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Monitoring Trace Gas Fluxes (N_2O, CH_4) from Different Soils Under the Same Climatic Conditions and the Same Agricultural Management

By

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Key words: Nitrous oxide, methane, undisturbed soil monoliths, climate, agriculture, soil properties.

Summary

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In order to determine the effects of soil type on flux rates of N_2O and CH_4 a 43-months field experiment with undisturbed soil monoliths (2 m height, 1 m^2 surface) was carried out. Four replicates of three sites in southern Germany were installed in a lysimeter station near Munich. All sites formerly were used as arable fields. The soil types varied in texture, gravel, pH and C and N content. The most important factor in this investigation was to expose the different soil types to the same climatic conditions and to the same agricultural management. Despite of the same conditions differences in both N_2O and CH_4 flux rates were found. Annual N_2O emissions ranged from 0.3 to 2 kg N_2O-N $ha^{-1}a^{-1}$ and CH_4 uptakes ranged from -1.13 to -0.59 kg CH_4-C $ha^{-1}a^{-1}$. N_2O emissions from 'Hohenwart' were 7 times higher than the emissions measured from 'Kelheim'. Furthermore, the CH_4 uptakes from 'Kelheim' were 4.5 times higher than the 'Hohenwart' measurements. Calculating the global warming potential (GWP) as CO_2-equivalents from N_2O and CH_4 fluxes of the investigated soils the atmospherical load from 'Kelheim' was 75±91, from 'Scheyern' it was 468±119 and from 'Hohenwart' it was 611±192 kg CO_2 $ha^{-1}a^{-1}$.

Introduction

Nitrous oxide (N_2O) contributes to global warming and is involved in the destruction of stratospheric ozone (CRUTZEN 1970). About 70% of the total emitted N_2O is derived from soils (BOUWMAN 1990) and agriculture contributes to 81% of the anthropogenic N_2O emissions (ISERMAN 1994). Recently a lot of work has been

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done to investigate trace gas fluxes from soils (EICHNER 1990) and to evolve strategies to reduce losses to the atmosphere. For example, MOSIER & al. 1996 suggested the use of nitrification inhibitors mixed with N fertilizers to mitigate N_2O emissions from agriculture. In soils, N_2O mainly originates from microbial nitrification and denitrification (DAVIDSON 1991). Therefore the production and consumption of N_2O depends on various controlling parameters. The main controllers are aeration, water content, temperature, N availability, organic material and others (GRANLI & BØCKMAN 1994).

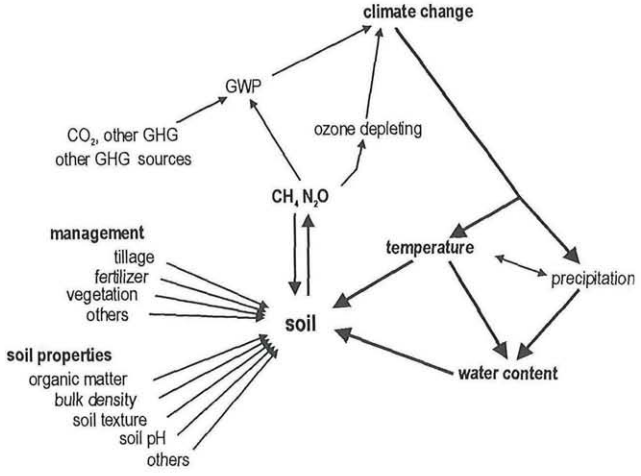


Fig. 1. Simplified scheme of the influence on N_2O and CH_4 fluxes from arable soils and its feedback via changing temperature and precipitation due to climate change. GWP = global warming potential (modified after KAMP & al. 1998).

