小麦残渣および肥料が施与された慣行耕起・省耕起・不耕起栽培体系における亜酸化窒素の発生

誌名	農業氣象
ISSN	00218588
著者名	永田,修 杉戸,智子 小林,創平 鮫島,良次
発行元	養賢堂
巻/号	65巻2号
掲載ページ	p. 151-159
発行年月	2009年6月

Full Paper

J. Agric. Meteorol. (農業気象) 65 (2): 151–159, 2009

Nitrous oxide emissions following the application of wheat residues and fertilizer under conventional-, reduced-, and zero-tillage systems in central Hokkaido, Japan

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Abstract

Nitrous oxide (N_2O) is a major greenhouse gas produced by agricultural systems, and has a higher greenhouse effect than carbon dioxide (CO_2) and methane (CH_4). Cultivation techniques (particularly tillage) and the incorporation of crop residues contribute to N_2O release. Our objective was to quantify the rates of N_2O emissions from conventional-, reduced-, and zero-tillage systems (CT, RT, and ZT, respectively) with the application of wheat residues and fertilizer. The study included CT, RT, and ZT systems, and a no-fertilizer (NF) treatment without basal and top dressing (CT/NF). N_2O flux in each treatment reached the highest value between mid- and late October (for ZT, RT, CT, and CT/NF, 1763, 2640, 1458, and 1620 μg N m^{-2} hr^{-1}, respectively). Immediately after snowmelt, large increases in N_2O emissions were observed in the ZT, RT, and CT plots, with maximum values of 413, 959, and 439μg N m^{-2} hr^{-1}, respectively. This trend was not apparent in the CT/NF plots, suggesting that basal dressing with nitrogen is responsible for large emissions after snowmelt. No remarkable N_2O emission occurred from snowmelt until harvest, indicating that nitrogen application by top dressing is not an important N_2O source. Total N_2O emissions from the ZT, RT, CT, and CT/NF plots during the sampling period (296 days) were 8.9, 11.1, 9.5, and 8.8 kg N ha^{-1}, respectively, and did not differ significantly. Our results suggest that incorporation of wheat straw residues, including surface mulching in the ZT plot, was an important factor that affected large N_2O emission. N_2O emission before and behind of snowmelt (27 days) accounted for 11% to 18% of total N_2O emission during the sampling period. Our results also suggest that full-year investigations are necessary to prevent underestimation of N_2O emission due to snowmelt.

Key words: Carbon dioxide, Nitrous oxide, Snowmelt, Tillage systems, Wheat residue.

1. Introduction

Nitrous oxide (N_2O) is a major greenhouse gas produced by agricultural systems, and has a higher greenhouse effect than carbon dioxide (CO_2) and methane (CH_4). Agriculture accounted for 10% to 12% of total global anthropogenic emissions of greenhouse gases, but contributed about 58% of total anthropogenic N_2O emissions (Smith *et al.*, 2007). The source of the nitrogen input, which includes chemical fertilizers (Breitenbeck and Bremner, 1986; Koga *et al.*, 2004), organic manures (Chang *et al.*, 1998; Dong *et al.*, 2001), and post-harvest crop residues (Aulakh *et al.*, 1991; Baggs *et al.*, 2003; Toma and Hatano, 2007), is a significant factor in determining the N_2O emission from agricultural systems. Because N_2O emission results from the microorganism activity, not only N-source but also C-source is a major factor for N_2O generation. Tillage practices contribute to N_2O emission or C availability through change in soil temperature, aeration and water content. In addition, application of plant residue is one of major N or C supply. As a result, tillage practices and plant residue might have a big influence on the microorganism activity that generates N_2O.

Received; March 21, 2008.
Accepted; November 4, 2008.

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It is also important to understand the variation in annual flux based on investigations through year. Unfortunately, most previous studies have focused on the growing season, and have considered the winter period to be of minor importance. However, CH_4 emission during the snow-covered period in peatland in central Hokkaido, Japan, accounted for more than 10% of the annual total (Nagata *et al.*, 2005), suggesting that N_2O may show a similar pattern. Under winter wheat in eastern Hokkaido, large part of N_2O fluxes occurred during the thawing of frozen soil and snow (Koga *et al.*, 2004). Thus, winter emissions, particularly in cold regions with abundant snowfall such as Hokkaido, should not be neglected if we plan to assess total N_2O emissions from agricultural soils.

