.

Gasche, R. & H. Papen, 1999. *A 3-year continuous record of nitrogen trace gas fluxes from untreated and limed soil of a N-saturated spruce and beech forest ecosystem in Germany - 2. NO and NO2 fluxes.* Journal of Geophysical Research-Atmospheres 104 (D15), 18505-18520.

Gasche, R. & H. Papen, 2002. *Spatial variability of NO and NO_2 flux rates from soil of spruce and beech forest ecosystems.* Plant and Soil 240 (1), 67-76.

Glatzel, S. & K. Stahr, 2001. *Methane and nitrous oxide exchange in differently fertilised grassland in southern Germany.* Plant and Soil 231 (1), 21-35.

Goodroad, L.L. & D.R. Keeney, 1984. *Nitrous-Oxide Emission from Forest, Marsh, and Prairie Ecosystems.* Journal of Environmental Quality 13 (3), 448-452.

Goossens, A., A. De Visscher, P. Boeckx & O. Van Cleemput, 2001. *Two-year field study on the emission of N_2O from coarse and middle-textured Belgian soils with different land use.* Nutrient Cycling in Agroecosystems 60 (1-3), 23-34.

Groffman, P.M., D.R. Zak, S. Christensen, A. Mosier & J.M. Tiedje, 1993. *Early Spring Nitrogen Dynamics in a Temperate Forest Landscape.* Ecology 74 (5), 1579-1585.

Hackl, E., G. Bachmann & S. Zechmeister-Boltenstern, 2004. *Microbial nitrogen turnover in soils under different types of natural forest.* Forest Ecology and Management 188 (1-3), 101-112.

Härtel-rigler, E., S. Zechmeister-Boltenstern & H. Gerzabek, 2001. *Gasförmige Stickstoffverluste an einem Waldstandort in den Nordtiroler Kalkalpen.* FBVA-Berichte 119, 85-92.

Härtel, E., S. Zechmeister-Boltenstern & M. Gerzabek, 2002. *Gaseous nitrogen losses from a forest site in the North Tyrolean Limestone Alps.* Environmental Science and Pollution Research, 23-30.

Henrich, M. & K. Haselwandter, 1997. *Denitrification and gaseous nitrogen losses from an acid spruce forest soil.* Soil Biology & Biochemistry 29 (9-10), 1529-1537.

Hollis, J.M., R.J.A. Jones, C.J. Marshall, A. Holden, J.R. Van de Veen & L. Montanarella, 2006. *SPADE-2: The soil profile analytical database for Europe, version 1.0.* Luxembourg, Office for Official Publications of the European Communities. European Soil Bureau Research Report No.19 EUR 22127 EN.

Horvath, L., E. Fuhrer & K. Lajtha, 2006. *Nitric oxide and nitrous oxide emission from Hungarian forest soils; linked with atmospheric N-deposition.* Atmospheric Environment 40 (40), 7786-7795.

IPCC, 2007. *Climate Change 2007: The Physical Science Basis.* Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Jordan, T.E., D.E. Weller & D.L. Correll, 1998. *Denitrification in surface soils of a riparian forest: Effects of water, nitrate and sucrose additions.* Soil Biology & Biochemistry 30 (7), 833-843.

Kaiser, E.A., K. Kohrs, M. Kucke, E. Schnug, J.C. Munch & O. Heinemeyer, 1998. *Nitrous oxide release from arable soil: importance of perennial forage crops.* Biology and Fertility of Soils 28 (1), 36-43.

Kaiser, E.A. & R. Ruser, 2000. *Nitrous oxide emissions from arable soils in Germany - An evaluation of six long-term field experiments.* Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde 163 (3), 249-259.

Keller, M., T.J. Goreau, S.C. Wofsy, W.A. Kaplan & M.B. McElroy, 1983. *Production of Nitrous-Oxide and Consumption of Methane by Forest Soils.* Geophysical Research Letters 10 (12), 1156-1159.

Kesik, M., S. Blagodatsky, H. Papen & K. Butterbach-Bahl, 2006. *Effect of pH, temperature and substrate on N_2O, NO and CO_2 production by Alcaligenes faecalis p.* Journal of Applied Microbiology 101 (3), 655-667.

Kirschbaum, M.U.F., 1995. *The Temperature-Dependence of Soil Organic-Matter Decomposition, and the Effect of Global Warming on Soil Organic-C Storage.* Soil Biology & Biochemistry 27 (6), 753-760.

Kitzler, B., S. Zechmeister-Boltenstern, C. Holtermann, U. Skiba & K. Butterbach-Bahl, 2006a. *Nitrogen oxides emission from two beech forests subjected to different nitrogen loads.* Biogeosciences 3 (3), 293-310.

Kitzler, B., S. Zechmeister-Boltenstern, C. Holtermann, U. Skiba & K. Butterbach-Bahl, 2006b. *Controls over N_2O, NOx and CO_2 fluxes in a calcareous mountain forest soil.* Biogeosciences 3 (4), 383-395.

Klemedtsson, L., A.K. Klemedtsson, F. Moldan & P. Weslien, 1997. *Nitrous oxide emission from Swedish forest soils in relation to liming and simulated increased N-deposition.* Biology and Fertility of Soils 25 (3), 290-295.

Klemedtsson, L., K. von Arnold, P. Weslien & P. Gundersen, 2005. *Soil CN ratio as a scalar parameter to predict nitrous oxide emissions.* Global Change Biology 11 (7), 1142-1147.

Koponen, H.T., C.E. Duran, M. Maljanen, J. Hytonen & P.J. Martikainen, 2006. *Temperature responses of NO and N_2O emissions from boreal organic soil.* Soil Biology & Biochemistry 38 (7), 1779-1787.

Lamers, M., J. Ingwersen & T. Streck, 2007. *Nitrous oxide emissions from mineral and organic soils of a Norway spruce stand in South-West Germany.* Atmospheric Environment 41 (8), 1681-1688.

MacDonald, J.A., U. Skiba, L.J. Sheppard, B. Ball, J.D. Roberts, K.A. Smith & D. Fowler, 1997. *The effect of nitrogen deposition and seasonal variability on methane oxidation and nitrous oxide emission rates in an upland spruce plantation and moorland.* Atmospheric Environment 31 (22), 3693-3706.

Machefert, S.E., N.B. Dise, K.W.T. Goulding & P.G. Whitehead, 2002. *Nitrous oxide emission from a range of land uses across Europe.* Hydrology and Earth System Sciences 6 (3), 325-337.

Maljanen, M., A. Liikanen, J. Silvola & P.J. Martikainen, 2003. *Nitrous oxide emissions from boreal organic soil under different land-use.* Soil Biology & Biochemistry 35 (5), 689-700.

Maljanen, M., H. Jokinen, A. Saari, R. Strommer & P.J. Martikainen, 2006a. *Methane and nitrous oxide fluxes, and carbon dioxide production in boreal forest soil fertilized with wood ash and nitrogen.* Soil Use and Management 22 (2), 151-157.

Maljanen, M., H. Nykanen, M. Moilanen & P.J. Martikainen, 2006b. *Greenhouse gas fluxes of coniferous forest floors as affected by wood ash addition.* Forest Ecology and Management 237 (1-3), 143-149.

Maree, M., 2007. *Uncertainty of soil characteristics used in models for NitroEurope, focusing on INTEGRATOR.* Alterra, Wageningen.

Matson, P.A., S.T. Gower, C. Volkmann, C. Billow & C.C. Grier, 1992. *Soil-Nitrogen Cycling and Nitrous-Oxide Flux in a Rocky-Mountain Douglas-Fir Forest - Effects of Fertilization, Irrigation and Carbon Addition.* Biogeochemistry 18 (2), 101-117.

Merino, A., P. Perez-Batallon & F. Macias, 2004. *Responses of soil organic matter and greenhouse gas fluxes to soil management and land use changes in a humid temperate region of southern Europe.* Soil Biology & Biochemistry 36 (6), 917-925.

Mogge, B., E.A. Kaiser & J.C. Munch, 1998. *Nitrous oxide emissions and denitrification N-losses from forest soils in the Bornhoved Lake Region (Northern Germany).* Soil Biology & Biochemistry 30 (6), 703-710.

Mosier, A.R., J.A. Morgan, J.Y. King, D. LeCain & D.G. Milchunas, 2002. *Soil-atmosphere exchange of CH_4, CO_2, NO_x, and N_2O in the Colorado shortgrass steppe under elevated CO_2.* Plant and Soil 240 (2), 201-211.

New, M., M. Hulme & P. Jones, 1999. *Representing twentieth-century space-time climate variability. Part I: Development of a 1961-90 mean monthly terrestrial climatology.* Journal of Climate 12 (3), 829-856.

Öquist, M.G., M. Nilsson, F. Sorensson, A. Kasimir-Klemedtsson, T. Persson, P. Weslien & L. Klemedtsson, 2004. *Nitrous oxide production in a forest soil at low temperatures - processes and environmental controls.* Fems Microbiology Ecology 49 (3), 371-378.

Oura, N., J. Shindo, T. Fumoto, H. Toda & H. Kawashima, 2001. *Effects of nitrogen deposition on nitrous oxide emissions from the forest floor.* Water Air and Soil Pollution 130 (1-4), 673-678.

Papen, H., B. Hellmann, H. Papke & H. Rennenberg, 1993. *Emission of N-oxides from acid irrigated and limed soils of a coniferous forest in Bavaria.* In: Oremland, R.S. (Ed). The biochemistry of global change: Radiatively active trace gases. New York, Chapman Hall, pp. 245-259.

Papen, H. & K. Butterbach-Bahl, 1999. *A 3-year continuous record of nitrogen trace gas fluxes from untreated and limed soil of a N-saturated spruce and beech forest ecosystem in Germany - 1. N_2O emissions.* Journal of Geophysical Research-Atmospheres 104 (D15), 18487-18503.

Papke, H. & H. Papen, 1998. *Influence of acid rain and liming on fluxes of NO and NO_2 from forest soil.* Plant and Soil 199 (1), 131-139.

Pennock, D.J., T. T Yates & J.T. Braidek, 2006. *Towards optimum sampling for regional-scale N2O emission monitoring in Canada.* Canadian Journal of Soil Science 86 (3), 441-450.

Pilegaard, K., U. Skiba, P. Ambus, C. Beier, N. Bruggemann, K. Butterbach-Bahl, J. Dick, J. Dorsey, J. Duyzer, M. Gallagher, R. Gasche, L. Horvath, B. Kitzler, A. Leip, M.K. Pihlatie, P. Rosenkranz, G. Seufert, T. Vesala, H. Westrate & S. Zechmeister-Boltenstern, 2006. *Factors controlling regional differences in forest soil emission of nitrogen oxides (NO and N_2O).* Biogeosciences 3 (4), 651-661.

Poth, M. & D.D. Focht, 1985. *N-15 Kinetic-Analysis of N_2O Production by Nitrosomonas-Europaea - an Examination of Nitrifier Denitrification.* Applied and Environmental Microbiology 49 (5), 1134-1141.

Regina, K., H. Nykanen, J. Silvola & P.J. Martikainen, 1996. *Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table level and nitrification capacity.* Biogeochemistry 35 (3), 401-418.

Regina, K., H. Nykanen, M. Maljanen, J. Silvola & P.J. Martikainen, 1998. *Emissions of N_2O and NO and net nitrogen mineralization in a boreal forested peatland treated with different nitrogen compounds.* Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 28 (1), 132-140.

Robertson, G.P. & J.M. Tiedje, 1987. *Nitrous oxide sources in aerobic soils: Nitrification, denitrification and other biological processes.* Soil Biology & Biochemistry 19, 187-193.

Rosenkranz, P., N. Bruggemann, H. Papen, Z. Xu, L. Horvath & K. Butterbach-Bahl, 2006. *Soil N and C trace gas fluxes and microbial soil N turnover in a sessile oak (Quercus petraea (Matt.) Liebl.) forest in Hungary.* Plant and Soil 286 (1-2), 301-322.

Rover, M., O. Heinemeyer & E.A. Kaiser, 1998. *Microbial induced nitrous oxide emissions from an arable soil during winter.* Soil Biology & Biochemistry 30 (14), 1859-1865.

Ruser, R., H. Flessa, R. Schilling, F. Beese & J.C. Munch, 2001. *Effect of crop-specific field management and N fertilization on N2O emissions from a fine-loamy soil.* Nutrient Cycling in Agroecosystems 59 (2), 177-191.

Ryan, M.G., 1991. *Effects of Climate Change on Plant Respiration.* Ecological Applications 1 (2), 157-167.

Schimel, D. & C.S. Potter, 1995. *Process modelling and spatial extrapolation.* In: Matson, P.A. & R.C. Harris (Eds). Biogenic trace gases: Measuring emissions from soil and water. Oxford, UK, Blackwell Science, pp. 358-383.

Schmidt, J., W. Seiler & R. Conrad, 1988. *Emission of Nitrous-Oxide from Temperate Forest Soils into the Atmosphere.* Journal of Atmospheric Chemistry 6 (1-2), 95-115.

Skiba, U., D. Fowler & K. Smith, 1994. *Emissions of NO and N_2O from Soils.* Environmental Monitoring and Assessment 31 (1-2), 153-158.

Skiba, U., L.J. Sheppard, C.E.R. Pitcairn, S. Van Dijk & M.J. Rossall, 1999. *The effect of N deposition on nitrous oxide and nitric oxide emissions from temperate forest soils.* Water Air and Soil Pollution 116 (1-2), 89-98.

Skiba, U.M., L.J. Sheppard, J. MacDonald & D. Fowler, 1998. *Some key environmental variables controlling nitrous oxide emissions from agricultural and semi-natural soils in Scotland.* Atmospheric Environment 32 (19), 3311-3320.

Smith, K.A., T. Ball, F. Conen, K.E. Dobbie, J. Massheder & A. Rey, 2003. *Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes.* European Journal of Soil Science 54 (4), 779-791.

Stehfest, E. & L. Bouwman, 2006. *N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions.* Nutrient Cycling in Agroecosystems 74 (3), 207-228.

Struwe, S. & A. Kjoller, 1989. *Field Determination of Denitrification in Water-Logged Forest Soils.* Fems Microbiology Ecology 62 (2), 71-78.

Teepe, R., R. Brumme & F. Beese, 2000. *Nitrous oxide emissions from frozen soils under agricultural, fallow and forest land.* Soil Biology & Biochemistry 32 (11-12), 1807-1810.

Tiedje, J., 1988. *Ecology of denitrification and dissimilatory nitrate reduction to ammonium.* In: Zehnder, J. (Ed). Biology of anaerobic microorganisms. New York, Wiley, pp. 179-244.

Tierney, G.L., T.J. Fahey, P.M. Groffman, J.P. Hardy, R.D. Fitzhugh & C.T. Driscoll, 2001. *Soil freezing alters fine root dynamics in a northern hardwood forest.* Biogeochemistry 56 (2), 175-190.

Tietema, A., W. Bouten & P.E. Wartenbergh, 1991. *Nitrous-Oxide Dynamics in an Oak Beech Forest Ecosystem in the Netherlands.* Forest Ecology and Management 44 (1), 53-61.

van den Pol-van Dasselaar, A., W.J. Corre, A. Prieme, A.K. Klemedtsson, P. Weslien, A. Stein, L. Klemedtsson & O. Oenema, 1998. *Spatial variability of methane, nitrous oxide, and carbon dioxide emissions from drained grasslands.* Soil Science Society of America Journal 62 (3), 810-817.

van Groenigen, J.W., G.L. Velthof, F.J.E. van der Bolt, A. Vos & P.J. Kuikman, 2005. *Seasonal variation in N_2O emissions from urine patches: Effects of urine concentration, soil compaction and dung.* Plant and Soil 273 (1-2), 15-27.

Velthof, G.L., A.B. Brader & O. Oenema, 1996. *Seasonal variations in nitrous oxide losses from managed grasslands in The Netherlands.* Plant and Soil 181 (2), 263-274.

Velthof, G.L., J.W. van Groenigen, G. Gebauer, S. Pietrzak, S.C. Jarvis, M. Pinto, W. Corre & O. Oenema, 2000. *Temporal stability of spatial patterns of nitrons oxide fluxes from sloping grassland.* Journal of Environmental Quality 29 (5), 1397-1407.

Von Arnold, K., M. Nilsson, B. Hanell, P. Weslien & L. Klemedtsson, 2005a. *Fluxes of CO_2, CH_4 and N_2O from drained organic soils in deciduous forests.* Soil Biology & Biochemistry 37 (6), 1059-1071.

Von Arnold, K., P. Weslien, M. Nilsson, B.H. Svensson & L. Klemedtsson, 2005b. *Fluxes of CO_2, CH_4 and N_2O from drained coniferous forests on organic soils.* Forest Ecology and Management 210 (1-3), 239-254.

Wagner-Riddle, C., G.W. Thurtell, G.K. Kidd, E.G. Beauchamp & R. Sweetman, 1997. *Estimates of nitrous oxide emissions from agricultural fields over 28 months.* Canadian Journal of Soil Science 77 (2), 135-144.

Wang, Y.S., M. Xue, X.H. Zheng, B.M. Ji, R. Du & Y.F. Wang, 2005. *Effects of environmental factors on N_2O emission from and CH_4 uptake by the typical grasslands in the Inner Mongolia.* Chemosphere 58 (2), 205-215.

