A comparison of N$_2$O and CO$_2$ concentrations and fluxes in the soil profile between a Gray Lowland soil and an Andosol

Kanako Kusa$^1$, Takuji Sawamoto$^2$, Ronggui Hu$^3$, Ryusuke Hatano$^4$

Graduate School of Agriculture, Hokkaido University, Sapporo 060-8589, Japan

National Agricultural Research Center, Research team for using rice as feed in Kanto area

3-1-1, Kannondai, Tsukuba, Ibaraki, 305-8666, Japan.

Tel. 029-838-8817, Fax 029-838-8484, e-mail kusakana@affrc.go.jp

Present addresses:

$^1$National Agricultural Research Center, Tsukuba, 305-8666 Japan. $^2$Faculty of Dairy Science, Rakuno Gakuen University, Ebetsu, 069-8501 Japan. $^3$College of Resource and Environment, Huazhong Agricultural University, Wuhan, Hubei, 430070 China.
1 Laboratory of Soil Science, Graduate School of Agriculture, Hokkaido University,

2 Sapporo 060-8589 Japan.
Abstract

We measured N₂O and CO₂ fluxes from the soil surface and in the soil through a depth of 0.3 m, and their concentration profiles through a depth of 0.6 m in both a Gray Lowland soil with macropores and cracks and an Andosol with undeveloped soil structure in central Hokkaido, Japan. The objective of this study was to elucidate the difference of N₂O production and flux in the soil profile between these two soil types. In the Gray Lowland soil, the N₂O concentration above 0.4 m increased with an increase in soil depth. In the Andosol, there were no distinctive N₂O concentration gradients in the topsoil when the N₂O flux did not increase. However, the N₂O concentration at a depth of 0.1 m significantly increased and this concentration was higher than the concentration below 0.2 m when the N₂O flux greatly increased. The N₂O concentration profiles were thus different between these two soils. The contribution ratios of the N₂O produced in the top soil (0-0.3 m depth) to the total N₂O emitted from the soil to the atmosphere in the Gray Lowland soil and the Andosol were 0.86 and 1.00, respectively. It indicates that the N₂O emitted from the soil to the atmosphere was mainly produced in the top soil. However, the contribution ratio of the subsoil to the N₂O emitted from the Gray Lowland soil was higher than that of the Andosol. There was a significant positive correlation between the N₂O flux through a 0.3 m depth and that flux from the
soil to the atmosphere in only the Gray Lowland soil. These results suggest that $N_2O$
production in the subsoil of the Gray Lowland soil could have been activated by $NO_3^-$
leaching through macropores and cracks, and subsequently the $N_2O$ produced in the
subsoil could have been rapidly emitted to the atmosphere through the macropores and
cracks.

**Key words:** Andosol, carbon dioxide, gas concentration in soil profile, Gray Lowland
soil, nitrous oxide
INTRODUCTION

Increased nitrous oxide (N\textsubscript{2}O) concentrations in the troposphere cause global warming and contribute to the depletion of the stratospheric ozone (Prather et al. 2001). Enhanced N\textsubscript{2}O emissions from agricultural and natural ecosystems are believed to be results mainly from the increased use of nitrogen (N) fertilizer. The contribution of agricultural activities to global N\textsubscript{2}O emission is estimated to be about 35% (FAO & IFA 2001, Prather et al. 2001). Therefore, elucidation of the mechanism of N\textsubscript{2}O emission from agricultural soil has been crucial to mitigate global N\textsubscript{2}O emission. Nitrification and denitrification by soil microbes are the dominant processes in the production of N\textsubscript{2}O in soils. These processes are strongly influenced by soil conditions such as temperature, water content, nitrate (NO\textsubscript{3}\textsuperscript{-}) and ammonium (NH\textsubscript{4}\textsuperscript{+}) concentrations, and organic matter content (FAO & IFA 2001). Marked increases in N\textsubscript{2}O emission rates have been observed immediately after the application of fertilizer and manure (Akiyama et al. 2000, Akiyama & Tsuruta 2002, Jambert et al. 1997, Lessard et al. 1996, Skiba et al. 1996). In addition, some studies reported that the high N\textsubscript{2}O emission rates were observed after heavy rain and irrigation (Koga et al. 2004, Kusa et al. 2002, Kusa et al. 2006, Lessard et al. 1996, Mosier & Hutchinson 1981), suggesting that N\textsubscript{2}O emissions from the soil to the atmosphere were influenced strongly by N dynamics and the
addition of water to soils. In a prismatic structured soil with interstitial pores, water
moves vertically through macropores, bypassing the soil matrix within peds (Hasegawa
1986, Hayashi & Hatano 1999, Inoue 1988). Gas movement is primarily associated with
macropores (Osozawa 1998). Also, rainwater or snowmelt water is likely to mix with
the soil solution in the topsoil and drain directly through the macropores in the subsoil
when large drainage takes place in prismatic structured soil (Hayashi & Hatano 1999).
However, in an Andosol characterized by the absence of cracks and fissures after drying,
rainwater moves mainly by a matrix flow (Hasegawa & Eguchi 2002) and the
movement of gas through macropores becomes minor (Osozawa 1998). Therefore, the
movement of NO$_3^-$ and the production and movement of N$_2$O in soils are influenced by
the soil structure. The concentration profiles of soil N$_2$O have been used to estimate the
depth of N$_2$O production in soils (Goodroad & Keeney 1985, Hosen et al. 2000). A
comprehension of N$_2$O movement in the soil profile is necessary to explain the
production and emission of N$_2$O in the soil.

Carbon dioxide (CO$_2$) is also one of the greenhouse gases produced by the respiration
of soil microbes and roots in soils. Soil microbes and roots are distributed mainly in the
top soil (Nakamoto 1993, Osozawa 1998). Therefore, most of the CO$_2$ emitted is
produced in the top soil (de Jong & Schappert 1971). Also, comparisons of N$_2$O and
CO₂ concentrations and fluxes among different soils in the soil profile could be useful to elucidate the influence of soil type on the mechanisms of N₂O production and fluxes in the soil profile. In this study, we measured N₂O and CO₂ fluxes from the soil surface, and both N₂O and CO₂ concentrations and fluxes in the soil profiles in a Gray Lowland soil with macropores and an Andosol without macropores, where N₂O emissions during the pluvial period and after heavy rains were higher than those observed immediately after fertilizer application (Kusa et al. 2002, Kusa et al. 2006). The objective of this study was to elucidate the difference of N₂O production and flux in the soil profile between these two soil types.

MATERIALS AND METHODS

Experimental sites

The experimental sites were a 2.0 × 10⁴ m² onion (Allium cepa L.) field in Mikasa City (43° 14' N, 141° 50' E) and a 1.8 × 10⁴ m² maize (Zea mays L.) field at the National Agricultural Research Center for Hokkaido Region in Sapporo City (43° 00' N, 141° 24' E) located in central Hokkaido, Japan. In the onion field, the soil was Humic Gray Lowland soil (Japanese Society of Pedology 2003); the soil texture at a 0–0.48 m depth was silty clay (SiC) and there were interstitial pores in the subsoil (Table 1). Saturated
For review

hydraulic conductivity was low at a depth of 0–0.28 m, and was higher at a depth below
0.28 m (Table 1) because of the presence of macropores (Hayashi & Hatano 1999).

