Nitrous oxide emissions from an Andosol upland field cropped to wheat and soybean with different tillage systems and organic matter applications

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Abstract

To elucidate effects of tillage systems and organic-matter applications on N₂O emissions, we assessed seasonal patterns and magnitudes of N₂O emissions from Andosol upland soil growing wheat and soybeans using different tillage systems (conventional tillage and no-tillage) and organic-matter applications (crop-residue, crop-residue and cattle manure, and none). Mean N₂O emissions during June 2008 - October 2010 were 41-134 mgN m⁻² yr⁻¹. The N₂O emissions were observed immediately after manure application, fertilizer application, and during the later growing season in soybean-cropped soil. ANOVA revealed that the kind of crop and the organic-matter applications affect N₂O emissions, unlike tillage systems. Greater N₂O emissions in soil with residues and manure suggest that NO₃⁻-N determines N₂O production by denitrification. Additionally, N₂O emissions are greater in soybean-cropped soil, probably because of denitrification. The presence of fresh organic matter such as shed roots and degraded root nodules, NO₃⁻-N, or NO₂⁻-N under wet soil conditions is necessary for N₂O production by denitrification. The water-filled pore space (WFPS) in no-tilled soil is consistently greater than that in conventionally tilled soil, but it does not affect N₂O emissions, suggesting that soil wetness changes are the cause: tillage is not the sole limiting factor for N₂O production in well-aerated soil. Greater N₂O emissions during warm, wet periods of the growing season imply that emissions are related to climatic conditions that affect the soil environment and the resultant microbial activity. Nevertheless, N₂O emissions from the study site with light-colored Andosol resembled those from Andosol, but were less than those from the other soil types such as those of Brown Forest soil, Brown Lowland soil, Grey Lowland soil, Wet Andosol, and Peat soil. Light-colored Andosol of this study site has lower background emissions.

Key words : Andosol, Nitrous oxide, Organic-matter application, Tillage systems

1. Introduction

Global warming is a growing concern that confronts humanity with declining current agricultural production not only through the rise of air temperatures, but also through climate change such as precipitation patterns. Of major greenhouse gases (GHGs), nitrous oxide (N₂O) has a 296-fold stronger greenhouse effect than carbon dioxide (CO₂) over a 100-year time frame (IPCC, 2001). Its emissions from agricultural land amount to 6 TgN per year (Mosier *et al.*, 1998a), which constitute approximately one-third of all annual anthropogenic N₂O emissions (Kroeze *et al.*, 1999).

No-tillage cropping systems are expected to save labor (Ribera *et al.*, 2004), reduce soil erosion (Langdale *et al.*, 1979), and maintain high levels of soil bearing capacity to facilitate work with farm machinery (Larney and Kladvik, 1989). Crop yields under no-tillage systems are reportedly comparable to those under conventional tillage systems (Ogawa *et al.*, 1988; Ito *et al.*, 1994). Therefore, it is considered a promising technique for reducing GHG emissions from farmlands. Omitting tillage reduces fuel consumption and industrial CO₂ sources (Koga *et al.*, 2006). It inhibits decomposition of soil organic matter (Koga *et al.*, 2006).

Application of crop-residues and animal manures is also effective to mitigate GHG emissions from farmlands through soil carbon sequestration (Sommerfeldt *et al.*, 1988; Haynes and Naidu, 1998). Soil carbon contents are known to vary greatly depending on the tillage system that is used (Gebhart *et al.*, 1994). Therefore, a combination of organic-matter application and a tillage system might produce effective soil carbon sequestration and mitigate global warming. However, some reports describe that no-tillage (Aulakh *et al.*, 1984; Linn and Doran, 1984a; Bouwman, 1996; Ball *et al.*, 1999; Baggs *et al.*, 2000) and the application of organic matter such as crop residues (Baggs *et al.*, 2003) and animal manure (Meng *et al.*, 2005; Khalil *et al.*, 2007) often increase N₂O emissions. Actually, data and knowledge related to differences in N₂O emissions between those of tillage systems and organic matter application are insufficient.

In Japan, rice paddy fields have been used increasingly as upland fields since the 1970s because of rice production adjustment policies. Approximately 42% of rice paddy fields in Hokkaido are growing upland crops (Ministry of Agriculture, Forestry, and Fisheries of Japan, 2008). Wheat and soybean are two major crops that are cultivated in upland fields converted from paddies in Hokkaido. Some reports have described that cultivation

of N-fixing plants such as legumes might increase N₂O emissions (Duxbury *et al.*, 1982; Rochette *et al.*, 2004). However, knowledge related to N₂O emissions in upland fields converted from paddies and that for fields planted with a different crop is insufficient. Therefore, we measured N₂O emissions in an Andosol-upland field cropped to wheat and soybean with different tillage systems and different organic-matter applications.