The objective of the present study was to quantify the rates of N_2O emission from conventional-, reduced-, and zero-tillage systems with the application of wheat residues and with fertilizer application over a complete crop season, including during the winter.

2. Materials and Methods

2.1 Site description and management schemes

Our field study was carried out in Bibai, central Hokkaido, Japan (43°19′ N, 141°45′ E). Two adjacent farm fields (30×135 m) on a peat soil covered by about 20 cm of dressed mineral soil were selected in August 2006. These fields had been converted into upland fields from rice paddies at least 10 years earlier, and had then been continuously used as wheat fields by conventional tillage (CT). The experimental site consisted of three treatments, conventional-, reduced-, and zero-tillage systems (CT, RT, and ZT), each of which was replicated as a single 3×15 m plot in each of the two fields. RT and ZT systems have been established from the start of this study in 2006. A plow pan had developed around 20cm depth in the experimental fields. In the CT plots, fields were harrowed four times by rotary tillers to a depth of roughly 10 to 15 cm and plowed once by disc plow to a depth of 25 cm before sowing; in the RT plots, fields were harrowed twice, with no plowing; in the ZT plots, there were no harrow and no plowing, residue in this plots was the mulch left on the surface. The details of the field management regimes are presented in Table 1.

All treatments received 6 t ha^{-1} of wheat (*Triticum aestivum* L.) straw from the previous crop on 7 August 2006 (C:N ratio=126:1). Except in the CT/NF plots, nitrogen was applied five times: 40 kg N ha^{-1} as ammonium sulfate before the first tillage to promote decomposition of the wheat straw (7 August 2006), 20 kg N ha^{-1} as compost (C:N ratio=11:1) for soil improvement (28 August 2006), 40 kg N ha^{-1} basal dressing as ammonium sulfate at the same time as sowing (13 September 2006), 80 kg N ha^{-1} top dressing as mainly ammonium sulfate and ammonium phosphate at the re-growing stage (17 April 2007), and 40 kg N ha^{-1} top dressing as ammonium sulfate at the flag leaf stage (22 May 2007). We set up subplots that did not receive basal and top dressings in the CT plots, but these subplots received wheat residue and compost. All plots received two times scatter of granular calcium carbonate (600 kg ha^{-1}) by broadcast in March 2007 in order to accelerate snowmelt. The harvest was conducted on 29 July 2007.

2.2 N_2O and CO_2 fluxes

N_2O and CO_2 fluxes were measured using a closed chamber method. In this study CO_2 flux showed soil respiration including autotrophic (plant root) and heterotrophic (microbial activity) respirations. Gas sampling was conducted once every two weeks from September to November, once a month during snowfall period, weekly after snowmelt until the harvest. We used a cylinder stainless-steel chamber (inner diameter=200 mm; height=250 mm) and pre-installed two stainless

Table 1. Field management regimes in the conventional-tillage (CT and CT/NF), reduced-tillage (RT), and zero-tillage (ZT) systems.

Tilage	2006										2007		
system	7-Aug.			28-Aug.		1-Sep.	3-Sep.	13-Sep.			17-Apr.	22-May	29-July
CT	H	NA	R	CA	R	P	R	BD	R	S	TD	TD	H
CT/NF	H		R	CA	R	P	R		R	S			H
RT	H	NA	R	CA				BD	R	S	TD	TD	H
ZT	H	NA		CA				BD		S	TD	TD	H