Subsurface drains were installed at a 0.8–1.0 m depth and the groundwater table was at
0.7–0.8 m depth throughout the year. Chemical fertilizer was applied to the field at a
rate of about 300 kg N ha\(^{-1}\) at the end of April. Onion seedlings were transplanted at the
beginning of May and harvesting was carried out in both early and mid-September
(Kusa et al. 2002). In the maize field, the soil was Silandic Andosol (Japanese Society
of Pedology 2003). The soil texture at a depth of 0–0.30 m was clay loam (CL) which is
rich in humus. An impermeable layer lay 1.3 m below ground level, and consequently
the groundwater table temporarily rose to near the ground surface level during the
snowmelt period and after heavy rains (Kanazawa et al. 1999). Respective saturated
hydraulic conductivity at a depth of 0–0.30 m was lower than that at 0.30–0.47 m (Table
1). Composted cattle manure was applied to the field at a rate of 300 kg N ha\(^{-1}\) (fresh
weight 3.0 kg m\(^{-2}\)) every year in mid-May. After furrowing, chemical fertilizer was
applied to the rows at a rate of 130 kg N ha\(^{-1}\). The row width was 0.75 m and inter-row
width was 0.25 m. Maize was sown in mid-May and harvested at the end of September.
The monitoring of gas emission rates and other factors in the maize field were
conducted only between the plants in each row (Kusa et al. 2006). For 3 years

http://mc.manuscriptcentral.com/sspn
(1998–2000), N$_2$O and CO$_2$ fluxes were usually measured every week on the same day during the snow–free season (Gray Lowland soil: from the end of May to October, Andosol: from June to the end of September) and additionally, N$_2$O fluxes were measured every week during the snow–free season from 1995 to 1997 in the Gray Lowland soil (Table 2, 3).

N$_2$O and CO$_2$ concentration in the soil profile

After the polyvinyl chloride pipes (soil-air sampling tubes: the inside diameter was 0.013 m, the outside diameter was 0.016 m) were installed in the soil, silicon stoppers which were threaded with rubber tubes with three-way cocks were connected to the top of the soil-air sampling tubes. The depths of the soil-air sampling tubes installed were 0.05, 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 m. Twenty soil-air sampling tubes were installed each at a depth of 0.05 and 0.1 m and ten tubes were installed at various depths between 0.2 to 0.6 m. Gas samples of the enclosed atmosphere in the soil-air sampling tubes were withdrawn using a 10 mL syringe; all gas samples from the same depth were transferred into a 1 L Tedlar®Bag and were mixed. The ambient air above the soil surface was also sampled to obtain the concentration at a 0 m depth. The N$_2$O concentrations in the gas samples were measured using a gas chromatograph equipped
with an electron capture detector (GC-14B; Shimadzu Corp., Kyoto, Japan). The CO₂ concentrations were analyzed using an infrared gas analyzer (ZFP-5; Fuji Electric Co., Ltd., Tokyo, Japan).

**Measurement of soil physical properties and rainfall**

The soil temperature was measured at a depth of 0.1 m using a digital thermometer.

Three undisturbed soil samples (0–0.05 m and 0.05–0.1 m) were collected using three 100 mL steel cylinders at each sampling date; the air-filled porosity, water-filled pore space (WFPS) and the relative gas diffusion coefficient ($D/D₀$) were measured using the method reported by Osozawa (1998).

To obtain the air-filled porosity and gas diffusion coefficient in the soil profile, undisturbed soil samples were collected once using three 100 mL steel cylinders from the Gray Lowland soil in October, 1996 and from the Andosol in May, 1998 (Gray Lowland soil: 0.05–0.1, 0.15–0.2, 0.23–0.28, 0.32–0.37, 0.43–0.48, and 0.54–0.59 m, Andosol: 0.13–0.18, 0.31–0.36, 0.40–0.45, and 0.58–0.63 m). The air-filled porosity and $D/D₀$ of these samples were measured at a water suction of −0.098 (water saturated), −0.31, −0.98, −3.1, −9.8, and −31 kPa. The $D/D₀$ of the water saturated sample was assumed as 0. Regression curves were obtained from the relationship of the soil water...
suction to the $D/D_0$ (Table 4) and air-filled porosity. Two tensiometers were installed at depths of 0.1, 0.2, 0.3, 0.4, and 0.5 m and the soil water suction was measured at each sampling date (Hasegawa & Kasubuchi 1988). The changes in the air-filled porosity and the $D/D_0$ in the soil profile were calculated using the value obtained from the soil water suction and the regression curves.

Rainfall data for the Gray Lowland soil and the Andosol sites were recorded at the Iwamizawa Weather Station (43° 12.6’ N, 141° 47.3’ E) (Sapporo Distinct Meteorological Observatory 1995-2000) and the National Agricultural Research Center for Hokkaido Region, respectively.

$N_2O$ and $CO_2$ fluxes in the soil profile and from the soil surface to the atmosphere

$N_2O$ and $CO_2$ fluxes through a depth of 0.3 m in the soil profile were calculated using the following equation, using Fick’s law (gradient method; Granli & Bøckman 1994) as follows:

$$F_{0.3} = D \times \rho \times \frac{dC}{dz} = \left( \frac{D}{D_0} \right) \times D_0 \times \rho \times \frac{C_{0.4} - C_{0.2}}{z} \times \frac{273}{273 + T}$$

(1)

where $F_{0.3}$ is the gas flux (mg m$^{-2}$ s$^{-1}$) in the soil through a depth of 0.3 m, $D$ is the gas diffusion coefficient (m$^2$ s$^{-1}$), $\rho$ is the gas density ($\rho_{CO_2} = \rho_{N_2O} = 1.98 \times 10^6$ (mg m$^{-3}$)), $[dC/dz]$ is the gas concentration gradient (m$^2$ m$^{-3}$), $D/D_0$ is the relative gas diffusion
coefficient at a depth of 0.3 m (these values were calculated from the regression curves of the soil water suction – $D/D_0$ of the Ap horizon at a depth of 0.23-0.28 m in the Gray Lowland soil and at a depth of 0.13-0.18 m in the Andosol, Table 4), $D_0$ is the $N_2O$ or CO$_2$-air inter-diffusion coefficient (m$^2$ s$^{-1}$), $C_{0.2}$ and $C_{0.4}$ are the gas concentrations at a depth of 0.2 and 0.4 m (m$^3$ m$^{-3}$), respectively, $z$ is the distance from 0.4 to 0.2 m, and $T$ is the soil temperature between 0.2 and 0.4 m ($^\circ$C) which was presumed to be 20 $^\circ$C. $D_0$ under the air pressure 1 atm and the soil temperature 20 $^\circ$C were calculated using the following equation (Pritchard & Currie 1982):

$$D_0 = D_s \times \left(\frac{273+20}{273}\right)^{1.79}$$

(2)

where $D_s$ (N$_2$O) and $D_s$ (CO$_2$) (m$^2$ s$^{-1}$, in standard condition) represent 0.143 × 10$^{-4}$ and 0.139 × 10$^{-4}$, respectively (Pritchard & Currie 1982).