Apart from that, soil's propensity for generating and emitting N_2O varied with soil physical characteristics. A strong relationship exists between soil texture and denitrification activity (GROFFMAN & TIEDJE 1989). Due to more capillary pores fine-textured soils (clayey soils and silty soils) can maintain a higher water content for a longer time than coarse-textured soils (sandy soils). Clayey soils can have a higher potential for sustained N_2O formation than sandy soils (GRANLI & BØCKMAN 1994). Furthermore, N_2O can be reduced to N_2 when diffusion is slow due to high water content in fine-textured soils (ARAH & al. 1991). Fine-textured soils seem to emit more N_2O than sandy soils, but this tendency can be masked or reversed by other factors (GRANLI & BØCKMAN 1994), especially climate and soil management practices (Fig. 1). Recently, KAMP & al. 1998 showed in a soil warming experiment on a wheat field and a fallow field that N_2O and CH_4 fluxes varied when soil temperature was manipulated due to global warming.

Flux rates of trace gases, nitrous oxide and methane, from different soils can hardly be compared when measured only during short periods or even at one single time. Some of the reasons are the differences in the climatic (precipitation, temperature e.g.) and geomorphological (slope, inclination e.g.) conditions at the

natural sites. Moreover the differences in management practices at the natural locations make comparisons in field experiments difficult. Especially with respect to serious changes in the N_2O and CH_4 fluxes induced by events like freezing and thawing, drying and rewetting, tillage, or fertilization the preconditions at the sites are hard to control in field experiments.

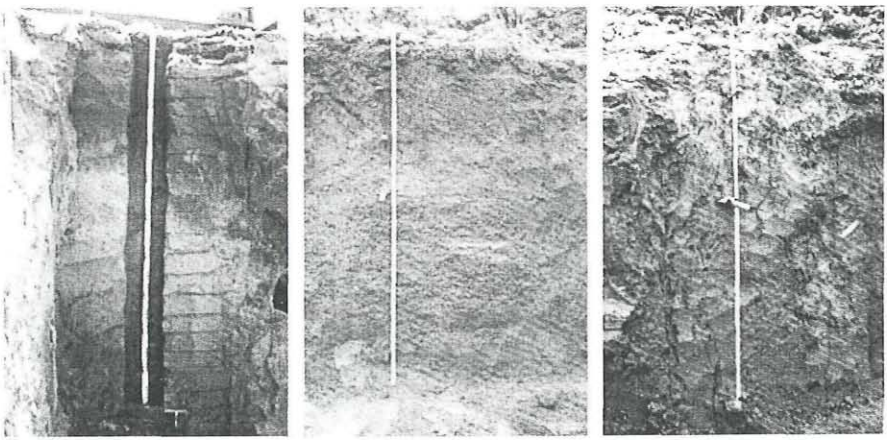
To compare nitrous oxide and methane fluxes from different soils under the same climatic conditions and the same management practices lysimeter studies with undisturbed soil monoliths were carried out.

Materials and Methods

Soils and sites

In spring 1995 three sites in southern Germany were choosen representing typical soils of the FAM (Munich Research Network on Agroecosystems) research farm in Scheyern (approximately 40 km north of Munich in the Bavarian tertiary hills). The research farm area is characterized by a broad variety of soils, mainly different Cambisols, partly Gleysols and Vertisols. Annual mean temperature is about 7.4°C and annual mean precipitation is about 833 mm (AUERSWALD & KAINZ 1990).

The first soil 'Kelheim' (KH) was taken near Regensburg, South Bavaria. Annual mean temperature at the sampling site is 8.0°C and mean annual precipitation is 797 mm. The soil was described as Humic Cambisol. The second soil, called 'Hohenwart' (HW) was identified as a Cumulic Anthrosol. The sampling site is located approximately 15 km north of the FAM research farm. The third soil, 'Scheyern' (SC) is a Mollic Gleysol and was taken from a field of the research farm. All sites were agriculturally used for at least 50 years. Soil profiles of the studied soils are shown in figure 2 and soil physical and chemical properties are shown in Table 1.



Kelheim Hohenwart Scheyern

Fig. 2. Soil profiles of the studied areas.