H, harvest; S, sowing; NA, nitrogen application (ammonium sulfate input to promote decomposition of the wheat straw in all plots); CA, compost application; BD, basal dressing; TD, top dressing; R, rotary harrow; P, plowing steel bases in each plot to mount the chamber during flux measurements, as described by Toma and Hatano (2007). Gas samples for CO_2 analysis were collected from the chamber in 1-L Tedlar bags using 50-mL plastic syringes, and samples for N_2O analysis were transferred into 10-mL vacuum glass vials using 25-mL plastic syringes. Gas samples were obtained before the chamber was closed (time=0 minutes) for the analysis of N_2O and CO_2. One gas sample for CO_2 analysis was collected after 6 minutes, and another sample for N_2O was collected after 20 or 30 minutes. To minimize the effects of diurnal variation in N_2O emission, gas samples were taken between 10:00 and 14:00 hours. Gas samples from December 2006 to March 2007, when the ground was covered by snow, were taken by putting rectangular vinyl chloride chamber on the snow surface. The chamber was sealed by compaction of the snow around it to prevent escape of the gases (Nagata *at al.*, 2005; Mu *et al.*, 2006).

2.3 Gas analysis

The N_2O concentration was quantified using a GC14B gas chromatograph equipped with an electron-capture detector (Shimadzu, Kyoto, Japan) and a Porapak N column within two weeks from gas sampling. The column and detector temperatures were 60 and 340℃, respectively. CO_2 analysis was conducted using an infrared CO_2 analyzer (Model ZFP9GC11, Fuji Electric systems, Tokyo, Japan) within 3 hours after sampling. N_2O and CO_2 fluxes were calculated using the linear-recurrence method described by Kusa *et al.* (2002) and Toma and Hatano (2007). Cumulative N_2O and CO_2 emissions during the monitoring period were calculated by means of successive linear interpolation between daily average fluxes, as described by Toma and Hatano (2007) and Naser *et al.* (2007). Gas monitoring of N_2O and CO_2 started on 25 September 2006, and was continued until 18 July 2007.

2.4 Soil physical analysis

Soil temperatures at a depth of 3 cm were determined at each sampling time using a digital thermometer (CT-410WR, Custom, Tokyo, Japan). One intact soil samples were taken each month from the top 5 cm of the soil using 100-cm^3 stainless steel core samplers in each plot to calculate the water-filled pore space (WFPS) at intervals of two weeks from the beginning of the experiment until December 2006, then at each sampling time after April. Further, the soil moisture content in the top 10 cm was determined using a time domain reflectometry (TDR) probe (Trime-IT, IMKO, Ettlingen, Germany) at each sampling time. To calculate WFPS in sampling days when core samples were not collected, we calculated regression equations for the relationship between WFPS and the volumetric moisture content measured by means of TDR. Subsequently, we estimated WFPS in sampling days when core samples were not collected, from the soil moisture content measured by TDR.

2.5 Soil chemical analysis

Three auger samples (top 5 cm of the soil) were obtained from each plot and bulked for subsequent analysis. Subsamples (15 g) of the fresh soil were extracted with 100 mL of 2 mol L^{-1} KCl solution to determine the NH_4^+-N concentration and with deionized water for the NO_3^--N concentration; the former extract was analyzed by colorimetry with indophenol blue (UV-1100, Hitachi, Tokyo, Japan), and the latter by ion chromatography (DX-AQ 2211, Dionex, Sunnyvale, Calif., USA). Total C and N were determined using a Vario Max CNS elemental analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). Samples of fresh soil (10 g) were shaken with 25 mL of deionized water, and pH (H_2O) was measured using a pH meter (F-13, Horiba, Kyoto, Japan).

2.6 Precipitation

Precipitation data were obtained from meteorological observations at the Bibai weather station of the Japan Meteorological Agency.

2.7 Statistical analysis

Statistical significance was tested by means of Tukey's multiple-comparison tests using version 5.0 of the Excel Statistics software (Esumi Company, Tokyo, Japan).