Webster, E.A. & D.W. Hopkins, 1996. *Contributions from different microbial processes to N_2O emissions from soils under different moisture regimes.* Biology and Fertility of Soils 22, 331-335.

Wrage, N., G.L. Velthof, M.L. van Beusichem & O. Oenema, 2001. *Role of nitrifier denitrification in the production of nitrous oxide.* Soil Biology & Biochemistry 33 (12-13), 1723-1732.

Wrage, N., G.L. Velthof, H.J. Laanbroek & O. Oenema, 2004. *Nitrous oxide production in grassland soils: assessing the contribution of nitrifier denitrification.* Soil Biology & Biochemistry 36 (2), 229-236.

Yashiro, Y., S. Mariko & H. Koizumi, 2006. *Emission of nitrous oxide through a snowpack in ten types of temperate ecosystems in Japan.* Ecological Research 21 (5), 776-781.

Yu, J.B., W.D. Sun, J.S. Liu, J.D. Wang, J.S. Yang & F.X. Meixner, 2007. *Enhanced net formations of nitrous oxide and methane underneath the frozen soil in Sanjiang wetland, northeastern China.* Journal of Geophysical Research-Atmospheres 112 (D7).

Zechmeister-Boltenstern, S., M. Hahn, S. Meger & R. Jandl, 2002. *Nitrous oxide emissions and nitrate leaching in relation to microbial biomass dynamics in a beech forest soil.* Soil Biology & Biochemistry 34 (6), 823-832.

Websites

Website of ISRIC; www.isric.org,
(http://www.isric.org/UK/About+ISRIC/Projects/Track+Record/WISE.htm)
Visited on the 14st of June 2007

Appendix 1 Database on field observations

The database of field observations was split into four parts since it does not fit into this report as one big table. This appendix includes four tables:
Site Characteristics
Soil Characteristics
N_2O measurements
NO measurements and references
Numbers 1- 132: European sites with a specific location and related coordinates.
Numbers 133-162: European sites without location and sites outside of Europe.
The numbers 1-132 could be used for the regression analyses.

A. Site Characteristics

Location		Coordinates		Annual temperature	Annual precipitation	Vegetation Type (dominant type)	Depth to groundwater	N input	Humus Type	parent material	Soil Class	Soil Texture
ID	Name	Latitude	Longitude	[°C]	[mm]		[cm]	[kg N ha^{-1} yr^{-1}]		m=mineral, o=organic		
FOREST												
1	Copenhagen, Denmark	55.5765	12.5872	*	*	Beech	*	*	*	m	Udalfs	Sandy loam
2	Copenhagen, Denmark	55.5765	12.5872	*	*	Spruce	*	*	*	m	Orthods	Loamy sand
5	Gyrstinge, Sorø, Denmark	55.4866	11.6452	*	*	Beech	*	25.6	*	m	*	*
6	Solling, ambient, Germany	51.5167	9.5667	6.4	1058	Beech	*	*	*	m	Dystric Cambisol	Loamy silt
7	Solling, ambient, Germany	51.5167	9.5667	6.4	673	Spruce	*	*	*	m	Dystric Cambisol	Loamy silt
8	Solling, Germany	51.7667	9.5667	7.2	1038	Beech	*	*	*	m	Dystric cambisols	28%clay, 58%silt, 14%sand
9	Unterlüß, Germany	52.8333	10.2833	8.4	837	Beech	*	*	Moder	m	Cambisols	3%clay, 23%silt, 74%sand

Location		Coordinates		Annual temperature	Annual precipitation	Vegetation Type (dominant type)	Depth to groundwater	N input	Humus Type	parent material	Soil Class	Soil Texture
ID	Name	Latitude	Longitude	[°C]	[mm]		[cm]	[kg N ha^{-1} yr^{-1}]		m=mineral, o=organic		
10	Unterlüß, Germany	52.8333	10.3000	8.4	837	Beech	*	26.6	Moder	m	Cambisols	8%clay, 16%silt, 77%sand
11	Unterlüß, Germany	52.8333	10.2667	8.4	837	Beech	*	*	Moder	m	Cambisols	4%clay, 16%silt, 81%sand
12	Solling, Germany	51.7667	9.5833	7.2	1038	Spruce	*	*	*	m	Dystric cambisols	19%clay, 54%silt, 27%sand
13	Solling, Germany	51.5667	9.6667	7.5	900	Beech	*	*	*	m	Dystric cambisols	15%clay, 46%silt, 39%sand
14	Solling, Germany	51.7667	9.5833	7.5	900	Beech	*	*	*	m	Dystric cambisols	Loamy silt
15	Solling, Germany	51.7667	9.5833	7.5	900	Beech	*	27.6	*	m	Dystric cambisols	Loamy silt
16	Solling, Germany	51.7667	9.5833	7.5	900	Beech	*	*	*	m	Dystric cambisols	Loamy silt
17	Solling, Germany	51.7667	9.5833	7.5	900	Spruce	*	*	*	m	Dystric cambisols	Loamy silt
133	Bousson Environmental Research Reserve, northwest Pennsylvania, USA	*	*	*	1050	Beech	*	*	*	m	Alfisols	Silty loam
134	Harvard forest, Petersham, Massachussets, USA	41.0000	-72.0000	*	*	Beech	*	*	*	m	Entic Haplorthods	Sandy loam
135	Harvard forest, Petersham, Massachussets, USA	41.0000	-72.0000	*	*	Beech	*	28.6	*	m	Entic Haplorthods	Sandy loam
19	Solling, Germany	51.7667	9.5833	*	*	Spruce	*	*	*	m	Acidic cambisol	*
21	Solling, Germany	51.7667	9.5833	6	1090	Beech	*	*	*	m	Dystric cambisol	*
22	Harz, Germany	51.8167	10.2333	6.9	1239	Beech	*	29.6	*	m	Dystric cambisol	*
24	Lappwald, Germany	52.2137	10.8936	8.5	650	Spruce	*	*	*	m	Dystric gleysol	*

Location		Coordinates		Annual temperature	Annual precipitation	Vegetation Type (dominant type)	Depth to groundwater	N input	Humus Type	parent material	Soil Class	Soil Texture
ID	Name	Latitude	Longitude	[°C]	[mm]		[cm]	[kg N ha^{-1} yr^{-1}]		m=mineral, o=organic		
25	Zierenberg, Germany	51.3795	9.3109	7	700	Beech	*	*	*	m	Eutric laptosol	*
26	Harste, Germany	51.6006	9.8401	8	750	Beech	*	*	*	m	Haplic lixisol	*
27	Lappwald, Germany	52.2137	10.8936	9	650	Beech	*	30.6	*	m	Eutric vertisol	*
28	Solling, Germany	51.7667	9.5833	6.4	1090	Beech	*	*	*	m	Dystric cambisol	*
29	Spanbeck, Germany	51.6082	10.0638	8.5	650	Spruce	*	*	*	m	Dystric cambisol	*
30	Göttinger Wald, Germany	51.5165	9.9898	8	680	Beech	*	*	*	m	Rendzic laptosol/Eutric cambisol	*
33	Höglwald, Germany	48.5000	11.1833	8.6	888	Beech	*	*	Moder	m	Typic Hapludalf	*
34	Höglwald, Germany	48.5000	11.1833	8.6	888	Spruce	*	*	Moder	m	Typic Hapludalf	*
35	Höglwald, Germany	48.5000	11.1833	8.6	888	Beech	*	*	Moder	m	Typic Hapludalf	*
36	Höglwald, Germany	48.5000	11.1833	8.6	888	Beech	*	*	Moder	m	Typic Hapludalf	*
37	Kienhorst, Germany	52.9667	68.3333	7.3	545	Beech	*	32.6	Raw humus	m	Orthic podzol	90% sand
38	Wildbahn, Germany	53.1333	33.3333	7.3	500	Pine	*	20.2	Raw humus/ moder	m	Dystric cambisols	89% sand
39	Hubertusstock, Germany	52.6667	13.6667	7.3	550	Pine	*	14.9	Raw humus/ moder	m	Dystric cambisols	93% sand
136	Whiteface Mt, NY, USA	44.4000	-73.9000	*	*	Fir	*	16	*	m	Spodosol	*
137	Mt Mansfield, VT, USA	44.5000	-72.8000	*	*	Spruce + fir	*	16	*	m	Spodosol	*
138	Saskatchewan region, Canada	105.7500	-53.0300	*	513	Aspen	*	15.0	*	m	*	Sandy
139	Saskatchewan region, Canada	105.7500	-53.0300	*	513	Aspen	*	15.0	*	m	*	Clay loam
40	Darmstadt, Germany	49.8600	8.6500	*	*	Beech + oak	*	*	*	m	Cambisol	*
140	New York, USA	27.0000	-82.0000	*	*	*	*	*	*	m	*	*

Location		Coordinates		Annual temperature	Annual precipitation	Vegetation Type (dominant type)	Depth to groundwater	N input	Humus Type	parent material	Soil Class	Soil Texture
ID	Name	Latitude	Longitude	[°C]	[mm]		[cm]	[kg N ha^{-1} yr^{-1}]		m=mineral, o=organic		
41	Nordtiroler Kalkalpen, Mühleggerköpfl, Austria	47.5656	11.6849	*	*	Spruce, fir, beech	*	16.5	*	m	*	*
42	Höglwald, Germany	48.5000	11.1833	7.3	800	Beech	*	20	*	m	Acid orthic Luvisols	*
43	Höglwald, Germany	48.5000	11.1833	7.3	800	Spruce	*	35	*	m	Acid orthic Luvisols	*
44	Höglwald, Germany	48.5000	11.1833	7.3	800	Beech	*	20	*	m	Acid orthic Luvisols	*
45	Höglwald, Germany	48.5000	11.1833	7.3	800	Spruce	*	35	*	m	Acid orthic Luvisols	*
141	University of Wisconsin Arboretum, Wisconsin, USA	43.0457	-89.4245	*	700	Oak	*	7.9	*	m	*	*
142	University of Wisconsin Arboretum, Wisconsin, USA	43.0457	-89.4245	*	700	Pine	*	15.8	*	m	*	*
46	Poppel, Belgium	51.4606	5.0537	11.2	807	Deciduous	*		*	m	*	Sand
47	North Tyrolean Alps, Austria	47.5656	11.6849	*	*	*	*	18	*	m	Rendzic leptosols + Chromic cambisols	*
48	Innsburck, Austria	47.2203	11.4463	*	*	Spruce	*	11.5	*	m	Cambisol	*
143	Rhode River, USA	38.8500	76.5333	*	*	Tulip poplar	*	*	*	m	Typic Hapludult	Sandy loam
144	Hubbard Brook, New hampshire, USA	*	*	*	*	*	*	*	*	m	Granitic glacial till	*
51	Achenkirch, Austria	47.5750	11.6368	6.5	1733	Spruce	*	11.3	*	m	Rendzic leptosols + Chromic cambisols	Loam
52	Achenkirch, Austria	47.5750	11.6368	6.5	1733	Spruce	*	11.3	*	m	Rendzic leptosols + Chromic cambisols	Loam

Location		Coordinates		Annual temperature	Annual precipitation	Vegetation Type (dominant type)	Depth to groundwater	N input	Humus Type	parent material	Soil Class	Soil Texture
ID	Name	Latitude	Longitude	[°C]	[mm]		[cm]	[kg N ha^{-1} yr^{-1}]		m=mineral, o=organic		
53	Gårdsjön, control well-drained, Sweden	58.6667	12.1667	*	*	Spruce	*	12.0	*	m	Orthic podzol	*
54	Wildmooswald 2, Germany	47.9500	8.1167	6.7	1060	Spruce	*	10	*	m	Chromic cambisol	*
55	Wildmooswald 1, Germany	47.9500	8.1167	6.7	1060	Spruce	*	10		m	Endoskeletic cambisol	*
56	Wildmooswald 3, Germany	47.9500	8.1167	6.7	1060	Spruce	*	10	*	m	Humic gleysol	*
57	Southern Finland, Finland	61.1900	24.9700	3.3	680	Spruce	*	*	*	m	Haplic podzol	*
145	Mount Taylor, NM, USA	35.2500	107.5667	14	1150	Douglas-fir	*		*	m	Clayey-skeletal Mollic Paleoboralf	*
58	Fingoi, Spain	42.9982	-7.5534	11.7	1022	Oak	*	*	*	m	Dystric cambisols	*
59	Bornhöved, Germany	54.1021	10.2240	7.3	829	Beech	*	23.8	*	m	Cambic arenosol	79% sand, 15% silt, 6.5% clay
146	Yasato, Central Japan	*	*	*	1307	Deciduos	*	15.7	*	m	Granitic brown soil	*
147	Kannondai, Central Japan	*	*	*	1076	Pine	*	30.6	*	m	Volcanic ash	*
60	Höglwald, Germany	48.5000	11.1833	7.6	850	Spruce	*	30.0	Moder	m	Typic Hapludalf	*
61	Höglwald, Germany	48.5000	11.1833	7.6	850	Spruce	*	30.0	Moder	m	Typic Hapludalf	*
62	Höglwald, Germany	48.5000	11.1833	7.6	850	Spruce	*	30.0	Moder	m	Typic Hapludalf	*
63	Höglwald, Germany	48.5000	11.1833	7.6	850	Beech	*	20.0	Moder	m	Typic Hapludalf	*
64	Höglwald, Germany	48.5000	11.1833	7.6	850	Beech	*	20.0	Moder	m	Typic Hapludalf	*
65	Höglwald, Germany	48.5000	11.1833	*	800	Spruce	*	40	*	m	Acid orthic Luvisols	41% sand, 36% silt, 23% clay
66	Höglwald, Germany	48.5000	11.1833	7.3	800	Spruce	*	*	*	m	Acid orthic Luvisols	*
67	Ober-Olm, Germany	49.9343	8.1895	*	*	Hornbeam-oak	*	*	*	m	Plostosolic brown soil	Loess loam

Location		Coordinates		Annual temperature	Annual precipitation	Vegetation Type (dominant type)	Depth to groundwater	N input	Humus Type	parent material	Soil Class	Soil Texture
ID	Name	Latitude	Longitude	[°C]	[mm]		[cm]	[kg N ha^{-1} yr^{-1}]		m=mineral, o=organic		
68	Ober-Olm, Germany	49.9343	8.1895	*	*	Hornbeam-oak	*	*	*	m	Pelosols	Loess loam
69	Bechenheim, Germany	49.7165	7.9984	*	*	Oak-beech-hornbeam	*	*	*	m	Grey-brown podzols	Loess
70	Langenlohnsheim, Germany	49.9097	7.8654	*	*	Oak	*	*	*	m	Grey-brown podzols	Loess
71	Langenlohnsheim, Germany	49.9097	7.8654	*	*	Oak	*	*	*	m	Brown soils	Sand
72	Bechenheim, Germany	49.7165	7.9984	*	*	Oak hornbeam	*	*	*	m	Pseudogley	Loess
73	Glencorse, UK	55.8477	-3.2250	*	*	Spruce	*	10.0	*	m	Brown forest soil	Clay loam/sandy clay loam
74	Glencorse, UK	55.8477	-3.2250	*	*	Birch	*	10	*	m	Brown forest soil	Clay loam/sandy clay loam
75	Glencorse, UK	55.8477	-3.2250	*	*	Alder	*	60	*	m	Brown forest soil	Clay loam/sandy clay loam
148	SE Scotland	*	*	*	*	Birch	*	20	*	m	*	Sandy clay loam
149	SE Scotland	*	*	*	*	Oak	*	20	*	m	*	Sandy clay loam
150	SE Scotland	*	*	*	*	Spruce	*	20	*	m	*	Sandy clay loam
151	SE Scotland	*	*	*	*	Alder	*	20	*	m	*	Sandy clay loam
76	Devilla forest, Central Scotland	56.0914	-3.6549	*	*	Pine	*	10	*	m	Brown forest soil	Sandy clay loam
78	Dyrehaven forest, Denmark	55.8069	12.5647	*	*	Ash	*	*	*	m	*	*
79	Dyrehaven forest, Denmark	55.8069	12.5647	*	*	Alder-N fixing	*	*	*	m	*	*
152	Central Germany	*	*	*	*	Oak	*	*	Moder	m	*	Loam
82	Steinerne Lahn, Austria	48.2333	16.2500	10.1	970	Beech	*	35.0	*	m	Dystric Cambisol	Silty loam
83	Klausenleopoldsdorf, Austria	48.1200	16.0500	8.6-8.9	763-1035	Beech	*	9.5-12.9	Moder	m	Dystic cambisol	Sandy clay loam