Four replicates of each soil type were taken as undisturbed round monoliths of 2 m height and 1 m^2 surface using a hydraulic system (Fig. 3a). Installed at ground level in the GSF Lysimeter Station near Munich the monoliths are surrounded by a 1 hectare agricultural field (Fig. 3c) to obtain micro-climatic conditions and to minimize negative effects (temperature, precipitation, wind e.g.) which might occur with isolated installations. The management of the monoliths and the sur-

rounding field is adapted to the practices of the FAM conventional farming system: maize (1996, 1999), winter wheat (1997) and winter barley (1998). Contrary to the common practices no potatoes were cultivated due to the technical possibilities.

Table 1. Parameters of the studied soils (C and N is total, reduction at 1020°C with copper and oxygen to CO_2 and N_2, analysed with a TCD), pH is analyzed in water.

Kelheim - Humic Cambisol

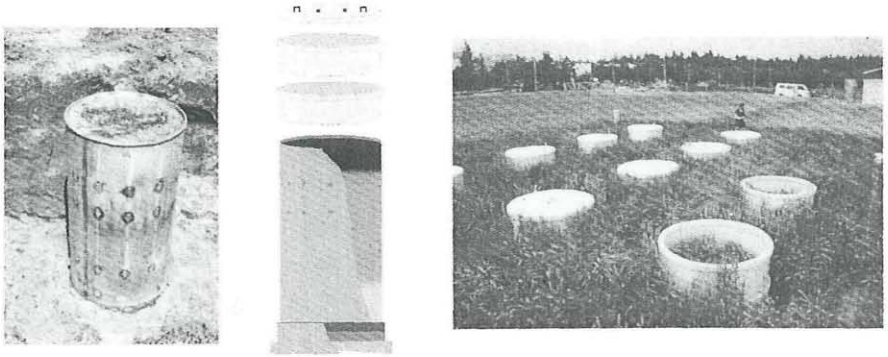
Depth (cm)	Soil horizon	C (%)	N (%)	Gravel (%)	Texture	pH
0-25	Ap	0.73	0.07	0	loamy sand	6.7
25-80	Bv	0.16	0.02	0	loamy sand	6.7
80-200	Cv	0.20	0.02	0	loamy sand	6.9

Hohenwart - Cumulic Anthrosol

Depth (cm)	Soil horizon	C (%)	N (%)	Gravel (%)	Texture	pH
0-30	Ap	1.44	0.14	13.2	loamy sand	7.2
30-70	M	0.98	0.10	13.2	loamy sand	6.5
70-100	Bv1	0.29	0.04	21.7	loamy sand	5.6
100-200	Bv2	0.08	0.02	57.3	clay loam	5.8

Scheyern - Mollic Gleysol

Depth (cm)	Soil horizon	C (%)	N (%)	Gravel (%)	Texture	pH
0-38	Ap	1.40	0.16	0	loamy silt	6.0
38-90	Sw	0.35	0.06	0	loamy silt	5.9
90-200	Sd	0.25	0.04	0	loamy silt	6.0



(a) (b) (c)

Fig. 3. Views of the soil monoliths and closed chambers. (a) Preparing undisturbed soil monoliths in the field. The monoliths are surrounded by a stain-less steel cylinder with several openings in different depths for mounting of sensors (Th2, TDR, suction e.g.). (b) Schematic view of a soil monolith and the used gas chambers compost of several segments to adjust the chambers' height to the growing plants. (c) Taking gas samples at the GSF Lysimeter station. The closed chambers were installed only during sampling and were removed from the lysimeters afterwards.

Gas flux measurements

For gas flux measurements closed chambers (HUTCHINSON & MOSIER 1981) were fitted to the monoliths (Fig. 3b, c). In the first two years chambers of 0.3 m of diameter were used and each monolith was equipped with two of these chambers. Afterwards a new chamber type was designed with 1.13 m of diameter enclosing the total surface of one monolith. With both chamber types extention segments could be used to adapt the chambers' height to the growing plants. The chambers were installed for gas measurements only and were removed afterwards.

