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Increasing the soil temperature to study global warming effects on the soil nitrogen cycle in agroecosystems

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Abstract. According to the GCMs air temperature will increase 3–5°C above ambient in Central Europe. As one consequence the element turnover in terrestrial ecosystems should change; in particular, the large soil carbon and nitrogen pools are crucial because of their potential to further 'pollute' the globe with liquid and gaseous compounds. According to the goals of the International Geosphere-Biosphere Programme (IGBP) an ecosystem manipulation was carried out to increase the temperature of the top soil in an agroecosystem 3°C above ambient and to study the effects on the nitrogen cycle. The experimental design, called HOTWORM, could be proved during a 3-month winter period to keep a constant temperature difference of 3°C above ambient including freezing–thawing cycles.

No changes in the soluble nitrogen pools could be measured at the end of the investigation, probably because of the short heating period and the high spatial variability. However, N_2O-N emissions were much higher in the unheated plot (0.233 kg ha^{-1}) compared with the heated one (0.058 kg ha^{-1}). This effect could be caused by more frequent freezing–thawing cycles in the unheated plots, which showed the highest emission rates. The importance of the reduced water content in the heated plot could not be evaluated in this investigation. Based on the experiences of this study a schedule for intensified field experiments was developed.

Key words. Global change, soil temperature, nitrogen cycle, N_2O-emissions, ecosystem manipulation.

INTRODUCTION

The assimilation of carbon into biomass and its decomposition to CO_2, DOC and humic substances is part of the most important element cycle in local to global ecosystems (Schlesinger, 1991). Closely interrelated are the turnover processes of other important biogeochemical elements, mainly of nitrogen which regulates the productivity of ecosystems. The kinetics of the turnover are dependent on temperature as shown for processes of the nitrogen cycle in many laboratory experiments (Ellert & Bettany, 1988, 1992).

GCMs are used nowadays to provide an estimate of future climate distribution on the globe. In Central Europe they prognose an air temperature increase of about 3–5°C and increasing precipitation (Grotch, 1991). The following changes in the energy, water and element budget of different ecosystems are the scope of the International Geosphere-Biosphere Programme (IGBP). One topic of the core project Global Change and Terrestrial Ecosystems (GCTE) is the quantification of the effect of increased CO_2 in the atmosphere and of the prognosed temperature increase on the biogeochemical cycles (Steffen *et al.*, 1992). It is necessary to get an estimate whether the turnover rates of elements in the soil will change. Does the soil act as a growing sink for carbon and nitrogen or does it release increasing amounts of those elements in liquid and gaseous forms?

To study the effect of a temperature increase on element cycles in ecosystems knowledge of known laboratory experiments is unsatisfactory. Therefore we have to manipulate the temperature regimes of different ecosystems to understand reactions on a system level. The objectives of this study are (1) to test using field equipment which increases the temperature of topsoils in agroecosystems 3°C above ambient and (2) to compare the nitrogen cycle of heated and unheated plots focusing on the N_2O-emission as a sensitive indicator of changes.

MATERIALS AND METHODS

The experiments are performed on the 'Scheyern' experimental farm (N 48°30,0′, E 11°20,7′) of the Forschungsverbund Agrarökosysteme München (FAM), an interdisciplinary network on agroecosystems. The FAM network is one of five German ecosystem research centres, linked to the Terrestrial Ecosystem Research Network of Germany (TERN). The Bavarian tertiary hillslopes north of Munich are characterized by a broad spectrum of soils, mainly different Cambisols, partly Gleysols and Vertisols. This study was done on a typic Cambisol, characterized by

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TABLE 1. Soil parameters of the studied cambisol (Schwertmann *et al.*, 1993).