Location		Coordinates		Annual temperature	Annual precipitation	Vegetation Type (dominant type)	Depth to groundwater	N input	Humus Type	parent material	Soil Class	Soil Texture
ID	Name	Latitude	Longitude	[°C]	[mm]		[cm]	[kg N ha^{-1} yr^{-1}]		m=mineral, o=organic		
84	Sorø, Denmark	55.4800	11.6300	8.8-8.6	1013-532	Beech	*	45.6-23.9	Moder	m	*	Loamy sand
153	Wildbahn, Germany	53.1333	14.3333	8.3	616	Pine	*	12.3	Moder	m	*	Loamy sand
154	Harvard Forest, USA	42.0000	-72.0000	7.4	1120	Hard-woods	*	2.2	Moder	m	*	Sandy loam
85	Copenhagen, Denmark	55.0000	12.0000	8.6	756	Spruce	*	11.3	Moder	m	*	Loamy sand
86	Parco Ticino, Italy	45.2000	9.0700	14.3-14.5	1066-602	Poplar	*	10.7-6.0	Moder	m	*	Sandy loam
87	Parco Ticino, Italy	45.2000	9.0700	14.3-14.5	1066-602	Hard-woods	*	10.7-6.0	Mull	m	*	Loamy sand
88	Achenkirch, Austria	47.5800	11.6500	6.8-6.9	1691-1976	Spruce	*	2.7-7.7	Mull	m	Rendzic cambisol	Loam
89	Achenkirch, Austria	47.5800	11.6500	7.5-7.0	1747-1275	Spruce	*	6.8-5.0	Mull	m	Rendzic cambisol	Loam
90	Glencorse, UK	55.5800	-2.1700	9.1-7.9	1183-840	Birch	*	12.9-9.2	Moder	m	*	Silty loam
91	Klausenleopoldsdorf, Austria	48.1200	16.0500	9.0-8.3	959-515	Beech	*	12.0-6.4	Moder	m	Dystic cambisol	Sandy clay loam
92	Hyytiälä, Finland	61.8500	24.2800	4.2-4.1	535-644	Pine	*	0.09-0.1	Moder	m	*	Sandy loam
93	Speulderbos, Netherlands	52.2200	5.6500	10.6-10.2	924-613	Douglas fir	*	56.7-37.6	Moder	m	*	Sand
94	Höglwald, Germany	48.5000	11.1700	9.1-8.9	1054-571	Spruce	*	26.3-14.3	Moder	m	*	Loam
95	Höglwald, Germany	48.5000	11.1700	6.1-10.1	731-1041	Spruce	*	18.3-26.0	Moder	m	*	Loam
96	Höglwald, Germany	48.5000	11.1700	6.1-10.1	731-1041	Beech	*	18.3-26.0	Mull	m	*	Loam
97	Höglwald, Germany	48.5000	11.1700	9.1-8.9	1054-571	Beech	*	26.3-14.3	Mull	m	*	Sandy loam
98	Schottenwald, Austria	48.2300	15.2500	10.3-10.0	959-467	Beech	*	33.6-16.3	Moder	m	Cambisol	Silty loam
99	Glencorse, UK	55.8500	-3.1700	9.1-7.9	1183-840	Sitka spruce	*	12.9-9.2	Moder	m	*	Silty loam
100	Matrafüred, Hungary	47.9800	19.9500	9.0-8.1	809-678	Spruce	*	13.3-7.3	Moder	m	*	Sandy loam
101	Matrafüred, Hungary	47.8700	19.9700	9.0-8.1	809-678	Oak	*	8.7-6.5	Mull	m	*	Sandy loam
102	San Rossore, Italy	43.7300	10.2800	14.4-14.7	1101-742	Pine	*	5.5-3.7	Raw humus	m	*	Sand

Location		Coordinates		Annual temperature	Annual precipitation	Vegetation Type (dominant type)	Depth to groundwater	N input	Humus Type	parent material	Soil Class	Soil Texture
ID	Name	Latitude	Longitude	[°C]	[mm]		[cm]	[kg N ha^{-1} yr^{-1}]		m=mineral, o=organic		
103	Schottenwald, Austria	48.23	15.25	9.4-9.7	718-973	Beech	*	25.1-34.1	Moder	m	Cambisol	Silty loam
Site, Country		Coordinates		Annual temperature	Annual precipitation	Vegetation Type (dominant type)	Depth to groundwater	N input	Humus Type	parent material	Soil Class	Soil Texture
ID	Location	Latitude	Longitude	[°C]	[mm]		[cm]	[kg N ha^{-1} yr^{-1}]		m=mineral, o=organic		
OTHER VEGETATION												
104	Copenhagen, Denmark	55.5765°	12.5872°	*	*	Grass	*	*	*	m	*	Sandy
155	Inner Mongolia, China	43.3667	116.6667	0.5	350	Grass	*	*	*	m	Dark chesnut	Sandy loam
105	Siggen, Germany	47.7500	9.9500	6.5	1400	Grass	*	*	*	m	Gleyi-cumulic antrosols	*
156	University of Wisconsin Arboretum, Wisconsin, USA	*	*	*	700	Prairie	*	*	*	m	Loess over glacial till	*
106	Gårdsjön, Sweden	58.6667	12.1667	*	*	Grass	*	12.0	*	m	Orthic podzol	*
157	Central plains Exp. Range, CO, USA	40.8333	-104.7000	*	320	Grass	*	5	*	m	Ustollic camborthids	Sandy loam
107	Glencorse, UK	55.8477	-3.2250	*	*	Grass	*	10.0	*	m	*	Clay loam/sandy clay loam
108	Heino, The Netherlands	52.4287	6.2545	*	932	Grass	*	0-122	*	m	Fimic Anthrosol	Sand
109	Lelystad, The Netherlands	52.4729	5.4441	*	962	Grass	*	26-189	*	m	Calcaric Fluviosol	Clay
158	Xilin River catchemnt, China	43.5333	116.6667	0.4	350	Grass	*	*	*	m	Dark chesnut	Sandy loam
159	Xilin River catchemnt, China	43.5333	116.5500	*	320	Grass	*	*	*	m	Chestnut	Sandy loam
110	Bugac-Puszta, Hungary	46.6863	19.6010	10.5	500	Grass	*	7	*	m	*	Sandy
111	Cowpark, Scotland, UK	55.8667	-3.2000	8.6	849	Grass	*	9	*	m	Gleysol	Clay loam
112	Laqueuille, France	45.6391	2.7348	8	1313	Grass	*	14	*	m	Basaltic andosol	*

Location		Coordinates		Annual temperature	Annual precipitation	Vegetation Type (dominant type)	Depth to groundwater	N input	Humus Type	parent material	Soil Class	Soil Texture
ID	Name	Latitude	Longitude	[°C]	[mm]		[cm]	[kg N ha^{-1} yr^{-1}]		m=mineral, o=organic		
113	Oensingen, Switserland	47.2833	7.7333	9	1109	Grass-clover	*	15	*	m	Stagnic cambisol	*
ORGANIC SOILS												
20	Bornhöved, Germany	54.1021	10.2448	8	697	Beech	*	*	*	o	Histosol	Peat
23	Bornhöved, Germany	54.1021	10.2448	8	697	Beech	*	*	*	o	Histosol	Peat
114	Copenhagen, Denmark	55.55	12.5333	*	*	European nettle	*	*	*	o	*	Peat
160	University of Wisconsin Arboretum, Wisconsin, USA	*	*	*	700	Undrained marsh	*	*	*	o	*	Peat
115	Wildmooswald, Germany	47.9500	8.1167	6.7	1060	Spruce	*	10	*	o	Histic gleysol	Peat
116	Wildmooswald, Germany	47.9500	8.1167	6.7	1060	Spruce	*	10	*	o	Histic gleysol	Peat
117	Wildmooswald, Germany	47.9500	8.1167	6.7	1060	Spruce	*	10	*	o	Sapric histosol	Peat
118	Eastern, Finland	62.5166	29.3833	2.6	643	Birch	130	*	*	o	*	Peat
120	Bornhöved, Germany	59.9700	35.8100	8.1	679	Alder	*	69.0	*	o	Fibric Histosol	Peat
121	Ilomantsi, Finland	62.7666	30.9666	1.9	650	Mixed, birch	32	2.7	*	o	*	Peat
161	SE Scotland	*	*	*	*	Spruce	*	24.3	*	o	*	Peat
162	SE Scotland	*	*	*	*	Moorland	*	24.3	*	o	*	Peat
122	Dunslair Heights, NW England	55.6107	-3.13021	*	*	Spruce	*	6.4	*	o	Brown forest soil	Peat
123	Dunslair Heights, NW England	55.6107	-3.13021	*	*	Grass	*	24.3	*	o	Peaty podzol	Peat
124	Dunslair Heights, NW England	55.6107	-3.13021	*	*	Spruce	*	46.2	*	o	Peaty podzol	Peat
125	Zegveld, The Netherlands	52.1333	4.8000	*	857	Grass	*	1 to 73	*	o	Terric Histosol	Peat
126	Zegveld, The Netherlands	52.1333	4.8000	*	857	Grass	*	2 to 88	*	o	Terric Histosol	Peat

Location		Coordinates		Annual temperature	Annual precipitation	Vegetation Type (dominant type)	Depth to groundwater	N input	Humus Type	parent material	Soil Class	Soil Texture
ID	Name	Latitude	Longitude	[°C]	[mm]		[cm]	[kg N ha^{-1} yr^{-1}]		m=mineral, o=organic		
127	Asa, Sweden	57.1333	14.7500	5.6	662	Spruce	27	*	*	o	*	Peat
128	Asa, Sweden	57.1333	14.7500	5.6	662	Spruce	22	*	*	o	*	Peat
129	Asa, Sweden	57.1333	14.7500	5.6	662	Pine	17	*	*	o	*	Peat
130	Asa, Sweden	57.1333	14.7500	5.6	662	Birch	15	*	*	o	*	Peat
131	Asa, Sweden	57.13333	14.7500	5.6	662	Black alder	18	*	*	o	*	Peat
132	Asa, Sweden	57.13333	14.7500	5.6	662	Black alder	-1	*	*	o	*	Peat

B. Soil Characteristics

Location		depth of organic layer	Clay		pH			Organic C			C/N ratio			Soil Temperature	soil water content	WFPS
ID	Name	[cm]	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	[°C]	[%]	[%]
FOREST																
1	Copenhagen, Denmark	*	*	*	*	5.8-5.4	5.8-5.4	*	*	*	*	*	*	*	*	52-55
2	Copenhagen, Denmark	*	*	*	*	3.7-4.7	3.7-4.7	*	*	*	*	*	*	*	*	52-77
5	Gyrstinge, Sorø, Denmark	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6	Solling, ambient, Germany	*	*	*	*	3.2	3.2	*	*	*	*	*	*	*	*	*
7	Solling, ambient, Germany	*	*	*	*	3.2	3.2	*	*	*	*	*	*	7.2	*	*
8	Solling, Germany	*	28	28	*	*	*	*	*	*	*	*	*	*	*	*
9	Unterlüß, Germany	*	3	3	*	*	*	*	*	*	*	*	*	*	*	*
10	Unterlüß, Germany	*	8	8	*	*	*	*	*	*	*	*	*	*	*	*
11	Unterlüß, Germany	*	4	4	*	*	*	*	*	*	*	*	*	*	*	*
12	Solling, Germany	*	19	19	*	*	*	*	*	*	*	*	*	*	*	*
13	Solling, Germany	*	15	15	*	*	*	*	*	*	*	*	*	*	*	*
14	Solling, Germany	*	*	*	*	*	*	*	*	*	*	*	*	9.8	39	*
15	Solling, Germany	*	*	*	*	*	*	*	*	*	*	*	*	9.9	42	*
16	Solling, Germany	*	*	*	*	*	*	*	*	*	25.6	*	*	9.8	42	*
17	Solling, Germany	*	*	*	*	*	*	*	*	*	19.1	*	*	10	48	*
133	Bousson Environmental Reseach Reserve, northwest Pennsylvania, USA	0-2	2	2	*	4	4	*	*	*	*	*	*	*	*	*
134	Harvard forest, Petersham, Massachussets, USA	*	*	*	*	3.2	3.2	*	*	*	*	*	*	*	*	*
135	Harvard forest, Petersham, Massachussets, USA	*	*	*	*	3.3	3.3	*	*	*	*	*	*	*	*	*
19	Solling, Germany	5	*	*	*	3	*	510	57	*	19.0	*	*	*	*	*
21	Solling, Germany	*	*	*	*	3.9	*	*	38.1	*	*	*	*	*	*	*
22	Harz, Germany	*	*	*	*	3.6	*	*	34	*	*	*	*	*	*	*
24	Lappwald, Germany	*	*	*	*	4.1	*	*	32.2	*	*	*	*	*	*	*

Location		depth of organic layer	Clay		pH			Organic C			C/N ratio			Soil Temperature	soil water content	WFPS
ID	Name	[cm]	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	[°C]	[%]	[%]
25	Zierenberg, Germany	*	*	*	*	5.6	*	*	49.5	*	*	*	*	*	*	*
26	Harste, Germany	*	*	*	*	4.3	*	*	18.6	*	*	*	*	*	*	*
27	Lappwald, Germany	*	*	*	*	5.1	*	*	47.2	*	*	*	*	*	*	*
28	Solling, Germany	*	*	*	*	3.9	*	*	46.3	*	*	*	*	*	*	*
29	Spanbeck, Germany	*	*	*	*	3.9	*	*	26.3	*	*	*	*	*	*	*
30	Göttinger Wald, Germany	*	*	*	*	5.2	*	*	51.8	*	*	*	*	*	*	*
33	Höglwald, Germany	7-8	*	*	3	3.5	3.5	*	*	*	24	17	17	*	*	*
34	Höglwald, Germany	7-8	*	*	3	3.4	3.4	*	*	*	25	14	14	*	*	*
35	Höglwald, Germany	7-8	*	*	3.9	3.7	3.7	*	*	*	22	17	17	*	*	*
36	Höglwald, Germany	7-8	*	*	4.2	3.5	3.5	*	*	*	21	16	16	*	*	*
37	Kienhorst, Germany	*	7	7	3.1	3.5	3.5	*	*	*	33	26	26	*	*	*
38	Wildbahn, Germany	*	7	7	3.1	3.4	3.4	*	*	*	27	25	25	*	*	*
39	Hubertusstock, Germany	*	10	10	3.2	3.6	3.6	*	*	*	28	19	19	*	*	*
136	Whiteface Mt, NY, USA	<10	*	*	2.9	*	*	*	*	*	*	*	*	*	*	*
137	Mt Mansfield, VT, USA	<10	*	*	2.9	*	*	*	*	*	*	*	*	*	*	*
138	Saskatchewan region, Canada	*	6	6	*	*	*	*	*	*	*	16	16	*	*	*
139	Saskatchewan region, Canada	*	30	30	*	*	*	*	*	*	*	13	13	*	*	*
40	Darmstadt, Germany	5	*	*	3.1	3.5	3.5	99	19	19	19	21	21	*	*	*
140	New York, USA	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
41	Nordtiroler Kalkalpen, Mühleggerköpfl, Austria	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
42	Höglwald, Germany	6	*	*		3.6	3.6	*	*	*	*	*	*	*	*	*
43	Höglwald, Germany	6	*	*	3	3.6	3.6	*	*	*	*	*	*	*	*	*
44	Höglwald, Germany	6	*	*		3.6	3.6	*	*	*	*	*	*	*	*	*
45	Höglwald, Germany	6	*	*	3	3.6	3.6	*	*	*	*	*	*	*	*	*
141	University of Wisconsin Arboretum, Wisconsin, USA	*	*	*	*	5	5	*	26	26	*	14	14	*	*	*
142	University of Wisconsin Arboretum, Wisconsin, USA	*	*	*	*	4.5	4.5	*	24	24	*	16	16	*	*	*
46	Poppel, Belgium	*	2.4	2.4	*	3.8	3.8	*	78	78	*	26	26	*	*	11-46

Location		depth of organic layer	Clay		pH			Organic C			C/N ratio			Soil Temperature	soil water content	WFPS
ID	Name	[cm]	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	[°C]	[%]	[%]
47	North Tyrolean Alps, Austria	*	*	*	*	5.8-7.0	5.8-7.0	*	150	150	*	17	17	10	56	*
48	Innsburck, Austria	3	*	*	*	3.8	3.8	*	*	*	*	*	*	*	*	*
143	Rhode River, USA	*	*	*	*	*	*	*	*	*	*	*	*	8.7-24	*	*
144	Hubbard Brook, New hampshire, USA	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
51	Achenkirch, Austria	*	*	*	*	6.4	6.4	*	150	150	*	17	17	*	*	8
52	Achenkirch, Austria	*	*	*	*	6.4	6.4	*	150	150	*	17	17	*	*	*
53	Gårdsjön, control well-drained, Sweden	*	*	*	*	4	4	*	*	*	*	*	*	*	*	*
54	Wildmooswald 2, Germany	9	*	*	3.2	3.3	3.3	268	116	116	21	14.5	14.5	*	*	*
55	Wildmooswald 1, Germany	11	18	18	2.9	3.1	3.1	309	109	109	20	15	15	*	*	*
56	Wildmooswald 3, Germany	18	17	17	2.9	3.2	3.2	295	128	128	24	21	21	*	*	*
57	Southern Finland, Finland	3	*	*	3.6	3.7	3.7	130	48	48	22	*	*	*	*	*
145	Mount Taylor, NM, USA	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
58	Fingoi, Spain	4-6	*	*	*	4	4	*	37.7	37.7	*	*	*	11.5	25	*
59	Bornhöved, Germany	*	6.5	6.5	*	4	4	*	34	34	*	17	17	*	*	*
146	Yasato, Central Japan	*	*	*	*	4.8	4.8	*	*	*	*	16.7	16.7	13.3 (3-24)	*	*
147	Kannondai, Central Japan	*	*	*	*	5.4	5.4	*	*	*	*	15.9	15.9	14.5 (5-25)	*	*
60	Höglwald, Germany	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
61	Höglwald, Germany	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
62	Höglwald, Germany	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
63	Höglwald, Germany	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
64	Höglwald, Germany	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
65	Höglwald, Germany	6	23	23	*	3.7	3.7	*	*	*	*	*	*	*	*	*
66	Höglwald, Germany	6	*	*	*	3.4	3.4	*	*	*	*	*	*	*	*	*
67	Ober-Olm, Germany	<1	12	12	*	4.7	4.7	*	28	28	*	18	18	9.3	26	26
68	Ober-Olm, Germany	<1	26	26	*	6.7	6.7	*	36	36	*	12	12	9.6	21	21
69	Bechenheim, Germany	1-2	19	19	*	3.7	3.7	*	24	24	*	22	22	8.6	25	25
70	Langenlohnsheim, Germany	1-5	11	11	*	3.6	3.6	*	28	28	*	13	13	10.7	24	24
71	Langenlohnsheim, Germany	1-3	18	18	*	3.7	3.7	*	72	72	*	25	25	11.2	23	23