The measurements were carried out once a week. Five gas samples were periodically collected from the chambers' atmosphere within 60 minutes into evacuated 0.1 l glass bottles using a portable vacuum pump system. The concentration of gases in the samples was analyzed by a gas-chromatograph with a ^{63}Ni electron capture detector (ECD) for nitrous oxide and a flame ionization detector (FID) for methane (LOFTFIELD & al. 1997). The calculations of the gas fluxes are described by FLESSA & al. 1995. Measurements were carried out from January 1996 to July 1999. Due to technical installations measurements were interrupted for short periods in July and September 1996 and in March 1998.

Results and Discussion

Climate at the investigation site

Regarding the effect of climate on trace gas fluxes it is obvious to obtain detailed and exact climate information of the weather during the investigation period, at least of air and soil temperature and of precipitation. For this reason extensive measurements were carried out. At the investigation site in Munich the annual mean air temperature is about 8.6°C and annual precipitation is about 860 mm (Fig. 4). The warmest months are July and August with daily mean temperatures of 18°C and maximum temperatures of about 40°C at noon. The coldest months are January and February with daily mean temperatures of -3°C and often daily mean temperatures of -10°C were reached. Although the annual mean soil temperature of the upper soil horizon (0 to 20 cm) is about 9.8°C freezing down to -20 cm (often more) appears throughout the winter months. The investigated site is a summer rain region which means that more than 50% of the annual precipitation is falling from May to August. As a result frequent drying and rewetting cycles occur in summer months.

N_2O and CH_4 flux rates

The cumulated flux rates of nitrous oxide were within a range from 1.2 to 1011 mg N_2O-N m^{-2} for the investigation period (18.01.1996 to 29.07.1999; Fig. 5). On the other hand, -3.1 to -289 mg CH_4-C m^{-2} were observed. Calculating the flux rates on an annual base the highest nitrous oxide emissions were measured with 2.9 kg N_2O-N m^{-2} a^{-1} and the highest methane uptake rates were measured with -0.82 kg CH_4-C m^{-2} a^{-1}. Within the investigation period high emissions of nitrous oxide were found in all monoliths (May 96, June 97, June 98, June 99) due to N-fertilization (BREITENBECK & BREMNER 1986, CLAYTON & al. 1994) and tillage (AULAKH & al. 1984, STALEY & al. 1990). However, high short term peaks due to freeze-thaw (GOODROAD & KEENEY 1984, CHRISTENSEN & TIEDJE 1990) were observed occasionally.

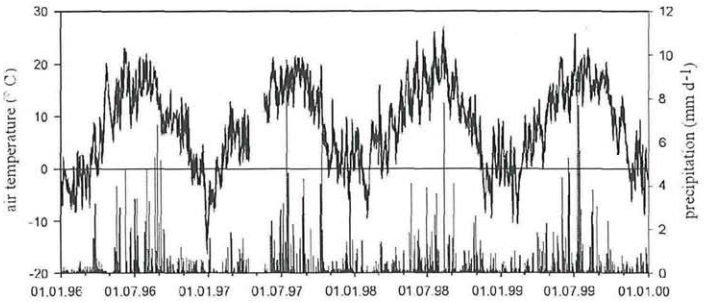


Fig. 4. Average daily air temperature and total daily precipitation within the investigation period.

Former results measured at the FAM research farm indicate that up to 50% of the annual N_2O emissions occurred in winter months due to freeze-thaw cycles (HANTSCHEL & al. 1995, FLESSA & al. 1995, KAMP & al. 1998). In contrast, in spite of occasionally frozen soils (Fig. 4) the present measurements at the lysimeter station in Munich only showed little N_2O fluxes. We calculated approximately 6% of the annual losses for the winter period (December to March) whereas in spring (March to June) 31 to 48% and in summer (June to September) 36% to 54% appeared. Up to now we do not have any idea about the cause of the different winter results measured at the research farm or the lysimeter station, respectively. Nevertheless, in accordance with formerly results (FLESSA & al. 1995, 1998a, 1998b, Kamp & al. 1998) the highest uptake rates of methane were observed in summer (latter not shown) when soils were dry and aeration was higher than in winter.