In our previous paper (Kusa et al. 2008), we revealed that the gradient method was useful in measuring the N$_2$O fluxes from the soil surface into the atmosphere (flux from the soil surface). However, there were differences in the CO$_2$ and extremely high N$_2$O fluxes between chamber and gradient methods when the production and consumption of these gases were active in the soil above the installed location of the soil-air sampling tube. Therefore, the N$_2$O and CO$_2$ fluxes from the soil surface were measured by a closed-chamber method. Cylindrical stainless steel chambers, 0.3 m in diameter and
0.35 m high for the Gray Lowland soil and 0.2 m in diameter and 0.2 m high for the Andosol, were used. Fifteen minutes after placement of the chamber, a gas sample was taken from the enclosed atmosphere. The mean gas emission rates of four replications in the Gray Lowland soil and of two replicates in the Andosol were calculated. The gas sampling method and the calculation of gas fluxes were described in detail in our previous papers (Kusa et al. 2002, 2008). The cumulative gas fluxes during the study period were calculated through linear interpolation.

Mass balance analysis

Hosen et al. (2000) showed that N₂O consumption in the top soil (above 0.24 m) does not have much effect on the N₂O emission rate. Although CO₂ can be dissolved in the soil water, Osozawa (1998) reported that the CO₂ runoff volume by water percolation was very small. Therefore, mass balance analyses were conducted to estimate the N₂O and CO₂ productions of topsoil (0–0.3 m) by the following equation:

\[ P = F_0 - F_{0.3} + (M_s - M_e) \]

where \( P \) is the N₂O and CO₂ production (mg m⁻²) in the topsoil during the study period, and \( F_0 \) and \( F_{0.3} \) are the cumulative N₂O and CO₂ fluxes (mg m⁻²) from the soil surface through a depth of 0.3 m during the study period. \( M_s \) and \( M_e \) signify the mass of N₂O
and CO$_2$ (mg m$^{-2}$) respectively, in the topsoil at the beginning and end of the investigation which is the product of air-filled porosity (m$^3$ m$^{-3}$), gas concentration (mg m$^{-3}$), and depth (m). The contribution ratios of the gas production ($P/F_0$) in the topsoil to the gas emitted from the soil surface to the atmosphere were estimated.

RESULTS

Seasonal patterns of rainfall and soil physical properties

The frequency of rainfall in both Gray Lowland and Andosol sites increased after July every year (Figs. 1 and 2). The mean values of WFPS from 1998 to 2000 at depths of 0–0.05 and 0.05–0.1 m were 45 and 59 % in the Gray Lowland soil and 48 and 57 % in the Andosol, respectively (Figs. 3 and 4). At a depth of 0–0.1 m, the values of $D/D_0$ were below 0.02 when the values of WFPS were above 60%. The values of $D/D_0$ in the Andosol were higher than those of the Gray Lowland soil when the values of WFPS were below 60% (Fig. 5). The mean values of soil water suction at depths of 0.2, 0.3, and 0.6 m from 1998 to 2000, were −15.6, −10.9, and −3.2 kPa in the Gray Lowland soil and −10.5, −9.9, and −3.6 kPa in the Andosol. There were no significant differences in WFPS (paired t-test: 0–0.05 m $|t|=2.02$, $p = 0.05$, $n = 61$ and 0.05–0.1 m $|t|=1.07$, $p = 0.29$, $n = 59$) and soil water suction (paired t-test: 0.2 m $|t|=1.82$, $p = 0.08$, $n = 24$, $|t|=1.07$, $p = 0.29$, $n = 59$) and soil water suction (paired t-test: 0.2 m $|t|=1.82$, $p = 0.08$, $n = 24$,
0.4 m $|t|=1.28$, $p=0.21$, $n=24$ 0.6 m $|t|=0.11$, $p=0.91$, $n=21$) between the Gray Lowland soil and the Andosol. The soil water suction increased with an increase in soil depth. The value of WFPS increased while the soil water suction decreased after rainfall (Figs. 1–5). Also, the soil temperature at a depth of 0.1 m increased from spring to summer and decreased after summer (Figs. 3 and 4).

In 1998–2000, the mean values of soil air porosity at a depth of 0–0.05, 0.05–0.1, 0.3, and 0.6 m were 32, 23, 5.5, and 4.9 % in the Gray Lowland soil and 35, 29, 8.7, and 7.6 % in the Andosol, respectively. The values of soil air porosity in the Andosol were higher than those of the Gray Lowland soil (paired t–test: depth of 0–0.05 m $|t|=2.65$, $p=0.01$, $n=61$, depth of 0.05–0.1 m $|t|=4.60$, $p<0.01$, $n=59$, depth of 0.3 m $|t|=1.84$, $p=0.08$, $n=18$, depth of 0.6 m $|t|=3.48$, $p<0.01$, $n=21$). The mean values of D/D_0 at depths of 0–0.05, 0.05–0.1, 0.3, and 0.6 m (1998–2000) were 0.097, 0.048, 0.003, and 0.003 in the Gray Lowland soil and 0.150, 0.080, 0.004, and 0.003 in the Andosol, respectively (Fig. 6). The values of D/D_0 above 0.3 m in the Andosol were higher than those in the Gray Lowland soil, but there was no significant difference at a depth of 0.6 m (paired t–test: depth of 0–0.05 m $|t|=4.41$, $p<0.01$, $n=61$, depth of 0.05–0.1 m $|t|=5.12$, $p<0.01$, $n=57$, depth of 0.3 m $|t|=2.39$, $p=0.03$, $n=18$, depth of 0.6 m $|t|=1.03$, $p=0.31$, $n=24$).
Concentration and flux of N$_2$O in the soil profile

The cumulative N$_2$O flux from the soil to the atmosphere during the study period from 1995 to 2000 ranged from 310 to 1190 mg N m$^{-2}$ in the Gray Lowland soil and that cumulative flux from 1998 to 2000 ranged from 630 to 1980 mg N m$^{-2}$ in the Andosol (Table 2). There was no significant difference in the cumulative N$_2$O flux between the Gray Lowland soil and the Andosol from 1998–2000 (t-test: |t|=1.11, p=0.33, n=3). Also, a significant increase in N$_2$O fluxes occurred during the increasing frequency of rainfall in the Gray Lowland soil (Fig. 1a) and after heavy rainfall (above 80 mm day$^{-1}$) in the Andosol (Fig. 2a).

In both the soils, the N$_2$O concentrations at a depth of 0.05 m were always higher than those of the ambient air, which is about 0.3 ppmv ($10^{-6}$ m$^{-3}$ = ppmv). A significant increase in soil N$_2$O concentrations occurred after July in the Gray Lowland soil, when the frequency of rainfall increased and after heavy rainfall occurred (above 80 mm day$^{-1}$) in the Andosol. These increases in concentration were greater than those that took place in June after fertilizer applications (Figs. 1 and 2). The seasonal pattern of the N$_2$O concentration in the soil was similar to the N$_2$O flux from the soil to the atmosphere.

The mean values of the N$_2$O concentration in the soil at depths of 0.05, 0.1, 0.2, 0.3, 0.4,
0.5, and 0.6 m were 2.2, 5.8, 15, 22, 54, 62, and 59 ppmv in the Gray Lowland soil and
8.4, 18, 7.7, 7.2, 11, 16, and 10 ppmv in the Andosol, respectively. The maximum
concentrations of N₂O at these depths were 21, 37, 83, 140, 240, 430, and 370 ppmv in
the Gray Lowland soil, and 93, 250, 55, 18, 59, 110, and 35 ppmv in the Andosol,
respectively. In the Gray Lowland soil, the N₂O concentrations above 0.4 m increased
with an increase in soil depth, however, there was no increase in concentration below a
0.4 m depth (Fig. 7). Furthermore, the N₂O concentration gradients of the soil profile
increased from August to October (Figs. 1 and 7). In the Andosol, there were no N₂O
concentration gradients in the topsoil in June when the N₂O flux did not increase.
However, the N₂O concentration at a depth of 0.1 m significantly increased (above 40
ppmv), and this concentration was higher than that at a depth of 0.2 m when the N₂O
(Figs. 2 and 8).