Location		depth of organic layer	Clay		pH			Organic C			C/N ratio			Soil Temperature	soil water content	WFPS
ID	Name	[cm]	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	[°C]	[%]	[%]
72	Bechenheim, Germany	1-3	17	17	*	3.4	3.4	*	34	34	*	19	19	10.2	25	25
73	Glencorse, UK	*	*	*	*	4.5	4.5	*	*	*	*	*	*	10	29	*
74	Glencorse, UK	*	*	*	*	4.9	4.9	*	*	*	*	*	*	10	26	*
75	Glencorse, UK	*	*	*	*	4.2	4.2	*	*	*	*	*	*	9	25	*
148	SE Scotland	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
149	SE Scotland	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
150	SE Scotland	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
151	SE Scotland	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
76	Devilla forest, Central Scotland	*	*	*	*	3.5	3.5	*	*	*	*	*	*	11	30	*
78	Dyrehaven forest, Denmark	1-3	*	*	*	7.0	7.0	*	*	*	*	*	*	*	*	*
79	Dyrehaven forest, Denmark	1-3	*	*	*	6.7	6.7	*	*	*	*	*	*	*	*	*
152	Central Germany	4	18	18	4.1	4.2	4.2	81	12	12	17	12	12	*	*	69
82	Steinerne Lahn, Austria	*	*	*	*	*	*	*	*	*	*	*	*	*	19-36	*
83	Klausenleopoldsdorf, Austria	*	27	27	5.2	4.5	4.5	*	51	51	*	16	16	8.4	41	59
84	Sorø, Denmark	*	9	9	4.3	4.5	4.5	*	40	40	*	17.7	17.7	7.6	25	36
153	Wildbahn, Germany	*	6	6	3.3	3.6	3.6	*	35	35	*	*	*	*	*	*
154	Harvard Forest, USA	*	9	9	3.3	3.8	3.8	*	76	76	*	*	*	*	*	*
85	Copenhagen, Denmark	*	6	6	3.7	3.7	3.7	*	61	61	*	*	*	*	*	*
86	Parco Ticino, Italy	*	9	9	5.8	5.9	5.9	*	10	10	*	15.3	15.3	13.9	29	51
87	Parco Ticino, Italy	*	6	6	4.1	4.2	4.2	*	67	67	*	17.9	17.9	12.2	31	44
88	Achenkirch, Austria	*	19	19	5.7	7	7	*	77	77	*	18	18	6.2	50	60
89	Achenkirch, Austria	*	19	19	5.7	7	7	*	77	77	*	*	*	*	*	*
90	Glencorse, UK	*	18	18	4.8	4.8	4.8	*	70	70	*	13.8	13.8	6.6	31	44
91	Klausenleopoldsdorf, Austria	*	27	27	5.2	4.5	4.5	*	51	51	*	*	*	*	*	*
92	Hyytiälä, Finland	*	9	9	3.2	3.7	3.7	*	29	29	*	37.7	37.7	4.6	26	38
93	Speulderbos, Netherlands	*	3	3	3.7	3.7	3.7	*	90	90	*	43	43	9.4	18	31
94	Höglwald, Germany	*	19	19	3.2	3.5	3.5	*	29	29	*	*	*	*	*	*
95	Höglwald, Germany	*	19	19	3.2	3.5	3.5	*	29	29	*	18.8	18.8	8.6	32	56
96	Höglwald, Germany	*	19	19	4	3.7	3.7	*	51	51	*	15.8	15.8	8.3	*	*
97	Höglwald, Germany	*	9	9	4.5	4	4	*	51	51	*	25.8	25.8	8.3	*	*
98	Schottenwald, Austria	*	18	18	5	4.2	4.2	*	68	68	*	*	*	*	*	*

Location		depth of organic layer	Clay		pH			Organic C			C/N ratio			Soil Temperature	soil water content	WFPS
ID	Name	[cm]	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	[°C]	[%]	[%]
99	Glencorse, UK	*	18	18	4.2	4.2	4.2	*	70	70	*	13.8	13.8	6.3	26	36
100	Matrafüred, Hungary	*	9	9	4.5	3.9	3.9	*	19	19	*	12.9	12.9	5.6	26	53
101	Matrafüred, Hungary	*	9	9	5.7	4.3	4.3	*	36	36	*	13.5	13.5	8.2	26	59
102	San Rossore, Italy	*	3	3	5	5.8	5.8	*	7	7	*	29.9	29.9	14	11	21
103	Schottenwald, Austria	*	18	18	5	4.2	4.2	*	68	68	*	13.4	13.4	8.1	27	60
OTHER VEGETATION																
104	Copenhagen, Denmark	*	*	*	*	6.5-7.4	6.5-7.4	*	*	*	*	*	*	*	*	14-89
155	Inner Mongolia, China	*	*	*	*	6.9	6.9	*	185	185	*	9.8	9.8	*	*	15-40
105	Siggen, Germany	*	33	33	*	*	*	*	35	35	*	8.3	8.3	*	*	*
156	University of Wisconsin Arboretum, Wisconsin, USA	*	*	*	*	6.0	6.0	*	65	65	*	13	13	*	*	*
106	Gårdsjön, Sweden	*	*	*	*	4	4	*	*	*	*	*	*	*	*	*
157	Central plains Exp. Range, CO, USA	*	11	11	*	7.8	7.8	*	7	7	*	8.1	8.1	11.4	*	*
107	Glencorse, UK	*	*	*	*	4.8	4.8	*	*	*	*	*	*	11	30	*
108	Heino, The Netherlands	*	*	*	*	*	*	*	*	*	*	*	*	0.4-20.1	*	*
109	Lelystad, The Netherlands	*	*	*	*	*	*	*	*	*	*	*	*	0.5-24.5	*	*
158	Xilin River catchemnt, China	*	*	*	*	6.6	6.6	*	*	*	*	*	*	*	*	*
159	Xilin River catchemnt, China	*	*	*	*	7.8	7.8	*	*	*	*	*	*	*	*	*
110	Bugac-Puszta, Hungary	*	20	20	*	7.7	7.7	*	55	55	*	16	16	1.9-23.5	*	11-43
111	Cowpark, Scotland, UK	*	25	25	*	6.4	6.4	*	38	38	*	14.1	14.1	3.2-15.1	*	52-100
112	Laqueuille, France	*	18	18	*	5.3	5.3	*	80	80	*	10.7	10.7	5.7-18.0	*	36-57
113	Oensingen, Switserland	*	43	43	*	7.5	7.5	*	24	24	*	9.7	9.7	1.7-21.9	*	32-80
ORGANIC SOILS																
20	Bornhöved, Germany	*	*	*	*	3.9	*	*	181	*	*	*	*	*	*	*
23	Bornhöved, Germany	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Location		depth of organic layer	Clay		pH			Organic C			C/N ratio			Soil Temperature	soil water content	WFPS
ID	Name	[cm]	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	org layer	0-10	10-20	[°C]	[%]	[%]
114	Copenhagen, Denmark	*	*	*	*	6.7-7.0	6.7-7.0	*	*	*	*	*	*	*	*	48-73
160	University of Wisconsin Arboretum, Wisconsin, USA	*	*	*	*	7.0	7.0	*	64	64	*	17	17	*	*	*
115	Wildmooswald, Germany	11	23	23	3.1	3.7	3.7	430	394	394	29	20	20	*	*	*
116	Wildmooswald, Germany	13	20	20	3.1	3.7	3.7	415	301	301	28	17	17	*	*	*
117	Wildmooswald, Germany	12	*	*	3.5	3.6	3.6	460	485	485	25	24	24	*	*	*
118	Eastern, Finland	50	*	*	*	4.5	4.5	490	*	*	*	20	20	*	*	15-90
120	Bornhöved, Germany	*	*	*	*	4	4	*	422	422	*	18	18	*	*	*
121	Ilomantsi, Finland	*	*	*	5.3	4.5	4.5	500	*	*	18	*	*	*	*	51-94
161	SE Scotland	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
162	SE Scotland	*	*	*	*	3.3	3.3	*	*	*	*	*	*	*	70	*
122	Dunslair Heights, NW England	10	*	*	*	3.1	3.1	*	*	*	*	*	*	7.8	104	*
123	Dunslair Heights, NW England	17-27	*	*	*	3.3	3.3	*	*	*	*	*	*	7.8	139	*
124	Dunslair Heights, NW England	20-30	*	*	*	3.2	3.2	*	*	*	*	*	*	6.9	167	*
125	Zegveld, The Netherlands	*	*	*	*	*	*	*	*	*	*	*	*	0.6-20.9	*	*
126	Zegveld, The Netherlands	*	*	*	*	*	*	*	*	*	*	*	*	0.2-22.3	*	*
127	Asa, Sweden	90	*	*	*	3.2	3.2	490	*	*	28	*	*	*	*	*
128	Asa, Sweden	70	*	*	*	3.3	3.3	480	*	*	26	*	*	*	*	*
129	Asa, Sweden	120	*	*	*	2.7	2.7	510	*	*	40	*	*	*	*	*
130	Asa, Sweden	82	*	*	*	3.4	3.4	530	*	*	22	*	*	*	*	*
131	Asa, Sweden	28	*	*	*	4.5	4.5	520	*	*	16	*	*	*	*	*
132	Asa, Sweden	53	*	*	*	4.2	4.2	540	*	*	21	*	*	*	*	*

C. N_2O measurements

Location		Period of measurement N_2O	Measuring Method N_2O	Measuring Frequency	Number of measuring devices	Number of replicates	Mean N_2O emission [kg N ha^{-1} yr^{-1}]
ID	Name						
FOREST							
1	Copenhagen, Denmark	Dec 1989 - Sep 1990 + Feb 1992 - Jan 1993	PVC cylinders	once every 2 or 4 weeks	30	*	0.292
2	Copenhagen, Denmark	Dec 1989 - Sep 1990 + Feb 1992 - Jan 1993	PVC cylinders	once every 2 or 4 weeks	30	*	0.292
5	Gyrstinge, Sorø, Denmark	1998	*	*	*	*	0.5
6	Solling, ambient, Germany	Jan 1993 - Jan 1994	closed chamber	weekly or biweekly	4	3	0.3
7	Solling, ambient, Germany	Apr 2000 - Apr 2001	closed chamber	weekly or biweekly	4	3	0.4
8	Solling, Germany	Oct 1997 - Dec 1999	PVC columns	10/97-4/98 monthly 4/98-12/99 biweekly	5	3	1998 1.0 ± 0.1 1999 0.6 ± 0.1
9	Unterlüß, Germany	Oct 1997 - Dec 1999	PVC columns	10/97-4/98 monthly 4/98-12/99 biweekly	5	3	1998 0.6 ±0.1 1999 0.4 ±0.1
10	Unterlüß, Germany	Oct 1997 - Dec 1999	PVC columns	10/97-4/98 monthly 4/98-12/99 biweekly	5	3	1998 0.6 ±0.1 1999 0.5 ±0.1
11	Unterlüß, Germany	Oct 1997 - Dec 1999	PVC columns	10/97-4/98 monthly 4/98-12/99 biweekly	5	3	1998 0.8 ±0.1 1999 0.4 ±0.1
12	Solling, Germany	Oct 1997 - Dec 1999	PVC columns	10/97-4/98 monthly 4/98-12/99 biweekly	5	3	1998 1.1 ±0.2 1999 0.5 ±0.0
13	Solling, Germany	Oct 1997 - Dec 1999	PVC columns	10/97-4/98 monthly 4/98-12/99 biweekly	5	3	1998 1.3 ±0.1 1999 0.6 ±0.1
14	Solling, Germany	May 1999 - May 2001	cylindrical PVC columns	biweekly to monthly	5	3	0.5
15	Solling, Germany	May 1999 - May 2001	cylindrical PVC columns	biweekly to monthly	5	3	0.8
16	Solling, Germany	May 1999 - May 2001	cylindrical PVC columns	biweekly to monthyl	5	3	0.8
17	Solling, Germany	May 1999 - May 2001	cylindrical PVC columns	biweekly to monthly	5	3	1.1
133	Bousson Environmental Reseach Reserve, northwest Pennsylvania, USA	Jul 1993 - 0ct 1994	PVC cylinders	monthly	4	4	0.2

Location		Period of measurement N_2O	Measuring Method N_2O	Measuring Frequency	Number of measuring devices	Number of replicates	Mean N_2O emission [kg N ha^{-1} yr^{-1}]
ID	Name						
134	Harvard forest, Petersham, Massachussets, USA	Jan - Dec	closed chamber	less than once a week	*	*	0.0
135	Harvard forest, Petersham, Massachussets, USA	Jan – Dec	closed chamber	less than once a week	*	*	0.0
19	Solling, Germany	1987 – 1988	automatic chamber	daily	3	3	5.6
21	Solling, Germany	Mar 1993 - Mar 1994	closed chamber	weekly	*	*	3.0
22	Harz, Germany	Aug 1994 - Nov 1995	closed chamber	biweekly	*	*	1.3
24	Lappwald, Germany	Mar 1993 - Mar 1994	closed chamber	biweekly	*	*	0.6
25	Zierenberg, Germany	May 1991 - May 1992	closed chamber	*	*	*	0.4
26	Harste, Germany	Mar 1993 - Mar 1994	closed chamber	biweekly	*	*	0.4
27	Lappwald, Germany	Mar 1993 - Mar 1994	closed chamber	biweekly	*	*	0.3
28	Solling, Germany	Mar 1993 - Mar 1994	closed chamber	weekly	*	*	0.3
29	Spanbeck, Germany	Mar 1993 - Mar 1994	closed chamber	biweekly	*	*	0.2
30	Göttinger Wald, Germany	Mar 1993 - Mar 1994	closed chamber	biweekly	*	*	0.2
33	Höglwald, Germany	Jan - Dec 1997	closed chamber	continuously	2	*	0.5
34	Höglwald, Germany	Jan - Dec 1997	Tree chamber: 4m2 covered around tree	continuously	2	*	0.8
35	Höglwald, Germany	Jan - Dec 1997	closed chamber	continuously	2	*	1.6
36	Höglwald, Germany	Jan - Dec 1997	Tree chamber: 4m2 covered around tree	continuously	2	*	4.3
37	Kienhorst, Germany	1996 – 1998	fully automated closed chambers	1/2 hours	5	*	1.7
38	Wildbahn, Germany	1995 – 1998	fully automated closed chambers	1/2 hours	5	*	5.7
39	Hubertusstock, Germany	1995 – 1998	fully automated closed chambers	1/2 hours	5	*	3.5
136	Whiteface Mt, NY, USA	1990	closed static chamber	*	6	4	0.2
137	Mt Mansfield, VT, USA	1990	closed static chamber	*	6	4	0.2
138	Saskatchewan region, Canada	Jun 1994 - May 1995	sealed chamber	weekly to monthly	10	*	0.0
139	Saskatchewan region, Canada	May 1993 - May 1995	sealed chamber	weekly to monthly	10	*	0.0
40	Darmstadt, Germany	Oct 1990 - Dec 1991	closed chamber	1-10 times per month	1	3	0.5
140	New York, USA	Jan – Dec	closed chamber	once or twice a week	*	*	0.9