However, flux rates of both nitrous oxide and methane varied between the four replicates of each soil type. For nitrous oxide variations of 25 to 99% CV and for methane variations of 13 to 40% CV within one soil type were found.

The highest variations were found at 'Kelheim' for N_2O and for CH_4. Furthermore, KH1 and KH2 occasionally showed uptake of N_2O into the system. This finding has not been reported very often (BOUWMAN 1990). We assume that these results occurred due to very low flux rates and the detection limit of the gaschromatographical system, respectively.

On the other hand occasionally we found CH_4 emissions from the soil into the atmosphere at HW1, showing that the production of methane surpassed the oxidation rate. Usually this is well known from saturated soils, e.g. wetlands, rice paddies (LINDAU & al. 1990, BRONSON & MOSIER 1991) or mires (NYKÄNEN & al. 1995, FLESSA & al. 1998a). In fact, in many cases the soil moisture of HW1 was very high, occasionally with saturated conditions in the upper horizon. We assume that there existed a clay accumulation at HW1 leading to stagnant water. Furthermore, we guess that the little methane uptake of the other 'Hohenwart' soils is due to temporarily anaerobic conditions as well which is justified in the high clay content.

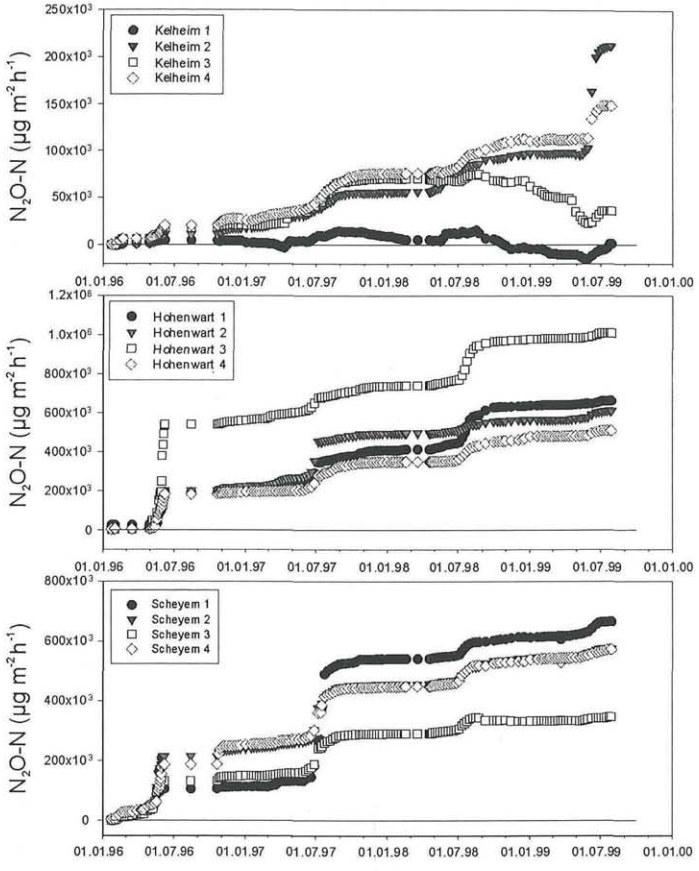


Fig. 5. Cumulated flux rates of nitrous oxide of the four soil monoliths 'Kelheim', 'Hohenwart' and 'Scheyern' as calculated from 18.01.1996 to 29.07.1999 (Note different scaling of y-axes).

