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Greenhouse Gas Fluxes and Global Warming Potentials in Crop Fields on Soil-Dressed Peatland in Hokkaido, Japan

By

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K e y w o r d s : Net primary production, net ecosystem production, global warming potential.

S u m m a r y

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This study was conducted to estimate greenhouse gas (GHG) fluxes in fields growing paddy and fallow (PF), soybean and winter wheat (SW), and spring and winter wheat (WW) on peatland dressed with mineral soil. Field measurements were carried out from June 2002 to May 2003. GHG fluxes were measured in a closed chamber. Soil respiration was measured in the SW and WW fields, and photosynthetic CO_2 flux during the daytime (net ecosystem production, NEP_{day}) was measured in the PF field. Microbial respiration (R_m) in the SW and WW fields was approximated as 60% of the total soil respiration. NEP was calculated as the difference between plant dry matter (net primary production, NPP) and R_m. Aboveground plant parts were collected from each field to calculate NPP of each crop. R_m in the PF field was calculated as $^3/_2$NPP – NEP_{day}, because aboveground respiration is 50% of NPP. The global warming potential (GWP) in each ecosystem was calculated using a 100-year time horizon, as recommended by the IPCC (with factors of 21 for CH_4 and 310 for N_2O).

R_m was 682 g C m^{-2} y^{-1} in PF, 533 in SW, and 388 in WW. NPP was 651, 397, and 152 g C m^{-2} y^{-1}, respectively. Therefore, NEP was –31, –136, and –236 g C m^{-2} y^{-1}, respectively. The PF field acted as a large CH_4 source (85.2 g C m^{-2} y^{-1}) because of flooding. The WW field was a small source of CH_4 (0.16 g C m^{-2} y^{-1}), and the SW field was a small sink (0.14 g C m^{-2} y^{-1}). All fields

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were sources of N_2O (1.36 g N m^{-2} y^{-1} in SW, 0.60 in WW, and 0.05 in PF). The rate of mineralization was higher than the rate of N fertilizer application in SW and WW.

The GWP was equivalent to 2522 g CO_2 m^{-2} y^{-1} in the PF field, 1161 g CO_2 m^{-2} y^{-1} in the WW field, and 1157 g CO_2 m^{-2} y^{-1} in the SW field. The high value in the PF field was due to high CH_4 emissions there.

Introduction

Peatlands, as both sinks and sources of greenhouse gases (GHGs), have both positive and negative consequences for global warming. Peatlands are the most important carbon (C) stores among soil ecosystems, containing 270–455 Pg of C (TURUNEN & al. 2002), equivalent to 35–60% of the C present in the atmosphere as carbon dioxide (CO_2). Drainage and agricultural use increase the aeration of peat, enhancing microbial degradation and thus CO_2 release (NYKÄNEN & al. 1995), whereas flooding increases anoxia and thus methane (CH_4) release (KELLY & al. 1997). Annual CH_4 emissions from boreal peatlands have varied between 0 and 52.5 g C m^{-2} y^{-1} (CRILL & al. 1993). Drained organic soils also release nitrous oxide (N_2O). In Finland, about 25% of the total anthropogenic N_2O emissions are produced by organic agricultural soils (KASIMIR-KLEMEDTSSON & al. 1997).

In Hokkaido, Japan, peat soils are distributed mainly in the lowlands along the main rivers. The total area of peat soils amounts to about 241 000 ha, more than 80% of which is used for agriculture or urbanization. The peat soils are generally not very deep, averaging 3 m; the maximum depth is usually 7 m but has been measured as high as 10 m (JSSSPN 1990). In the 1960s, many peat soils were drained, top-dressed with about 30 cm of mineral soil, and turned into productive crop fields (ITOH & al. 2001). Changes in land use and global warming may have altered the fluxes of CO_2, CH_4, and N_2O (GHGs) in soil-dressed peatland in ways not well understood. MALJANEN & al. 2004 reported that the incorporation of mineral soil into peatland to improve soil properties did not enhance GHG emissions. We hypothesized that the mineral soil suppresses the decomposition of peat and consequently the emissions of CO_2, CH_4, and N_2O from peat soils. The objective of this study was to quantify the annual CO_2, CH_4, and N_2O fluxes of soil-dressed peatland under different cropping patterns and cultivation management practices.