3. Results

3.1 Soil inorganic N and pH

The soil NH_4^+ content in the CT/NF plot remained consistently very low, whereas those of the fertilized plots (ZT, RT, CT) were high in September and decreased gradually until November (Fig. 1a). In addition, after the first top dressing (April), there were rapid increases in soil NH_4^+ in the fertilized plots. Similarly, soil NO_3^- in the CT/NF plots remained consistently very low, whereas NO_3^- levels in the fertilized plots were high in September and then decreased gradually until November (Fig. 1b). Soil NO_3^- contents in the fertilized plots increased remarkably not only after both top dressings, but also after snowmelt at the beginning of April, when a high content was also evident in the CT/NF plot. The seasonal variations of pH in the ZT, RT, and CT plots were all similar: pH increased gradually from September to November, then decreased immediately after top dressing (Fig. 1c). The pH in the CT/NF plot changed higher than those in the fertilized plots throughout the monitoring period,

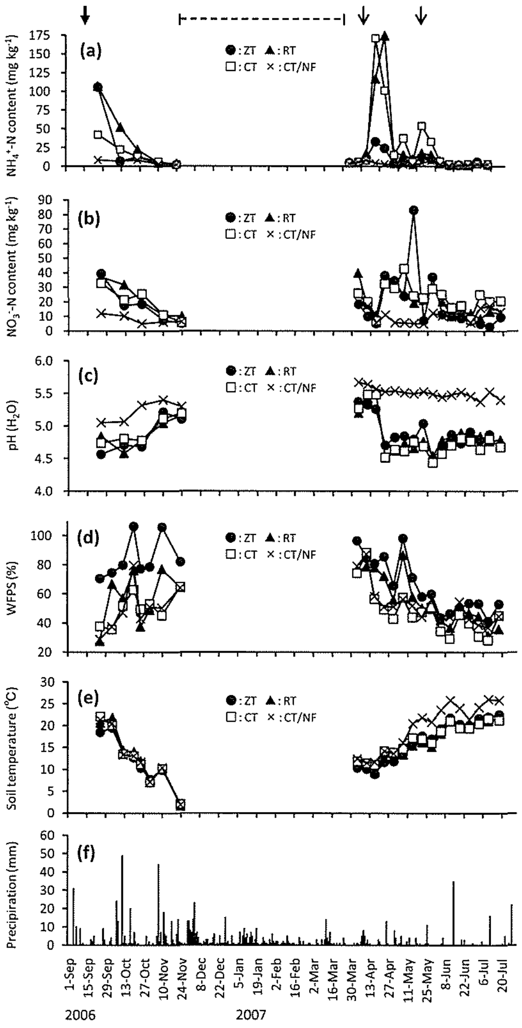

Fig. 1. (a) Soil NH_4^+-N content, (b) soil NO_3^--N content, (c) soil pH, (d) water-filled pore space (WFPS), (e) soil temperature, and (f) precipitation in the ZT (zero tillage), RT (reduced tillage), CT (conventional tillage), and CT/NF (conventional tillage/no fertilizer application) plots. Only precipitation data is available from the beginning of December to the end of March because of snow cover on the ground. Bold and narrow arrows indicate the time of application of the basal dressing and the top dressings, respectively. The period of dotted line indicate snowfall.

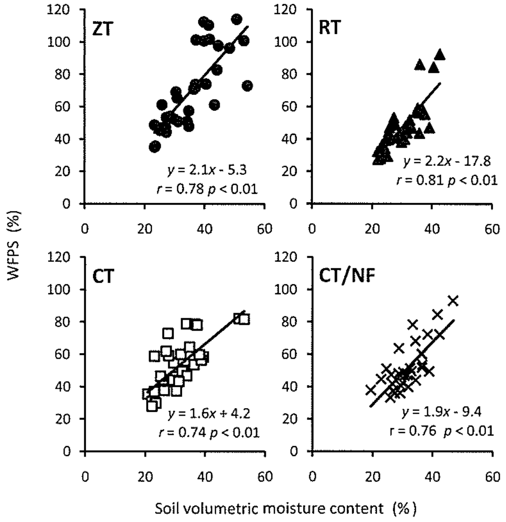

Fig. 2. Relationship between volumetric soil moisture content and WFPS in the ZT (zero tillage), RT (reduced tillage), CT (conventional tillage), and CT/NF (conventional tillage/no fertilizer application) plots. Soil volumetric moisture content was measured by TDR probe. WFPS (water-filled pore space) was calculated from the dry bulk density and water content of core samples.