The mean value of N₂O fluxes in the soil through a depth of 0.3 m in the Gray
Lowland soil was 0.026 mg N m⁻² h⁻¹ and it was about ten times higher than that in the
Andosol (0.002 mg N m⁻² h⁻¹). The N₂O fluxes in the soil through a depth of 0.3 m
were much lower than those from the soil to the atmosphere (Figs. 1 and 2). There was a
significant positive correlation between the N₂O flux at a depth of 0.3 m and the N₂O
flux from the soil to the atmosphere in the Gray Lowland soil ($r = 0.54$, $p < 0.01$, $n = 90$).

However, there was no significant correlation in the Andosol.

The cumulative $\text{N}_2\text{O}$ flux in the soil through a depth of 0.3 m during the study period ranged from 56 to 160 mg N m$^{-2}$ (mean value: 87 mg N m$^{-2}$) in the Gray Lowland soil and from 1.3 to 7.8 mg N m$^{-2}$ (mean value: 5.1 mg N m$^{-2}$) in the Andosol (Table 2). The cumulative $\text{N}_2\text{O}$ flux of the Gray Lowland soil was significantly higher than that of the Andosol in 1998 to 2000 (t-test: $|t| = 3.21$, $p < 0.05$, $n = 3$). In both the soils, the cumulative $\text{N}_2\text{O}$ fluxes in the soil through a depth of 0.3 m were lower than those from the soil to the atmosphere. The $\text{N}_2\text{O}$ produced in the soil above a depth of 0.3 m during the study period were 240–1030 mg N m$^{-2}$ (mean value: 590 mg N m$^{-2}$) in the Gray Lowland soil and 640–1980 mg N m$^{-2}$ (mean value: 1350 mg N m$^{-2}$) in the Andosol (Table 2). The contribution ratios of the $\text{N}_2\text{O}$ produced in the topsoil (above the depth of 0.3 m) to the emitted $\text{N}_2\text{O}$ from the soil to the atmosphere were 0.77–0.91 in the Gray Lowland soil and 0.99–1.01 in the Andosol (Table 2). These contribution ratios of the Gray Lowland soil were significantly higher than those of the Andosol from 1998 to 2000 (t-test: $|t| = 6.40$, $p < 0.01$, $n = 3$). In other words, the proportion of the $\text{N}_2\text{O}$ produced in the subsoil (below a depth of 0.3 m) to the $\text{N}_2\text{O}$ emitted from the soil to the atmosphere was 9–23 % in the Gray Lowland soil and 0–1 % in the Andosol.
Concentration and flux of CO₂ in the soil profile

The cumulative CO₂ fluxes from the soil to the atmosphere in the Gray Lowland soil and the Andosol during the study period were 360–430 g C m⁻² and 340–540 g C m⁻², respectively (Table 3). There was no significant difference in the CO₂ emission from the soil into the atmosphere between the Gray Lowland soil and the Andosol (t-test: |t|=0.20, p=0.85, n=3). In both the soils, the CO₂ flux increased in July and August with an increase in soil temperature (Figs. 3 and 4).

The mean values of the CO₂ concentration in the soil at depths of 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 m were 2.1, 3.5, 7.6, 12, 20, 21, and 21×10³ ppmv in the Gray Lowland soil and 3.5, 6.4, 10, 13, 17, 22, and 21×10³ ppmv in the Andosol, respectively. In both the soils, CO₂ concentrations at a depth of 0.05 m were always higher than that of the ambient air (0.36×10³ ppmv). The CO₂ concentration gradient in the soil profile also increased from July to September with an increase in soil temperature. The seasonal pattern of CO₂ concentration in the soil was similar to that of the CO₂ flux from the soil surface (Figs. 3 and 4). The CO₂ concentration in the soil above a depth of 0.4 m increased with an increase in depth; however, the concentration below a depth of 0.4 m did not increase (Figs. 7 and 8).

The mean value of CO₂ fluxes in the soil through a depth of 0.3 m was 5.5 mg C m⁻².
h$^{-1}$ in the Gray Lowland soil and 2.6 mg C m$^{-2}$ h$^{-1}$ in the Andosol. The CO$_2$ fluxes in the soil through a depth of 0.3 m were much lower than those from the soil to the atmosphere (Figs. 3 and 4). There was no significant correlation between the CO$_2$ flux in the soil through a depth of 0.3 m and CO$_2$ flux from the soil to the atmosphere in both the soils.

The range of the cumulative CO$_2$ flux in the soil through a depth of 0.3 m during the study period through a depth of 0.3 m was 16–44 g C m$^{-2}$ (mean value 27 g C m$^{-2}$) in the Gray Lowland soil and 3.7–7.1 g C m$^{-2}$ (mean value 5.2 g C m$^{-2}$) in the Andosol, and this cumulative CO$_2$ flux of the Gray Lowland soil was higher than that of the Andosol from 1998 to 2000 (t-test: $|t|=2.51$, $p=0.07$, $n=3$) (Table 3). In both soils, the cumulative CO$_2$ fluxes in the soil through a depth of 0.3 m were lower than those from the soil to the atmosphere. The CO$_2$ produced in the soil above a depth of 0.3 m during the study period was 330–410 g C m$^{-2}$ (mean value 370 g C m$^{-2}$) in the Gray Lowland soil and 320–530 g C m$^{-2}$ (mean value 410 g C m$^{-2}$) in the Andosol. The contribution ratios of the CO$_2$ produced in the topsoil (above the depth of 0.3 m) to the CO$_2$ emitted from the soil into the atmosphere were 0.89–0.96 in the Gray Lowland soil and 0.99 in the Andosol (Table 3). These contribution ratios of the Andosol were significantly higher than that of the Gray Lowland soil from 1998 to 2000 (t-test: $|t|=2.88$, $p=0.04$, ...
In other words, the proportions of the CO₂ produced in the subsoil (below the depth of 0.3 m) to the CO₂ emitted from soil to the atmosphere were 4–11% in the Gray Lowland soil and 1% in the Andosol.

