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Effect of soil moisture and temperature on N_2O and CO_2 concentrations in soil irrigated with purified wastewater

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A b s t r a c t. Flooded organic soils are potentially important sources of greenhouse gases. The effect of soil temperature and moisture on the concentration of N_2O and CO_2 at two depths of organic soil flooded with two doses of purified wastewater was studied. Nitrous oxide concentrations at the 10-30 cm depth range were generally increased with an increase in soil moisture, showing dependence on the aeration status of soil. The maximum values of N_2O concentrations were higher at the 50-100 than 10-30 cm depth range, but a similar pattern of increasing maximum values of N_2O concentration with an increasing input of nitrogen in treatments at both depth ranges was observed. The maximum concentrations of carbon dioxide within the 50-100 cm depth range remained at a similar level in all treatments reaching 7.1-7.7%, which indicated weak relations with the input of water and nitrogen at this depth range. We conclude that the N_2O and CO_2 concentrations at 10-30 cm depths in the examined organic soil flooded with 600 mm year^{-1} of purified wastewater exhibited a similar level as the concentrations in soil watered only by precipitation.

K e y w o r d s: nitrous oxide, soil temperature, soil moisture, carbon dioxide, wastewater

INTRODUCTION

Under anaerobic conditions, organic soils are important sources of a number of greenhouse gases (GHGs) such as N_2O and CO_2 (Koponen *et al*., 2006; Maljanen *et al*., 2003). Accurate quantification of nitrous oxide emission is difficult and uncertain (van den Heuvel *et al*., 2009; Stehfest and Bouwman, 2006). The emission of N_2O from soil may be dominated by emission from hotspots characterized by favourable conditions for production of N_2O. McClain *et al*. (2003) defined biogeochemical hotspots as patches that show disproportionately high reaction rates relative to the surrounding matrix. The high temporal and spatial variability of gas emissions from soil makes measurements at small scales impractical (Giltrap *et al*., 2010). According to this, analyses that will help in more robust estimation of N_2O production and emission from soil at large scales that can be based on general relations between N_2O production in the soil profile and soil properties are needed.

Irrigation of soil with treated municipal wastewater can be treated as a last step of purification thereof. Soils irrigated with substantial doses of wastewater can induce anoxic conditions in which nitrate (NO_3^-) and nitrite (NO_2^-) are converted to dinitrogen gas (N_2) (Nosalewicz *et al*., 2005). N_2O, which is mainly emitted from wastewater treatment systems, is an intermediate in the process of denitrification (Schalk-Otte *et al*., 2000); additionally, N_2O can also be produced from nitrification in aerobic conditions (Szarlip *et al*., 2010).

The relations between production of two gases *ie* N_2O and CO_2, and soil moisture and temperature are dependent on their effect on overall soil microbial activity. Various enzymatically catalyzed transformations have different optimum temperature and moisture (Müller, 2000).

In this study, relations between the concentrations of soil gases (N_2O and CO_2) at two depth ranges of organic soil and soil moisture and temperature were studied. The experiment was conducted to find general relations between formation of these GHGs and soil moisture and soil temperature at different doses of wastewater and to assess the strength of these relations.

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MATERIAL AND METHODS

The field experiment on CO_2 and N_2O production at two depth ranges 10-30 and 50-100 cm of the soil profile was conducted for 3 years. The organic soil Eutric Histosol (Tables 1 and 2) planted with willow (*Salix Americana* and *Salix viminalis*) was divided into three subplots of an area equal to 0.38 ha each. The subplots were watered by precipitation and ground water (P), single (SD) and double dose (DD) of purified wastewater. A single dose of treated municipal wastewater corresponded to 600 and the double dose to 1 200 mm a year in ten watering cycles per year. The lower dose of wastewater provided 180 kg N, 30 kg P and 110 kg K ha^{-1} a year, and the higher dose provided two times higher amounts of minerals (Brzezińska, 2006; Kotowski, 1998). The average yearly precipitation in the study area was 550 mm.

Soil moisture and soil temperature were measured with FP/mts probes (EasyTest) - TDR probes with temperature sensor, installed at the 10, 30, 50, 70, and 100 cm depths. The average values of gas concentrations at 10 and 30 cm were used to analyse gas concentrations within the 10-30 cm depth range; similarly, gas concentrations from 50, 70, and 100 cm were averaged to analyse the 50-100 cm depth ranges. To the evaluate N_2O and CO_2 concentrations, open plastic cups were installed at the same depths as the TDR probes. Soil air within the cups was collected with syringes through elastic tubes that ended above soil surface. Gas samples were collected daily, during the first 5-7 days after each soil flooding.