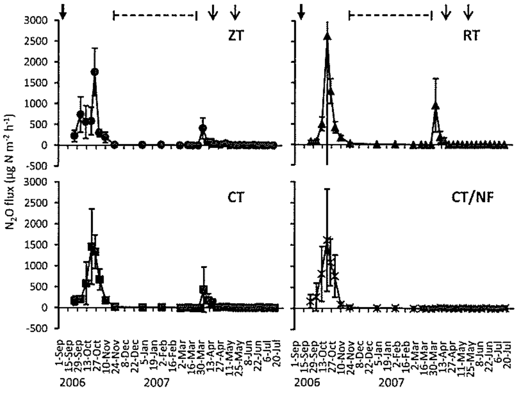

Fig. 3. Fluxes of N_2O from the ZT (zero tillage), RT (reduced tillage), CT (conventional tillage), and CT/NF (conventional tillage/no fertilizer application) plots. Fluxes represent average values and error bars indicate standard deviations (n=4). Bold and narrow arrows indicate the time of application of the basal dressing and the top dressings, respectively. The period of dotted line indicate snowfall.

particularly after May.

3.2 Soil moisture and temperature

There were significant correlations between WFPS calculated from 100-cm^3 soil cores and soil moisture content determined by TDR in all four plot types (Fig. 2). We estimated WFPS in sampling days when core samples were not collected, from the soil moisture content measured by TDR at every sampling time from the regression equations presented in Fig. 2. The seasonal changes in WFPS in the tillage plots (RT, CT, CT/NF) were very similar (Fig. 1d). WFPS increased remarkably from September to November, and reached about 70% by the end of November. WFPS in the ZT plot remained continuously greater than 70% during the same period. After snowmelt, WFPS values in all plots were greater than 70%, but decreased steadily to about 40% by June. The change was greater in the ZT plots than in the tillage plots, particularly between sowing and snowfall and from snowmelt to May 2007.

3.3 Other soil factors and precipitation

The soil bulk density at the study site averaged 1.1×10^3 kg m^{-3}, and the soil had a loam texture (sand 24%, silt 50%, clay 26%). Total C, total N, and the C:N ratio were 3.5%, 0.2%, and 18:1, respectively. Soil temperatures at a depth of 3 cm were similar in all plots (Fig. 1e). However, the soil temperature in the CT/NF plots increased to a higher level than in other plots after May. Total precipitation equaled 185 mm during the 4 months between snowmelt and harvest, versus 370 mm during the 3 months from sowing to snowfall (Fig. 1f).

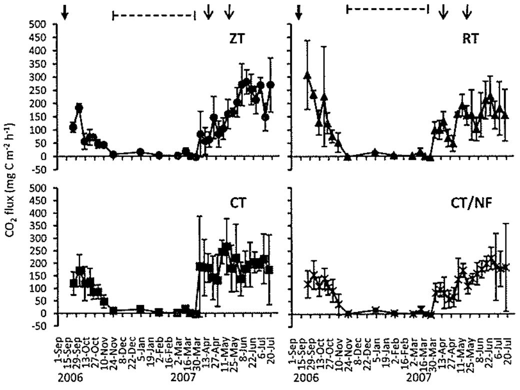

Fig. 4. Fluxes of CO_2 from the ZT (zero tillage), RT (reduced tillage), CT (conventional tillage), and CT/NF (conventional tillage/no fertilizer application) plots. Fluxes represent average values and error bars indicate standard deviations (n=4, RT include average values of three repetitions because of some data losses). Bold and narrow arrows indicate the time of application of the basal dressing and the top dressings, respectively. The period of dotted line indicate snowfall.