Location		Period of measurement N_2O	Measuring Method N_2O	Measuring Frequency	Number of measuring devices	Number of replicates	Mean N_2O emission [kg N ha^{-1} yr^{-1}]
ID	Name						
41	Nordtiroler Kalkalpen, Mühleggerköpfl, Austria	1998 – 1999	*	*	*	*	0.7
42	Höglwald, Germany	*	*	*	*	*	*
43	Höglwald, Germany	*	*	*	*	*	*
44	Höglwald, Germany	*	*	*	*	*	*
45	Höglwald, Germany	*	*	*	*	*	*
141	University of Wisconsin Arboretum, Wisconsin, USA	Jun - Nov 1979 + Mar - Dec 1980	closed chamber	weekly	3	4	0.9
142	University of Wisconsin Arboretum, Wisconsin, USA	Jun - Nov 1979 + Mar - Dec 1980	closed chamber	weekly	3	4	3.2
46	Poppel, Belgium	Apr 1997 - Jan 1999	vented closed chambers	1997:every 3 weeks 1998: event based (after rainfall)	6	5	-0.8
47	North Tyrolean Alps, Austria	May 1998 - 0ct 1999	closed chamber	biweekly	6	3	0.9125
48	Innsburck, Austria	Jun 1990 - Jul 1991	*	biweekly	12	*	0.073
143	Rhode River, USA	Oct1993 - Sep 1994	moveable flow through chambers	continuously	1993: 1, 1994:2	*	0.657
144	Hubbard Brook, New hampshire, USA	Jan – Dec	closed chamber	daily	*	*	0.9
51	Achenkirch, Austria	May 2002 - Jul 2004	automatic gas sampler	1/day	1	*	0.219
52	Achenkirch, Austria	May 2002 - Jul 2004	closed chamber	biweekly	*	2	0.365
53	Gårdsjön, control well-drained, Sweden	Apr 1993 - Oct 1994	closed chamber	2/month	3	3	0.1
54	Wildmooswald 2, Germany	Jan 2003 - Dec 2004	closed chamber	weekly to biweekly	2	4	0.365
55	Wildmooswald 1, Germany	Jan 2003 - Dec 2004	closed chamber	weekly to biweekly	2	4	0.73
56	Wildmooswald 3, Germany	Jan 2003 - Dec 2004	closed chamber	weekly to biweekly	2	4	1.533
57	Southern Finland, Finland	2000 – 2003	static dark chambers	monthly	3	*	1.241
145	Mount Taylor, NM, USA	May - Oct 1986 + May - Oct 1987	PVC ring	*	12	5	0.2
58	Fingoi, Spain	Jul 1998 - Jul 2000	static closed chamber	every 2-3 weeks	*	2	0.803
59	Bornhöved, Germany	Jan - Dec 1993	closed soil cover boxes	weekly	6	*	0.4015

Location		Period of measurement N_2O	Measuring Method N_2O	Measuring Frequency	Number of measuring devices	Number of replicates	Mean N_2O emission [kg N ha^{-1} yr^{-1}]
ID	Name						
146	Yasato, Central Japan	Jun 1999 - May 2000	closed chamber	every 2 weeks	6	4	0.2
147	Kannondai, Central Japan	Jun 1999 - May 2000	closed chamber	every 2 weeks	6	4	0.4
60	Höglwald, Germany	1994	*	*	*	*	0.4
61	Höglwald, Germany	1996	*	*	*	*	3.1
62	Höglwald, Germany	1995	*	*	*	*	0.8
63	Höglwald, Germany	1995	*	*	*	*	3.7
64	Höglwald, Germany	1996	*	*	*	*	6.6
65	Höglwald, Germany	Dec – Sep	closed chamber	continously	*	*	2.6
66	Höglwald, Germany	*	*	*	*	*	*
67	Ober-Olm, Germany	Jul 1981 - Aug 1982	closed chamber	every 2 weeks	3	6	0.3
68	Ober-Olm, Germany	Jul 1981 - Aug 1982	closed chamber	every 2 weeks	3	6	0.3
69	Bechenheim, Germany	Jul 1981 - Aug 1982	closed chamber	every 2 weeks	3	6	0.7
70	Langenlohnsheim, Germany	Jul 1981 - Aug 1982	closed chamber	every 2 weeks	3	6	0.7
71	Langenlohnsheim, Germany	Jul 1981 - Aug 1982	closed chamber	every 2 weeks	3	6	0.7
72	Bechenheim, Germany	Jul 1981 - Aug 1982	closed chamber	every 2 weeks	3	6	0.9
73	Glencorse, UK	Oct 1992 - dec 1993	static chamber	2/month	3	*	0.3
74	Glencorse, UK	Oct 1992 - dec 1993	static chamber	biweekly	3	*	0.6205
75	Glencorse, UK	Oct 1992 - dec 1993	static chamber	biweekly	3	*	1.679
148	SE Scotland	*	closed chamber	*	*	*	0.4
149	SE Scotland	*	closed chamber	*	*	*	0.3
150	SE Scotland	*	closed chamber	*	*	*	0.9
151	SE Scotland	*	closed chamber	*	*	*	0.7
76	Devilla forest, Central Scotland	May - Oct 1993 + Apr 1994 - Feb 1995	closed chamber	every 2-3 weeks	9	*	0.4
78	Dyrehaven forest, Denmark	Sep 1984 - Aug 1985	closed chamber	less than once a week	2	*	0.3
79	Dyrehaven forest, Denmark	Sep 1984 - Aug 1985	closed chamber	less than once a week	2	*	1.8
152	Central Germany	Dec 1995 - Nov 1996	closed chamber	once a week	5	*	1.387
82	Steinerne Lahn, Austria	Jan 1996 - Dec 1998	closed chamber	weekly to monthly	4	2	4.1
83	Klausenleopoldsdorf, Austria	1996 – 1997	*	*	*	*	1.9-2.4
84	Sorø, Denmark	2002 – 2003	static closed chamber	1/day	1	*	0.5-0.9
153	Wildbahn, Germany	1997	*	*	*	*	0.6
154	Harvard Forest, USA	1989	*	*	*	*	*
85	Copenhagen, Denmark	1992	*	*	*	*	0.8
86	Parco Ticino, Italy	2002 – 2003	static closed chamber	1/day	1	*	0.2-0.3

Location		Period of measurement N_2O	Measuring Method N_2O	Measuring Frequency	Number of measuring devices	Number of replicates	Mean N_2O emission [kg N ha^{-1} yr^{-1}]
ID	Name						
87	Parco Ticino, Italy	2002 – 2003	static closed chamber	1/day	1	*	0.2-0.5
88	Achenkirch, Austria	1998 – 1999	static closed chamber	biweekly	6	3	0.9-1.5
89	Achenkirch, Austria	2002 – 2003	static closed chamber	1/day	1	*	0.3-0.4
90	Glencorse, UK	2002 – 2003	static closed chamber	1/day	1	*	0.2
91	Klausenleopoldsdorf, Austria	2002 – 2003	static closed chamber	1/day	1	*	0.5-0.7
92	Hyytiälä, Finland	2002 – 2003	static closed chamber	2/month	6	*	0.04-0.07
93	Speulderbos, Netherlands	2002 – 2003	static closed chamber	1/hour	4	*	0.4-0.3
94	Höglwald, Germany	2002 – 2003	static closed chamber	2/hour	5	*	0.4-0.7
95	Höglwald, Germany	1994 – 1797	*	*	*	*	0.4-3.1
96	Höglwald, Germany	1994 – 1997	*	*	*	*	1.0-6.6
97	Höglwald, Germany	2002 – 2003	static closed chamber	2/hour	5	*	0.8-1.4
98	Schottenwald, Austria	2002 – 2003	static closed chamber	1/day	1	*	3.6-4.1
99	Glencorse, UK	2002 – 2003	static closed chamber	1/day	1	*	0.07
100	Matrafüred, Hungary	2002 – 2003	static closed chamber	2/month	8	*	1.5-2.4
101	Matrafüred, Hungary	2002 – 2003	static closed chamber	2/month	8	*	1.8
102	San Rossore, Italy	2002 – 2003	static closed chamber	1/day	1	*	0.07-0.3
103	Schottenwald, Austria	1996 – 1997	*	*	*	*	4.9-5.8
OTHER VEGETATION							
104	Copenhagen, Denmark	Dec 1989 - Sep 1990 + Feb 1992 - Jan 1993	PVC cylinders	once every 2 or 4 weeks	34	*	0.438
155	Inner Mongolia, China	1995 + 1998 + 2001-2003	closed chamber	twice a week to monthly	3	4	0.27 ± 0.2

Location		Period of measurement N_2O	Measuring Method N_2O	Measuring Frequency	Number of measuring devices	Number of replicates	Mean N_2O emission [kg N ha^{-1} yr^{-1}]
ID	Name						
105	Siggen, Germany	Sep 1996 - Mar 1998	closed chamber	1-3 times a week	4	*	0.2
156	University of Wisconsin Arboretum, Wisconsin, USA	Jun - Nov 1979 + Apr - Nov 1980	closed chamber	weekly	3	4	0.2
106	Gårdsjön, Sweden	Apr 1993 - Oct 1994	closed chamber	2/month	6	3	0.1
157	Central plains Exp. Range, CO, USA	Apr 1997 - Oct 2000	vented closed chambers	weekly	2	3	0.1
107	Glencorse, UK	Oct 1992 - Dec 1993	static chamber	every 2 weeks	3	*	0.8
108	Heino, The Netherlands	Mar 1992 - Mar 1994	vented closed chambers	weekly	18	4	1.1
109	Lelystad, The Netherlands	Mar 1992 - Mar 1994	vented closed chambers	weekly	18	4	0.8
158	Xilin River catchemnt, China	1998 – 1999	static chamber	weekly to monthly	3	4	0.2
159	Xilin River catchemnt, China	1998 - 1999	static chamber	weekly to monthly	3	4	0.1
110	Bugac-Puszta, Hungary	2002 – 2004	manual static chamber	biweekly	5	*	1.5
111	Cowpark, Scotland, UK	2002 – 2004	manual static chamber	weekly to monthly	3	*	0.5
112	Laqueuille, France	2002 – 2004	manual static chamber	biweekly	8-10	*	0.3
113	Oensingen, Switserland	2002 – 2004	manual static chamber	biweekly	2-6	*	0.6
ORGANIC SOILS							
20	Bornhöved, Germany	Mar 1993 - Mar 1994	closed chamber	weekly	*	*	7.3
23	Bornhöved, Germany	Jul 1995 - Jul 1996	closed chamber	weekly	*	*	0.8
114	Copenhagen, Denmark	Dec 1989 - Sep 1990 + Feb 1992 - Jan 1993	PVC cylinders	once every 2 or 4 weeks	30	*	0.2555
160	University of Wisconsin Arboretum, Wisconsin, USA	Jul - Nov 1979 + Apr - Nov 1980	closed chamber	weekly	3	4	0.09
115	Wildmooswald, Germany	Jan 2003 - Dec 2004	closed chamber	weekly to biweekly	2	4	1.752
116	Wildmooswald, Germany	Jan 2003 - Dec 2004	closed chamber	weekly to biweekly	2	4	2.117
117	Wildmooswald, Germany	Jan 2003 - Dec 2004	closed chamber	weekly to biweekly	2	4	3.796
118	Eastern, Finland	Apr 1996 - Apr 1998	static dark chambers	weekly, in winter monthly	3	5	4.1975
120	Bornhöved, Germany	Jan - Dec 1993	closed chamber	weekly	6	4	4.9
121	Ilomantsi, Finland	1992 – 1995	aluminium chamber	weekly to monthly	1	4	5.183

Location		Period of measurement N_2O	Measuring Method N_2O	Measuring Frequency	Number of measuring devices	Number of replicates	Mean N_2O emission [kg N ha^{-1} yr^{-1}]
ID	Name						
161	SE Scotland	*	closed chamber	*	*	*	0.5
162	SE Scotland	*	closed chamber	*	*	*	1.2
122	Dunslair Heights, NW England	Apr 1994 - Nov 1995	closed chamber	weekly	3	*	0.1
123	Dunslair Heights, NW England	Apr 1994 - Nov 1995	closed chamber	weekly	3	*	0.3
124	Dunslair Heights, NW England	Apr 1994 - Nov 1995	closed chamber	weekly	3	*	0.3
125	Zegveld, The Netherlands	Mar 1992 - Mar 1994	vented closed chambers	weekly	18	4	2.0
126	Zegveld, The Netherlands	Mar 1992 - Mar 1994	vented closed chambers	weekly	18	4	8.6
127	Asa, Sweden	2000 – 2002	dark, static chambers	weekly and biweekly	10	3	0.8 ±0.5
128	Asa, Sweden	1999 – 2001	dark, static chambers	weekly and biweekly	10	3	0.5 ±0.3
129	Asa, Sweden	2000 – 2002	dark, static chambers	weekly and biweekly	10	3	0.4 ±0.5
130	Asa, Sweden	2000 – 2002	dark, static chambers	weekly and biweekly	10	3	2.0 ±1.1
131	Asa, Sweden	2000 – 2002	dark, static chambers	weekly and biweekly	10	3	9.0 ±3.5
132	Asa, Sweden	2000 – 2002	dark, static chambers	weekly and biweekly	10	3	1.0 ±0.5

D. NO measurements

Site ID	Period of measurement NO	Measuring Method NO	Measuring Frequency	Number of measuring devices	Number of replicates	Mean NO emission [g N ha^{-1} d^{-1}]	References
FOREST							
1	*	*	*	*	*	*	(Ambus & Christensen, 1995)
2	*	*	*	*	*	*	(Ambus & Christensen, 1995)
5	*	*	*	*	*	*	(*Beier et al.*, 2001)
6	*	*	*	*	*	*	(*Borken et al.*, 2002)
7	*	*	*	*	*	*	(*Borken et al.*, 2002)
8	*	*	*	*	*	*	(Borken & Beese, 2005)
9	*	*	*	*	*	*	(Borken & Beese, 2005)
10	*	*	*	*	*	*	(Borken & Beese, 2005)
11	*	*	*	*	*	*	(Borken & Beese, 2005)
12	*	*	*	*	*	*	(Borken & Beese, 2005)
13	*	*	*	*	*	*	(Borken & Beese, 2005)
14	*	*	*	*	*	*	(Borken & Beese, 2006)
15	*	*	*	*	*	*	(Borken & Beese, 2006)
16	*	*	*	*	*	*	(Borken & Beese, 2006)
17	*	*	*	*	*	*	(Borken & Beese, 2006)
133	*	*	*	*	*	*	(*Bowden et al.*, 2000)
134	*	*	*	*	*	*	(*Bowden et al.*, 1990)
135	*	*	*	*	*	*	(*Bowden et al.*, 1990)
19	*	*	*	*	*	*	(Brumme & Beese, 1992)
21	*	*	*	*	*	*	(*Brumme et al.*, 1999)
22	*	*	*	*	*	*	(*Brumme et al.*, 1999)
24	*	*	*	*	*	*	(*Brumme et al.*, 1999)
25	*	*	*	*	*	*	(*Brumme et al.*, 1999)
26	*	*	*	*	*	*	(*Brumme et al.*, 1999)
27	*	*	*	*	*	*	(*Brumme et al.*, 1999)
28	*	*	*	*	*	*	(*Brumme et al.*, 1999)
29	*	*	*	*	*	*	(*Brumme et al.*, 1999)
30	*	*	*	*	*	*	(*Brumme et al.*, 1999)
33	*	*	*	*	*	*	(*Butterbach-Bahl et al.*, 2002b)

Site ID	Period of measurement NO	Measuring Method NO	Measuring Frequency	Number of measuring devices	Number of replicates	Mean NO emission [g N ha^{-1} d^{-1}]	References
34	*	*	*	*	*	*	(*Butterbach-Bahl et al.*, 2002b)
35	*	*	*	*	*	*	(*Butterbach-Bahl et al.*, 2002b)
36	*	*	*	*	*	*	(*Butterbach-Bahl et al.*, 2002b)
37	1996 - 1998	dynamic	1/2hours	5	*	1.1 ± 0.9	(*Butterbach-Bahl et al.*, 2002a)
38	1995 - 1998	dynamic	1/2hours	5	*	14.3 ± 6.6	(*Butterbach-Bahl et al.*, 2002a)
39	1995 - 1998	dynamic	1/2hours	5	*	3.2 ± 1.1	(*Butterbach-Bahl et al.*, 2002a)
136	*	*	*	*	*	*	(*Castro et al.*, 1993)
137	*	*	*	*	*	*	(*Castro et al.*, 1993)
138	*	*	*	*	*	*	(*Corre et al.*, 1999)
139	*	*	*	*	*	*	(*Corre et al.*, 1999)
40	*	*	*	*	*	*	(*Dong et al.*, 1998)
140	*	*	*	*	*	*	(*Duxbury et al.*, 1982)
41	*	*	*	*	*	*	(*Härtel-rigler et al.*, 2001)
42	Jan - Dec 1997	open chamber	Continously	5	*	3.5	(Gasche & Papen, 2002)
43	Jan - Dec 1997	open chamber	Continously	5	*	7.8	(Gasche & Papen, 2002)
44	1994 - 1996	open chamber	Continously	5	*	2.5	(Gasche & Papen, 1999)
45	1994 - 1996	open chamber	Continously	5	*	8.0	(Gasche & Papen, 1999)
141	*	*	*	*	*	*	(Goodroad & Keeney, 1984)
142	*	*	*	*	*	*	(Goodroad & Keeney, 1984)
46	*	*	*	*	*	*	(*Goossens et al.*, 2001)
47	*	*	*	*	*	*	(*Härtel et al.*, 2002)
48	*	*	*	*	*	*	(Henrich & Haselwandter, 1997)
143	*	*	*	*	*	*	(*Jordan et al.*, 1998)
144	*	*	*	*	*	*	(*Keller et al.*, 1983)
51	*	*	*	*	*	*	(Kitzler et al., 2006b)
52	*	*	*	*	*	*	(Kitzler et al., 2006b)
53	*	*	*	*	*	*	(*Klemedtsson et al.*, 1997)
54	*	*	*	*	*	*	(*Lamers et al.*, 2007)
55	*	*	*	*	*	*	(*Lamers et al.*, 2007)