2. Materials and Methods

2.1 Site description

Field measurements were conducted during April 2008–October 2010 in an upland field converted from a paddy of light-colored Andosol in Sapporo (43°00'N, 141°25'E, approximately 70 m a.s.l.). The record during 1981–2000 at the meteorological station at the National Agricultural Research Center for the Hokkaido Region (NARCH), located 1 km west of the experimental field indicates that the mean annual temperature was 7.1°C. The monthly air temperature was -5.7 (January) to 20.8°C (August). The mean annual precipitation was 957 mm; approximately one-fourth of that amount fell as winter snow. The maximum snow depth was 0.9 m (Sameshima *et al.*, 2009).

This field was reclaimed for use as a rice paddy field. It was used as a rice paddy until fall of 2003. After conversion to an upland field, the following crops were cultivated: spring wheat seeded in early winter (seeded in November 2003, with turned in seedlings in May 2004), soybean (seeded in June and harvested in September 2004), pumpkin (seeded in May and harvested in September 2005), soybean (seeded in May and harvested in October 2006), and winter wheat (inter-seeded on the soybean row in September 2006 and harvested in July 2007). The experimental field was prepared to a depth of 12 cm using a rotary tiller after the wheat harvest in mid-August 2007. Hard pan had developed to a depth of around 22 cm from the soil surface. Table 1 presents selected physical and chemical properties of the soil.

2.2 Management scheme

Spring wheat (*Triticum aestivum* L., cv. Haruyokoi) and soybean (*Glycine max* (L.) Merr., cv. Yukihomare) were cultivated alternately in blocks of experimental fields for three years. In “Rotation 1”, wheat, soybean, and wheat were cropped in 2008, 2009, and 2010, and in “Rotation 2”, soybean, wheat, and soybean in 2008, 2009, and 2010. Each crop was cultivated using two tillage systems: conventional- (CT: once tilled using a chisel plow to a depth of 15 cm and twice harrowed using a rotary tiller to a depth of 12 cm each for cropping) and no-tillage (NT: no soil disturbance with the exception of opening seed slots) systems set alternately in 2.4-m rows. Organic matter application plots of three kinds were each 5.0 m long: crop-residue and cattle-manure applications (+R+M), crop-residue application (+R/NM), and no residue and no manure application (NR/NM) were the respective tillage rows. Each of 12 experimental plots had three replications.

Prior to seeding spring wheat and soybean, weeds were controlled using glufosinate in NT soil. In the NT soils cropped to wheat and soybean, the number of biocides used (9) was greater than that (8) in the CT soils. Each is less than those of conventional cultivation in the Hokkaido region (12 in wheat and 13 in soybean-cropped field). Spring wheat was seeded in late April using a seeder machine. The row distance of spring wheat was 30 cm, and the seeding rate was 160 kg ha⁻¹. Soybean was seeded in late May into hand-opened seed slots. The row distance was 60 cm. The slot width and depth were approximately 5 cm. Three soybean seeds were placed at intervals of 22 cm. Chemical fertilizer was applied along the row. The rate of N fertilizer was 74 kg ha⁻¹ (ammonia nitrogen) to wheat field, and 20 kg ha⁻¹ (15 kg as urea compound and 5 kg as ammonia nitrogen) to the soybean field as basal dressing on the same day of sowing. No top dressing was given to either the wheat or the soybean treatment.

Wheat and soybean were harvested respectively in early August and in late September - mid-October in each year. Application of crop residues or cattle manure was done in mid-October of 2008 and 2009 in both wheat and soybean cropped soil. Crop residues, with the exception of stubble, roots, and dead leaves, were removed temporarily from the field on 18 April (before 2008 cropping) and in mid-October (after 2008 and 2009 soybean harvests). On 18 April 2008, wheat residues were spread uniformly on the +R/NM and +R+M soil surface. The amounts of applied residues in June 2008 were set to 5 Mg ha⁻¹, which was the average wheat-residue production of the prior crop (Table 2). In mid-October, residues of each crop were spread uniformly on the +R/NM and +R+M soil surface and the amount of applied residues in October 2008 and October 2009 was dependent on the average residue production in each treatment in 2008 and 2009 croppings (Table 2). The 20 Mg ha⁻¹ of cattle manure manufactured at NARCH was applied to the +R+M soil surface to avoid exceeding the upper limit of compost application (30 Mg ha⁻¹) recommended by Hokkaido Government, on the same day of crop-residue application. Applied residues and cattle manure were incorporated immediately into soil using a rotary tiller in CT, but were left on the soil surface in NT. Properties of applied residues and cattle manure are presented in Table 2.