3.4 N_2O and CO_2 fluxes

N_2O fluxes in each tillage system increased dramatically between the middle and end of October (Fig. 3), then decreased sharply to zero by the end of November. The maximum mean values in the ZT, RT, CT, and CT/NF plots were 1763, 2640, 1458, and 1620 μg N m^{-2} hr^{-1}, respectively. Immediately after snowmelt, at the beginning of April, large increases in N_2O emissions were observed in the ZT, RT, and CT plots, reaching maximum mean values of 413, 959, and 439 μg N m^{-2} hr^{-1}, respectively. On the other hand, there was no similar tendency in the CT/NF plot. Subsequently, there was no remarkable N_2O emission from the end of April until the end of July, even though nitrogen was applied twice during this period as a top dressing in all but the CT/NF plots. Figure 4 shows CO_2 fluxes over monitoring period. CO_2 fluxes in all plots reached high value after sowing and then gradually decreased. CO_2 fluxes from all plots were remarkably increasing

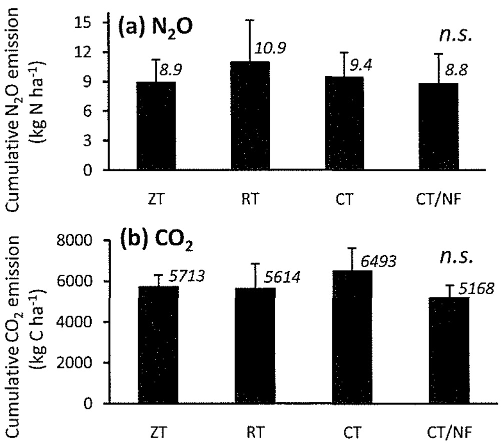

Fig. 5. Cumulative (a) N_2O and (b) CO_2 emissions. Values were obtained from the end of September 2006 to the end of July 2007 (296 days) for N_2O, and from the end of September 2006 to the end of April 2007 (211 days) for CO_2. Numbers above each bar represent the average value, and error bars represent the standard deviation (n=4, number of CO_2 data in RT is three because the flux data with the data loss was excluded.). n.s.; not significant

after snowmelt unlike the pattern for N_2O. CO_2 flux in the RT plot (308 mg C m^{-2} h^{-1}) reached a maximum after sowing, the end of September, on the other hand CO_2 fluxes in ZT (280 mg C m^{-2} h^{-1}), CT (265 mg C m^{-2} h^{-1}) and CT/NF (220 mg C m^{-2} h^{-1}) CO_2 fluxes reached their maximum from May to June.

3.5 Cumulative N_2O and CO_2 emissions

Cumulative N_2O emissions from the ZT, RT, CT, and CT/NF plots during the sampling period (a total of 296 days) were 8.9, 10.9, 9.4, and 8.8 kg N ha^{-1}, respectively (Fig. 5a). The cumulative N_2O emissions did not differ significantly among the four treatments. Cumulative CO_2 emissions from the ZT, RT, CT, and CT/NF plots were 5713, 5614, 6493, and 5168 kg C ha^{-1}, respectively (Fig. 5b). There were no significant differences between treatments as well as N_2O fluxes.

4. Discussion

4.1 Effect of fertilizer on N_2O emission

The application of chemical fertilizers to soils is an important factor that determines N_2O production (Akiyama *et al.*, 2004; Bouwman, 1996; Breitenbeck and Bremner, 1986). In the present study, N_2O flux in each treatment including CT/NF that was the absence of a basal dressing (Table 1), reached their maximum value by the end of October, about 2 months after the basal dressing (Fig. 3). There were no remarkable peaks in N_2O emissions in the fertilized plots after the top dressing, at the ends of April and May, as well as in the CT/NF plot (Fig. 3). Therefore, our results suggest that the contribution of chemical fertilizer to N_2O emission was small.

4.2 Effect of crop residue on N_2O emission

Crop residues may affect N_2O emission because labile-C or N mineralized from organic matter may increase microbial activity (Velthof *et al.*, 2002). The C:N ratio of the wheat residues incorporated in the soils of our study area was 126:1. Possibly as a result of this high ratio, the maximum N_2O emissions occurred about 70 days after incorporation of the residues (Fig. 3). In general, the incorporation of residues with a high C:N ratio can immobilize soil N, and this may have occurred after the incorporation of winter wheat straw (Baggs *et al.*, 2000).