Depth (cm)	Soil horizon	pH ($CaCl_2$)	C_t ($g\ kg^{-1}$)	N_t ($g\ kg^{-1}$)	Density ($g\ cm^{-3}$)	Gravel (%)	Clay (%)	Silt (%)	Sand (%)
0–19	Ap	5.8	0.122	0.012	1.38	18.3	16.9	38.7	44.3
19–29	Btv	6.3	0.121	0.012	1.62	13.1	06.8	48.4	44.8
29–52	Bv1	5.2	0.026	0.004	1.45	03.0	10.5	43.5	45.9

the parameters shown in Table 1. Winter wheat was sown in late autumn 1993 and grew to 0.12 m during the investigation period.

To heat the soil we used a Teflon–copper–Teflon wire with an outer diameter of 0.0032 m which was buried in 0.02 m depth. The wire was laid on the top of the soil in a distance of 0.03 m. This distance has been tested in a previous experiment to avoid severe temperature gradients between the cable strings. Fig. 1 shows a scheme of the technical design of the heating equipment, called 'HOTWORM', and gives some physical data. The control unit, with its temperature sensors in the heated and the unheated plots, makes it possible to keep a constant temperature difference between both plots. In this study $dT = 3°C$ was chosen.

The heated and unheated plots are 1 m^2 each. Consequently 33 m of heating wire were used on the heated plot. About 11% of the soil surface is covered with the cable. Effects of this physical alteration of the environment were not under investigation in this study (middle of January to end of March 1994). N_2O gas samples were collected using the closed gas chambers technique (Dörsch, Flessa & Beese, 1993), i.e. plastic rings of 0.3 m diameter, buried in the soil. The heating cable runs through the chamber which is raised about 0.04 m above the soil surface. To enrich N_2O emissions a second plastic cover was fixed tightly on the buried one with metal clamps for about 60 min. Through a septum five gas samples were taken using evacuated 0.1 l glass bottles. In the laboratory these bottles were suspended into a valve controlled autosampler, connected to a gas chromatograph (Shimadzu GC-14B) with an ^{63}Ni electron capture detector. To monitor soil temperatures on both plots five thermistors were installed, each to a depth of 0.02 m. The sensors were put in the middle between the heating cables. On some dates temperature profiles were measured down to 0.3 m using a mobile temperature sensor. Water content and mineral nitrogen content were measured at four depths (0–0.05 m, 0.05–0.1 m, 0.1–0.2 m, 0.2–0.3 m) on five sampling dates.