Site ID	Period of measurement NO	Measuring Method NO	Measuring Frequency	Number of measuring devices	Number of replicates	Mean NO emission [g N ha^{-1} d^{-1}]	References
56	*	*	*	*	*	*	(*Lamers et al.*, 2007)
57	*	*	*	*	*	*	(*Maljanen et al.*, 2006b)
145	*	*	*	*	*	*	(*Matson et al.*, 1992)
58	*	*	*	*	*	*	(*Merino et al.*, 2004)
59	*	*	*	*	*	*	(*Mogge et al.*, 1998)
146	*	*	*	*	*	*	(*Oura et al.*, 2001)
147	*	*	*	*	*	*	(*Oura et al.*, 2001)
60	*	*	*	*	*	*	(Papen & Butterbach-Bahl, 1999)
61	*	*	*	*	*	*	(Papen & Butterbach-Bahl, 1999)
62	*	*	*	*	*	*	(Papen & Butterbach-Bahl, 1999)
63	*	*	*	*	*	*	(Papen & Butterbach-Bahl, 1999)
64	*	*	*	*	*	*	(Papen & Butterbach-Bahl, 1999)
65	*	*	*	*	*	*	(*Papen et al.*, 1993)
66	Dec 1990 + Mar-Dec 1991 + Mar 1992	open chamber	6 periods continously	2	*	1.8	(Papke & Papen, 1998)
67	*	*	*	*	*	*	(*Schmidt et al.*, 1988)
68	*	*	*	*	*	*	(*Schmidt et al.*, 1988)
69	*	*	*	*	*	*	(*Schmidt et al.*, 1988)
70	*	*	*	*	*	*	(*Schmidt et al.*, 1988)
71	*	*	*	*	*	*	(*Schmidt et al.*, 1988)
72	*	*	*	*	*	*	(*Schmidt et al.*, 1988)
73	*	*	*	*	*	*	(*Skiba et al.*, 1998)
74	*	*	*	*	*	*	(*Skiba et al.*, 1998)
75	*	*	*	*	*	*	(*Skiba et al.*, 1998)
148	*	open chamber	*	*	8	-0.10	(*Skiba et al.*, 1994)
149	*	open chamber	*	*	8	0.02	(*Skiba et al.*, 1994)
150	*	open chamber	*	*	8	0.17	(*Skiba et al.*, 1994)

Site ID	Period of measurement NO	Measuring Method NO	Measuring Frequency	Number of measuring devices	Number of replicates	Mean NO emission [g N ha^{-1} d^{-1}]	References
151	*	open chamber	*	*	*	0.27	(*Skiba et al.*, 1994)
76	*	*	*	*	*	*	(*Skiba et al.*, 1998)
78	*	*	*	*	*	*	(Struwe & Kjoller, 1989)
79	*	*	*	*	*	*	(Struwe & Kjoller, 1989)
152	*	*	*	*	*	*	(*Teepe et al.*, 2000)
82	*	*	*	*	*	*	(*Zechmeister-Boltenstern et al.*, 2002)
83	1996 - 1997	*	*	*	*	0.07	(*Butterbach-Bahl*, 2007)
84	2002 - 2003	dynamic chamber	4/hour	10	*	0.29	(*Butterbach-Bahl*, 2007)
153	1997	*	*	*	*	0.99	(*Butterbach-Bahl*, 2007)
154	1989	*	*	*	*	*	(*Butterbach-Bahl*, 2007)
85	1992	*	*	*	*	*	(*Butterbach-Bahl*, 2007)
86	*	*	*	*	*	*	(*Butterbach-Bahl*, 2007)
87	*	*	*	*	*	*	(*Butterbach-Bahl*, 2007)
88	*	*	*	*	*	*	(*Butterbach-Bahl*, 2007)
89	2002 - 2003	dynamic chamber	2/hour	5	*	0.04-0.07	(*Butterbach-Bahl*, 2007)
90	2002 - 2003	dynamic chamber	1/hour	4	*	0.04-0.37	(*Butterbach-Bahl*, 2007)
91	2002 - 2003	dynamic chamber	2/hour	5	*	0.07-0.18	(*Butterbach-Bahl*, 2007)
92	2002 - 2003	dynamic chamber	1/hour	3	*	0-0.04	(*Butterbach-Bahl*, 2007)
93	2002 - 2003	dynamic chamber	1/hour	4	*	5.6-7.5	(*Butterbach-Bahl*, 2007)
94	2002 - 2003	dynamic chamber	1/hour	5	*	5.6-11.8	(*Butterbach-Bahl*, 2007)
95	1994 - 1997	*	*	*	*	6.4-9.1	(*Butterbach-Bahl*, 2007)
96	1994 - 1997	*	*	*	*	0.8-3.6	(*Butterbach-Bahl*, 2007)
97	2002 - 2003	dynamic chamber	1/hour	5	*	1.0-2.5	(*Butterbach-Bahl*, 2007)

Site ID	Period of measurement NO	Measuring Method NO	Measuring Frequency	Number of measuring devices	Number of replicates	Mean NO emission [g N ha^{-1} d^{-1}]	References
98	2002 - 2003	dynamic chamber	2/hour	5	*	1.3-2.0	(*Butterbach-Bahl*, 2007)
99	2002 - 2003	dynamic chamber	1/hour	4	*	1.8-2.8	(*Butterbach-Bahl*, 2007)
100	2002 - 2003	dynamic chamber	1/month	2	*	*	(*Butterbach-Bahl*, 2007)
101	2002 - 2003	dynamic chamber	4/year	2	*	*	(*Butterbach-Bahl*, 2007)
102	2002 - 2003	dynamic chamber	1/hour	5	*	*	(*Butterbach-Bahl*, 2007)
103	1996 - 1997	*	*	*	*	*	(*Butterbach-Bahl*, 2007)
OTHER VEGETATION							
104	*	*	*	*	*	*	(Ambus & Christensen, 1995)
155	*	*	*	*	*	*	(*Du et al.*, 2006)
105	*	*	*	*	*	*	(Glatzel & Stahr, 2001)
156	*	*	*	*	*	*	(Goodroad & Keeney, 1984)
106	*	*	*	*	*	*	(*Klemedtsson et al.*, 1997)
157	*	*	*	*	*	*	(*Mosier et al.*, 2002)
107	*	*	*	*	*	*	(*Skiba et al.*, 1998)
108	*	*	*	*	*	*	(*Velthof et al.*, 1996)
109	*	*	*	*	*	*	(*Velthof et al.*, 1996)
158	*	*	*	*	*	*	(*Wang et al.*, 2005)
159	*	*	*	*	*	*	(*Wang et al.*, 2005)
110	*	*	*	*	*	*	(*Flechard et al.*, 2007)
111	*	*	*	*	*	*	(*Flechard et al.*, 2007)
112	*	*	*	*	*	*	(*Flechard et al.*, 2007)
113	*	*	*	*	*	*	(*Flechard et al.*, 2007)
ORGANIC SOILS							
20	*	*	*	*	*	*	(*Brumme et al.*, 1999)
23	*	*	*	*	*	*	(*Brumme et al.*, 1999)
114	*	*	*	*	*	*	(Ambus & Christensen, 1995)
160	*	*	*	*	*	*	(Goodroad & Keeney, 1984)

Site ID	Period of measurement NO	Measuring Method NO	Measuring Frequency	Number of measuring devices	Number of replicates	Mean NO emission [g N ha^{-1} d^{-1}]	References
115	*	*	*	*	*	*	(Lamers et al., 2007)
116	*	*	*	*	*	*	(Lamers et al., 2007)
117	*	*	*	*	*	*	(Lamers et al., 2007)
118	*	*	*	*	*	*	(Maljanen et al., 2003)
120	*	*	*	*	*	*	(Mogge et al., 1998)
121	1992 - 1994	dynamic chamber	Monthly	3	1	1.1	(Regina et al., 1998)
161	*	open chamber	*	*	*	0.0	(Skiba et al., 1994)
162	*	open chamber	*	*	*	0.0	(Skiba et al., 1994)
122	*	*	*	*	*	*	(Skiba et al., 1998)
123	*	*	*	*	*	*	(Skiba et al., 1998)
124	*	*	*	*	*	*	(Skiba et al., 1998)
125	*	*	*	*	*	*	(Velthof et al., 1996)
126	*	*	*	*	*	*	(Velthof et al., 1996)
127	*	*	*	*	*	*	(Von Arnold et al., 2005b)
128	*	*	*	*	*	*	(Von Arnold et al., 2005b)
129	*	*	*	*	*	*	(Von Arnold et al., 2005b)
130	*	*	*	*	*	*	(Von Arnold et al., 2005a)
131	*	*	*	*	*	*	(Von Arnold et al., 2005a)
132	*	*	*	*	*	*	(Von Arnold et al., 2005a)

Appendix 2 Input to regression analyses

This appendix lists the records used as input for the regression analyses. The three main inputs are:
Estimated soil parameters
Measured soil parameters
Measured data with added estimates: "measured+"

A. Regression analysis on estimated soil parameters
This input was used to derive empirical relations based on estimated soil parameters for Europe.

Location		Climate			Depo-sition	Clay %		pH		Organic C (g/kg)		C/N ratio		Bulk-density		Classes		Mean N_2O flux	Reference
ID	name	mean T	mean monthly P	fraction months T<0	N dep (kg N/yr)	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	Vege-tation type[4]	parent material[5]	[g N ha^{-1} d^{-1}]	Coded A-AM[6]
1	Copenhagen, Denmark	10.0	49.3	0.0	28.3	*	10.6	5.2	5.2	201	111	22.3	20.6	0.29	0.79	con	m	0.3	A
2	Copenhagen, Denmark	10.0	49.3	0.0	28.3	*	10.6	5.2	5.2	201	111	22.3	20.6	0.29	0.79	con	m	0.3	A
5	Gyrstinge, Sorø, Denmark	8.7	51.6	0.1	25.0	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	0.5	B
6	Solling, ambient, Germany	7.9	72.1	0.3	30.8	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	0.3	C
7	Solling, ambient, Germany	8.9	66.7	0.2	25.5	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	0.4	C
8	Solling, Germany	8.8	72.1	0.1	26.8	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	0.6	D
9	Unterlüß, Germany	9.2	64.4	0.1	25.4	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	con	m	0.5	D
10	Unterlüß, Germany	9.2	64.4	0.1	25.4	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	mix	m	0.5	D
11	Unterlüß, Germany	9.2	64.4	0.1	25.4	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	con	m	0.6	D
12	Solling, Germany	8.8	72.1	0.1	26.8	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.8	D
13	Solling, Germany	8.8	72.1	0.1	26.8	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.9	D
14	Solling, Germany	8.9	66.7	0.2	25.9	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.5	E
15	Solling, Germany	8.9	66.7	0.2	25.9	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.8	E
16	Solling, Germany	8.9	66.7	0.2	25.9	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.8	E
17	Solling, Germany	8.9	66.7	0.2	25.9	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	1.1	E

[4] Four vegetation classes: con = coniferous forest, dec = deciduous forest, mix = mixed forest, and sv = short vegetation.
[5] Two classes of parent material: m = mineral soils, o = organic soils.
[6] References are coded A-AM. Corresponding references can be found at the end of this table.

Location		Climate			Depo-sition	Clay %		pH		Organic C (g/kg)		C/N ratio		Bulk-density		Classes		Mean N_2O flux	Reference
ID	name	mean T	mean monthly P	fraction months T<0	N dep (kg N/yr)	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	Vege-tation type[4]	parent material[5]	[g N ha^{-1} d^{-1}]	Coded A-AM[6]
19	Solling, Germany	8.4	71.8	0.1	32.7	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	5.6	F
20	Bornhöved, Germany	8.0	74.0	0.2	35.3	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	mix	m	7.3	G
21	Solling, Germany	8.2	70.9	0.2	30.3	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	3.0	G
22	Harz, Germany	9.3	88.6	0.2	28.4	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	1.3	G
23	Bornhöved, Germany	8.4	37.1	0.3	33.2	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	mix	m	0.8	G
24	Lappwald, Germany	8.6	61.5	0.2	30.4	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	0.6	G
25	Zierenberg, Germany	9.3	53.0	0.2	33.6	21.8	21.8	7.3	7.3	65	65	26.1	26.1	*	*	dec	m	0.4	G
26	Harste, Germany	8.5	66.5	0.2	30.3	*	10.6	5.2	5.2	201	111	22.3	20.6	0.29	0.79	dec	m	0.4	G
27	Lappwald, Germany	8.6	61.5	0.2	30.4	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	0.3	G
28	Solling, Germany	8.2	70.9	0.2	30.3	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.3	G
29	Spanbeck, Germany	8.3	71.5	0.2	29.4	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.2	G
30	Göttinger Wald, Germany	8.5	66.5	0.2	27.7	21.8	21.8	7.3	7.3	65	65	26.1	26.1	*	*	dec	m	0.2	G
33	Höglwald, Germany	9.8	54.4	0.2	34.2	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.5	H
34	Höglwald, Germany	9.8	54.4	0.2	34.2	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.8	H
35	Höglwald, Germany	9.8	54.4	0.2	34.2	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	1.6	H
36	Höglwald, Germany	9.8	54.4	0.2	34.2	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	4.3	H
37	Kienhorst, Germany	8.8	47.4	0.3	21.1	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	con	m	1.7	I
38	Wildbahn, Germany	9.0	49.7	0.2	21.9	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	con	m	5.7	I
39	Hubertusstock, Germany	8.9	49.4	0.3	21.4	3.9	4.3	4.7	4.7	86	50	39.6	34.6	0.87	1.14	dec	m	3.5	I
40	Darmstadt, Germany	9.2	38.4	0.3	28.9	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	0.5	J
41	Mühleggerköpfl, Austria	5.7	102.1	0.4	15.8	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.7	K
42	Höglwald, Germany	9.8	54.4	0.2	34.2	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	*	L
43	Höglwald, Germany	9.8	54.4	0.2	34.2	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	*	L
44	Höglwald, Germany	9.4	61.9	0.3	35.5	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	*	M
45	Höglwald, Germany	9.4	61.9	0.3	35.5	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	*	M
46	Poppel, Belgium	11.2	79.8	0.0	50.6	*	2.5	3.1	3.9	437	123	31.3	30.1	0.17	0.67	con	m	-0.8	N
47	North Tyrolean Alps, Austria	7.6	113.5	0.3	15.8	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.9	O
48	Innsburck, Austria	6.7	90.0	0.4	16.5	21.8	21.8	7.3	7.3	65	65	26.1	26.1	*	*	con	m	0.1	P
51	Achenkirch, Austria	6.4	87.6	0.4	15.3	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	0.2	Q
52	Achenkirch, Austria	6.4	87.6	0.4	15.3	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	0.4	Q
53	Gårdsjön, Sweden	8.3	78.5	0.3	16.3	20.8	12.4	6.1	5.9	*	0	*	*	0.32	0.66	mix	m	0.1	R
54	Wildmooswald 2, Germany	7.0	97.6	0.4	23.1	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.4	S
55	Wildmooswald 1, Germany	7.0	97.6	0.4	23.1	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.7	S
56	Wildmooswald 3, Germany	7.0	97.6	0.4	23.1	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	1.5	S

Location		Climate			Depo-sition	Clay %		pH		Organic C (g/kg)		C/N ratio		Bulk-density		Classes		Mean N_2O flux	Reference
ID	name	mean T	mean monthly P	fraction months T<0	N dep (kg N/yr)	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	Vege-tation type[4]	parent material[5]	[g N ha^{-1} d^{-1}]	Coded A-AM[6]
57	Southern Finland, Finland	4.1	49.0	0.5	5.7	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	mix	m	1.2	T
58	Fingoi, Spain	12.5	88.9	0.0	14.3	23.3	21.0	4.9	5.0	107	70	21.0	19.2	*	*	dec	m	0.8	U
59	Bornhöved, Germany	8.4	71.2	0.2	35.9	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	mix	m	0.4	V
60	Höglwald, Germany	10.4	56.7	0.3	36.5	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.7	W
61	Höglwald, Germany	8.4	57.6	0.3	34.8	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.8	W
62	Höglwald, Germany	9.3	71.3	0.3	35.3	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.9	W
63	Höglwald, Germany	9.3	71.3	0.3	35.3	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	3.5	W
64	Höglwald, Germany	8.4	57.6	0.3	34.8	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	5.4	W
65	Höglwald, Germany	6.8	62.9	0.3	39.5	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	2.6	X
66	Höglwald, Germany	6.8	62.9	0.3	39.5	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	*	Y
67	Ober-Olm, Germany	10.7	54.9	0.2	30.0	21.8	21.8	7.3	7.3	65	65	26.1	26.1	*	*	sv	m	0.3	Z
68	Ober-Olm, Germany	10.7	54.9	0.2	30.0	21.8	21.8	7.3	7.3	65	65	26.1	26.1	*	*	sv	m	0.3	Z
69	Bechenheim, Germany	10.3	61.4	0.2	28.7	21.8	21.8	7.3	7.3	65	65	26.1	26.1	*	*	sv	m	0.7	Z
70	Langenlohnsheim, Germany	10.8	56.7	0.2	28.7	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	mix	m	0.7	Z
71	Langenlohnsheim, Germany	10.8	56.7	0.2	28.7	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	mix	m	0.7	Z
72	Bechenheim, Germany	10.3	61.4	0.2	28.7	21.8	21.8	7.3	7.3	65	65	26.1	26.1	*	*	sv	m	0.9	Z
73	Glencorse, UK	7.2	74.0	0.1	21.5	18.0	17.5	4.3	4.4	73	53	17.9	16.2	0.74	0.96	con	m	0.3	AA
74	Glencorse, UK	7.2	74.0	0.1	21.5	18.0	17.5	4.3	4.4	73	53	17.9	16.2	0.74	0.96	dec	m	0.6	AA
75	Glencorse, UK	7.2	74.0	0.1	21.5	18.0	17.5	4.3	4.4	73	53	17.9	16.2	0.74	0.96	dec	m	1.7	AA
76	Devilla forest, Central Scotland	9.7	85.5	0.1	17.3	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.4	AA
77	Devilla forest, Central Scotland	9.7	85.5	0.1	17.3	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.0	AB
78	Dyrehaven forest, Denmark	7.6	58.2	0.3	27.9	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	0.3	AC
79	Dyrehaven forest, Denmark	7.6	58.2	0.3	27.9	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	1.8	AC
82	Steinerne Lahn, Austria	9.6	56.4	0.3	20.1	18.0	17.5	4.3	4.4	73	53	17.9	16.2	0.74	0.96	dec	m	4.1	AD
83	Klausenleopoldsdorf, Austria	8.4	65.8	0.3	18.4	18.0	17.5	4.3	4.4	73	53	17.9	16.2	0.74	0.96	dec	m	2.2	AE
84	Sorø, Denmark	8.8	46.0	0.1	24.0	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	0.7	AE
85	Copenhagen, Denmark	9.6	43.9	0.0	25.8	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.8	AE
86	Parco Ticino, Italy	13.2	85.6	0.1	28.3	*	10.6	5.2	5.2	201	111	22.3	20.6	0.29	0.79	dec	m	0.2	AE
87	Parco Ticino, Italy	13.2	85.6	0.1	28.3	*	10.6	5.2	5.2	201	111	22.3	20.6	0.29	0.79	dec	m	0.3	AE
88	Achenkirch, Austria	6.4	99.2	0.4	15.8	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	1.2	AE