**DISCUSSION**

**The N₂O concentration in the soil profile**

In both Gray Lowland and Andosol soils, the seasonal pattern of the N₂O flux from the soil surface was similar to that of the N₂O concentration in the soil from depths of 0.05 to 0.6 m (Figs. 1 and 2). In the Gray Lowland soil, the N₂O concentration gradient from the surface soil to a depth of 0.6 m increased when the N₂O flux significantly increased (Figs. 1 and 7). On the other hand, the N₂O concentration gradient of the surface soil increased when the N₂O flux significantly increased in the Andosol (Figs. 2 and 8). Therefore, it suggests that the N₂O produced in the soil profile was emitted into the atmosphere. In several studies, a similar N₂O flux from the soil into the atmosphere and a concentration gradient in the soil profile was reported after fertilizer application and irrigation (Mosier & Hutchinson 1981, Goodroad & Keeney 1985, Lessard et al. 1996, Li et al. 2002, Müller et al. 2004, Clough et al. 2006, van Groenigen et al. 2005, Hirose & Tsuruta 1996). In our previous paper, we reported that a significant amount of N₂O
emission from the Gray Lowland soil and the Andosol occurring during the increasing
frequency of rainfall and after heavy rainfall was derived from the denitrification
process (Kusa et al. 2002, Kusa et al. 2006). In some reports, it was suggested that the
effect of soil moisture to the N$_2$O production by the denitrification process was greater
than that of the NO$_3^-$ concentration in the soil. This is because N$_2$O could be produced
by denitrification in the subsoil (below the depth of 0.2 m) with high soil moisture
levels and a low NO$_3^-$ concentration (Li et al. 2002, Müller et al. 2004, Van Groenigen
et al. 2005). In both the Gray Lowland soil and the Andosol, a significant increase in the
N$_2$O flux with an increase in soil moisture and after heavy rainfall, and with the
increasing N$_2$O concentrations in the top soil and the decreasing soil water suction
occurred at the same time (Figs. 1 and 2). These results suggest that denitrification is the
main process attributed to the production of N$_2$O in the soil.

The maximum N$_2$O concentrations around a depth of 0.1 m were reported to be
0.9–180 ppmv (Mosier & Hutchinson 1981, Goodroad & Keeney 1985, Arah et al. 1991,
Groenigen et al. 2005, Itahashi et al. 1998). In our study, the maximum N$_2$O
collection at a depth of 0.1 m in the Gray Lowland soil was 37 ppmv (this N$_2$O flux
was 1.5 mg N m$^{-2}$ h$^{-1}$) (Fig. 1), this value remained within the reported maximum N$_2$O
concentrations (Mosier & Hutchinson 1981, Goodroad & Keeney 1985, Arah et al. 1991, Lessard et al. 1996, Li et al. 2002, Jacinthe & Lal 2004, Müller et al. 2004, van Groenigen et al. 2005, Itahashi et al. 1998) and it was similar to the report from a corn field in Colorado (the N\textsubscript{2}O concentration at the depth of 0.1 m was about 40 ppmv and the N\textsubscript{2}O flux was about 2.3 mg N m\textsuperscript{-2} h\textsuperscript{-1}) (Mosier and Hutchinson 1981). On the other hand, the maximum N\textsubscript{2}O concentrations around a depth of 0.1 m were about 0.4–4.2 ppmv in the Japanese Andosols, when maximum N\textsubscript{2}O fluxes (0.04–0.2 mg N m\textsuperscript{-2} h\textsuperscript{-1}) were measured just after fertilizer application (Tsuruta 1997, Yoh et al. 1997, Li et al. 2002, Hirose & Tsuruta 1996). The N\textsubscript{2}O concentrations in Japanese Andosols were lower than those in other soils (Mosier & Hutchinson 1981, Goodroad & Keeney 1985, Arah et al. 1991, Lessard et al. 1996, Jacinthe & Lal 2004, Müller et al. 2004, van Groenigen et al. 2005), and this result is consistent with the values reported by Akiyama and Tsuruta (2003), who concluded that N\textsubscript{2}O emissions from Japanese Andosols were lower than those from other soils in Japan and the world. The reason for low N\textsubscript{2}O concentrations in Japanese Andosols was pointed out to be the high gas diffusivity due to high porosity and low N\textsubscript{2}O production by denitrification (Li et al. 2002). However, the Andosol of our study site showed that the maximum N\textsubscript{2}O concentration at a depth of 0.1 m was 250 ppmv and this concentration was higher than the other reported values,
especially from Japanese Andosols (Figs. 1 and 2). Therefore, a lot of N₂O could have possibly been emitted from the Japanese Andosols which had high groundwater levels and a high soil moisture level after heavy rainfall (as in our study site). This is because the N₂O concentration in the soil surface might have increased due to denitrification after heavy rain on these soils.

The N₂O concentration profiles in the soils were different between the Gray Lowland soil and the Andosol (Figs. 7 and 8). N₂O concentration profiles of some studies (Mosier & Hutchinson 1981, Arah et al. 1991, Burton & Beauchamp 1994, Yoh et al. 1997, Li et al. 2002, Müller et al. 2004, Jacinthe & Lal 2004, van Groenigen et al. 2005) were similar to the profile in the Gray Lowland soil of our study site, where the concentration in the soil increased in the deeper layer. In Japanese Andosols, it was reported that N₂O concentrations in the soil surface (depth of 0.1 to 0.2 m) were higher than that in the deeper layers (Hirose & Tsuruta 1996, Itahashi et al. 1998, Tsuruta 1997).

Although this result is consistent with our study, the N₂O concentration profile in the soil varied according to the seasons and was different among the Japanese Andosols (Yoh et al. 1997, Verchot et al. 1999, Li et al. 2002). In this way, there are no consistent results about the N₂O concentration profiles in the soil.
The CO₂ concentration in the soil profile

In both soil types, the CO₂ concentration in the soil increased from spring to summer and decreased in autumn. The seasonal pattern of this concentration was similar to that of the CO₂ flux from the soil to the atmosphere (Figs. 3 and 4). The CO₂ concentrations at a depth of 0.05 m were always higher than that of the ambient air. Similar types of results have been frequently reported (de Jong & Schappert 1971, Hendry et al. 1999, Jacinthe & Lal 2004, Osozawa 1998). Also, it is reported that the peak of the CO₂ concentration in the soil profile gradually dropped from a depth of 0.2–0.4 m with growing plants and the CO₂ concentration increased with the depth at both fallow and cultivated soils after the autumn season (de Jong & Schappert 1971, Hendry et al. 1999, Jacinthe & Lal 2004, Osozawa 1998). Similar results were confirmed in our study sites (Figs. 3, 4, 7, 8).

N₂O and CO₂ concentrations and fluxes after rainfall

The CO₂ concentration in the soil was greatly influenced by rain. This is because, at first, the CO₂ concentration in the surface soil increased just after rainfall when the soil porosities were filled by rainwater. Thus, the CO₂ concentration in the surface soil could have been vertically diffused after drainage and evaporation from the soil surface,
resulting in a decrease in CO₂ concentrations around the soil surface (Osozawa 1998).

In the Andosol, the CO₂ concentration at a 0.1 m depth increased after heavy rainfall (the precipitation during a week before the day of investigation exceeded 80 mm in July 1999, July 2000, and September 2000), but the CO₂ fluxes decreased (Figs. 3, 4). This could possibly be due to the fact that the gas diffusion from the soil into the atmosphere could have been restricted by rainfall, as reported by Osozawa (1998). This is because the D/D₀ of the surface soil at this time was below 0.02 (Figs 3, 4, and 5), which might have restricted gas diffusion from the soil into the atmosphere (Hatano 1997). However, the N₂O concentrations in the surface soil and N₂O flux from the soil surface increased at the same time (Figs. 1, 2). Therefore, it suggests that anaerobic conditions with increasing soil moisture levels and the restriction of gas diffusion could have accelerated the production of N₂O by denitrification, in the surface soil.

