Nitrous Oxide Emission and Methane Consumption Following Compaction of Forest Soils

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ABSTRACT

Fluxes of the greenhouse gases, N_2O and CH_4, were measured across a skid trail at three beech (*Fagus sylvatica* L.) forest sites with soils of different texture. At each site three skid trails were established by applying two passes with a forwarder. Soil compaction in the middle of the wheel track caused a considerable increase of N_2O emissions with values elevated by up to 40 times the uncompacted ones. Compaction reduced the CH_4 consumption at all sites by up to 90%, and at the silty clay loam site its effect was such that CH_4 was even released. These changes in N_2O and CH_4 fluxes were caused by a reduction in macropore volume and an increase of the water-filled pore space (WFPS). Additionally, the slipping of the forwarder's wheels led to a mixing of the humus layer with the mineral soil, which resulted in a new layer. This layer reduced gas exchange between the soil and the atmosphere. Trace gas fluxes were altered in the trafficked soil and in the adjacent areas. Despite the significant changes in the trace gas fluxes on the skid trails, the cumulative effect of the two gases on the atmosphere was small with respect to total emissions. However, if soil trafficking is not restricted to the established skid trail system the area of compaction and consequently the atmospheric load by greenhouse gases may increase with every harvesting operation.

THE GREENHOUSE GASES N_2O and CH_4 are of concern because their increase in the atmosphere contributes approximately 25% to the predicted global warming (IPCC, 1994). Additionally, N_2O is involved in the ozone depletion process in the stratosphere (Crutzen, 1981). Soils are the most important source of atmospheric N_2O. Furthermore, they contribute approximately by 3 to 9% to the global atmospheric sink for atmospheric methane (Prather et al., 1995). Land use practices have been shown to change the emissions of N_2O from and the consumption of CH_4 by agricultural soils (Eichner, 1990; Moiser et al. 1991; Dobbie et al. 1996; Priemé et al., 1997; Smith et al., 2000). The effect of forest management on trace gas fluxes has been investigated, for example, for clear cutting in tropical forests (Keller et al., 1993). However, the effect of soil compaction in forest soils on trace gas flux is not well known.

The use of a forwarder and harvester machines with a total weight of up to 20 Mg for wood harvesting may cause serious soil compaction in forests. However, these machines are commonly used because of their economic efficiency. For an optimum and efficient use of harvester machines a skid trail distance of 20 m is required, because the grip arms of harvester machines have mostly a 10-m radius of action to both sides of the skid trail. This means that skid trails make up approximately 12 to 16% of the total operational area. In Germany a permanent skid trail system with a skid trial distance of 20 m is recommended by the Forestry Commissions (Anonymous, 1991) to ensure efficient wood harvesting but also to avoid the risk of unrestricted soil trafficking during harvesting.

Soil compaction by harvesting machines alters many important soil properties, such as bulk density, aeration porosity (McNabb et al., 2001), hydraulic conductivity (Gent et al., 1983), and even the root density (Wronski, 1984; Wasterlund, 1985). The effect of soil compaction on the fluxes of N_2O and CH_4 in forest soil has not received as much attention as in agricultural systems (Bakken et al., 1987; Hansen et al., 1993; Ruser et al., 1998). Therefore, the objectives of this study were (i) to quantify the change of N_2O and CH_4 fluxes across skid trails on three soils of different texture, (ii) to evaluate the changes in these trace gases with regard to their overall contribution to the greenhouse effect, and (iii) to determine whether soil temperature and moisture control the flux rates at differently disturbed soils.

MATERIALS AND METHODS

Experimental Sites and Treatment

Three 60- to 90-yr old beech stands, which exhibited similar climatic and site conditions, were selected in southern Lower Saxony (Germany). The sites are located 250 to 300 m above sea level; they have an average annual precipitation of 700 mm and an average annual temperature of 7.8°C. The sites differed distinctly in soil texture and can be described as silty clay loam, sandy loam, and silt (Table 1). The three sites are additionally distinguished by differences in other soil chemical and physical properties (Table 1). This is primarily due to the differences in their respective parent material. At the silty clay loam site a mull humus had developed; whereas at the silt and sandy loam sites a moder humus was present.

Three skid trails were established at each site. Soil compaction was performed with a forwarder (Cat Skogsjan 1088Lt with Nokia TRS LS2 700/22.5 tires) to ensure conditions comparable with those occurring during harvest practices in these forests. Compaction treatments were applied by two passes of a half-loaded, eight-wheeled forwarder (total weight about 16 000 kg, speed approximately 2 m s^{-1}). The tires had a pressure of 0.25 MPa (2.5 bar) and a width of 0.70 m. The soil water content in the 0- to 15-cm layer was close to the field capacity of the soils. The gravimetric moisture contents for sandy loam, silt, and silty clay loam were 21, 24, and 28% respectively.