In the present study, all plots received N immediately after harvesting of the previous crop in order to improve decomposition of the wheat residues (Table 1), which is the conventional form of residue management in the study region, where the incineration of wheat residues has been prohibited since 2004. Nitrogen application along with the incorporation of the wheat residues decreased the C:N ratio, resulting in increased mobilization of mineral N. As a result, both soil NH_4^+-N (included in the basal dressing) and NO_3^--N content were high (Fig. 1a,b). In a wheat field where crop residues were removed after harvesting (Koga *et al.*, 2004), soil NH_4^+-N and NO_3^--N were remarkably lower, 10 mg kg^{-1} or less, than in the present study.

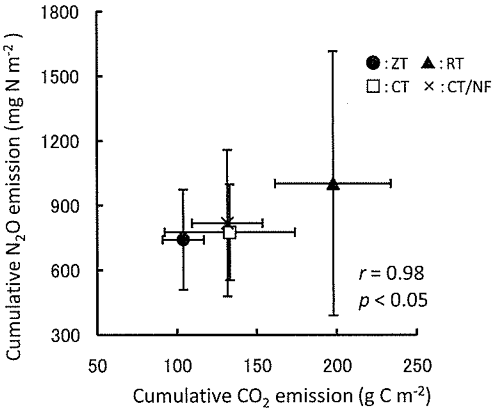

Fig. 6. Relationships between cumulative CO_2 fluxes and cumulative N_2O fluxes in the ZT (zero tillage), RT (reduced tillage), CT (conventional tillage), and CT/NF (conventional tillage/no fertilizer application) plots (a) between sowing and the start of snowfall in November and (b) from the end of November to the end of March. Cumulative flux values represent the means, with error bars representing the standard deviation (n=4, number of data in RT is three because of data loss of CO_2 flux.

N_2O emissions were significantly and positively correlated with CO_2 emissions from September through November (Fig. 6). During this period, the contribution of root respiration in soil respiration could be much small compared with microbial respiration because the development of wheat root system might be small from sowing (Sep. 2006) to the re-growing stage (Apr. 2007). Therefore, it is suggested that the decomposition of wheat residue contribute to N_2O emission.

4.3 Effect of tillage practice on N_2O emission

Tillage practices affect the emission of N_2O mainly through their effect on the water content of the topsoil with increased wetness, resulting in strongly anaerobic conditions (Ball *et al.*, 1999). Previous studies reported higher N_2O emissions in no tillage systems than in conventional tillage (Mackenzie *et al.*, 1997, Palma *et al.*, 1997, Baggs *et al.*, 2003).But in this study N_2O emission was not significantly difference among tillage systems (Fig. 5a). The WFPS parameter was closely related to denitrification (Linn and Doran, 1984). WFPS in the ZT plot was remarkably higher than that in the other tillage systems especially during N_2O fluxes increased dramatically (Fig. 1d), but WFPS values in RT, CT and CT/NF also were high. WFPS in each plot increased in response to the increased rainfall from September to October 2006 (Fig. 1d, 1f). The soil temperatures and air temperatures from the middle of October to the end of October (when N_2O emission was high) maintained about 10℃ (Fig. 1e). This temperature might be enough to maintain the activity of the microorganism. Hou and Tsuruta (2003) showed that the high N_2O emission after the incorporation of Chinese cabbage residues lasted until the temperature fell below 6℃. Soil NO_3^--N also decreased rapidly from October to November (Fig. 1b). It was estimated that carbon source from the incorporated wheat straw residues, combined with nitrogen application and surface mulching in the ZT plot, wet soil condition by frequent rain enhanced the generation of N_2O by denitrification without tillage practice.

All treatments received compost, C:N ratio of which was 11:1, at 28 August 2007 (Table 1). However, it might not be concluded the influence of application of compost on N_2O emission because the start of sampling was after sowing, the end of September. But C applications by compost and wheat residue were 220 kg C ha^{-1} and 2640 kg C ha^{-1}, respectively. Therefore, we guess the influence of compost is much smaller than that of wheat residue. We have been examining on the influence of application of compost on N_2O emission in the next study.