Location		Climate			Depo-sition	Clay %		pH		Organic C (g/kg)		C/N ratio		Bulk-density		Classes		Mean N_2O flux	Reference
ID	name	mean T	mean monthly P	fraction months T<0	N dep (kg N/yr)	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	Vege-tation type[4]	parent material[5]	[g N ha^{-1} d^{-1}]	Coded A-AM[6]
89	Achenkirch, Austria	6.4	87.6	0.4	15.3	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	0.3	AE
90	Glencorse, UK	8.5	63.2	0.0	15.3	18.0	17.5	4.3	4.4	73	53	17.9	16.2	0.74	0.96	dec	m	0.2	AE
91	Klausenleopoldsdorf, Austria	9.3	60.8	0.3	17.9	18.0	17.5	4.3	4.4	73	53	17.9	16.2	0.74	0.96	dec	m	0.6	AE
92	Hyytiälä, Finland	3.6	50.2	0.5	5.3	34.0	34.0	4.3	4.3	420	420	23.4	23.4	0.18	0.18	con	o	0.1	AE
93	Speulderbos, Netherlands	10.0	70.3	0.1	45.0	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	mix	m	0.2	AE
94	Höglwald, Germany	9.4	60.0	0.3	32.4	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.5	AE
95	Höglwald, Germany	9.5	60.0	0.3	35.2	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	1.8	AE
96	Höglwald, Germany	9.5	60.0	0.3	35.2	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	3.8	AE
97	Höglwald, Germany	9.4	60.0	0.3	32.4	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	1.1	AE
98	Schottenwald, Austria	9.1	61.8	0.3	16.4	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	3.9	AE
99	Glencorse, UK	8.6	67.8	0.1	18.1	18.0	17.5	4.3	4.4	73	53	17.9	16.2	0.74	0.96	con	m	0.1	AE
100	Matrafüred, Hungary	8.9	55.7	0.4	13.2	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	1.9	AE
101	Matrafüred, Hungary	8.9	55.7	0.4	13.2	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	dec	m	1.8	AE
102	San Rossore, Italy	15.0	75.1	0.0	19.4	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.2	AE
103	Schottenwald, Austria	8.0	70.9	0.3	17.6	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	dec	m	5.3	AE
104	Copenhagen, Denmark	10.0	49.3	0.0	28.7	*	10.6	5.2	5.2	201	111	22.3	20.6	0.29	0.79	con	m	0.4	A
105	Siggen, Germany	7.7	78.6	0.3	31.8	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	con	m	0.2	AF
106	Gårdsjön, Sweden	8.3	78.5	0.3	16.3	20.8	12.4	6.1	5.9	*	0	*	*	*	*	mix	m	0.1	R
107	Glencorse, UK	7.2	74.0	0.1	21.5	18.0	17.5	4.3	4.4	73	53	17.9	16.2	0.74	0.96	sv	m	0.8	AA
108	Heino, The Netherlands	9.6	71.1	0.1	51.5	0.0	2.5	3.1	3.9	437	123	31.3	30.1	0.17	0.67	con	m	1.1	AG
110	Bugac-Puszta, Hungary	11.5	44.1	0.2	15.4	3.9	4.3	4.7	4.7	86	50	39.6	34.6	0.87	1.14	sv	m	1.5	AH
111	Cowpark, Scotland, UK	8.6	67.8	0.1	18.1	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	sv	m	0.5	AH
112	Laqueuille, France	6.9	93.7	0.4	19.0	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	sv	m	0.3	AH
113	Oensingen, Switserland	9.4	83.0	0.3	22.9	*	10.6	5.2	5.2	201	111	22.3	20.6	0.29	0.79	sv	m	0.6	AH
114	Copenhagen, Denmark	10.0	49.3	0.0	28.7	*	10.6	5.2	5.2	201	111	22.3	20.6	0.29	0.79	con	m	0.3	A
115	Wildmooswald, Germany	7.0	97.6	0.4	23.1	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	1.8	S
116	Wildmooswald, Germany	7.0	97.6	0.4	23.1	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	2.1	S
117	Wildmooswald, Germany	7.0	97.6	0.4	23.1	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	3.8	S
118	Eastern, Finland	2.5	48.9	0.6	4.7	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	mix	m	4.2	AI
120	Bornhöved, Germany	8.5	70.1	0.2	35.9	19.5	21.1	5.3	5.5	101	62	15.1	15.0	0.63	0.93	mix	m	4.9	V
121	Ilomantsi, Finland	2.3	54.1	0.5	4.2	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	mix	m	5.2	AJ
122	Dunslair Heights, NW England	8.4	94.9	0.1	19.4	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.1	AK
123	Dunslair Heights, NW England	8.4	94.9	0.1	19.4	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	sv	m	0.3	AK

Location		Climate			Depo-sition	Clay %		pH		Organic C (g/kg)		C/N ratio		Bulk-density		Classes		Mean N_2O flux	Reference
ID	name	mean T	mean monthly P	fraction months T<0	N dep (kg N/yr)	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	Vege-tation type[4]	parent material[5]	[g N ha^{-1} d^{-1}]	Coded A-AM[6]
124	Dunslair Heights, NW England	8.4	94.9	0.1	19.4	15.1	15.0	4.9	4.8	63	45	21.8	20.5	0.72	0.96	con	m	0.3	AK
125	Zegveld, The Netherlands	10.0	76.6	0.0	48.3	33.7	33.7	6.6	6.6	28	28	9.8	9.8	1.22	1.22	sv	m	2.0	AG
126	Zegveld, The Netherlands	10.0	76.6	0.0	48.3	33.7	33.7	6.6	6.6	28	28	9.8	9.8	1.22	1.22	sv	m	8.6	AG
127	Asa, Sweden	6.3	60.6	0.4	10.6	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	mix	m	0.8	AL
128	Asa, Sweden	6.3	60.6	0.4	10.8	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	mix	m	0.5	AL
129	Asa, Sweden	6.3	60.6	0.4	10.6	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	mix	m	0.4	AL
130	Asa, Sweden	6.3	60.6	0.4	10.6	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	mix	m	2.0	AM
131	Asa, Sweden	6.3	60.6	0.4	10.6	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	mix	m	9.0	AM
132	Asa, Sweden	6.3	60.6	0.4	10.6	12.3	8.7	4.1	4.1	344	213	14.5	16.2	0.21	0.13	mix	m	1.0	AM

List of references

A (Ambus & Christensen, 1995)
B (Beier et al., 2001)
C (Borken et al., 2002)
D (Borken & Beese, 2005)
E (Borken & Beese, 2006)
F (Brumme & Beese, 1992)
G (Brumme et al., 1999)
H (Butterbach-Bahl et al., 2002b)
I (Butterbach-Bahl et al., 2002a)
J (Dong et al., 1998)
K (Härtel-rigler et al., 2001)
L (Gasche & Papen, 2002)
M (Gasche & Papen, 1999)
N (Goossens et al., 2001)
O (Härtel et al., 2002)
P (Henrich & Haselwandter, 1997)
Q (Kitzler et al., 2006b)
R (Klemedtsson et al., 1997)
S (Lamers et al., 2007)
T (Maljanen et al., 2006b)
U (Merino et al., 2004)
V (Mogge et al., 1998)
W (Papen & Butterbach-Bahl, 1999)
X (Papen et al., 1993)
Y (Papke & Papen, 1998)
Z (Schmidt et al., 1988)
AA (Skiba et al., 1998)
AB (Skiba et al., 1999)
AC (Struwe & Kjoller, 1989)
AD (Zechmeister-Boltenstern et al., 2002)
AE (Butterbach-Bahl, 2007)
AF (Glatzel & Stahr, 2001)
AG (Velthof et al., 1996)
AH (Flechard et al., 2007)
AI (Maljanen et al., 2003)
AJ (Regina et al., 1998)
AK (MacDonald et al., 1997)
AL (Von Arnold et al., 2005b)
AM (Von Arnold et al., 2005a)

B. Regression analysis on measured soil parameters

This input was used to derive empirical relations based on measured soil parameters for Europe.

Location		Climate variables		Depo-sition	Clay %		pH		Organic C (g/kg)		C/N ratio		Classes	Mean N_2O flux		Reference
ID	name	mean T	mean monthly P	N dep (kg N/yr)	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	parent material[7]	Vege-tation type[8]	[g N $ha^{-1}d^{-1}$]	Coded A-D[9]
55	Wildmooswald 1, Germany	6.7	88.33	10	18	18	3.1	3.1	109	109	15	15	m	con	0.7	A
56	Wildmooswald 3, Germany	6.7	88.33	10	17	17	3.2	3.2	128	128	21	21	m	con	1.5	A
59	Bornhöved, Germany	7.3	69.08	23.8	6.5	6.5	4	4	34	34	17	17	m	dec	0.4	B
83	Klausenleopoldsdorf, Austria	8.8	74.92	11.2	27	27	4.5	4.5	51	51	16	16	m	dec	2.2	C
84	Sorø, Denmark	8.7	64.38	34.6	9	9	4.5	4.5	40	40	18	18	m	dec	0.7	C
86	Parco Ticino, Italy	14.4	69.50	8.4	9	9	5.9	5.9	10	10	15	15	m	dec	0.2	C
87	Parco Ticino, Italy	14.4	69.50	8.4	6	6	4.2	4.2	67	67	18	18	m	dec	0.3	C
88	Achenkirch, Austria	6.9	152.79	5.2	19	19	7	7	77	77	18	18	m	con	1.2	C
90	Glencorse, UK	8.5	84.29	11.1	18	18	4.8	4.8	70	70	14	14	m	dec	0.2	C
92	Hyytiälä, Finland	4.15	49.13	0.1	9	9	3.7	3.7	29	29	38	38	m	con	0.1	C
93	Speulderbos, Netherlands	10.4	64.04	47.2	3	3	3.7	3.7	90	90	43	43	m	con	0.2	C
95	Höglwald, Germany	8.1	73.83	22.2	19	19	3.5	3.5	29	29	19	19	m	con	1.8	C
96	Höglwald, Germany	8.1	73.83	22.2	19	19	3.7	3.7	51	51	16	16	m	dec	3.8	C
97	Höglwald, Germany	9	67.71	20.3	9	9	4	4	51	51	26	26	m	dec	1.1	C
99	Glencorse, UK	8.6	84.29	11.1	18	18	4.2	4.2	70	70	14	14	m	con	0.1	C
100	Matrafüred, Hungary	8.55	61.96	10.3	9	9	3.9	3.9	19	19	13	13	m	con	1.9	C
101	Matrafüred, Hungary	8.55	61.96	7.6	9	9	4.3	4.3	36	36	14	14	m	dec	1.8	C
102	San Rossore, Italy	14.55	76.79	4.6	3	3	5.8	5.8	7	7	30	30	m	con	0.2	C
103	Schottenwald, Austria	9.55	70.46	29.6	18	18	4.2	4.2	68	68	13	13	m	dec	5.3	C

[7] Two classes of parent material: m = mineral soils, o = organic soils.

[8] Four classes of vegetation: con = coniferous forest, dec = deciduous forest, mix = mixed forest, and sv = short vegetation.

[9] References are coded A-D. Corresponding references can be found at the end of the table.

Location		Climate variables		Depo-sition	Clay %		pH		Organic C (g/kg)		C/N ratio		Classes	Mean N_2O flux		Reference
ID	name	mean T	mean monthly P	N dep (kg N/yr)	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	parent material[7]	Vege-tation type[8]	[g N $ha^{-1}d^{-1}$]	Coded A-D[9]
110	Bugac-Puszta, Hungary	10.5	41.67	7	20	20	7.7	7.7	55	55	16	16	m	sv	1.5	D
111	Cowpark, Scotland, UK	8.6	70.75	9	25	25	6.4	6.4	38	38	14	14	m	sv	0.5	D
112	Laqueuille, France	8	109.42	14	18	18	5.3	5.3	80	80	11	11	m	sv	0.3	D
113	Oensingen, Switserland	9	92.42	15	43	43	7.5	7.5	24	24	9.7	9.7	m	sv	0.6	D
115	Wildmooswald, Germany	6.7	88.33	10	23	23	3.7	3.7	394	394	20	20	o	con	1.8	A
116	Wildmooswald, Germany	6.7	88.33	10	20	20	3.7	3.7	301	301	17	17	o	con	2.1	A

List of references

A (Lamers et al., 2007)
B (Mogge et al., 1998)
C (Butterbach-Bahl, 2007)
D (Flechard et al., 2007)

C. Regression analysis based on measured data with added estimates: 'Measured +'

This input was used to derive empirical relations based on measured soil parameters for Europe. The measured data were completed with estimates based on soil class.

Location		Climate variables		Deposition	Clay %		pH		Organic C (g/kg)		C/N ratio		Classes		Mean N_2O flux	Reference
ID	name	mean T	mean monthly P	N dep (kg N/yr)	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	Parent material	Vege-tation type	[g N ha^{-1} d^{-1}]	
1	Copenhagen, Denmark	10.0	49.3	29	19	21	5.6	5.6	101	62	15.1	15	m	dec	0.3	A
2	Copenhagen, Denmark	10.0	49.3	29	12	9	4.2	4.2	344	21	14.5	16.2	m	con	0.3	A
5	Gyrstinge, Sorø, Denmark	8.7	51.6	25.6	*	*	*	*	*	*	*	*	m	dec	0.5	B
6	Solling, Germany	6.4	88.2	36.0	15	15	3.2	3.2	63	46	21.8	20.5	m	con	0.3	C
7	Solling, Germany	6.4	56.1	36.0	15	15	3.2	3.2	63	46	21.8	20.5	m	con	0.4	C
8	Solling, Germany	7.2	86.5	26.8	28	28	4.9	4.8	63	46	21.8	20.5	m	con	0.6	D
9	Unterlüß, Germany	8.4	69.8	25.4	3	3	5.3	5.5	101	62	15.1	15	m	con	0.5	D
10	Unterlüß, Germany	8.4	69.8	25.4	8	8	5.3	5.5	101	62	15.1	15	m	dec	0.5	D
11	Unterlüß, Germany	8.4	69.8	25.4	4	4	5.3	5.5	101	62	15.1	15	m	con	0.6	D
12	Solling, Germany	7.2	86.5	26.8	19	19	4.9	4.8	63	46	21.8	20.5	m	dec	0.8	D
13	Solling, Germany	7.5	75.0	26.8	15	15	4.9	4.8	63	46	21.8	20.5	m	con	0.9	D
14	Solling, Germany	7.5	75.0	25.67	15	15	4.9	4.8	63	46	21.8	20.5	m	con	0.5	E
15	Solling, Germany	7.5	75.0	25.67	15	15	4.9	4.8	63	46	21.8	20.5	m	dec	0.8	E
16	Solling, Germany	7.5	75.0	25.67	15	15	4.9	4.8	63	46	21.8	20.5	m	con	0.8	E
17	Solling, Germany	7.5	75.0	25.67	15	15	4.9	4.8	63	46	21.8	20.5	m	dec	1.1	E
19	Solling, Germany	8.4	71.8	35.0	15	15	3	4.8	57	46	21.8	20.5	m	dec	5.6	F
20	Bornhöved, Germany	8.1	58.1	33.0	34	34	3.9	4.3	181	421	23.4	23.4	o	dec	7.3	G
21	Solling, Germany	6.4	90.8	35.0	15	15	3.85	4.8	38.1	46	21.8	20.5	m	dec	3.0	G
22	Harz, Germany	6.9	103.3	20.0	15	15	3.6	4.8	34	46	21.8	20.5	m	con	1.3	G
23	Bornhöved, Germany	8.1	58.1	33.0	34	34	*	4.3	421	421	23.4	23.4	o	dec	0.8	G
24	Lappwald, Germany	8.5	54.2	30.4	18	18	4.13	4.4	32.2	54	17.9	16.2	m	con	0.6	G
25	Zierenberg, Germany	7.0	58.3	21.0	*	*	5.6	5.6	49.5	49.5	*	*	m	dec	0.4	G
26	Harste, Germany	8.0	62.5	26.0	*	*	4.33	4.33	18.6	18.6	*	*	m	dec	0.4	G
27	Lappwald, Germany	8.5	54.2	30.4	54	54	5.05	5.05	47.2	47.2	14.1	14.1	m	dec	0.3	G
28	Solling, Germany	6.4	90.8	41.0	15	15	3.86	3.86	46.3	46.3	21.8	20.5	m	con	0.3	G
29	Spanbeck, Germany	8.5	54.2	31.0	15	15	3.93	3.93	26.3	26.3	21.8	20.5	m	con	0.2	G
30	Göttinger Wald, Germany	7.8	56.7	28.0	19	21	5.24	5.24	51.8	51.8	15.1	15	m	dec	0.2	G
33	Höglwald, Germany	8.6	74.0	30.0	19	21	3.5	3.5	101	62	17	17	m	con	0.5	H
34	Höglwald, Germany	8.6	74.0	40.0	19	21	3.4	3.4	101	62	14	14	m	con	0.8	H
35	Höglwald, Germany	8.6	74.0	16.0	19	21	3.7	3.7	101	62	17	17	m	dec	1.6	H
36	Höglwald, Germany	8.6	74.0	36.0	19	21	3.5	3.5	101	62	16	16	m	dec	4.3	H
37	Kienhorst, Germany	7.3	45.4	15.8	7	7	3.5	3.5	344	214	26	26	m	con	1.7	I
38	Wildbahn, Germany	7.3	41.7	20.2	7	7	3.4	3.4	63	46	25	25	m	con	5.7	I