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Abbreviations: GWP, global warming potential; TS_M, compacted soil in the middle of the trafficked soil; TS_B, compacted soil at the border of the trafficked soil; US_M, uncompacted soil between the two wheel tracks (middle of the skid trail); US_B, uncompacted soil at the border of the trafficked soil; WFPS, water-filled pore space.

Table 1. Soil chemical properties and particle-size distribution in 10- to 15-cm depth.†

	pH H_2O	C	N	CEC	Bs	Sand	Silt	Clay
		$g\ kg^{-1}$		$\mu mol_c\ g^{-1}$	%			
Holzerode (sandy loam)	4.5 (0.1)‡	11.3 (3.5)	0.6 (0.2)	42 (13)	11.0 (4.6)	69	23	8
Ebergötzen (silt)	4.5 (0.0)	9.3 (0.1)	8.5 (0.6)	130 (17)	11.0 (0.2)	5	87	8
Billingshausen (silty clay loam)	5.0 (0.3)	14.7 (1.1)	1.3 (0.1)	42 (1.0)	64.5 (27.8)	5	64	31

† CEC, cation exchange capacity; Bs, base saturation in percentage of the CEC.

‡ Mean of $n = 4$, and standard deviation in parentheses.

Trace Gas Measurements

The fluxes of N_2O and CH_4 at the silt and silty clay loam sites were measured at four different locations across the skid trail: (i) compacted soil in the middle of the trafficked soil (TS_M); (ii) compacted soil at the border of the trafficked soil (TS_B); (iii) uncompacted soil between the two wheel tracks (middle of the skid trail) (US_M), and (iv) uncompacted soil at the border directly adjacent to the trafficked soil (US_B) (Fig. 1). At the sandy loam site trace gases were measured only in the TS_M. These fluxes were compared with the flux on the uncompacted forest soil (control) located about 10 m away from the skid trail. Three plots (each about 10 × 25 m) were established at each site (Fig. 1). The gas fluxes at the sandy loam and silty clay loam sites were measured for 1 yr from April 1999 to March 2000 at 2- to 3-wk intervals using the closed chamber method (Matthias et al., 1980). At the silt site, gas measurements were conducted from April 1999 to the beginning of November 1999. Annual fluxes of this site were estimated by assuming that lowest fluxes measured in October/November and April also occurred during the period from November to March. This assumption was based on the low values of trace gas flux measured at the sandy loam and silty clay loam sites in October/November and April, and on a similar level of trace gas fluxes during winter (November–March).

Cylindrical chambers with a height of 25 cm and a diameter of 30 cm were used for gas measurement. Six replicate measurements were made on the uncompacted soil (control) and in the TS_M and three replicate measurements at the other sampling points. During the time of gas flux measurement the chambers were sealed with covers for 30 min in the summer and for 60 min in the winter. During this time three gas samples were taken using evacuated gas flasks. A detailed description of the gas sampling is given by Flessa et al. (1995). The concentrations of N_2O and CH_4 in the gas samples were determined in the laboratory with an automated gas chromatographic system equipped with a ^{63}Ni electron-capture detector (Loftfield et al., 1997). The trace gas fluxes were calculated using the slope of the temporal change of the gas concentration in the chamber. The cumulative values of gas fluxes were calculated by assuming that the average gas flux on the successive measurement dates was the average gas flux during the entire interval. The cumulative gas fluxes were calculated for each time interval and then the amounts of each interval were totaled up to the cumulative gas fluxes for the growing season and for the year. The growing season was defined as the period from April to October.

Calculation of the Global Warming Effect

To assess the climatic impact of N_2O and CH_4 resulting from trafficking in forests, the annual fluxes of N_2O and CH_4 were calculated on a field scale with and without the contribution of the N_2O and CH_4 fluxes derived from the differently affected areas (Table 2) of the skid trail. The difference between these two calculated values provided the increase of N_2O emission and the decrease of CH_4 consumption due to soil trafficking. The fractional area of the skid trails to total area calculated in our study was 13.2% (Table 2), assuming a distance of 20 m between skid trails. The annual N_2O emissions and CH_4 consumption derived from soil compaction were converted into CO_2 equivalents using the appropriate factors of global warming potential (GWP). A GWP of 296 was determined for N_2O and a GWP of 23 for CH_4 (IPCC, 2001).