2.3 N₂O flux measurements

Nitrous oxide flux was measured using the closed chamber method during 12 June 2008–17 October 2010 (857 days). Gas sampling was conducted once every ten days or more often while wheat or soybean was cultivated, and at least once every two weeks during other periods. To stir the air, we used a vinyl-chloride

chamber (60 cm × 30 cm, with 30 cm height) equipped with a DC fan on its interior wall. An aluminum base was pre-installed in each plot to mount the chamber during flux measurements, as described in Toma and Hatano (2007). Gas samples for N₂O analysis were transferred into 10-mL vacuumed glass vials using 25-mL plastic syringes. One gas sample was obtained one minute after the chamber was mounted on the base. Other gas samples were obtained as 20, 25, 30, or 40 min after the first gas sampling. To minimize the effects of diurnal variation on the bias of N₂O accumulated emissions, these gases were collected at 8:00-11:00. Gas samples were taken during December-March, when the soil surface was covered with snow, by putting a rectangular vinyl-chloride chamber (30 cm × 30 cm, with 30 cm height) on the snow surface. The chamber was sealed by compaction of snow around the chamber to prevent the escape of gas from inside the chamber.

The N₂O concentration was quantified using a gas chromatograph equipped with an electron-capture detector (GC14B and GC2014; Shimadzu Corp., Kyoto, Japan) and a Porapak N column within two weeks of gas sampling. The column and detector temperatures were, respectively, 60°C and 340°C. The N₂O flux was calculated using the linear-recurrence method (Kusa *et al.*, 2002). Total N₂O emissions were calculated using the cumulative value of daily emissions. Daily N₂O emissions were estimated through linear interpolation of observed fluxes (Kusa *et al.*, 2002).

2.4 Meteorology, and physical and chemical soil conditions

Data of air temperature and precipitation were obtained from NARCH meteorological observations (Sameshima *et al.*, 2009). Soil temperatures at 3 cm depth were measured at an interval of 1 hr using thermocouples connected to dataloggers (CR10X; Campbell Scientific Inc., Logan, Utah, USA) in the +R/NM in CT, the NR/NM in NT soil and the +R/NM in NT soil.

Changes in soil bulk density in CT and NT soils were measured using 100-mL soil core samples. On 12 June 2008, 13 April 2009, 17 April 2010, and 17 October 2010, undisturbed soil cores were collected at 0-10 cm from the soil surface including NR/NM, +R/NM, and +R+M in both wheat-cropped and soybean-cropped fields. These soil cores were oven dried (105°C) for two days. Their bulk density was measured using gravimetry.

We used the water-filled pore space (WFPS) as an index of the soil wetness. Soil WFPS was calculated as shown below (Linn and Doran, 1984b).

$$\text{WFPS} = \frac{\theta}{P_T} \quad (1)$$

Therein, θ is the volumetric water content (m³ m⁻³) and P_T is the total porosity (m³ m⁻³). Total porosity was estimated using soil bulk and the actual density (ρ_b and ρ_p) as follows.

$$P_T = \left(1 - \frac{\rho_b}{\rho_p} \right) \times 100 \quad (2)$$

In this study, we applied ρ_p to 2.65 Mg m⁻³, and ρ_b to average bulk density at depth of 0-10 cm in CT and NT soil in April 2009, April 2010, and October 2010 to calculate WFPS in 2008, 2009, and 2010. Soil water content was monitored every hour using 30-cm-long water-content meters (CS616; Campbell Scientific Inc.) that were installed horizontally at 6.5 cm depth from the surface in NR/NM and +R+M of both CT and NT soil and which were corrected using WFPS data obtained at 0-10 cm depth using the average of two portable water-content meters (Hydrosense; Campbell Scientific Inc.) at each sampling.

Calibration of the CS616 water-content meters was conducted as reported by Iwata *et al.* (2008). Then, WFPS values from CS616 were obtained using eqs. (1) and (2). Calibration of the water-content meter was conducted with respect to each tillage system. In calibration of CT soil, we filled the cylindrical container (8.3 cm diameter, 13 cm height) with air-dried soil collected from the CT site so that the bulk density of the soil became the same value as that at the CT site. The water-content meter probes were inserted vertically at the center of the top face of the soil-filled container. The relation between the gravimetric-measured water content and the output was observed at various moisture conditions. For calibration of NT soil, we collected undisturbed soil samples in a polyvinyl chloride pipe (8.1 cm diameter, 13.5 cm height). The relation between the gravimetrically measured water content and the output of the water-content meter was monitored at various moisture conditions. We produced a cubic regression formula using least-squares method. The volumetric water content was calculated based on the output of water-content meters using the formula. Then, WFPS data from water-content meters were also obtained from eqs. (1) and (2).

We corrected CS616 WFPS using a linear regression equation between Hydrosense WFPS and CS616 WFPS at the time of gas sampling. We did not measure the water content using CS616 in +R/NM. Therefore, we used CS616 WFPS in +R+M for the estimation of WFPS in +R/NM using the relation between Hydrosense WFPS in +R/NM and CS616 WFPS in +R+M.