Nevertheless, differences between the three investigated soils were significant and unequivocal pattern of emissions and uptake have been found (Fig. 6). The sandy and well aerated 'Kelheim' soil emitted approximately 10% of the nitrous oxide (0.28±0.28 kg N_2O-N ha^{-1} a^{-1}) emmited from the heavy and loamy 'Hohenwart' soil (2.0±0.6 kg N_2O-N ha^{-1} a^{-1}). Whereas the emissions of nitrous oxide from the 'Scheyern' soil was in a range of 1.5±0.4 kg N_2O-N ha^{-1} a^{-1}. On the other hand, the uptake of methane into the 'Kelheim' soil was 0.59±0.24 kg CH_4-C ha^{-1} a^{-1} - approximately seven times higher than the 'Hohenwart' soil (0.13±0.04 kg CH_4-C ha^{-1} a^{-1}). And again, the uptake of the 'Scheyern' soil varied between these two rates (0.32±0.04 kg CH_4-C ha^{-1} a^{-1}).

BOUWMAN 1990 gave a total range of -0.6 to 41.8 kg N_2O-N ha^{-1} a^{-1} for mineral soils. Therefore it seems, that the present soils do not emitt a lot of N_2O. However, recently KAISER & RUSER 2000 summarized nitrous oxide emissions from 99 arable soils from six long-term field experiments in Germany and found a

range of 0.5 to 16.8 kg N_2O-N ha^{-1} a^{-1} (for the years 1992 to 1997), whereas the largest part of the investigated soils emitted 1 to 5 kg N_2O-N ha^{-1} a^{-1}. Furthermore, field measurements were performed from 1994 to 1996 in just that field where the 'Scheyern' soil monoliths were taken from. There the annual flux rates ranged from 3 to 5 kg N_2O-N ha^{-1} a^{-1} and from -0.7 to -1.0 kg CH_4-C ha^{-1} a^{-1} (KAMP & al. 1998). Considering the discriminating climate and management practices between the research farm and the lysimeter station the present results correspond very well with the findings mentioned above.

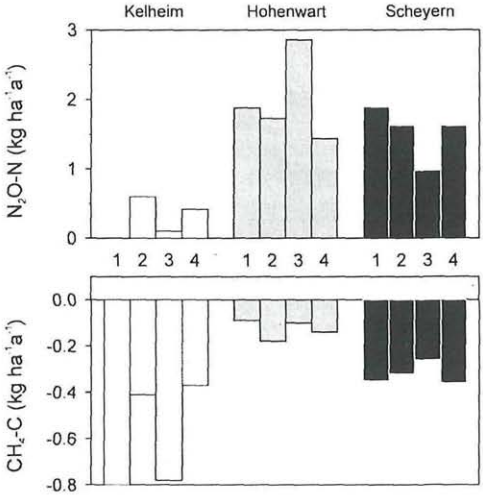


Fig. 6. Overall flux rates of nitrous oxide and methane of the four soil monoliths 'Kelheim', 'Hohenwart' and 'Scheyern' as calculated from 18.01.1996 to 29.07.1999.

We assume that the higher emissons of nitrous oxide from 'Hohenwart' and 'Scheyern' in contrast to 'Kelheim' might also be justified by higher N contents in the Ap horizons (0.14% N and 0.16% N compared to 0.07% N; Table 1). Because all monoliths were fertilized at the same time with the same amounts of N this leads to the assumption that nitrous oxide emissions might be caused rather by N mineralization than by fertilization. Unfortunately we have few data of nitrate leaching and of nitrate content of soils and plants up to now. Tracer experiments determined a percolation rate of 1.5 to 2.5 years for the soil monoliths. This means that translocation of N fertilizer in the run-out might just be visible in the far future. Furthermore, sampling of soil probes is possible during tillage only due to the undisturbed character of the monoliths. However, up to now we did not find higher nitrate contents in the leachate of the 'Kelheim' soil compared to the others. Contrary, nitrate concentrations of the 'Hohenwart' leachate were approximately three times higher than of the 'Kelheim' soil. Moreover, nitrate concentrations from 'Kelheim' were quite the same as from 'Scheyern' (data not shown). In the future missing N data from plants and soils must be worked out to come to a N balance of the

total monoliths, and to answer the question if the fertilizer N of 'Kelheim' is immobilized in deeper horizons or reduced to N_2.