Gas samples were analyzed for CO_2 and N_2O by gas chromatography using Shimadzu GC-14A and GC-14B equipped with a thermal conductivity detector (TCD) and an electron capture detector (ECD), respectively. Carbon dioxide was detected with the TCD with a column packed with Porapak Q. The temperatures of the column and detector were 40 and 60°C, respectively, with helium (He) as a carrier gas. Nitrous oxide was detected by the ECD detector at 300°C and the column temperature was 60°C. Nitrogen (N_2) was used as a carrier gas. Analyses of gas concentration were performed in 3 replicates.

T a b l e 1. Basic soil characteristics

Depth (cm)	Organic matter (%)	pH $CaCl_2$	Bulk density ($Mg\ m^{-3}$)
10-30	38.1	7.80	0.60
30-100	37.5	8.49	0.44

T a b l e 2. Concentration of mineral N in soil solution and drain waters (Kotowska and Włodarczyk, 2005)

Depth (cm)	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$
	($g\ m^{-3}$)	
10	1.89	4.56
30	0.96	4.05
50	1.34	6.69
70	1.26	6.29
100	0.31	3.15

RESULTS AND DISCUSSION

Nitrous oxide concentrations in the 10-30 cm soil depth range were generally increasing with the increase in the soil moisture, showing dependence on the aeration status of soil, irrespectively of the treatment (Fig. 1). These trends were dominated by a high N_2O concentration above 75% of the volumetric soil water content. N_2O emissions increase when denitrification is supported by a high water content in soil, contributing to the lack of oxygen (Koponen *et al*., 2006; Szarlip *et al*., 2010). The optimum soil moisture for maximum NO emission is slightly lower than that for N_2O, enhancing emission of N_2O at the higher soil moisture. A high soil moisture content also strongly decreases gas diffusion through soil, increasing N_2O concentrations in soil. The assumption that the beginning of N_2O formation in the denitrification process takes place at water-filled porosity equal to 0.5 and reaches a maximum value at 0.85 was adopted in the model 'Nitrogen transformation in soil' of Müller (2000). However, soil microorganisms taking part in production of N_2O were reported to show enormous adaptability to different soil moisture conditions (Włodarczyk *et al*., 2011). The maximum N_2O concentrations measured at the 10-30 cm depth increased with the increasing input of mineral nitrogen reaching 6.1; 89.3, and 860 ppm in the P and SD treatments, respectively. Higher maximum N_2O concentrations were measured within the 50-100 cm depth range, and a similar pattern of increasing maximum values was observed from 17.3 through 1920 up to 2362 ppm in the DD treatment. Increased concentrations of N_2O observed in soils flooded with purified wastewater, indicating accumulation of this intermediate in the process of denitrification, are stimulated when the bacteria feeding regime is unbalanced. A decrease in C availability may increase N_2O production by some bacteria up to 32-64% of total N-feed (Schalk-Otte *et al*., 2000). In field conditions, especially in wetland soil, a significant fraction of total N_2O emission originates from a limited number of small areas (hotspots) as a result of highly variable and heterogeneous N_2O production rates (van den Heuve *et al*., 2009).

The maximum concentrations of N_2O within the 50-100 cm soil layer, in both SD and DD treatments occurred at temperatures 19-22°C, indicating conditions for formation of 'hotspots' in the soil studied (Fig. 2). The temperature effect on denitrification activity in the model of Müller (2000) assumes that the denitrification activity is optimal at higher temperature, equal to 30°C.