Measurement of Soil Parameters

Temperatures were recorded at 2-h intervals for 1 yr (April 1999 to March 2000) at 5 cm of soil depth and 1 m above the

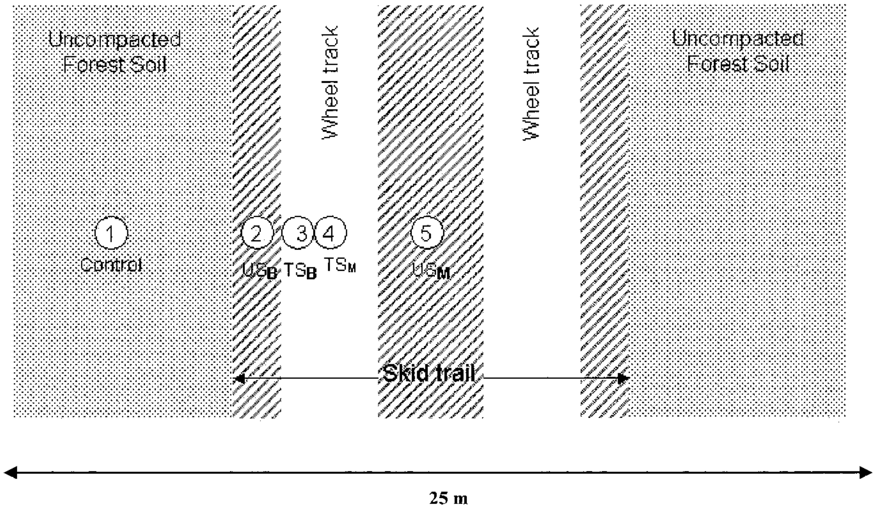

Fig. 1. Description of the location of gas flux measurement on the skid trail and on the undisturbed forest soil: 1 (control) = uncompacted soil, 2 (US_B) = untrafficked soil bordering one side of the trafficked soil, 3 (TS_B) = trafficked soil bordering one side on the untrafficked soil, 4 (TS_M) = middle of the trafficked soil, 5 (US_M) = untrafficked soil between the two wheel tracks.

Table 2. Width of the investigated locations and fractional area of the skid trail assuming a distance of 20 m between the trails (=4 skid trails per ha each with 100 length).†

Skid trail sections	Width	Fractional area
	m	%
TS_M	**0.4**	**1.6**
TS_B	**1.0**	**4.0**
US_M	**0.9**	**3.6**
US_B	**1.0**	**4.0**
Control		**86.8**

† TS_B, trafficked soil bordering one side on the untrafficked soil; TS_M, middle of the trafficked soil; US_B, untrafficked soil bordering one side of the trafficked soil; US_M, untrafficked soil between the two wheel tracks.

soil surface at the sandy loam site. Additionally, on each site temperatures of the air, humus layer, and at 5 cm of soil depth were determined at the time of gas collection. Soil samples (at depths of 0–5 and 5–10 cm) for determining the soil moisture were collected from the trafficked and the uncompacted zones every time the trace gas samples were taken. The WFPS of the soils was calculated using the following relationship:

$$\text{WFPS} = (\text{gravimetric water content} \times \text{bulk density})/\text{soil porosity}$$

where the porosity was calculated by 1 − bulk density/density of the soil matrix. The bulk density was determined for the compacted and uncompacted soils on each site using soil cores taken with a metal cylinder having a height of 5 cm and a diameter of 8 cm.

Statistical Analysis

The cumulative gas fluxes for each site and treatment were expressed as arithmetic means with standard deviation (n = 6 for the control and TS_M and n = 3 for US_B, US_M, and TS_B). The cumulative gas fluxes, bulk densities, pore spaces, and macropores on different sections of the skid trail were compared using analysis of variance. A nonparametric test was selected because trace gas fluxes are not normally distributed. The Mann-Whitney U-Test was used with the factors treatment (control, US_B, US_M, TS_M, and TS_B) and spatial replication. The factor spatial replication was considered to be a random factor.

The relations between soil temperature (at a depth of 5 cm), WFPS (at a depth of 5–10 cm) and the trace gas fluxes were tested by applying a stepwise multiple linear regression. Before these analyses were performed, the frequency distributions were tested for normality using the Kolmogrof-Smirnov test. The CH_4 fluxes were normally distributed except for the skid trails of the clayey site where they were lognormally distributed ($p < 0.05$). The N_2O fluxes were normally distributed except for the skid trails of the sandy site where a lognormal distribution was observed. The soil temperature and WFPS were normally distributed. Lognormally distributed data were log-transformed before the statistical analyses were run.