Recently, FLESSA & al. 1998b compared the flux rates from two arable sites in northern and southern Germany. Although a similar management practice was used (intensive/extensive N fertilizer, winter wheat) they found differences between the sites of 24% for N_2O and 30% for CH_4. FLESSA & al. 1998b suggest that the findings were due to different rainfall (amount and temporal distribution) and due to a different gas diffusion rate of the compared soils. Furthermore, after scrutinizing N_2O emissions from 99 sites in Germany, KAISER & RUSER 2000 emphazises that there was no significant relationship between annual N_2O emissions and the respective N fertilization rate. He concluded, that the site effect on N_2O emission was more important than the effect of N fertilization.

Table 2. Global Warming Potential (GWP) of the studied soils, calculated as CO_2-equivalents: after IPCC 1996: N_2O = 310 CO_2, CH_4 = 21 CO_2 (mean = mean value, stdv. = standard deviation)

	N_2O	CH_4	(N_2O + CH_4)	mean	stdv.
	GWP (CO_2-equivalents, kg CO_2 ha^{-1} a^{-1})				
Kelheim 1	1.1	-17.2	-19	75	91
Kelheim 2	186.8	-8.6	178		
Kelheim 3	31.7	-16.3	15		
Kelheim 4	130.2	-7.7	123		
Hohenwart 1	582.8	-1.9	581	611	192
Hohenwart 2	537.3	-3.8	534		
Hohenwart 3	888.1	-2.1	886		
Hohenwart 4	447.7	-2.9	445		
Scheyern 1	585.7	-7.3	578	468	119
Scheyern 2	506.6	-6.7	500		
Scheyern 3	304.8	-5.5	299		
Scheyern 4	503.7	-7.5	496		

Global warming potential

Nevertheless, one aim of the investigations was to compare the global warming potential of the studied soils. Therefore we calculated the CO_2-equivalents of the measured nitrous oxide and methane flux rates using the findings of IPCC 1996. Following the idea that nitrous oxide corresponds to 310 CO_2-equivalents and methane corresponds to 21 CO_2-equivalents the atmospheric load increases in the order 'Kelheim' << 'Scheyern' < 'Hohenwart' (Table 2). This means that the pollution of the atmosphere from 'Hohenwart' and 'Scheyern' is 8 times and 6 times higher than from 'Kelheim' when cultivated at the same climatic conditions and the same management practices. Up to now we do not have reliable information concerning the yield of the cultivated crops and the possible pollution of drinking water with nitrate. Therefore we can not give recommendations for manage-

ment practices in the field which have to take into account a multitude of ecological and economical factors.

In the present investigation we have shown that there are factors controlling flux rates of N_2O and CH_4 from soils that have to be justified by the physical and chemical properties of the soils.

Conclusion

We demonstrated that even when climatic conditions and management practices are the same for different investigated soil types there are differences in N_2O and CH_4 flux rates. Obviously this attributes to the physical and chemical properties of the soils and not to the management practices or the climate. Nevertheless, MOSIER 1989 concluded that interactions between the physical, chemical and biological variables are complex, thus N_2O fluxes are variable in time and space. However, FLESSA & al. 1998b and KAISER & RUSER 2000 expressed that N_2O emissions from German sites are not only driven by the amount of N fertilizer. Approximately 40% of the annual N_2O fluxes are caused by climate, soil type and crops.

Therefore management practices should be well adapted to the physical and chemical properties of the cultivated soils (precision farming e.g.). And one has to proof if N fertilizers can be reduced on high-GWP soils or if cultivation can be intensified on low-GWP soils.

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