Material and Methods

Study site

The study was carried out in Bibai, Hokkaido, Japan (43°18′N, 141°44′E), on soil-dressed peatland. Three adjacent fields were used, representing three cropping systems: paddy and fallow (PF), soybean and winter wheat (SW), and spring and winter wheat (WW). The annual mean temperature during the study period was 6.7 °C (range, –15 to 25 °C), and the annual total precipitation was 1120 mm (Fig. 1). Snow laid on the ground from November 2002 to April 2003. During the study period, snow depth ranged from 0 to 115 cm. The initial soil pH was 5.68 in PF, 5.15 in SW, and 5.45 in WW. The soil C contents in the 0- to 10-cm layer were 6.64% in PF, 4.67% in SW, and 3.73% in WW, and in the 30- to 40-cm layer were 17.1%, 15.7%, and 7.17%, respectively. The soil N contents in the 0- to 10-cm layer were 0.48% in PF, 0.31% in SW, and 0.26% in WW, and in the

30- to 40-cm layer were 1.02%, 1.02%, and 0.51%, respectively. Dates of planting or sowing; name and source of chemical fertilizers; dates, methods, and rates of fertilizer application; and harvest dates are presented in Table 1. The cultivars planted were 'Kirara 397' rice, 'Tsurumusume' soybean, 'Haruyutaka' spring wheat, and 'Hokushin' winter wheat. In the PF field, rice straw remained in the field as crop residue after harvesting rice grain by the combine harvester (ISEKI Frontier 60) in the previous year. During the experiment, in the PF field, rice straw containing 2644 kg C ha^{-1} remained from the rice crop. In the SW field, soybean leaves containing 423 kg C ha^{-1} remained from the soybean crop. However, spring wheat straw containing 796 kg C ha^{-1} was removed from the WW field for use as animal bedding. The PF field was drained midseason on 25 July, flooded again on 23 August, and drained finally on 24 August.

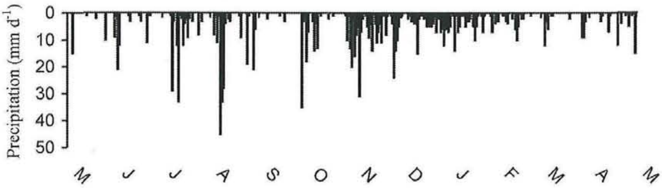

Fig. 1. Precipitation in the study area during May 2002 to May 2003.

Table 1. Dates of planting/sowing, name of fertilizers with source of N, dates, methods, and rates of fertilizer application, dates of harvest of PF, SW and WW fields during May 2002 to May 2003.

Crop name	Dates of planing /sowing	Name of fertilizers	Source of N	Dates & methods of application	Application rates (kg N ha^{-1})	Dates of harvest
Rice	–	BB 645	NH_4-N	*3 May 2002 (basal)	64	–
	20 May 2002	444	NH_4-N	20 May 2002 (basal)	28	1 Oct. 2002
Soybean	7 May 2002	BB S343	NH_4-N	7 May 2002 (basal)	12	1-5 Oct. 2002
Winter wheat	9 Sept. 2002	083	NH_4-N	22 Oct. 2002 (basal)	50	Continued
		NKC-6	NH_4-N	5 April 2003 (topdress)	102	
Spring wheat	21 April 2002	BB 282	NH_4-N	21 April 2002 (basal)	72	5 Aug. 2002
Winter wheat	12 Sept. 2002	BB Cu860	NH_4-N	12 Sept. 2002 (basal)	48	Continued
		NKC-6	NH_4-N	16 April 2003 (topdress)	102	

Gas flux measurement and analysis

Gas fluxes were measured from about 9:00 am to 16:00 pm on every sampling day, using a closed-chamber technique (ROLSTON 1986). A rectangular transparent acrylic chamber (100 cm high, 60 cm wide), placed over the rice plants, was used for gas sampling in the PF field. Cylindrical steel dark chambers (23 cm high, 20 cm diameter) were used in the SW and WW fields (no plants inside). In winter, gas samples from all fields were collected from the snow surface with a rectangular transparent acrylic chamber (60 cm high, 30 cm wide). Collected gas samples were analyzed in the laboratory. CO_2 was analyzed within 24 h with an infrared gas analyzer (Fuji ZFP-5). CH_4 was analyzed with a gas chromatograph with a hydrogen flame ionized detector (Shimadzu GC 8A). N_2O was analyzed with a gas chromatograph with an electron capture detector (Shimadzu GC 14B).