Total carbon (T-C), total nitrogen (T-N), and the CN ratio of the soil from all 36 plots at depths of 0-10 cm, 10-20 cm, and 20-30 cm from the surface were measured. Soil was collected at three points in a plot using a hand auger. The collected soil sample was air-dried, passed through a 2-mm sieve, and ground using a mortar

to analyze T-C, T-N, and the CN ratio using a CN analyzer (Vario-Max CN; Elementar Analysensysteme GmbH, Germany).

2.5 Statistical analyses

Statistical analyses were conducted using software (R, ver. 2.10.0; The R Foundation for Statistical Computing). Student's *t*-test was conducted to compare bulk densities in CT and NT soils and N₂O emissions in wheat-cropped and soybean-cropped soils. To detect quantitative relations among the tillage systems, organic-matter application, and N₂O emissions, ANOVA was used. Tukey's multiple-comparison test was performed to compare the rate of N₂O emissions in each year.

3. Results

3.1 Meteorology and physical condition in soil

Figure 1 shows the monthly mean air temperature and precipitation during the observation. The air temperature during the growing season (April-October) was similar to that of the average of 1981-2000 (13.9°C) in 2008 (14.6°C) and 2009 (14.2°C), but it was considerably higher in 2010 (15.1°C). Total precipitation during April-October was less in 2008 (345 mm) than the average (500 mm), but it was greater in 2009 (549 mm) and 2010 (683 mm). In 2008, it continued in a dry condition. In 2009, wet conditions with much rainfall occurred only in July. In 2010, the wettest conditions were recorded through the growing season. The winter climate was milder in both 2008-2009 and 2009-2010 winter than the average of 1981-2000. Monthly average air temperatures were higher in both years than the average by 1-2°C. The maximum snow depth was 99 cm in winter 2008-2009 and 103 cm in winter 2009-2010, each of which is not much different from the average (91 cm).

The bulk density of soil in the 0-10 cm layer from the surface was consistently higher in NT (0.905-1.013 Mg m⁻³) than in CT soil (0.855-0.930 Mg m⁻³) (Table 3). Soil WFPS was 20-100% during the observation period (Figs. 2 and 3). The WFPS changed similarly in all experimental plots, but it was higher in NT soil than in CT soil by up to 20% during April - mid-October. After tillage in mid-October 2008, WFPS in the CT plot dropped to approximately 20%, although that in the NT plot remained at around 65% until snow coverage. The WFPS after snowmelt dropped from 80-100% to less than 60% in all experimental plots. Furthermore, the WFPS in the crop-residue applied soil (+R/NM and +R/M) of NT soil was continuously higher than in the other soil (CT and NR/NM in NT). Daily mean soil temperatures (Fig. 4) were -5.0 to 27.9°C. The soil temperature at CT was as high as that at NR/NM in NT soil, but slightly higher (within 2°C) during May-August and slightly lower (within 2°C) during October-December at +R/NM in NT soil. The interannual soil-temperature variation was greater (Fig. 5). The mean soil temperature during June-August was higher in 2010 by 3-4°C than in either 2008 or 2009.

3.2 N₂O emissions from the soil

The seasonal pattern of N₂O emissions differs among crops and organic-matter applications (Figs. 2 and 3). In wheat-cropped soil, N₂O emissions remained near zero in all soils in 2008 and in the NR/NM and +R/NM soils in 2009. In +R+M soil in 2009 and all soils in 2010, N₂O was emitted immediately after manure application, after 10-60 days of sowing (with basal dressing), and around harvest with maximum flux 22-128 µgN m⁻² h⁻¹. In soybean-cropped soil, N₂O was emitted during August-October (18-147 µgN m⁻² h⁻¹ at maximum). In 2010, emissions were observed in June (43-69 µgN m⁻² h⁻¹) as well as during August-October. At +R+M in soybean-cropped soil, the largest N₂O emissions (291 µgN m⁻² h⁻¹) were observed after manure application in November 2009. Only slight emissions were observed during snow cover.

The N₂O emissions are often larger in soybean-cropped soil than in wheat-cropped soil during the growing season (Figs. 2 and 3) in the same tillage system and organic-matter application (Fig. 5). Yearly variation of N₂O emissions was also found: the emissions in 2010 were often higher than those in either 2008 or 2009 with the same current-year and prior-year crops (Table 4).

The kind of crops incorporated into soil did not affect N₂O emissions. The N₂O emissions (mean ± standard deviation) from wheat-cropped soil at +R/NM in CT were 0.070±0.017 mgN m⁻² d⁻¹ (Fig. 5) in 2008-growing season (wheat-residue incorporated soil), which is as much as 0.075±0.018 mgN m⁻² d⁻¹ (Table 4) in the 2009-growing season (soybean-residue incorporated soil).