RESULTS AND DISCUSSION

Change of Soil Physical Properties

Soil trafficking resulting from two passes of a forwarder had a small effect on the bulk density with an insignificant increase of about 0.1 g cm^{-3} at both depths (0–5 cm and 10–15 cm) except for a significant increase of 0.3 g cm^{-3} at a depth of 0 to 5 cm at the sandy loam site (Table 3). However, a significant reduction in macropore volume (>50-μm diameter) was observed on all soils after compaction. The macropore volumes were reduced by about 50% at 0- to 15-cm of soil depth. The reduction was accompanied by an increase in the micropore volume (<10 μm) and a decrease of the total pore space. This change in pore-size distribution resulted in an increase of the WFPS (Fig. 2–4). During the growing season the average WFPS of the compacted soils was about 6% (sandy loam site) to 25% (silt site) higher than at the respective control plots (Table 4). The fraction of the mesopores (50–10 μm) was low and did not change with compaction.

The changes of bulk density measured in our study are in agreement with the study of McNabb et al. (2001). They measured a change of the bulk density in a range of 0 to 0.5 g cm^{-3} at several forest sites after different numbers of passes by a forwarder and pointed out the importance of site conditions during trafficking, especially that of the soil moisture.

Soil trafficking and the slipping of the wheels mixed the humus layer with the mineral soil and created a new soil layer, which had a different organic matter content than that found on the forest floor and in the surface mineral soil (Table 5).

Effect of Soil Compaction on N_2O Emission

The N_2O emissions from the control plots were very low (Fig. 2–4) amounting to <50 mg N_2O-N m^{-2} yr^{-1}. Low emission rates of <100 mg N_2O-N m^{-2} yr^{-1} have been observed in most temperate forests (Brumme et al., 1999). The very low N_2O emissions from the three sites were probably related to the low precipitation of 700 mm ha^{-1} yr^{-1} on these sites. In a temperate deciduous forest in the northwestern USA, N_2O emissions of the same order of magnitude were measured as in the present study (Bowden et al., 2000), even when N fertilizer was applied, confirming the generally low annual N_2O emissions from many temperate forests.

Soil compaction increased N_2O emissions significantly. The high N_2O emissions occurring after compaction were restricted to short periods at the sandy loam (Fig. 2) and silty clay loam sites (Fig. 4) whereas emissions at the silt site (Fig. 3) remained high throughout the entire growing season. During the growing season the highest cumulative emissions at the TS_M microsites were observed at the silt site (272 mg N_2O-N m^{-2}), followed by the sandy loam (216 mg N_2O-N m^{-2}) and silty clay loam (116 mg N_2O-N m^{-2}) sites (Table 4).

Higher N_2O emissions after compaction are probably due to a change in the pore-size distribution (Table 3) affecting the gas exchange between soils and the atmosphere. A macropore volume of <10% is usually considered to be too low to maintain a sufficient supply of oxygen into the soil (Startsev and McNabb, 2001; Xu et al., 1992). This effects a reduction in aerobic processes and therefore may change the gaseous N emissions (Granli and Bøckman, 1994). The reduction in macropore volume will also increase the WFPS. The average WFPS of the compacted soil (TS_M) was much higher at

Table 3. Bulk density, pore space, and average volume of the macro-, meso-, and micropores in the trafficked soil and in the uncompacted soil (control) at the three forest sites.

Site	Treatment	Depth	Bulk density	Pore space	Macropore >50 μm	Mesopore 50–10 μm	Micropore <10 μm
		cm	g cm^{-3}	Vol. %			
Holzerode (sandy loam)	control	0–5	1.22^{a} (0.07)‡§	53^{a} (3)	13^{a} (4)	4 (0.4)	36 (3)
	TS$_M$†	0–5	1.52^{b} (0.05)	40^{b} (2)	4^{b} (2)	5 (1.4)	31 (1)
	control	10–15	1.36^{c} (0.05)	48^{a} (3)	14^{a} (4)	5 (1.0)	29 (3)
	TS$_M$	10–15	1.36^{c} (0.07)	48^{a} (2)	6^{b} (2)	3 (0.3)	39 (5)
Ebergötzen (silt)	control	0–5	1.15^{a} (0.05)	55^{a} (2)	10^{a} (3)	6 (1.1)	39 (3)
	TS$_M$	0–5	1.26^{a} (0.08)	48^{b} (3)	5^{b} (3)	4 (0.8)	39 (1)
	control	10–15	1.29^{ab} (0.10)	51^{ab} (4)	11^{ab} (6)	8 (0.8)	32 (3)
	TS$_M$	10–15	1.42^{b} (0.05)	46^{b} (2)	6^{b} (2)	3 (0.3)	37 (1)
Billingshausen (silty clay loam)	control	0–5	1.07^{a} (0.06)	58^{a} (2)	15^{a} (5)	4 (0.1)	39 (3)
	TS$_M$	0–5	1.01^{a} (0.04)	59^{a} (2)	7^{b} (2)	5 (0.5)	47 (3)
	control	10–15	1.27^{b} (0.03)	51^{b} (1)	14^{a} (2)	3 (0.3)	34 (2)
	TS$_M$	10–15	1.35^{b} (0.10)	49^{b} (4)	4^{b} (3)	4 (0.6)	41 (4)