Total soluble nitrogen, NO_3-N and NH_4-N were deter-

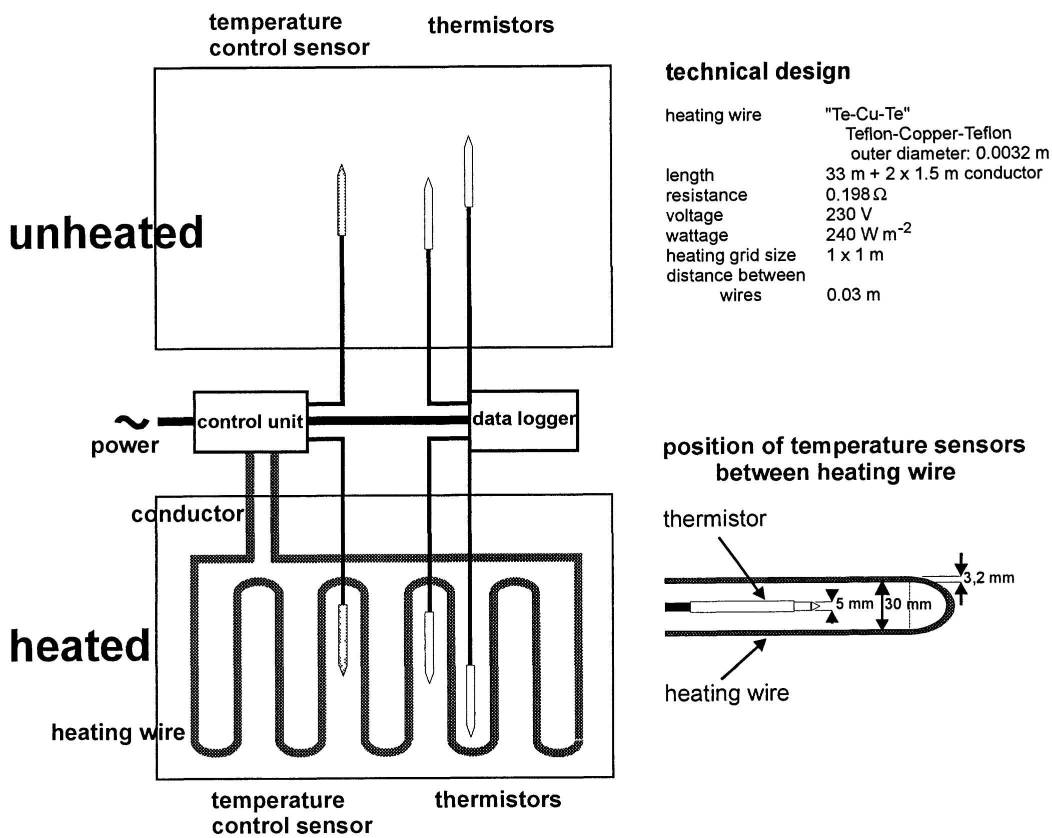

FIG. 1. Technical design of the soil heating equipment HOTWORM.

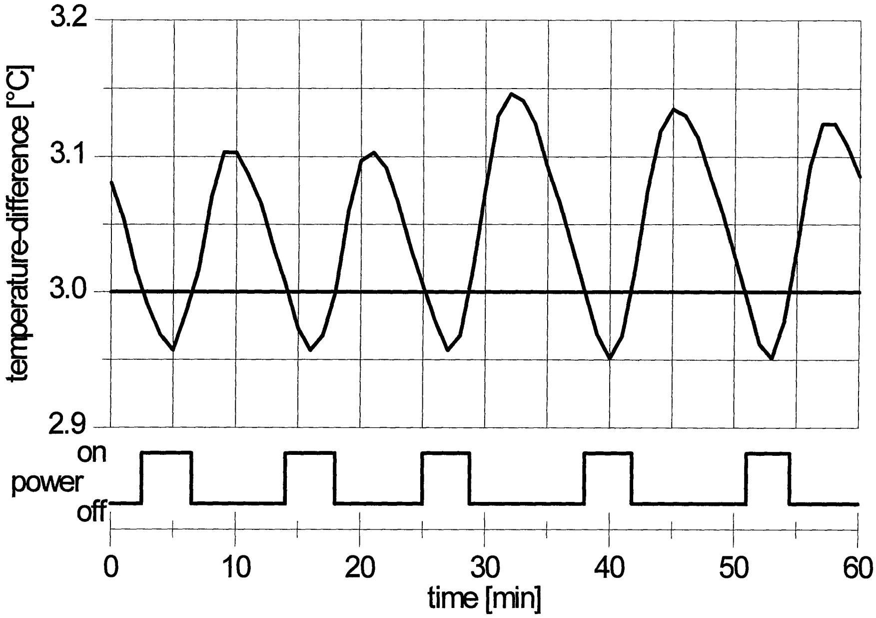

FIG. 2. Temperature difference (°C) between the sensors of the control unit and the circuit diagram of the power supply.