Mean yearly N₂O emissions from 12 June 2008 - 17 October 2010 (857 days) in rotation 1 were 47-68 in NR/NM, 41-44 in +R/NM, and 96-113 mgN m⁻² yr⁻¹ in +R+M, and in rotation 2 were 52-64 in NR/NM, 61-67 in +R/NM, and 100-134 mgN m⁻² yr⁻¹ in +R+M (Fig. 6). Results of ANOVA (Table 5) show that organic-matter application (OMA; +R+M, +R/NM, and NR/NM) influences the total N₂O emissions in rotation 1 and rotation 2; residue and manure applications enhance N₂O emissions. Contrarily, the tillage system (Tillage; CT and NT) did not affect N₂O emissions. No interaction was found with a factorial ANOVA.

4. Discussion

4.1 Mechanism of N₂O production

Nitrous oxide is produced by soil bacteria through two processes: nitrification and denitrification. Nitrification is the oxidation of ammonia with oxygen into nitrite by microbial activity under aerobic conditions; N₂O is produced as a byproduct in the nitrification process. Denitrification is, contrarily, the reduction of NO₃⁻

by microbial activity under anaerobic conditions; N_2O is produced as an intermediate product (Tsuruta, 2000). Enhancement of denitrification in soil requires three conditions: (1) supply of fresh organic matter as an electron donor, (2) presence of NO_3^- as an electron acceptor, and (3) anaerobic conditions formed in soil with high WFPS (Burford and Bremner, 1975). In soils, N_2O is produced under drier conditions ($\text{WFPS} < 60\%$) mainly by nitrification, but under wetter conditions ($\text{WFPS} > 60\%$), mainly by denitrification (Tsuruta, 2000). In denitrification processes, when fresh organic matter is supplied to soil, then oxygen in the soil is consumed through organic matter decomposition. Under wet conditions with low air permeability, NO_3^- plays a role as an electron acceptor to the organic matter, engendering denitrification (Conrad, 1996).

4.2 Difference in N_2O emissions between crops

In wheat-cropped soil, most emissions were attributable to denitrification because 74 kgN ha^{-1} of NH_4^+-N applied in late April in all years probably changed to NO_3^--N through nitrification during the course of a month. Most applied NH_4^+-N reportedly disappeared within a month of application, and the NO_3^--N concentration increased (Kusa *et al.*, 2006; Nagata *et al.*, 2009). The N_2O emissions on 6 May 2010, at +R/NM in CT of rotation 1, were attributable to nitrification, probably because NH_4^+ was present in the soil. In soybean-cropped soil, 20 kgN ha^{-1} (including 5 kg NH_4^+ and $15 \text{ kg urea compound}$) was applied in late April in all years and changed to NO_3^--N by nitrification by August.

Application of residues with a low C:N ratio such as soybean heightens N_2O emissions (e.g. Toma and Hatano, 2007). In this study, the kind of applied residue did not influence N_2O emissions because the difference in all nitrogen containing the applied residue is small between wheat and soybean residues (Table 3) unlike the example presented by Toma and Hatano (2007).

The N_2O emissions were observed during August - mid-October only in soybean-cropped soil in 2008 and 2009 (Figs. 2 and 3). Therefore, total N_2O emissions are greater in soybean-cropped soil than in wheat-cropped soil (Fig. 5) even though the wheat-cropped soil (74 kgN ha^{-1}) received approximately four times as much of its nitrogen from fertilizer as the soybean-cropped soil did (20 kgN ha^{-1}). Our results agreed with the suggestion that legumes raise N_2O emissions more than non N_2 -fixing plants do (Rochette *et al.*, 2004). The presence of *Rhizobium* in legume root nodules increases NH_3 input from atmospheric N_2 (Dilworth and Glenn, 1984). N_2O production in legume-planted soils is considered to occur in two processes: (1) oxidation of NH_3 produced by root nodules (nitrification) and (2) denitrification of the nitrified NO_3^- (NO_2^-). In this study, emissions were slight during July-August (35-80 days after sowing) in 2008 and 2009, when the N-fixing activity of root nodules is high (Klucas, 1974; Kim *et al.*, 2005). In contrast, emissions were observed during July-August in 2010. N_2O emissions in this period are regarded as originating from the denitrification process. In 2010 summer, soil WFPS was high (60-80%) because of heavy and frequent rainfall. Kim *et al.* (2005) reported that N_2O is produced through denitrification after heavy rainfall during the N-fixing period (50-80 days after sowing) simultaneously with the decline of nitric oxide (NO) emissions. In all years, N_2O was emitted during late August-October. Degradation of root nodules occurs during grain-filling to ripening (over 100 days after sowing; Yang and Cai, 2005), which agrees with the results of our study. Fresh organic matter such as degraded root nodules and shed roots were supplied in soil. Consequently, under wet soil conditions following a rainfall, the presence of both NO_3^- (NO_2^-) and fresh organic matter in soil are necessary factors producing N_2O . Overall, symbiotic N fixation itself does not largely stimulate N_2O emission, but rather senescence and decomposition of the roots and nodules in the late growing season stimulate N_2O emissions (Yang and Cai, 2005).