The effect of soil structure to production and emission of N₂O

N₂O production in the lower soil profile was reported in several studies when NO₃⁻ leached from the surface layer after rain (Goodroad & Keeney 1985, Müller et al. 2004, van Groenigen et al. 2005). It suggests that a N₂O production spot in the soil could be greatly influenced by water movement and the NO₃⁻ concentration in the soil. In the
Gray Lowland soil of our study, the NO$_3^-$ in the surface soil leached through macropores after rain (Hayashi & Hatano 1999), and the total N concentration of the groundwater rapidly increased after applications of slurry in the grassland (Kanazawa et al. 1999) adjoining the Andosol site of our study. Therefore, it seemed that the NO$_3^-$ in the surface soil leached with rain water in both soils. In the Gray Lowland soil of our study site, the NO$_3^-$ concentrations of the soil solution at a depth of 0.7 m were always below 3 mg N L$^{-1}$, while the concentrations of the pipe drain were always around 10 mg N L$^{-1}$ (Hayashi & Hatano 1999), therefore the subsoil around the macropores could have been in contact with high concentrations of NO$_3^-$. On another front, it was reported that the NO$_3^-$ concentrations in the soil solution at a depth of 0.8 m and those in the seepage water were at the comparable level in the other Andosol in Hokkaido, Japan (Suzuki & Shiga 2004). Hasegawa and Eguchi (2002) reported the rainwater moved mainly by a matrix flow in an Andosol without cracks and fissures in Tsukuba, Japan. Therefore, the NO$_3^-$ concentration in the surface soil could have been higher than in the subsoil, because water and NO$_3^-$ infiltrated from the surface soil to the subsoil by matrix flow. This suggests that the activity of N$_2$O production in the subsoil of the Gray Lowland soil was higher than that in the Andosol. It corresponded with the difference in N$_2$O concentration profiles in the soil (Figs 1 and 2) and with the contributing ratio of N$_2$O.
production in the top soil between both soils (Table 2).

An important factor regarding N$_2$O emission from the soil into the atmosphere is that it was not only the activity of N$_2$O production in the soil, but also the gas diffusivity.

Under the usual upland soil moisture conditions, the gas diffusivity of an Andosol with high porosity is higher than in a Gray Lowland soils, however the gas movement through macropores and cracks were not active in an Andosols (Osozawa 1998). On the one hand, the gas movement through macropores and cracks is dominant in a Gray Lowland soil (Osozawa 1998). Although the gas diffusivity estimated by the value of D/D$_0$ in the surface soil (0–0.1m) disturbed by the plowing of the Andosol was higher than that of the Gray Lowland soil (Fig. 6), there were no differences in the value of D/D$_0$ at a depth of more than 0.3 m between the Andosol and the Gray Lowland soil. However, the value of D/D$_0$, which measured by 100 mL core, could not take into account the gas flowing through macropores and cracks. It suggests that the gas flowing in the subsoil of the Gray Lowland soil with macropores and cracks was higher than the value of D/D$_0$. It is considered that the gas diffusivity around macropores and cracks in the subsoil of the Gray Lowland soil might be higher than in the Andosol. Therefore, mobility of N$_2$O in the subsoil around the macropores and cracks of the Gray Lowland soil might be higher than that in the Andosol. Additionally, the N$_2$O produced in the
subsoil of the Andosol without macropores and cracks might have been reduced to N$_2$ before it was emitted to the atmosphere. These results indicate that the difference in water mobility, NO$_3^-$, O$_2$, and N$_2$O in the soils, especially the subsoil, between the Gray Lowland and the Andosol might be the reason for variation in the seasonal pattern of N$_2$O fluxes, the N$_2$O concentration profile in the soil, and the ratio of contribution of the subsoil to N$_2$O production in the soil between both soils (Figs. 7–9, Table 2).

The CO$_2$ emitted from the soil into the atmosphere is produced by the respiration of plant roots and soil microbes (Smith et al. 2003). In spite of the differences in soil type, CO$_2$ could be produced in the top soil, because plant roots and soil microbes were distributed in the top soil (Nakamoto 1993, Osozawa 1998). More than 90% of the CO$_2$ emitted from the soil to the atmosphere was produced in the top soil in both the soil types (Table 3). Unlike N$_2$O, there was no significant correlation between the CO$_2$ flux through a 0.3 m depth and that from the soil into the atmosphere in both soils. In this way, our results corresponded to the previous reports (Nakamoto 1993, Osozawa 1998, Smith et al. 2003).

**Conclusions**

In the Gray Lowland soil and the Andosol, N$_2$O and CO$_2$ were mainly produced in the
top soil (0–0.3m depth). The seasonal patterns of the CO\textsubscript{2} concentration profile were similar in both the soil types. However, the N\textsubscript{2}O concentration profile in the soil was different between the two soils. Additionally, the ratio of contribution of the subsoil to the N\textsubscript{2}O production in the soil of the Gray Lowland soil was higher than that of the Andosol, because the N\textsubscript{2}O production in the subsoil around macropores and cracks of the Gray Lowland soil might have been activated by the leaching of NO\textsubscript{3}\textsuperscript{-} through macropores and cracks. Subsequently the N\textsubscript{2}O produced in the subsoil could have been rapidly emitted from the soil into the atmosphere through macropores and cracks. This suggests that the variations in the N\textsubscript{2}O concentration profile between the two soils are caused by the differences in soil structure. This is especially because of the presence of macropores and cracks in the soil structure, which influenced the production and movement of N\textsubscript{2}O in the soil.

ACKNOWLEDGMENTS

We thank Dr. Ohashi, Dr. Yoshida, Dr. Hayakawa, Dr. Kanazawa, and Dr. Tsuruta for their contribution in operating the gas chromatograph and for their valuable suggestions. This study was partly supported by the Japanese Grant-in Aids for Science Research from the Ministry of Education (08456038) and by a Global Environment Research
Fund from the Environment Agency (Ministry) of Japan B–51 (6)
REFERENCES


FAO, IFA 2001: *Global estimates of gaseous emissions of NH\textsubscript{3}, NO and N\textsubscript{2}O from...*
agricultural land., Food and Agriculture Organization and International Fertilizer industry Association, Rome.


1 Hendry MJ, Mendoza CA, Kirkland RA, Lawrence JR 1999: Quantification of transient
2 CO₂ production in a sandy unsaturated zone. *Water resources research*, 35, 2189-2198.
3 Hirose T, Tsuruta H 1996: Measurement of NO and N₂O fluxes from the soils with the
5
6 Hosen Y, Tsuruta H, Minami K 2000: Effects of the depth of NO and N₂O production in
7 soil on their emission rates to the atmosphere: analysis by a simulation model. *Nutr.
8 Cycling Agroecosyst.*, 57, 83-98.
9
12
14 from nitrogen fertilized soil (3) -Vertical distributions of gas concentrations in soils
16 Environ. Planning NIAES*, 14, 47-76.
17
18 Jacinthe PA, Lal R 2004: Effects of soil cover and land-use on the relations
20
21 Jambert C, Serca D, Delmas R 1997: Quantification of N-losses as NH₃, NO, N₂O and
22 N₂ from fertilized maize fields in southwestern France. *Nutr. Cycling Agroecosyst.* , 48,
For review

1  91-104.


8  Lessard R, Rochette P, Gregorich EG, Pattey E, Desjardins RL 1996: Nitrous oxide


1. *Intergovernmental Panel on Climate Change,* pp. 241-287. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.