Net ecosystem Production (NEP)

The net CO_2 balance of an agricultural ecosystem depends on the magnitude of two fluxes having opposite signs: CO_2 uptake by gross photosynthesis and CO_2 release by shoot, root, and soil respiration (LOHILA & al. 2003). In a specific soil–plant ecosystem, carbon flux between the ecosystem and the atmosphere (NEP) as a net ecosystem product can be calculated from measured net primary production (NPP) and microbial respiration (R_m) as NEP = NPP – R_m.

Net primary production (NPP)

Aboveground parts were collected from three 1-m^2 quadrates in each field and dried in an oven at 50 °C for 2–3 days. Dry matter was weighed, and plant samples were ground for measurement of C concentration to calculate NPP (g C m^{-2}) of each crop. A Sumigraph NC-1000 analyzer was used to determine C concentrations.

Microbial respiration (R_m)

R_m was calculated for SW and WW as $0.6 \cdot R_s$ (60% of soil respiration) (SILVOLA & al. 1996). NEP was estimated for PF on the basis that aboveground respiration $R_a = 0.5 \cdot NPP$ (TANAKA & YAMAGUCHI 1968). If we assume that aboveground respiration occurred only during the night, since we measured CO_2 flux corresponding to daytime NEP (NEP_{day}), gross primary production can be calculated as $NEP = NEP_{day} - R_a$. Substituting $NEP = NPP - R_m$ and $R_a = 0.5 \cdot NPP$ into the equation, we have $R_m = {}^3/_2 NPP - NEP_{day}$.

Global Warming Potentials (GWP)

The GWP of each crop field was computed from the GHG emissions, using a 100-year time horizon, as recommended by IPCC 1997 (factors of 21 for CH_4 and 310 for N_2O). GWP was calculated as follows:

CO_2 GWP (g CO_2 m^{-2} y^{-1}) = CO_2 (g C m^{-2} y^{-1}) × (1 g CO_2) × (44 g CO_2/12 g C);

CH_4 GWP (g CO_2 m^{-2} y^{-1}) = CH_4 (g C m^{-2} y^{-1}) × (21 g CO_2/1 g CH_4) × (16 g CH_4/12 g C);

N_2O GWP (g CO_2 m^{-2} y^{-1}) = N_2O (g N m^{-2} y^{-1}) × (310 g CO_2/1 g N_2O) × (44 g N_2O/28 g N).

Results and Discussion

Carbon dioxide flux

The annual cumulative fluxes of CO_2 showed clear differences among the PF, SW, and WW fields under identical environmental conditions (Fig. 2). Photosynthetic CO_2 uptake was 295 g C m^{-2} y^{-1} in the PF field. Soil respiration was 888 g C m^{-2} y^{-1} in SW and 647 in WW; these values differed significantly ($P < 0.01$). The PF field took up C from the atmosphere because of the inclusion of rice plants in the measurement chamber. The SW and WW fields emitted large amounts of C, 1.6 to 2.2 times the amount emitted from organic agricultural soils under barley (400 g C m^{-2} y^{-1}) in Finland (MALJANEN & al. 2001). This result indicates the higher decomposition rate of soil-dressed peatland in Hokkaido.

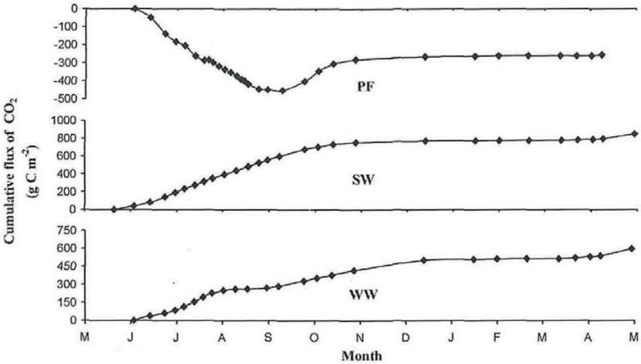

Fig. 2. Cumulative flux of CO_2 from PF, SW and WW fields during May 2002 to May 2003.