4.3 Difference in N_2O emissions between tilled and no-tilled soil

Many researchers have documented the effects of no-tillage techniques on the amounts of N_2O emissions. In fact, some studies show that N_2O emissions in no-tillage systems are greater (Aulakh *et al.*, 1984; Linn and Doran, 1984a; Bouwman, 1996; Ball *et al.*, 1999; Baggs *et al.*, 2000) than, equivalent to (Mosier *et al.*, 1998b; Choudhary *et al.*, 2002; Yamulki and Jarvis, 2002; Elmi *et al.*, 2003), or less than (Jacinthe and Dick, 1997) the N_2O emissions of conventional tillage systems. No-tilled soil has higher soil WFPS than tilled soil does because no-tilled soil has high bulk density and small pore size (Ball *et al.*, 1999) as a result of soil particle coagulation (Aulakh *et al.*, 1984). Therefore, the water retention ability of soil will increase in NT soil, engendering formation of soil-anaerobic and reductive conditions. Our results demonstrated, however, that tillage systems do not affect N_2O emissions significantly (Table 5) even though WFPS is higher in NT soil than CT soil (Figs. 2 and 3), implying that soil moisture alone did not contribute to control of the N_2O production.

Rochette (2008) reported that no-tillage increases N_2O emissions only in poorly aerated soils. The soil in this upland field, Andosol (a soil developed from parent material of volcanic origin) is characterized as a well-drained and highly aerated soil. Although the field had been used as a rice paddy field, it had been used as an upland field for five years at the beginning of this study. It is probable that the cultivation history influences the soil physical conditions, thereby altering effects of tillage on N_2O emissions between those of tilled and no-tilled soils.

4.4 Differences in N_2O emissions by organic-matter application

High N_2O emissions from +R+M soil (Fig. 5) are attributed to the denitrification of NO_3^- from manure under high WFPS. Reportedly, manure applications increase N_2O emissions from agricultural soils (Mogge *et al.*,

1999; Meng *et al.*, 2005). These emissions are associated with manures that have high contents of inorganic N as well as easily mineralizable N and easily mineralizable C (Velthof *et al.*, 2003). In this study, the 3.7 kgN ha⁻¹ of mineral N (0.47 kgN ha⁻¹ of NH₄⁺ and 3.2 kgN ha⁻¹ of NO₃⁻) from manure was applied to the manure-applied soil per year, which reaches 3-25% of the N applied as basal dressing. When fresh organic matter was supplied to soil, N₂O was produced under poorly aerated wet conditions. NO₃⁻ plays a role as an electron acceptor to the organic matter.

Coverage of the soil surface with crop residues (Unger, 1984) maintains wetter conditions in NT soil (Figs. 2 and 3). Crop residues on the soil surface prevent solar radiation and wind from reaching the soil surface. Residues therefore control the evaporative water loss from the soil. Coverage of crop residues on the no-tilled soil produces consistently wetter conditions in wetter NT soil surfaces. However, at this study site, N₂O production was not accelerated by residue coverage because moisture did not solely affect the N₂O emissions.

4.5 Yearly variation of N₂O emissions

Emission rates of N₂O during the growing season tend to be higher in years with warmer and wetter weather conditions (2010) than in other years (2008 or 2009) at this study site (Table 4). This result agrees with earlier reports describing that the emissions factor is positively correlated with annual mean air temperature and total precipitation during September-October (Toma *et al.*, 2007). Yearly variation of N₂O emissions is regarded as associated with the climatic conditions that affect the soil environment and microbial activity. Soil temperatures might affect the N₂O emissions because the temperature coefficient (Q_{10} value) of N₂O emissions is approximately 1.6-6.4 in a boreal forest soil (Koponen *et al.*, 2006).

4.6 N₂O emissions from soils of various soil groups in Hokkaido

The cumulative number of days used for observations differs among previous reports. Therefore, we compare the observed emissions with reported values of average daily emissions in units of mgN m⁻² d⁻¹ during each observation. The N₂O emissions at this study site (0.11-0.37 mgN m⁻² d⁻¹) were approximately within the range reported in a well-drained Andosol upland field cropped to winter wheat and azuki bean (*Vigna angularis* (Willd.) Ohwi & Ohashi) in Hokkaido, Japan (0.052-0.15 mgN m⁻² d⁻¹; Koga *et al.*, 2004), but smaller than those observed in Gray Lowland soil cropped to onion (*Allium cepa* L.) or winter wheat (0.43-8.6 mgN m⁻² d⁻¹), Brown Lowland soil (0.19-1.7 mgN m⁻² d⁻¹), Brown Forest soil (0.74-3.0 mgN m⁻² d⁻¹), wet Andosol (3.9-11 mgN m⁻² d⁻¹), or Peat Soil with soil dressing cropped to wheat (3.0-3.7 mgN m⁻² d⁻¹) in Hokkaido (Sawamoto and Hatano, 2000; Kusa *et al.*, 2002; Kusa *et al.*, 2006; Toma *et al.*, 2007; Mu *et al.*, 2008; Nagata *et al.*, 2009).