KB 2005: Subsoil $^{15}$N-N$_2$O concentrations in a sandy soil profile after application of


Captions

**Table 1** Soil texture, structure, and saturated hydraulic conductivity of the study site

**Table 2** Cumulative flux, production, and mass balance of N$_2$O during the study period

**Table 3** Cumulative flux, production, and mass balance of CO$_2$ during the study period

**Table 4** The regression curves of the soil water suction (pF)–D/D$_0$ used to the calculation of the gas fluxes in the soil profile.

**Figure 1** The seasonal patterns of (a) rainfall and N$_2$O fluxes from the soil surface and through a 0.3 m depth in the soil profile, (b, c) N$_2$O concentration in soil air (at 0.05, 0.1, 0.3, and 0.5 m depths), (d) soil water suction (at 0.2, 0.3, and 0.6 m depths) in the Gray Lowland soil from 1995 to 2000. Chemical fertilizer was applied at the end of
April. The surface fluxes were reported by Kusa et al. 2002.

Figure 2 The seasonal pattern of (a) rainfall and N₂O fluxes from the soil surface and through a 0.3 m depth in the soil profile, (b, c) N₂O concentration in soil air (at 0.05, 0.1, 0.3 and 0.5 m depths), (d) soil water suction (at 0.2, 0.3 and 0.6 m depths) in the Andosol from 1998 to 2000. Chemical fertilizer was applied in mid-May. The surface fluxes were reported by Kusa et al. 2006.

Figure 3 The seasonal pattern of (a) rainfall and WFPS of the soil surface, (b) CO₂ fluxes from the soil surface and through a 0.3 m depth in the soil profile, (c) CO₂ concentrations of soil air (0.1, 0.3 and 0.5 m depths), (d) soil temperature at a 0.1 m depth from the Gray Lowland soil from 1998 to 2000. WFPS (0-0.05 m) and the soil temperature were reported by Kusa et al. 2002.

Figure 4 The seasonal pattern of (a) rainfall and WFPS in the soil surface, (b) CO₂ fluxes from the soil surface and through a 0.3 m depth in the soil profile, (c) CO₂ concentrations in soil air (at 0.1, 0.3 and 0.5 m depths), (d) soil temperature at a 0.01 m depth from the Andosol from 1998 to 2000. WFPS (0-0.05m), the surface fluxes and the soil temperature were reported by Kusa et al. 2006.

Figure 5 The relationships between the relative gas coefficient (D/D₀) and soil moisture (WFPS) from 1998 to 2000. WFPS (0-0.05m) was reported by Kusa et al.
2002 and 2006.

Figure 6 Seasonal patterns of the relative gas coefficient (D/D₀) for the Gray Lowland soil and the Andosol in 1998.

Figure 7 Monthly average concentrations of N₂O and CO₂ in the soil profile from the Gray Lowland soil from 1995 to 2000 (N₂O) and from 1998 to 2000 (CO₂).

Figure 8 Monthly average concentrations of N₂O and CO₂ in the soil profile from the Andosol from 1998 to 2000.
Table 1 Soil texture, structure, and saturated hydraulic conductivity of the study site

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (m)</th>
<th>Texture</th>
<th>Grade</th>
<th>Size</th>
<th>Type</th>
<th>Saturated hydraulic conductivity (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Humic Gray Lowland soil</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap</td>
<td>0-0.28</td>
<td>SiC</td>
<td>Strong</td>
<td>Medium</td>
<td>Subangular blockly</td>
<td>1.0*10⁻⁷</td>
</tr>
<tr>
<td>B</td>
<td>0.28-0.48</td>
<td>SiC</td>
<td>Strong</td>
<td>Medium</td>
<td>Subangular blockly</td>
<td>1.8*10⁻⁶</td>
</tr>
<tr>
<td>C1</td>
<td>0.48-0.68</td>
<td>HC</td>
<td>Strong</td>
<td>Coarse</td>
<td>Prismlike</td>
<td>4.6*10⁻⁶</td>
</tr>
<tr>
<td>C2</td>
<td>0.68-1.0+</td>
<td>SiC</td>
<td>-</td>
<td>-</td>
<td>Massive</td>
<td>2.2*10⁻⁴</td>
</tr>
<tr>
<td><strong>Andosol</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap</td>
<td>0-0.3</td>
<td>CL</td>
<td>-</td>
<td>-</td>
<td>Granular</td>
<td>3.3*10⁻⁶</td>
</tr>
<tr>
<td>AB</td>
<td>0.3-0.37</td>
<td>LiC</td>
<td>Moderate</td>
<td>Medium</td>
<td>Subangular blockly</td>
<td>2.2*10⁻⁵</td>
</tr>
<tr>
<td>B</td>
<td>0.37-0.47</td>
<td>LiC</td>
<td>Moderate</td>
<td>Medium</td>
<td>Subangular blockly</td>
<td>2.3*10⁻⁵</td>
</tr>
<tr>
<td>BC1</td>
<td>0.47-0.75</td>
<td>CL</td>
<td>Weak</td>
<td>Coarse</td>
<td>Subangular blockly</td>
<td>4.3*10⁻⁵</td>
</tr>
<tr>
<td>BC2</td>
<td>0.75-0.9</td>
<td>LiC</td>
<td>Weak</td>
<td>Coarse</td>
<td>Subangular blockly</td>
<td>ND</td>
</tr>
<tr>
<td>C</td>
<td>0.9-1.0+</td>
<td>SL</td>
<td>-</td>
<td>-</td>
<td>Massive</td>
<td>ND</td>
</tr>
</tbody>
</table>
# Table 2 Cumulative flux, production, and mass balance of N₂O during the study period

<table>
<thead>
<tr>
<th>Year</th>
<th>Period</th>
<th>Cumulative N₂O flux during study period</th>
<th>Mass of N₂O in the topsoil (above 0.3m)</th>
<th>N₂O production by topsoil</th>
<th>Contribution ratio of topsoil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Surface flux (F₀)</td>
<td>Through 0.3 m (F₀.3)</td>
<td>Beginning (Ms)</td>
<td>End (Me)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(mg N m⁻²)</td>
<td>(mg N m⁻²)</td>
<td>(mg N m⁻²)</td>
<td>(mg N m⁻²)</td>
</tr>
<tr>
<td>Gray Lowland soil</td>
<td>1995</td>
<td>6/13-10/28 760±140</td>
<td>86±6</td>
<td>0.35</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1996 7/2-10/31 310±33</td>
<td>71±4</td>
<td>0.26</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1997 6/13-10/23 450±200</td>
<td>56±5</td>
<td>0.32</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1998 6/23-10/27 430±76</td>
<td>65±4</td>
<td>0.20</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1999 5/26-10/20 930±250</td>
<td>80±7</td>
<td>0.69</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2000 5/30-10/24 1190±450</td>
<td>160±10</td>
<td>0.21</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>680±96</td>
<td>87±3</td>
<td>0.34</td>
<td>0.72</td>
</tr>
<tr>
<td>Andosol</td>
<td>1998</td>
<td>6/15-9/29 630±88</td>
<td>1.3±0.1</td>
<td>0.23</td>
<td>8.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1999 6/6-9/13 1980±230</td>
<td>6.2±0.6</td>
<td>0.12</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2000 7/17-9/18 1430±140</td>
<td>7.8±1.1</td>
<td>0.20</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>1350±94</td>
<td>5.1±0.4</td>
<td>0.18</td>
<td>3.00</td>
</tr>
</tbody>
</table>

F₀ was measured by chamber method and F₀.3 was measured by gradient method.