† TS$_M$, middle of the trafficked soil.
‡ Within each site, same letters indicate no significant differences ($p < 0.05$).
§ Mean of $n = 4$ and standard deviation in parentheses.

the silt and silty clay loam sites than at the sandy loam site (Table 4) and may explain the lower N_2O emissions on the sandy loam site. Similarly, the WFPS can be related to the high N_2O emissions from the compacted silt site, which showed a constant decrease of the WFPS during the growing season (Fig. 3). However, on the silty clay loam site low N_2O emissions (Fig. 4) were observed despite the high WFPS values. The slipping of the wheels probably sealed the surface of the silty clay loam to a greater extent than at the other sites and thus reduced the O_2 diffusivity with the result that a higher proportion of N_2O was reduced to N_2 (Davidson, 1991).

The N_2O emissions from the compacted soil were not similar on all parts of the skid trail. Emission values increased from TS$_M$ to TS$_B$ (Table 4). Compared with TS$_M$ the emissions at the border area, TS$_B$, were about 25% (silt site) and 50% (silty clay loam site) higher.

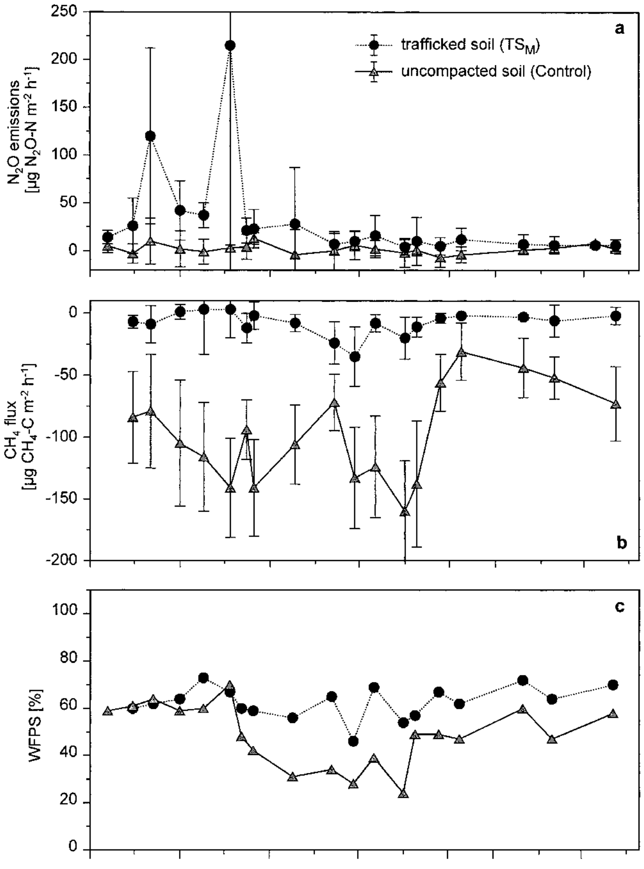

Fig. 2. (a) Nitrous oxide and (b) CH_4 flux (mean of $n = 6$ and standard deviation) and (c) water-filled pore space (WFPS) at 5- to 10-cm depth in the trafficked soil (TS$_M$) and in the control (uncompacted soil) at the Holzerode site (sandy loam) from April 1999 to March 2000.