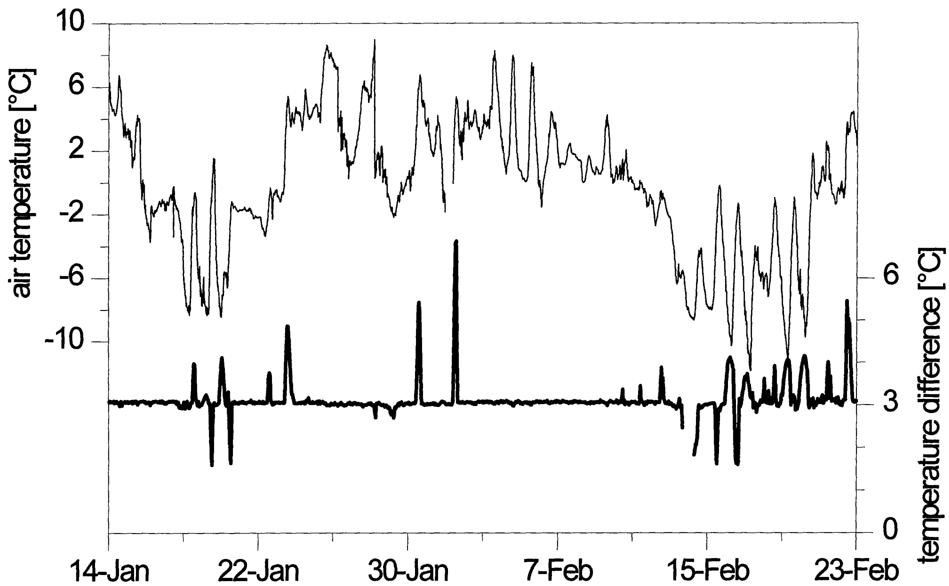

FIG. 3. Air temperature (°C) (|) and soil temperature difference (°C) (‖) between heated and unheated plots over 6 weeks.

mined with a Scalar analyser after extracting the fresh soil sample with a 0.01 M $CaCl_2$ (1 wt/2 wt).

RESULTS AND DISCUSSION

Soil heating

The control unit was set to keep the temperature difference at 3°C. As Fig. 2 shows, the power unit was switched on every 8 min for about 3–4 min to heat the soil. Maximum differences reached after the currency pulse were generally about 3.1°C. Only after rapid increases of air temperature, e.g. in mid-January, did temperature differences become larger or smaller (Fig. 3). In early February failures in the heating unit caused a much higher difference over some hours. During the rest of the investigation period the soil temperature in the heated plot tracks the curve of the unheated plot very well, as the hourly mean values of air