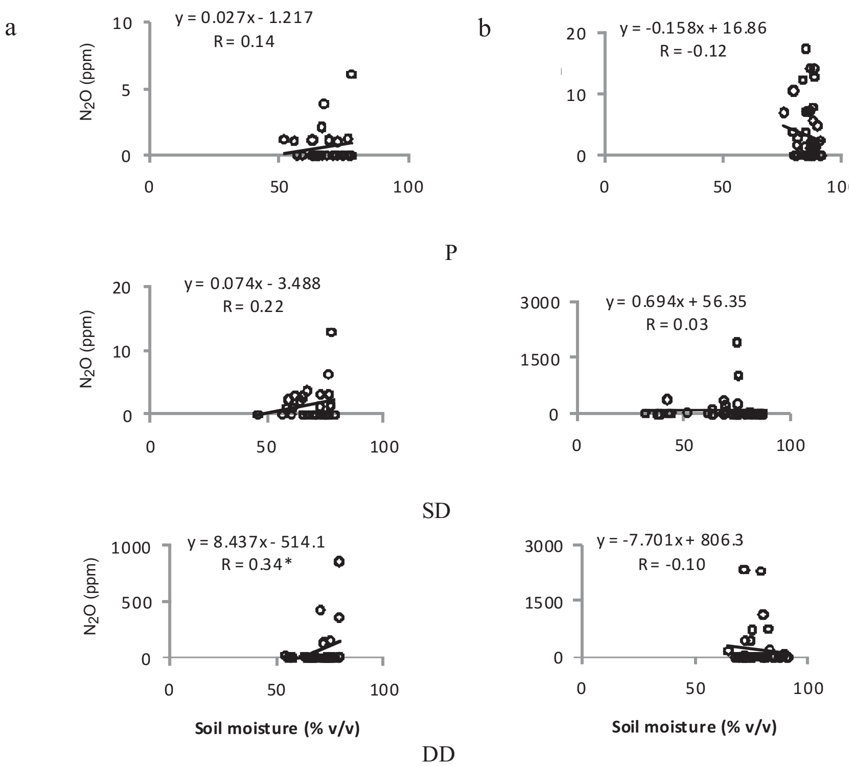

Fig. 1. Relations between soil moisture and the N_2O concentration within: a – 10-30, b – 50-100 cm soil depth range irrigated by P – precipitation, SD – single and DD – double doses of wastewater, *indicates a significant correlation ($p<0.05$).

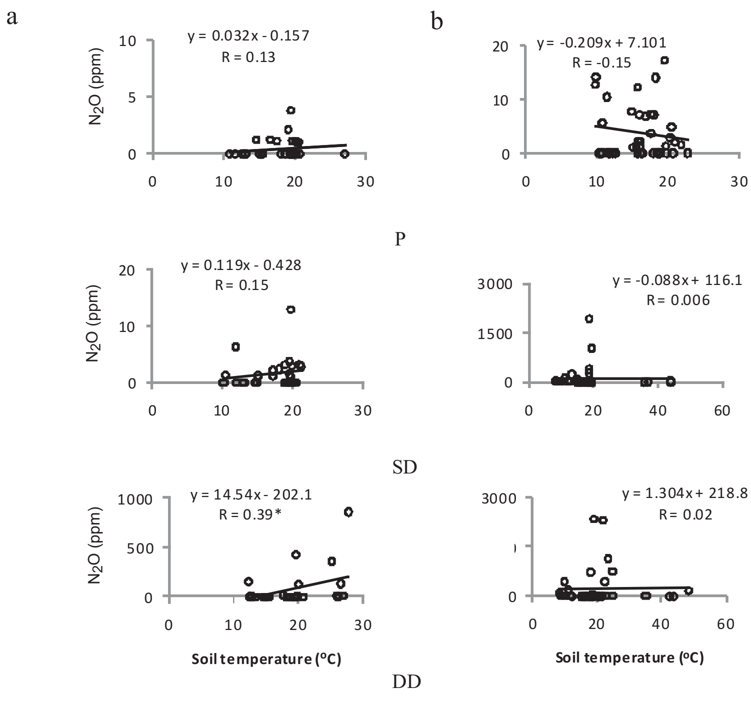

Fig. 2. Relations between soil temperature and the N_2O concentration within: a – 10-30, b – 50-100 cm soil depth range. Explanations as in Fig. 1.