The NPP values are shown in Table 2.We estimated the NPPs of SW and WW, as we did not include the NPP of winter wheat because the fields remained under snow until after sowing. The NPP of spring wheat was smallest among the crops, because of the low yield, but it was in the range typical of the area (MAFF 2001). The NPPs of rice and soybean were higher than those of similar crops growing in mineral soil in Hokkaido. For example, SHINANO & al. 1991 reported values of 632 g C m^{-2} y^{-1} for rice, 292 for soybean, and 570 for spring wheat.

The R_m values are shown in Table 2. These values were 2 to 3 times those of previous studies (PAUSTIAN & al. 1990, HU & al. 2004). R_m was higher in SW than in WW, presumably because of the *Rhizobium* bacteria in the roots of soybean. The high values of R_m could be ascribed to the mixing of peat with the top-dressed mineral soil, which can enhance microbial activity. However, R_m was higher in PF than in SW or WW. This implies that the R_m in organic soils is sensitive to crop type and management practice.

The NEP values are shown in Table 2. A higher R_m than NPP resulted in a negative NEP in all fields. Negative values of NEP mean the ecosystem emits CO_2 to the atmosphere. The different values indicate that crop type and cultivation practices are the dominant factors determining CO_2 emissions in soil–plant ecosystems.

Table 2. NPP, R_m and NEP of PF, SW and WW fields during May 2002 to May 2003 (g C m^{-2} y^{-1}).

Crop	NPP*	R_m	NEP
PF	651	681.5	- 30.5
SW	397	533	- 136
WW	152	388	- 236

* NPP for rice, soybean and spring wheat.

Methane flux

The PF field emitted a large amount of CH_4 (85.2 g C m^{-2} y^{-1}), the WW field emitted a small amount (0.16 g C ha^{-1} y^{-1}) (Fig. 3), and the SW field acted as a small sink (0.14 g C m^{-2} y^{-1}). There was a highly significant difference ($P < 0.00001$) between these CH_4 fluxes. The large amount of CH_4 emitted from PF was due to high activities of methanogenic bacteria. The peatland used in this study presumably has high microbial activities under anaerobic conditions after irrigation. Continuous flooding in PF favored CH_4 emission, and the dry period in the middle of the season impeded CH_4 production and enhanced CH_4 oxidation, resulting in low CH_4 emission rates even after the field was flooded again (Fig. 3). TSURUTA & al. 1997 reported similar results. The WW field emitted a low amount of CH_4, which could be due to the effect of the previous paddy crop. In contrast, SW was a net sink for CH_4, possibly due to the drained and aerobic conditions, which suppress methanogenic processes. The higher CH_4 emission in PF than previously reported values under paddy cultivation in tropical peatland (INUBUSHI & al. 2003, 45 times) and Japanese mineral soil (NISHIMURA & al. 2004, 36 times) could be due to the favorable condition for methanogenic bacteria in the soil-dressed peatland.

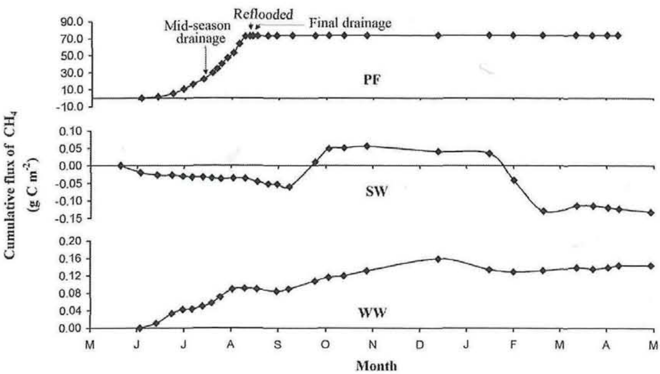

Fig. 3. Cumulative flux of CH_4 from PF, SW and WW fields during May 2002 to May 2003.

Nitrous oxide flux

Emissions of N_2O differed significantly ($P < 0.01$) among the fields (Fig. 4). Total N_2O emissions were 1.36 g N m^{-2} y^{-1} in SW, 0.60 in WW, and only 0.05 in PF. The annual N_2O emissions from the soil-dressed peatland were higher than those reported for cultivated mineral soils (0.02–0.4 g N m^{-2} y^{-1}, TEEPE & al. 2000). The low N_2O emission from PF was probably due to the long period of flooding. Previous studies in mineral soil have also shown low N_2O emissions from paddy fields during continuous flooding (NISHIMURA & al. 2004). However, N_2O