4.4 Importance of full-year investigations of N_2O emission

N_2O emissions from agricultural fields during the winter were formerly not considered to be important (Mosier *et al.*, 1998), since the activity of soil microorganisms was believed to stop under snow. However, Sommerfeld *et al.* (1993) suggested that soil microorganisms continue to respire beneath the snow, even at about 0℃, and emphasized that greenhouse gas emissions during the snow-covered period represented an important part of the annual release of these gases.

In our study, we observed remarkable N_2O emissions in all plots except CT/NF immediately after snowmelt (Fig. 3), and N_2O emission from the ZT, RT, and CT plots from the end of March to the middle of April (a total of 27 days) amounted to 11%, 18%, and 12%, respectively, of the total N_2O emissions during the sampling period (a total of 296 days). The soil temperature was comparatively high (about 10℃; Fig. 1e), furthermore high WFPS (80% to 100%; Fig. 1d) immediately after snowmelt might enhance denitrification activity through improving soil anaerobic condition. On the other hand, in every plot the soil NO_3^--N content after snowmelt was higher than that before snowmelt (Fig. 1b), but there was no remarkable N_2O peak in CT/NF. This reason is not clear now. Changes in the communities of microorganism might arise from the differences in the fertilizer management. Further studies will be necessary to explain this observation.

The high N_2O emission during the winter, and particularly the emission observed immediately after snowmelt, clearly represents a major uncertainty factor in estimates of annual emissions. Our results suggest that investigation of this emission over the course of a whole year, including during the winter, is thus necessary to prevent underestimation of the N_2O emission and the effects of snowmelt.

Acknowledgments

This study was partly supported by the Evaluation, Adaptation and Mitigation of Global Warming program of the Ministry of Agriculture, Forestry and Fisheries of Japan. The authors thank Hiroshi Kawashima for the establishment and management of our experiment at his farms. We also thank Mr. Matsuo Komiyama and Mr. Takahiro Mikuni (National Agricultural Research Center for Hokkaido Region) for technical support during our field measurements.

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小麦残渣および肥料が施与された慣行耕起・省耕起・不耕起栽培体系における亜酸化窒素の発生

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要　約

亜酸化窒素は農業活動によって発生する主要な温室効果ガスであり，二酸化炭素やメタンに比べて強い温室効果を有している。化学肥料や有機物の施与とともに，耕起や収穫後の残渣の鋤込みは，亜酸化窒素ガスを発生させる要因であると考えられる。本研究は，小麦を栽培する水田転換畑を対象とし，麦わら残渣，肥料が施与された慣行耕起 (CT；conventional tillage)，省耕起 (RT; reduced tillage)，不耕起 (ZT; zero tillage) 体系における亜酸化窒素発生量と発生要因を明らかにすることを目的とした。CT においては基肥，追肥を行わない無施肥区 (CT/NF) を合わせて設けた。各処理区，亜酸化窒素フラックスは 10 月中旬から下旬にかけて顕著に高くなり，最高値は，ZT，RT，CT，CT/NF でそれぞれ，1763，2640，1458，1620 $\mu g\ N\ m^{-2}\ hr^{-1}$ となった。2006 年 9 月から 2007 年 7 月 (296 日) における亜酸化窒素積算発生量は，ZT，RT，CT，CT/NF でそれぞれ，8.9，11.1，9.5，8.8 $kg\ N\ ha^{-1}$ となり，処理間で有意差は認められず，施肥を行っていない処理区 (CT/NT) においても施肥された処理区 (ZT，RT，CT) と同程度の亜酸化窒素発生が認められた。この結果から，麦わら残渣の鋤込みが亜酸化窒素発生をもたらす要因の一つであることが示唆された。亜酸化窒素フラックスは，融雪直後においても顕著な上昇傾向がみられ，測定期間における発生量の 11 ～ 18％が，融雪前後の 27 日間でもたらされた。本研究から，年間を通じた測定が亜酸化窒素発生量を正確に算出するためにも必要であることが示された。

キーワード：亜酸化窒素，耕起体系，小麦残渣，二酸化炭素，融雪