±, standard deviation
### Table 3  Cumulative flux, production, and mass balance of CO2 during the study period

<table>
<thead>
<tr>
<th>Year</th>
<th>Period</th>
<th>Cumulative CO2 flux during the study period</th>
<th>Mass of CO2 in the topsoil (above 0.3 m)</th>
<th>CO2 production by topsoil</th>
<th>Contribution ratio of topsoil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Surface (F₀)</td>
<td>Through 0.3 m (F₀.₃)</td>
<td>Beginning (Ms)</td>
<td>End (Me) (P)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(g C m⁻²)</td>
<td>(g C m⁻²)</td>
<td>(g C m⁻²)</td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>6/23-10/27</td>
<td>360±29</td>
<td>22±1</td>
<td>0.32</td>
<td>0.23</td>
</tr>
<tr>
<td>1999</td>
<td>5/26-10/20</td>
<td>410±26</td>
<td>44±2</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>2000</td>
<td>5/30-10/24</td>
<td>430±27</td>
<td>16±1</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>6/15-9/29</td>
<td>380±9</td>
<td>4.8±0.1</td>
<td>0.34</td>
<td>0.70</td>
</tr>
<tr>
<td>1999</td>
<td>6/6-9/13</td>
<td>540±9</td>
<td>7.1±0.3</td>
<td>0.25</td>
<td>1.31</td>
</tr>
<tr>
<td>2000</td>
<td>7/17-9/18</td>
<td>340±6</td>
<td>3.7±0.3</td>
<td>0.53</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Gray Lowland soil**

- F₀ was measured by chamber method and F₀.₃ was measured by gradient method.
- ±, standard deviation.

**Andosol**
Table 4 The regression curves of the soil water suction (pF)–D/D0 in the soil profile.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Regression curve</th>
<th>R²</th>
<th>Mean square of residual</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gray Lowland soil</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15–0.20</td>
<td>Y = 4.6×10⁻⁴x³−2.2×10⁻⁴x²+3.5×10⁻³x+6.0×10⁻⁵</td>
<td>0.973</td>
<td>5.0×10⁻⁸</td>
</tr>
<tr>
<td>0.23–0.28</td>
<td>Y = 1.0×10⁻³x³−3.7×10⁻³x²+4.9×10⁻²x−2.0×10⁻⁵</td>
<td>0.972</td>
<td>2.0×10⁻⁷</td>
</tr>
<tr>
<td>0.32–0.37</td>
<td>Y = 9.8×10⁻⁴x³−3.5×10⁻³x²+4.7×10⁻³x−2.0×10⁻⁵</td>
<td>0.999</td>
<td>7.8×10⁻⁸</td>
</tr>
<tr>
<td>0.43–0.48</td>
<td>Y = 1.1×10⁻³x³−3.8×10⁻³x²+5.3×10⁻²x−1.0×10⁻⁵</td>
<td>0.991</td>
<td>1.4×10⁻⁷</td>
</tr>
<tr>
<td>0.54–0.59</td>
<td>Y = 4.0×10⁻³x³−1.1×10⁻²x²+9.5×10⁻³x−1.7×10⁻⁴</td>
<td>0.994</td>
<td>4.3×10⁻⁷</td>
</tr>
<tr>
<td><strong>Andosol</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.13–0.18</td>
<td>Y = −8.0×10⁻³x³+2.2×10⁻³x²−3.4×10⁻²x+1.3×10⁻³</td>
<td>0.998</td>
<td>1.0×10⁻⁷</td>
</tr>
<tr>
<td>0.31–0.36</td>
<td>Y = −5.2×10⁻³x³+4.2×10⁻³x²−6.7×10⁻³x−1.2×10⁻³</td>
<td>0.993</td>
<td>1.3×10⁻⁶</td>
</tr>
<tr>
<td>0.40–0.45</td>
<td>Y = −9.6×10⁻³x³+5.8×10⁻³x²−1.6×10⁻²x−1.1×10⁻³</td>
<td>0.983</td>
<td>2.9×10⁻⁶</td>
</tr>
<tr>
<td>0.58–0.63</td>
<td>Y = −5.0×10⁻³x³+8.6×10⁻³x²+1.8×10⁻³x−1.2×10⁻³</td>
<td>0.993</td>
<td>3.5×10⁻⁷</td>
</tr>
</tbody>
</table>

Y denotes the value of D/D₀, x denote the soil water suction (pF), pF = \log(-10.2 \phi), \phi is the soil water suction (kPa)
Figure 1 The seasonal patterns of (a) rainfall and N₂O fluxes from the soil surface and through a 0.3 m depth in the soil profile, (b, c) N₂O concentration in soil air (at 0.05, 0.1, 0.3, and 0.5 m depths), (d) soil water suction (at 0.2, 0.3, and 0.6 m depths) in the Gray Lowland soil from 1995 to 2000. Chemical fertilizer was applied at the end of April. The surface fluxes were reported by Kusa et al. 2002.

281x185mm (150 x 150 DPI)
Figure 2 The seasonal pattern of (a) rainfall and N$_2$O fluxes from the soil surface and through a 0.3 m depth in the soil profile, (b, c) N$_2$O concentration in soil air (at 0.05, 0.1, 0.3 and 0.5 m depths), (d) soil water suction (at 0.2, 0.3 and 0.6 m depths) in the Andosol from 1998 to 2000. Chemical fertilizer was applied in mid-May. The surface fluxes were reported by Kusa et al. 2006.
Figure 3  The seasonal pattern of (a) rainfall and WFPS of the soil surface, (b) CO₂ fluxes from the soil surface and through a 0.3 m depth in the soil profile, (c) CO₂ concentrations of soil air (0.1, 0.3 and 0.5 m depths), (d) soil temperature at a 0.1 m depth from the Gray Lowland soil from 1998 to 2000. WFPS (0-0.05 m) and the soil temperature were reported by Kusa et al. 2002.
Figure 4  The seasonal pattern of (a) rainfall and WFPS in the soil surface, (b) CO$_2$ fluxes from the soil surface and through a 0.3 m depth in the soil profile, (c) CO$_2$ concentration in soil air (at 0.1, 0.3 and 0.5 m depths), (d) soil temperature at a 0.01 m depth from the Andosol from 1998 to 2000. WFPS (0-0.05m), the surface fluxes and the soil temperature were reported by Kusa et al. 2006.

161x187mm (150 x 150 DPI)
Figure 5. The relationships between the relative gas coefficient ($D/D_0$) and soil moisture (WFPS) from 1998 to 2000. WFPS (0-0.05m) was reported by Kusa et al. 2002 and 2006.
Figure 6 Seasonal patterns of the relative gas coefficient (D/D₀) for the Gray Lowland soil and the Andosol in 1998.
152x76mm (150 x 150 DPI)
Figure 7 Monthly average concentrations of N$_2$O and CO$_2$ in the soil profile from the Gray Lowland soil from 1995 to 2000 (N$_2$O) and from 1998 to 2000 (CO$_2$).

197x121mm (150 x 150 DPI)
Figure 8 Monthly average concentrations of N$_2$O and CO$_2$ in the soil profile from the Andosol from 1998 to 2000.
144x106mm (150 x 150 DPI)