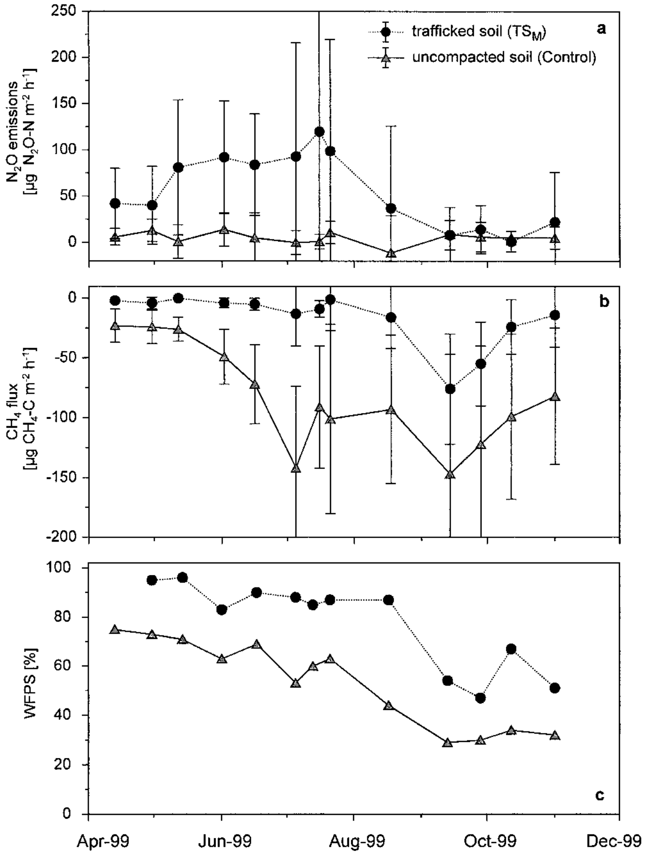

Fig. 3. (a) Nitrous oxide and (b) CH_4 flux (mean of $n = 6$ and standard deviation) and (c) water-filled pore space (WFPS) at 5- to 10-cm depth in the trafficked soil (TS$_M$) and in the control (uncompacted soil) at the Ebergötzen site (silt) from April 1999 to October 1999.

However, these differences were not significant. Nevertheless, it can be speculated that lower emission values in the middle of the track were probably related to an increased level of reduction of N_2O to N_2. Nitrous oxide emissions do not provide an evaluation of the degree of compaction, because under extremely anaerobic conditions the N_2/N_2O ratio will rapidly alter with small changes in oxygen concentration (Davidson, 1991).

The increase in N_2O emissions following soil trafficking was not confined to the compacted area, because higher N_2O emissions were observed in the areas adjacent to the impacted ones (US_B and US_M, Fig. 1) than in the nearby control plot (Table 4). The enhanced N_2O emissions from the soils bordering to the trafficked soil may partly be explained by a lateral diffusion of N_2O from the compacted soil to the undisturbed soil forced by the high N_2O concentration in the compacted soil.

Soil compaction did not change the N_2O emissions in the autumn and winter months. It has been observed that soil frost plays a significant role in N_2O emissions due to high N_2O emission rates during soil thawing (Papen and Butterbach-Bahl, 1999; Teepe et al., 2000). In the present study the effect of frost combined with that of soil compaction was not observed due to the absence of soil freezing at these sites during the measuring period. Low soil temperatures (0–5°C) from November to March resulted in emission values of <10 μg N_2O-N m^{-2} h^{-1} for both the trafficked and the undisturbed soil (control).

A small fraction of the temporal variability in N_2O emissions released from the undisturbed soils (control) was related to soil temperature and soil moisture conditions. The variance in N_2O emissions of the trafficked soil explained by soil temperature was 13% at the silty clay loam site, 25% at the silt site and 39% at the sandy loam site. The variance explained in relation to WFPS in the trafficked soils was 50% at the silt site and <10% at the other two sites.

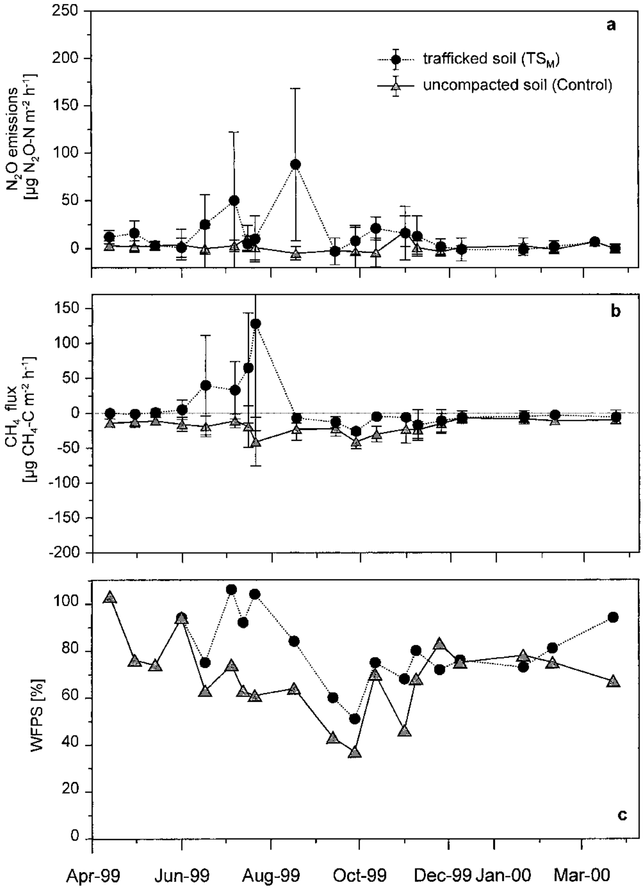

Fig. 4. (a) Nitrous oxide and (b) CH_4 flux (mean of $n = 6$ and standard deviation) and (c) water-filled pore space (WFPS) at 5- to 10-cm depth in the trafficked soil (TS_M) and of the control (uncompacted soil) at the Billingshausen site (silty clay loam) from April 1999 to March 2000.