was emitted after final drainage when the emission of CH_4 had stopped. This clearly indicates that the emissions of CH_4 and N_2O have an inverse relationship (TSURUTA & al. 1997). The SW field emitted about 2.3 times as much N_2O as the WW field, even though SW previously received 164 kg N ha^{-1}, whereas WW received 222 kg N ha^{-1}. The difference was probably due to a higher mineralization rate in SW than in WW. We estimated the N mineralization rate from R_m and the C/N ratio $[(R_m)/(C/N)]$. The rate of N mineralization in SW (354 kg N ha^{-1} y^{-1}) was 1.3 times that in WW (270 kg N ha^{-1} y^{-1}), whereas the total rate of N (applied N and rate of N mineralization) was similar (518 and 492 kg N ha^{-1} y^{-1}, respectively). Moreover, soybean is an N-fixing plant, so it could enhance N_2O emission (MOSIER 1998). However, the rate of mineralization was higher than the rate of N fertilizer application in both fields. This could be due to the fact that soil dressing

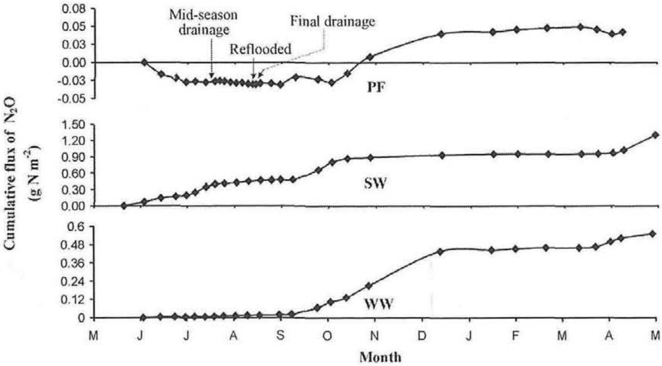

Fig. 4. Cumulative flux of N_2O from PF, SW and WW fields during May 2002 to May 2003.

enhanced microbial activity and thereby enhanced N mineralization. Our results indicate that N_2O emission was enhanced by decomposition of organic matter and not by application of N fertilizer. In contrast, KUSA & al. 2002 reported that the annual N_2O emission (0.35–1.56 g N m^{-2} y^{-1}) from onion fields in mineral soil was enhanced by application of N fertilizer (242–322 kg N ha^{-1}). Our results highlight the importance of N mineralization in soil-dressed peatland for N_2O production. The N_2O emissions from SW and WW (1.36 and 0.60 g N m^{-2} y^{-1}) are within the range of 0.17–3.69 g N m^{-2} y^{-1} reported in other studies conducted in boreal or temperate organic agricultural soils (e.g., MALJANEN & al. 2004).

Atmospheric impact of the soil-dressed peatland fields

Net GWP (CO_2 equivalent) was higher in PF than in WW and SW (Table 3). In PF, CH_4 accounted for 95% of GWP. In SW, N_2O accounted for 57%. On the other hand, in WW, NEP accounted for 75%. MALJANEN & al. 2004 reported that

GWP from peat soils mixed with mineral soil was 2540–2680 g CO_2 m^{-2} y^{-1} in barley fields and 1060–1320 g CO_2 m^{-2} y^{-1} in grasslands, where CO_2 was responsible for 85–95%, N_2O for 5–15%, and CH_4 for less than 0.5% of the total annual GWP of the soil. The high GWPs in the present study may be ascribed to the soil type—the soil-dressed peatland—where the high R_m associated with CH_4 and N_2O emissions enhanced the GWP.

Table 3. Net GWP for PF, SW and WW fields in soil-dressed peatland during May 2002 to May.

Crop	GWP (g CO_2 m^{-2} y^{-1})			Net GWP (g CO_2 m^{-2} y^{-1})	Proportion of contribution to Net GWP (%)
	NEP	CH_4	N_2O		
PF	112	2386	24	2522	95 from CH_4
SW	499	- 4	662	1157	57 from N_2O
WW	865	4	292	1161	75 from NEP

Conclusions

The high CH_4 flux in PF and the high N_2O flux in SW enhanced the GWPs in both fields. NPP in WW was much lower than R_m and, thus, the NEP became negative, resulting in a high GWP due to CO_2. Moreover, R_m was also high in all fields, suggesting that soil dressing of peatland enhances the GWP through higher microbial activities.

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