Location		Climate variables		Deposition	Clay %		pH		Organic C (g/kg)		C/N ratio		Classes		Mean N_2O flux	Reference
ID	name	mean T	mean monthly P	N dep (kg N/yr)	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	Parent material	Vege-tation type	[g N ha^{-1} d^{-1}]	
39	Hubertusstock, Germany	7.3	45.8	14.9	10	10	3.6	3.6	63	46	19	19	m	con	3.5	I
40	Darmstadt, Germany	9.2	38.4	29.3	19	21	3.5	3.5	19	19	21	21	m	dec	0.5	J
41	Mühleggerköpfl, Austria	5.7	102.1	16.5	*	*	*	*	*	*	*	*	m	mix	0.7	K
42	Höglwald, Germany	7.3	66.7	20	19	21	3.6	3.6	63	46	15.1	15	m	dec	*	L
43	Höglwald, Germany	7.3	66.7	35	19	21	3.6	3.6	63	46	15.1	15	m	con	*	L
44	Höglwald, Germany	7.3	66.7	20	19	21	3.6	3.6	63	46	15.1	15	m	dec	*	M
45	Höglwald, Germany	7.3	66.7	35	19	21	3.6	3.6	63	46	15.1	15	m	con	*	M
46	Poppel, Belgium	11.2	67.3	50.6	2.4	2.4	3.8	3.8	78	78	26	26	m	dec	-0.8	N
47	North Tyrolean Alps, Austria	7.6	113.5	18	19	21	6.4	6.4	150	150	17	17	m	con	0.9	O
48	Innsburck, Austria	6.7	90.0	11.5	19	21	3.8	3.8	63	46	15.1	15	m	con	0.1	P
51	Achenkirch, Austria	6.5	144.4	11.3	19	21	6.4	6.4	150	150	17	17	m	con	0.2	Q
52	Achenkirch, Austria	6.5	144.4	11.3	19	21	6.4	6.4	150	150	17	17	m	con	0.4	Q
53	Gårdsjön, Sweden	8.3	78.5	12.0	12	9	4	4	344	214	14.5	16.2	m	con	0.1	R
54	Wildmooswald 2, Germany	6.7	88.3	10	19	21	3.3	3.3	116	116	14.5	14.5	m	con	0.4	S
55	Wildmooswald 1, Germany	6.7	88.3	10	18	18	3.1	3.1	109	109	15	15	m	con	0.7	S
56	Wildmooswald 3, Germany	6.7	88.3	10	17	17	3.2	3.2	128	128	21	21	m	con	1.5	S
57	Southern Finland, Finland	3.3	56.7	5.6	12	9	3.7	3.7	48	48	14.5	16.2	m	con	1.2	T
58	Fingoi, Spain	11.7	85.2	14.33	15	15	4	4	37.7	37.7	21.8	20.5	m	dec	0.8	U
59	Bornhöved, Germany	7.3	69.1	23.8	6.5	6.5	4	4	34	34	17	17	m	dec	0.4	V
60	Höglwald, Germany	8.9	79.3	30.0	19	21	5.3	5.5	101	62	15.1	15	m	con	0.7	W
61	Höglwald, Germany	5.7	78.0	30.0	19	21	5.3	5.5	101	62	15.1	15	m	con	0.8	W
62	Höglwald, Germany	7.6	79.6	30.0	19	21	5.3	5.5	101	62	15.1	15	m	con	0.9	W
63	Höglwald, Germany	7.4	79.6	20.0	19	21	5.3	5.5	101	62	15.1	15	m	dec	3.5	W
64	Höglwald, Germany	5.6	78.0	20.0	19	21	5.3	5.5	101	62	15.1	15	m	dec	5.4	W
65	Höglwald, Germany	6.8	66.7	40	23	23	3.7	3.7	63	46	21.8	20.5	m	con	2.6	X
66	Höglwald, Germany	7.3	66.7	40.03	15	15	3.4	3.4	63	46	21.8	20.5	m	con	*	Y
67	Ober-Olm, Germany	10.7	54.9	35.3	12	12	4.7	4.7	28	28	18	18	m	dec	0.3	Z
68	Ober-Olm, Germany	10.7	54.9	35.3	26	26	6.7	6.7	36	36	12	12	m	dec	0.3	Z
69	Bechenheim, Germany	10.3	61.4	33.8	19	19	3.7	3.7	24	24	22	22	m	dec	0.7	Z
70	Langenlohnsheim, Germany	10.8	56.7	33.8	11	11	3.6	3.6	28	28	13	13	m	dec	0.7	Z
71	Langenlohnsheim, Germany	10.8	56.7	33.8	18	18	3.7	3.7	72	72	25	25	m	dec	0.7	Z
72	Bechenheim, Germany	10.3	61.4	33.8	17	17	3.4	3.4	34	34	19	19	m	dec	0.9	Z
73	Glencorse, UK	7.2	74.0	10.0	15	15	4.5	4.5	63	46	21.8	20.5	m	con	0.3	AA
74	Glencorse, UK	7.2	74.0	10	15	15	4.9	4.9	63	46	21.8	20.5	m	dec	0.6	AA
75	Glencorse, UK	7.2	74.0	60	15	15	4.2	4.2	63	46	21.8	20.5	m	dec	1.7	AA
76	Devilla forest, Central Scotland	9.7	85.5	10	15	15	3.5	3.5	63	46	21.8	20.5	m	con	0.4	AA
77	Devilla forest, Central Scotland	9.7	85.5	18	15	15	3.5	3.5	63	46	21.8	20.5	m	con	0.0	AB
78	Dyrehaven forest, Denmark	7.6	58.2	30.25	*		7.0	7.0	*	*	*	*	m	dec	0.3	AC
79	Dyrehaven forest, Denmark	7.6	58.2	30.25	*		6.7	6.7	*	*	*	*	m	dec	1.8	AC

Location		Climate variables		Deposition	Clay %		pH		Organic C (g/kg)		C/N ratio		Classes		Mean N_2O flux	Reference
ID	name	mean T	mean monthly P	N dep (kg N/yr)	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	Parent material	Vege-tation type	[g N ha^{-1} d^{-1}]	
82	Steinerne Lahn, Austria	10.1	80.8	35.0	15	15	4.9	4.8	63	46	21.8	20.5	m	dec	4.1	AD
83	Klausenleopoldsdorf, Austria	8.8	74.9	11.2	27	27	4.5	4.5	51	51	16	16	m	dec	2.2	AE
84	Sorø, Denmark	8.7	64.4	34.6	9	9	4.5	4.5	40	40	17.7	17.7	m	dec	0.7	AE
85	Copenhagen, Denmark	8.6	63.0	11.3	6	6	3.7	3.7	61	61	*	*	m	con	0.8	AE
86	Parco Ticino, Italy	14.4	69.5	8.4	9	9	5.9	5.9	10	10	15.3	15.3	m	dec	0.2	AE
87	Parco Ticino, Italy	14.4	69.5	8.4	6	6	4.2	4.2	67	67	17.9	17.9	m	dec	0.3	AE
88	Achenkirch, Austria	6.9	152.8	5.2	19	19	7	7	77	77	18	18	m	con	1.2	AE
89	Achenkirch, Austria	7.3	125.9	5.9	19	19	7	7	77	77	15.1	15	m		0.3	AE
90	Glencorse, UK	8.5	84.3	11.1	18	18	4.8	4.8	70	70	13.8	13.8	m	dec	0.2	AE
91	Klausenleopoldsdorf, Austria	8.7	61.4	9.2	27	27	4.5	4.5	51	51	21.8	20.5	m	dec	0.6	AE
92	Hyytiälä, Finland	4.2	49.1	0.1	9	9	3.7	3.7	29	29	37.7	37.7	m	con	0.1	AE
93	Speulderbos, Netherlands	10.4	64.0	47.2	3	3	3.7	3.7	90	90	43	43	m	con	0.2	AE
94	Höglwald, Germany	9.0	67.7	20.3	19	19	3.5	3.5	29	29	*	*	m	con	0.5	AE
95	Höglwald, Germany	8.1	73.8	22.2	19	19	3.5	3.5	29	29	18.8	18.8	m	con	1.8	AE
96	Höglwald, Germany	8.1	73.8	22.2	19	19	3.7	3.7	51	51	15.8	15.8	m	dec	3.8	AE
97	Höglwald, Germany	9.0	67.7	20.3	9	9	4	4	51	51	25.8	25.8	m	dec	1.1	AE
98	Schottenwald, Austria	10.2	59.4	25	18	18	4.2	4.2	68	68	15.1	15	m	dec	3.9	AE
99	Glencorse, UK	8.6	84.3	11.1	18	18	4.2	4.2	70	70	13.8	13.8	m	con	0.1	AE
100	Matrafüred, Hungary	8.6	62.0	10.3	9	9	3.9	3.9	19	19	12.9	12.9	m	con	1.9	AE
101	Matrafüred, Hungary	8.6	62.0	7.6	9	9	4.3	4.3	36	36	13.5	13.5	m	dec	1.8	AE
102	San Rossore, Italy	14.6	76.8	4.6	3	3	5.8	5.8	7	7	29.9	29.9	m	con	0.2	AE
103	Schottenwald, Austria	9.6	70.5	29.6	18	18	4.2	4.2	68	68	13.4	13.4	m	dec	5.3	AE
104	Copenhagen, Denmark	10.0	49.3	29	*		7	7	*	*	*	*	m	sv	0.4	A
105	Siggen, Germany	6.5	116.7	31.8	33	33	*	*	35	35	8.3	8.3	m	sv	0.2	AF
106	Gårdsjön, Sweden	8.3	78.5	12.0	12	9	4	4	344	214	*	*	m	sv	0.1	R
107	Glencorse, UK	7.2	74.0	10.0	*		4.8	4.8	*	*	*	*	m	sv	0.8	AA
108	Heino, The Netherlands	9.6	77.7	51.53	*		*	*	*	*	*	*	m	sv	1.1	AG
109	Lelystad, The Netherlands	*	80.2	107	16	16	7.7	7.7	19	19	*	*	m	sv	0.8	AG
110	Bugac-Puszta, Hungary	10.5	41.7	7	20	20	7.7	7.7	55	55	16	16	m	sv	1.5	AH
111	Cowpark, Scotland, UK	8.6	70.8	9	25	25	6.4	6.4	38	38	14.1	14.1	m	sv	0.5	AH
112	Laqueuille, France	8.0	109.4	14	18	18	5.3	5.3	80	80	10.7	10.7	m	sv	0.3	AH
113	Oensingen, Switserland	9.0	92.4	15	43	43	7.5	7.5	24	24	9.7	9.7	m	sv	0.6	AH
114	Copenhagen, Denmark	10.0	49.3	29	34	34	6.9	6.9	42	42	23.4	23.4	o	sv	0.3	A
115	Wildmooswald, Germany	6.7	88.3	10	23	23	3.7	3.7	394	394	20	20	o	con	1.8	S
116	Wildmooswald, GermanyS	6.7	88.3	10	20	20	3.7	3.7	301	301	17	17	o	con	2.1	S
117	Wildmooswald, Germany	6.7	88.3	10	34	34	3.6	3.6	485	485	24	24	o	con	3.8	S
118	Eastern, Finland	2.6	53.6	4.73	34	34	4.5	4.5	421	421	20	20	o	dec	4.2	AI
120	Bornhöved, Germany	8.1	56.6	69.0	34	34	4	4	422	422	18	18	o	dec	4.9	V
121	Ilomantsi, Finland	1.9	54.2	2.7	34	34	4.5	4.5	421	421	23.4	23.4	o	dec	5.2	AJ

Location		Climate variables		Deposition	Clay %		pH		Organic C (g/kg)		C/N ratio		Classes		Mean N_2O flux	Reference
ID	name	mean T	mean monthly P	N dep (kg N/yr)	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	0-10 cm	0-20 cm	Parent material	Vege-tation type	[g N ha^{-1} d^{-1}]	
122	Dunslair Heights, NW England	8.4	94.9	6.4	34	34	3.1	3.1	421	421	23.4	23.4	o	con	0.1	AK
123	Dunslair Heights, NW England	8.4	94.9	24.3	34	34	3.3	3.3	421	421	23.4	23.4	o	sv	0.3	AK
124	Dunslair Heights, NW England	8.4	94.9	46.2	34	34	3.2	3.2	421	421	23.4	23.4	o	con	0.3	AK
125	Zegveld, The Netherlands	10.0	71.4	48.3	34	34	4.3	4.3	421	421	23.4	23.4	o	sv	2.0	AI
126	Zegveld, The Netherlands	10.0	71.4	48.3	34	34	4.3	4.3	421	421	23.4	23.4	o	sv	8.6	AI
127	Asa, Sweden	5.6	55.2	10.5	34	34	3.2	3.2	421	421	23.4	23.4	o	con	0.8	AL
128	Asa, Sweden	5.6	55.2	10.67	34	34	3.3	3.3	421	421	23.4	23.4	o	con	0.5	AL
129	Asa, Sweden	5.6	55.2	10.5	34	34	2.7	2.7	421	421	23.4	23.4	o	con	0.4	AL
130	Asa, Sweden	5.6	55.2	10.5	34	34	3.4	3.4	421	421	23.4	23.4	o	dec	2.0	AM
131	Asa, Sweden	5.6	55.2	10.5	34	34	4.5	4.5	421	421	23.4	23.4	o	dec	9.0	AM
132	Asa, Sweden	5.6	55.2	10.5	34	34	4.2	4.2	421	421	23.4	23.4	o	dec	1.0	AM

List of references

A (Ambus & Christensen, 1995)
B (Beier et al., 2001)
C (Borken et al., 2002)
D (Borken & Beese, 2005)
E (Borken & Beese, 2006)
F (Brumme & Beese, 1992)
G (Brumme et al., 1999)
H (Butterbach-Bahl et al., 2002b)
I (Butterbach-Bahl et al., 2002a)
J (Dong et al., 1998)
K (Härtel-rigler et al., 2001)
L (Gasche & Papen, 2002)
M (Gasche & Papen, 1999)
N (Goossens et al., 2001)
O (Härtel et al., 2002)
P (Henrich & Haselwandter, 1997)
Q (Kitzler et al., 2006b)
R (Klemedtsson et al., 1997)
S (Lamers et al., 2007)
T (Maljanen et al., 2006a)
U (Merino et al., 2004)
V (Mogge et al., 1998)
W (Papen & Butterbach-Bahl, 1999)
X (Papen et al., 1993)
Y (Papke & Papen, 1998)
Z (Schmidt et al., 1988)
AA (Skiba et al., 1998)
AB (Skiba et al., 1999)
AC (Struwe & Kjoller, 1989)
AD (Zechmeister-Boltenstern et al., 2002)
AE (Butterbach-Bahl, 2007)
AF (Glatzel & Stahr, 2001)
AG (Velthof et al., 1996)
AH (Flechard et al., 2007)
AI (Maljanen et al., 2003)
AJ (Regina et al., 1998)
AK (MacDonald et al., 1997)
AL (Von Arnold et al., 2005b)
AM (Von Arnold et al., 2005a)