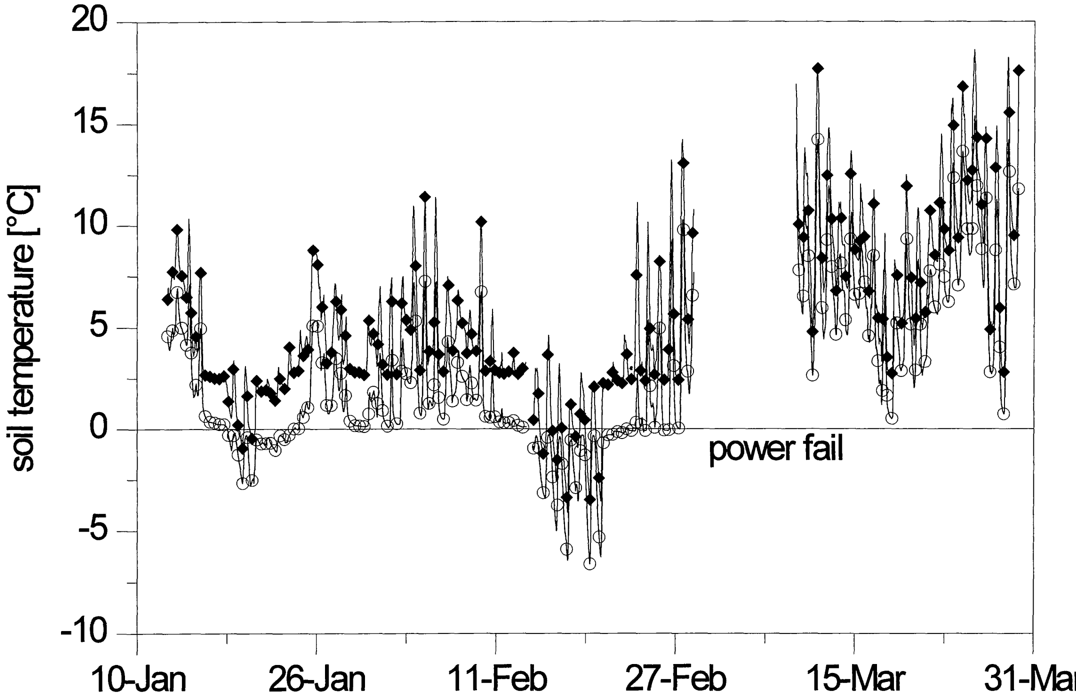

FIG. 4. Soil temperature (°C, hourly mean values) in 0.02 m depth in the heated (◆) and the unheated (○) plots through the investigation period.

and top soil temperature shows (Fig. 4). Most peaks could be simulated. During freezing–thawing cycles the difference of 3°C could not be exactly kept. A major breakdown of the power supply on the farm dropped the system down for about 8 days at the beginning of March.

Fig. 5 shows the soil temperature profile for 24 January and 12 March, measured at noon. In January the soil has already thawed after a frost period in the upper 0.05 m, but at this depth only in the control plot is a thin ice layer still present. Because it has already thawed in the heated plot, the heat flux downwards causes a temperature difference > 3°C in the 0.06–0.1 m layer. At a depth of 0.3 m the soil temperature of the treated plot was still 1°C higher. In March the difference could also be tracked down to 0.3 m. These temperature measurements prove the applicability of the HOTWORM equipment to simulate soil warming.

Discussion of global warming on an ecosystem level shows the problems of the HOTWORM approach. Because there is no increase of air temperature plants only experience change in their root systems and will therefore react differently to that expected in natural circumstances. Other techniques available to simulate global warming are the heating of the air with radiation-based systems (Göttlein, 1994, pers. comm.) and the heating of soil columns (Ineson, 1991). These techniques do not offer the possibility to apply constant, well defined temperature differences to a plot of several square meters. Because our focus is study of the soil internal nitrogen cycle we suggest that the equipment presented is well suited to study effects of global warming on soil ecological processes. However, because of the restriction referring to shoot reactions the transfer of the results to an ecosystem level must be done with care.

Water content of soils

Starting at the same water content in January both treatments differentiate during the investigation (Fig. 6). In the top layer of the heated plot a distinct reduction of the water content is obvious for all dates. With increasing soil depth the differences diminish. Because the soil physical condi-

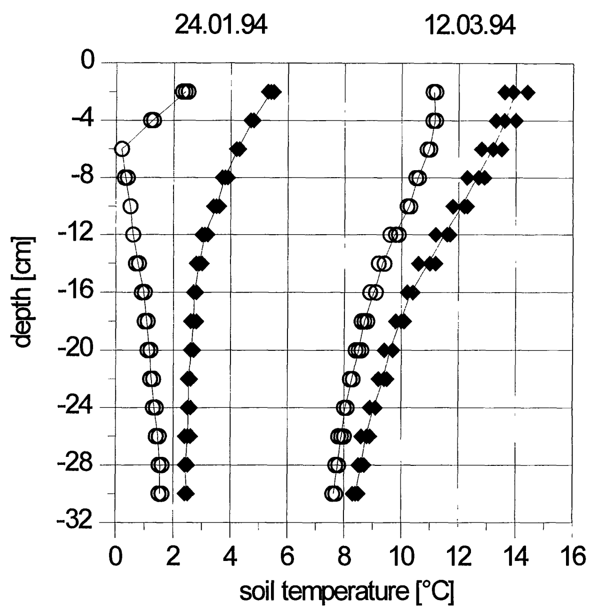

FIG. 5. Depth profile of soil temperatures (°C) in the heated (◆) and the unheated (○) plots on 24 January and 12 March.

tions do not vary between both plots an increased evapotranspiration on the heated plot probably decreased the water content. This important change will influence water and element transport as well as the microbial turnover of C and N and therefore has to be included as a secondary factor. Peterjohn *et al.* (1994) showed only a weak relationship between water content and gaseous emissions in a mixed deciduous forest.