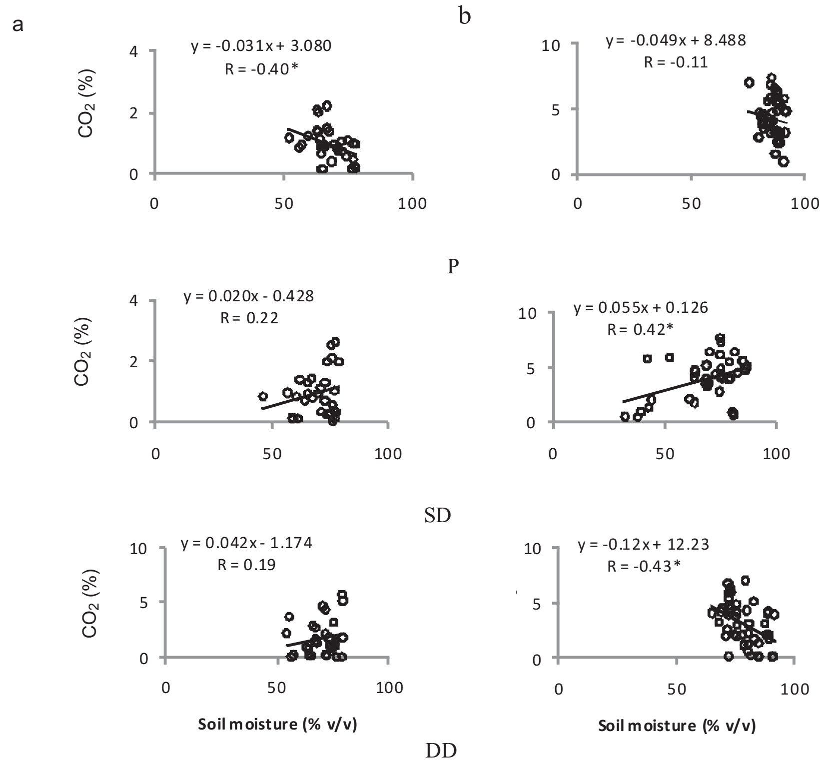

Fig. 3. Relations between soil moisture and the CO_2 concentration within: a – 10-30, b – 50-100 cm soil depth range. Explanations as in Fig. 1.

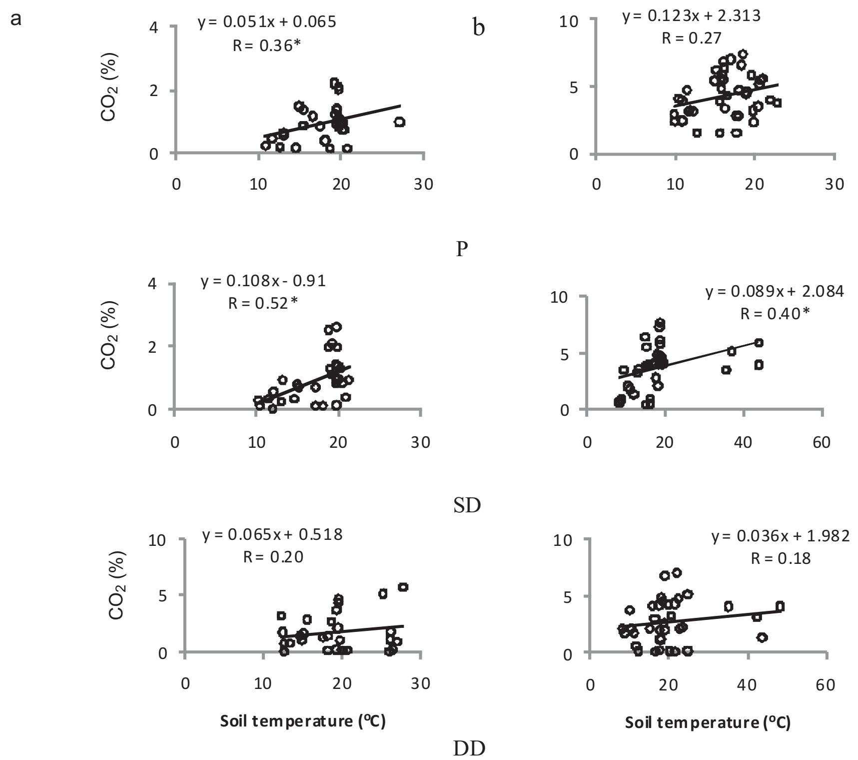

Fig. 4. Relations between soil temperatures and the CO_2 concentration within: a – 10-30, b – 50-100 cm soil depth range. Explanations as in Fig. 1.

The relations between soil moisture and CO_2 concentrations were different according to the depth and treatment. The increase of CO_2 concentration with soil moisture was observed in SD treatment at both depths (Fig. 3). However, these relations were not clear in the two other treatments, probably as a result of combined effect of various gas diffusivity and plant root activity at different soil moistures.

The carbon dioxide concentration at both analyzed depth ranges showed a general increase with soil temperature irrespectively of the treatment (Fig. 4). The relations between the CO_2 concentration and temperature were significant in treatments P and SD. These two treatments were also characterized by a similar level of the maximum CO_2 concentration within the 0-30 cm depth range. The double increase in the maximum concentration of CO_2 was observed in treatment DD within the 10-30 cm depth range. The maximum concentrations of carbon dioxide measured within the 50-100 cm depth range remained at a similar level in all treatments reaching 7.1-7.7% and showing poor relations with the water and nitrogen input. These maxima occurred within the 18.4-22.0°C temperature range.