Akiyama *et al.* (2006) classified background N₂O emissions (annual emissions from soil without N fertilizer application) according to the drainage performance of soils. The background N₂O emissions in well-drained upland soils were 0.36 kgN ha⁻¹ yr⁻¹, but those in poorly drained upland soils were 1.4 kgN ha⁻¹ yr⁻¹. Well-drained soils have lower background emissions. The N₂O emissions described for this study site were similar to the background emissions in well-drained soil. The emissions at this study site with chemical fertilizer applications (equivalent to 0.41-0.68 kgN ha⁻¹ yr⁻¹) are similar to background emissions in well-drained soil, but less than those in poorly drained soil, even with chemical-fertilizer application. Therefore, the emissions from the soil at the study site resembled those in well-drained soils.

The N₂O emissions are closely related to both soil groups and soil moisture condition. Results of some studies associate the magnitude of N₂O emissions with the soil wetness and soil texture. Kusa *et al.* (2006) reported that N₂O emissions are influenced by the soil wetness generated by geographical factors. McTaggart *et al.* (2002) associated the N₂O emissions with soil texture, which affects the soil air permeability.

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Fig.1. Variations of monthly (A) air temperature (closed circles) and (B) precipitation (bars) during 2008-2010. Solid lines in (A) and (B) show averages for 1981-2000.

Fig.2. Temporal changes in (A) soil WFPS and (B) N₂O flux in conventionally tilled (CT) and no-tilled (NT) soil in rotation 1 (wheat-soybean-wheat cropping system) with applications of no crop residues or cattle manure (NR/NM), crop residues (+R/NM), and crop-residues and cattle manure (+R+M). Bold, solid, and shaded lines in (A) denote WFPS in +R/NM in CT soil, NR/NM in NT soil, and +R/NM in NT soil, respectively. Closed and open circles in (B) denote averages of three replicates in CT and NT soils. Error bars in (B) show standard deviations. Arrows indicate the date of field management: A, organic-matter application, if any; T, tillage; S, sowing and basal dressing; H, harvest.

Fig.3. The same figure as Fig. 2 in rotation 2 (soybean-wheat-soybean cropping systems).

Fig. 4. Daily mean soil temperature in (A) rotation 1 and (B) rotation 2.

Fig. 5. Comparison of N₂O emissions (mgN m⁻² g.s.⁻¹, g.s.: growing season) between wheat and soybean cropped fields during growing season (15 April - 15 October) of 2008, 2009, and 2010 cropping years. The bar and error bar show the mean and the standard deviation ($n=3$). Daggers and asterisks denote significant differences between emissions, † $P<0.1$, * $P<0.05$, ** $P<0.01$, using Student's t -test.

Fig. 6. Yearly N₂O emissions in fields of rotation 1 and rotation 2 during June 2008 - October 2010. Values are the emissions per year (365 days). Bars and error bars show the mean and standard deviation ($n=3$).

Table 1. Physical and chemical properties of soil at the study site before observation (13 April 2008). s.d., standard deviation.

Depth	Texture	Bulk density (<i>n</i> =30)	Fraction of solid phase (<i>n</i> =10)	Mean saturated hydraulic conductivity (<i>n</i> =18)	pH (H ₂ O) (<i>n</i> =3)	Total C (<i>n</i> =36)	Total N (<i>n</i> =36)	Mean C/N
		mean ± s.d. Mg m ⁻³	mean ± s.d. %		mean ± s.d.	mean ± s.d. %	mean ± s.d. %	
cm				m s ⁻¹				
0–10	SiCL	0.892±0.061	34.8±4.1	3.85×10^{-4}	6.6±0.1	3.69±0.02	0.28±0.00	13.1
10–20	SiCL	0.959±0.068	35.5±3.2	2.66×10^{-5}	6.5±0.0	3.68±0.02	0.28±0.00	13.4
20–30	SiCL	1.11±0.06	41.1±2.7	1.01×10^{-5}	6.4±0.0	3.51±0.04	0.28±0.00	14.2

Table 2. Selected chemical properties of organic matter applied to the soil.