Effect of Soil Compaction on CH_4 Flux

The CH_4 consumption values on the sandy loam site (Fig. 2) and silt site (Fig. 3) are some of the highest in northern European soils (Smith et al., 2000). In contrast, the CH_4 consumption at the silty clay loam site was much lower during the entire year (Fig. 4) resulting in a cumulative CH_4 consumption of 1.5 kg CH_4–C ha^{-1} yr^{-1}. The high CH_4 consumption on the sandy loam and silt sites showed a distinct seasonal pattern with maximum rates of 160 μg CH_4–C m^{-2} h^{-1} (Fig. 2 and

Table 4. Cumulative N_2O emissions and CH_4 consumption and the average water-filled pore space (WFPS) at 5- to 10-cm depth at the control site and within the skid trail during the growing season (April 1999 to October 1999) at the three forest sites.†

		N_2O-N	CH_4–C	WFPS
Site	**Treatment**	mg m^{-2}		%
Holzerode (sandy loam)	control	11^a (34)‡§	-554^a (172)	49
	TS_M	216^b (173)	-46^b (37)	55
Ebergötzen (silt)	control	23^a (39)	-430^a (234)	55
	TS_M	272^b (209)	-101^b (81)	80
	TS_B	334^b (177)	-85^b (75)	nd¶
	US_B	194^{ab} (263)	-232^{ab} (137)	nd
	US_M	151^b (80)	-191^{ab} (246)	nd
Billingshausen (silty clay loam)	control	4^a (28)	-110^a (37)	68
	TS_M	116^b (65)	$+70^b$ (103)	83
	TS_B	182^b (113)	-5^b (38)	nd
	US_B	177^b (32)	-66^{ab} (40)	nd
	US_M	89^b (45)	-54^{ab} (67)	nd

† TS_B, trafficked soil bordering one side on the untrafficked soil; TS_M, middle of the trafficked soil; US_B, untrafficked soil bordering one side of the trafficked soil; US_M, untrafficked soil between the two wheel tracks. Mean of $n = 6$ (TS_M, control) and $n = 3$ (TS_B, US_B, US_M).

‡ Within each site, same letters indicate no significant differences ($p < 0.05$).

§ Standard deviation in parentheses.

¶ Not determined.

Table 5. Carbon content (percentage of dry soil) in different depths of the uncompacted soil (control) and of the middle of the trafficked soil (TS_M).

Treatment	Depth, cm	Holzerode (sandy loam)	Ebergötzen (silt)	Billingshausen (silty clay loam)
			C, %	
Control	Humus layer	30.8	34.3	42.3
	0–5	3.3	3.2	3.7
	10–15	0.9	0.9	1.3
TS_M	Humus layer†	4.8	9.2	–
	0–5†	4.2	1.5	8.9
	10–15	0.9	0.9	1.3

† Humus layer and mineral soil at 0- to 5-cm depth disturbed due to slipping of the wheels.

3). The temporal pattern of CH_4 consumption in soils depends primarily on the soil water status. Soil temperature plays a minor role because the substrate limitation of the methanotrophic bacteria is primarily controlled by soil water content (Castro et al., 1994; Crill et al., 1994; King and Adamsen, 1992). However, approximately 35% (sandy loam and silty clay loam sites) to 44% (silt site) of the temporal variation of the CH_4 consumption could be explained by soil temperature in our study.

The correlation between CH_4 consumption and soil moisture provided different results for the three sites. For the silt site the moisture content of the surface mineral soil could explain 55% of the temporal variation in CH_4 consumption with low values for the silty clay loam site ($r^2 = 34\%$) and very low for the sandy loam site ($r^2 = 9\%$). The degrees of explanation of the variability in CH_4 consumption explained by both soil temperature and moisture parameters, as obtained using multiple regression equations, were 87% (silt), 49% (silty clay loam), and 41% (sandy loam). The importance of the WFPS as a regulator for CH_4 consumption was evident from field scale data, in which cumulative values of CH_4 consumption increased with decreasing mean values of WFPS during the growing season; whereas the WFPS of the various sites conformed to the following order: silty clay loam > silt > sandy loam (Table 4).