Both the carbon dioxide and nitrous oxide concentrations exhibited a general increase with increasing soil moisture and soil temperature in the upper 10-30 cm soil layer of treatment SD (Figs 1-4). The increase is visible by the coefficient of fitted linear equations; however, only the relation between CO_2 and temperature in this layer is significant ($p<0.05$). The slight increase in N_2O with moisture and temperature in the upper layer of this treatment was caused by single high concentration measurements at the high range of soil moisture and temperature equal to 78% (v/v) and 18.8°C, respectively (Figs 1a, 2a). Studies of Teiter and Mander (2005) on N_2O and CO_2 showed a significant increase during the warmer periods; however, no significant correlation between gas fluxes and soil temperature were found. Different soil-related factors are involved in the regulation of NO and N_2O emissions with temperature. The results obtained by Koponen *et al*. (2006) showed that soil temperature, moisture, and availability of nitrate (NO_3^-) are among the strongest factors affecting the production rates of N_2O.

Higher variation of the N_2O in comparison to the CO_2 concentrations can be seen from variation coefficients calculated for selected temperature and soil moisture ranges (Table 3). These differences in variation between CO_2 and N_2O result from both: measurement indicating no N_2O in the soil (or below detection limits) and relatively infrequent, very high concentrations of this gas.

The maintenance and growth of microbial biomass is inseparable from the decrease in soil carbon in the form of CO_2 (Müller, 2000). The comparison of maximum concentrations of both GHGs analyzed showed that generally the maximum concentration of CO_2 and N_2O occurs at similar values of temperature and soil moisture in corresponding depth ranges and watering regimes. This may indicate that increased microbial or root respiration created more anaerobic conditions, favouring denitrification. The effect may be amplified at higher temperatures that increase soil respiration and create more anaerobic conditions (Koponen *et al*., 2006).

Table 3. Average values and the variation coefficient (in the brackets) of CO_2 and N_2O concentrations within soil temperature and soil moisture ranges

Treatment	Depth (cm)	Temperature range (°C)			Soil moisture (% v/v)		
		<15	15-20	>20	<60	60-70	>70
				CO_2			
P	10-30	0.54(0.83)	1.16(0.45)	0.72(0.47)	0.99(0.16)	1.14(0.54)	0.67(0.50)
	50-100	3.36(0.33)	4.69(0.38)	4.12(0.18)	-	4.36(0.46)	4.22(0.38)
SD	10-30	0.42(0.70)	1.24(0.63)	0.73(0.40)	0.52(0.84)	0.94(0.43)	1.07(0.82)
	50-100	2.00(0.60)	4.10(0.45)	4.60(0.23)	2.44(0.97)	3.78(0.28)	4.44(0.40)
DD	10-30	1.16(0.87)	2.19(1.50)	1.90(1.20)	1.55(1.12)	1.33(0.73)	2.13(0.88)
	50-100	1.77(0.66)	2.90(0.65)	3.01(0.69)	-	4.02(0.13)	3.03(0.66)
				N_2O			
P	10-30	0.18(2.64)	0.50(2.05)	0.43(1.37)	0.77(0.87)	0.48(2.19)	0.67(0.50)
	50-100	4.62(1.25)	3.76(1.34)	2.30(0.88)	-	5.30(0.85)	3.10(1.51)
SD	10-30	0.94(2.33)	2.00(1.58)	2.02(0.87)	0.87(1.30)	1.41(1.06)	2.11(1.67)
	50-100	51.77(1.55)	159.3(2.8)	9.09(1.48)	62.59(2.29)	63.76(1.86)	135.9(3.15)
DD	10-30	21.74(2.49)	49.51(2.52)	173.7(1.75)	9.77(1.26)	3.74(1.59)	128.2(1.78)
	50-100	112.1(1.5)	211.9(2.9)	347.9(1.9)	-	46.06(1.89)	217.7(2.5)

CONCLUSIONS

1. Nitrous oxide concentrations at the 10-30 cm depth range generally increased with the increase in soil moisture, showing dependence on the aeration status of soil. These trends were dominated by the high concentration of N_2O at high water contents.

2. The maximum values of the N_2O concentration at the 10-30 cm depth range increased with the increasing input of nitrogen in the treatments. N_2O concentrations were higher at the 50-100 than 10-30 cm depth range, but a similar pattern of increasing maximum values of the N_2O concentration in the treatments at both depth ranges were observed.

3. The carbon dioxide concentration at both depths showed a general increase with the increase in soil temperature. The maximum concentrations of CO_2 within 10-30 cm reached a similar level in treatments that involved watering with precipitation and a single dose of purified waste water. A two times higher maximum CO_2 concentration was observed in the treatment that involved watering with the double dose of purified wastewater.

4. The maximum concentrations of carbon dioxide measured within the 50-100 cm depth range remained at a similar level in all treatments, reaching 7.1-7.7%. This indicates weak relations with the input of water and nitrogen at this depth range.

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