Organic matter	Date of application	Mean application g m ⁻²	No. of samples	Water content %	pH (H ₂ O)	Total C %	Total N %	NH ₄ ⁺ -N ppm	NO ₃ ⁻ -N ppm	C/N
Residues										
wheat	18 Apr. 2008	500	2	8	—	41.6	0.68	—	—	61
wheat	15 Oct. 2008	604	1	8	—	41.9	0.37	—	—	113
soybean	15 Oct. 2008	183	1	11	—	42.7	0.83	—	—	51
wheat	23 Oct. 2009	502	1	20	—	35.6	0.32	—	—	111
soybean	23 Oct. 2009	208	1	16	—	38.7	0.76	—	—	51
Manure										
cattle manure	18 Apr. 2008	2000	3	47	7.9	16.2	1.9	134	428	8.5
cattle manure	15 Oct. 2008	2000	2	51	7.0	14.5	1.8	28.5	780	8.3
cattle manure	23 Oct. 2009	2000	2	60	7.9	14.8	1.7	48.2	922	8.7

Table 3. Soil bulk density (mean $\pm$ standard deviation) in conventionally tilled (CT) and no-tilled (NT) soil at depths of 0-10 cm from the surface. Asterisks denote significant differences, * P <0.05, ** P <0.01, using Student's t -test.

Date of sampling	Number of samples	CT Mg m ⁻³	NT Mg m ⁻³	
12 Jun. 2008	6	0.872 $\pm$ 0.017	0.928 $\pm$ 0.047	*
13 Apr. 2009	18	0.903 $\pm$ 0.051	0.993 $\pm$ 0.037	**
17 Apr. 2010	18	0.911 $\pm$ 0.072	1.014 $\pm$ 0.046	**
17 Oct. 2010	18	0.930 $\pm$ 0.092	1.013 $\pm$ 0.082	**

Table 4. Yearly variations of daily N₂O emission (mean $\pm$ standard deviation) from soils with the same current-year and previous-year crops during the growing season (15 April - 15 October). Asterisks denote significant differences, * P <0.05, by one-way ANOVA. Different alphabetical letters with values represent significant differences among treatments (Tukey's test, P <0.05).

Crop	Crop in the prior year	Tillage	Organic-matter application	2008	2009	2010
				mgN m ⁻² d ⁻¹	mgN m ⁻² d ⁻¹	mgN m ⁻² d ⁻¹
Wheat	Soybean	CT	NR/NM		0.071 $\pm$ 0.020	0.267 $\pm$ 0.074 *
			+R/NM		0.075 $\pm$ 0.018	0.231 $\pm$ 0.053 *
			+R+M		0.314 $\pm$ 0.494	0.473 $\pm$ 0.168
		NT	NR/NM		0.057 $\pm$ 0.031	0.207 $\pm$ 0.035
			+R/NM		0.042 $\pm$ 0.035	0.243 $\pm$ 0.078 *
			+R+M		0.328 $\pm$ 0.214	0.459 $\pm$ 0.127
Soybean	Wheat	CT	NR/NM	0.201 $\pm$ 0.111	0.133 $\pm$ 0.017	0.317 $\pm$ 0.141
			+R/NM	0.307 $\pm$ 0.136	0.148 $\pm$ 0.040	0.382 $\pm$ 0.197
			+R+M	0.417 $\pm$ 0.135	0.558 $\pm$ 0.225	0.376 $\pm$ 0.324
		NT	NR/NM	0.154 $\pm$ 0.055a	0.294 $\pm$ 0.009ab	0.476 $\pm$ 0.148b *
			+R/NM	0.189 $\pm$ 0.078ab	0.110 $\pm$ 0.043a	0.446 $\pm$ 0.194b *
			+R+M	0.343 $\pm$ 0.057	0.381 $\pm$ 0.087	0.790 $\pm$ 0.312

Table 5. Factorial ANOVA showing the effects of tillage system, and organic matter application on N₂O emissions from the soil surface: tillage, either conventional tillage (CT) or no tillage (NT); organic-matter application (OMA), either crop-residue and cattle-manure application, +R+M, crop-residue application, +R/NM, and no application, NR/NM. Asterisks denote significant differences (** $P < 0.01$).

Factor	$df^{\dagger}$	Mean Sq. ^{††}	F value	Pr.($>F$) ^{†††}
Rotation 1				
Tillage	1	1.867	0.005	0.950
Organic-matter application (OMA)	2	6228	16.084	0.002 **
Tillage & OMA	2	585.0	1.511	0.278
Residuals	8	387.2		
Rotation 2				
Tillage	1	795.8	3.043	0.223
Organic-matter application (OMA)	2	6346	13.731	0.003 **
Tillage & OMA	2	630.7	1.365	0.309
Residuals	8	462.2		

[†] df , degrees of freedom; ^{††}Mean Sq., mean square; ^{†††}Pr., Probability