Soil compaction by trafficking, for example, at TS_M, caused a large reduction in the CH_4 consumption. The extent of reduction in the cumulative value of CH_4 consumption during the growing season at different sites was as follows: −92% (sandy loam), −77% (silt), and greater than −100% (silty clay loam). The silty clay loam became a source of CH_4 emissions in June when WFPS increased to approximately 100% (Fig. 4). A similar large reduction in CH_4 consumption after compaction has been found in agricultural soils (Hansen et al., 1993; Ruser et al., 1998; Sitaula et al., 2000).

The decrease in the CH_4 consumption in compacted soil is probably directly related to a reduction in macropore volume (Table 3). Both parameters, CH_4 consumption and macropore volume, were significantly different for the trafficked and untrafficked soil (Table 3 and 4) at each site. The reduction in macropore volume caused an increase in WFPS (Fig. 2–4), which, in turn, reduced CH_4 consumption due to retardation of CH_4 diffusion from the atmosphere into the soil. However, at the sandy loam site even a small increase in the WFPS significantly reduced the CH_4 consumption, indicating that factors associated with the soil surface are probably more important than those that could be determined by bulk density measurements. For example, the soil surface may be sealed due to soil compaction and due to soil surface disturbance associated with the wheel slip, which significantly reduces diffusion processes.

In the trafficked area, the reduction of CH_4 consumption differed in the TS_M and the TS_B areas of the wheel tracks without any clear trend (Table 4). At the silty clay loam site the cumulative CH_4 flux for TS_M calculated for the growing season indicated CH_4 emissions; whereas in the TS_B the cumulative value was zero. The cumulative value of CH_4 consumption at the border and between the trafficked soil (US_B and US_M) was reduced by approximately 50% (44–60%) compared with the values at the control site.

Effect of Wood Harvesting on N_2O and CH_4 Flux

The impact of wood harvesting on the fluxes of N_2O and CH_4 were calculated for the harvested area by considering the different fractional areas of the skid trail and by assuming a distance of 20 m between the skid trails (Table 2). The decrease in the CH_4 consumption on the skid trails reduced the cumulative CH_4 consumption of the total area only by <10%, whereas the N_2O emissions doubled. The cumulative values of increase due to compaction were approximately 0.1 N_2O-N kg ha^{-1} yr^{-1} for the sandy loam and silty clay loam sites and 0.3 kg N_2O-N kg ha^{-1} yr^{-1} for the silt site.

The estimate of the trace gas flux due to trafficking was based on a small compacted area of approximately 6% of the total area. Soil compaction on a higher fraction of the harvested area is often observed on forests harvested by clear cutting and will change the trace gas flux considerably when calculated on a whole field scale. Therefore, we recommend that the fraction of trafficked area should be restricted to <10%. This can be achieved by establishing a permanent skid trail system with a distance of 20 m between the trails used for all harvest operations.

The greenhouse effect of CH_4 and N_2O fluxes were calculated as CO_2 equivalents using GWP (IPCC, 2001). For the undisturbed area (control) (Table 3) the CO_2 equivalents calculated from the N_2O emissions were as follows: 49 (silty clay loam), 60 (sandy loam), and 158 kg CO_2 ha^{-1} yr^{-1} (silt); and the CO_2 equivalents calculated from the CH_4 consumption were: 47 (silty clay loam), 157 (silt) and 249 kg CO_2 ha^{-1} yr^{-1} (sandy loam). Assuming that soil compaction was restricted to 6% of the harvested area, the CH_4 consumptions expressed in CO_2 equivalents would be reduced by 4, 11, and 13 kg CO_2 ha^{-1} yr^{-1} and the CO_2 equivalents of the N_2O emissions would be enhanced by 57 kg (silty clay loam), 60 kg (sandy loam), and 134 kg (silt) CO_2 ha^{-1} yr^{-1}. Thus, the total impact of soil trafficking on the greenhouse effect was <150 kg CO_2 ha^{-1} ha^{-1} yr^{-1}. This indicates that the impact of harvesting on the greenhouse gas emissions remains small, but this needs to be viewed with respect to other C fluxes on the harvested site, for example, the effects of woody detritus left on the site (Harmon et al., 1996) or the amount of harvested wood. In Germany the latter amounts to approximately 3.7 m^3 ha^{-1} yr^{-1} (BMELF, 1996). The value of approximately 150 kg CO_2 equivalents ha^{-1} yr^{-1} can also be viewed in relation to 12 Mg CO_2 emissions ha^{-1} yr^{-1} from forest soils measured in Lower Saxony (Brumme and Beese, 1992).

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