Nitrogen turnover

The extractable nitrogen fractions were reduced comparing the samples taken before the experiment began and after it ended (Table 2). This is probably due to leaching, with precipitation of 127 mm during the period. No clear difference between the heated and the unheated plot could be shown for the different fractions because the spatial variability of mineral nitrogen content is high and the experimental period rather short. Peterjohn *et al.* (1993) could show a 30% decrease of total nitrogen in plots heated 5°C above ambient for 1 year.

Besides the soluble nitrogen components the gaseous nitrogen emissions, mainly N_2O, are important from an ecological point of view. In Fig. 7 the N_2O-N fluxes are shown, comparing the behaviour of the heated and the unheated plots. Two phenomena are obvious: first, a rapid increase of trace-gas emissions during freezing–thawing periods. This fact could also be measured by Dörsch *et al.* (1993). Secondly, the unheated plot was characterized by much higher gas fluxes than the heated plot during those cycles.

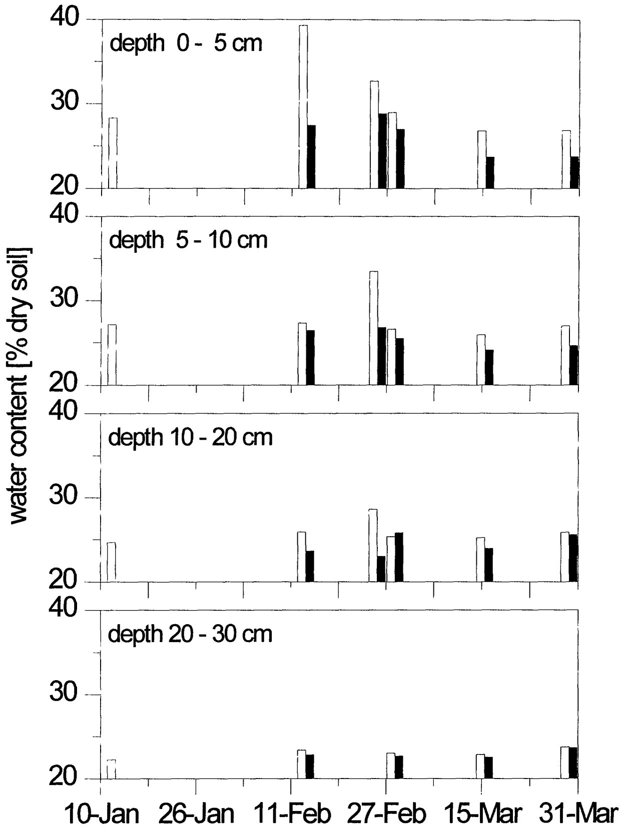

FIG. 6. Gravimetric water content (kg/kg^{-}1) of four soil layers on the heated (■) and the unheated (□) plots.

TABLE 2. Nitrogen fractions extracted from several soil depth at the beginning and the end (U = unheated plot, H = heated plot) of the experiment in mg kg^{-1} ($N_{org} = N_t - NH_4^+ - NO_3^-$).

Depth (cm)	N_t			NO_3^-			NH_4^+			N_{org}		
	Start	End		Start	End		Start	End		Start	End	
		U	H		U	H		U	H		U	H
0–5	5.0	3.4	4.1	3.4	1.9	2.1	0.3	0.4	0.5	1.3	1.1	1.5
5–10	9.0	4.7	4.0	7.2	3.1	2.2	0.4	0.4	0.5	1.4	1.2	1.3
10–20	11.1	4.2	3.5	9.0	2.7	2.0	0.3	0.3	0.3	1.8	1.2	1.2
20–30	10.0	3.2	2.8	7.8	2.0	1.6	0.3	0.2	0.3	1.9	1.0	0.9

On days with temperatures up to 15°C only very small fluxes >5 μg N_2O-N m^2 h could be measured, not differentiating between the treatments. Calculating the sum curve of the N_2O-N emissions during the 74 days 0.233 kg N ha^{-1} were lost on the unheated plot compared to 0.058 kg N ha^{-1} on the heated plot. Peterjohn *et al.* (1993, 1994) did not measure different N_2O-emissions in heated and unheated plots during winter or during summer. The N_2O-emissions seem to increase most, if after freezing during the night, the topsoil only just thawed during the day. Also the weakly freezing of the top centimetres, as measured in the third decade of February, kept the emissions at a high level. We assume that the freezing–thawing cycle provides new substrate to N_2O-building microbes by the cracking of aggregates or the lysis of dead microbes (Wang & Bettany, 1993). This necessitates quick action of the microbes, within hours, in spite of temperatures around freezing point. Based on the existing knowledge of microbial physiology (Richards, 1987) this high activity is very surprising. At present we cannot decide whether the increased temperature on the heated plot or its decreased water content is the causative factor for the different emissions. Therefore it is necessary to measure emissions, water content, soluble N- and C-compounds at each sampling date and use the

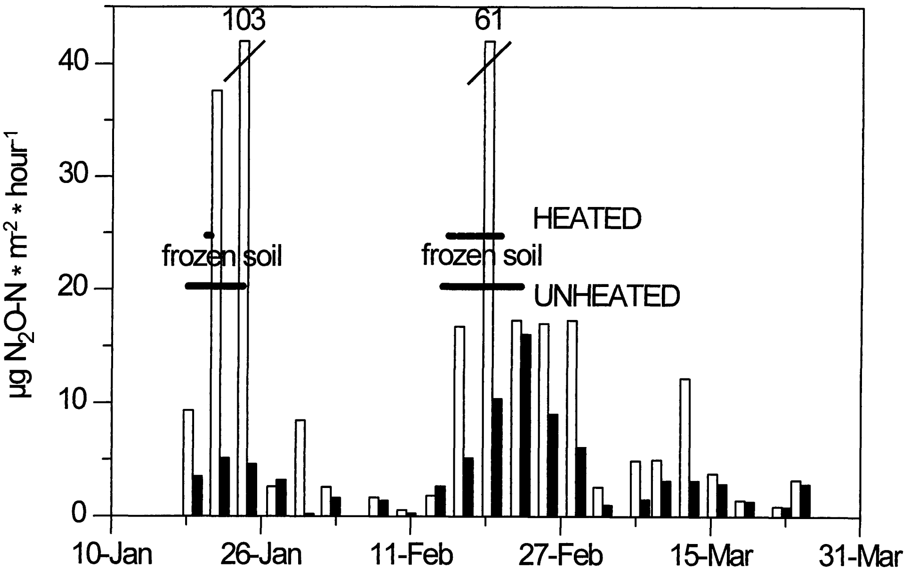

FIG. 7. N_2O-N emissions (μg N_2O-N $m^{-2}h^{-1}$) from the heated (■) and the unheated (□) plots through the investigation period.

data in a deterministic model combining water temperature as well as nitrogen balances. Additionally, laboratory experiments on the effect of freezing–thawing cycles on the substrate availability and the microbial activity should elucidate the ongoing processes.

To evaluate the effect of an increased air temperature on the nitrogen cycle it is necessary to install the experimental equipment over a longer time on the same plot, and then the change in different nitrogen pools and fluxes can be studied during subsequent winter and vegetation periods. The collected data can be used to calculate different scenarios for landscapes and cultivation systems similar to the one studied. Based on these goals and experience so far, the new HOTWORM experiment will be carried out on larger plots (5 × 5 m) in a crop rotation and a barrow for next 2 years.

ACKNOWLEDGMENT

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