Title of the paper

Comparison between closed-chamber and gas concentration gradient methods for measurement of CO_2 and N_2O fluxes in two upland field soils

Full names of the authors

Kanako Kusa[1], Takuji Sawamoto[2], Ronggui Hu[3], Ryusuke Hatano[4]

Addresses of the institutions at which work

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

Full postal and e-mail address, facsimile and telephone numbers etc.

Corresponding author: Kanako Kusa

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

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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 [4]Research Faculty of Agriculture, Hokkaido University, Sapporo, 060-8589 Japan

Abstract

We measured N_2O and CO_2 fluxes from Gray Lowland soil (onion field) and Andosol (maize filed) using the closed-chamber method and the concentration-gradient method based on Fick's law (gradient method). Measurements of gas concentration (at 0.05 m depth) and relative gas diffusion coefficients (D/D_0) (0-0.05 m depth) in the soil were carried out every week during the snow-free season (May-October) each year for 6 years in the Gray Lowland soil (1995-2000) and for 3 years in the Andosol (1998-2000). The seasonal pattern of N_2O and CO_2 fluxes by the chamber method was similar to those by the gradient method, and there were significant positive correlations between those fluxes using the chamber and gradient method when excluding the value of extremely high N_2O flux (Smirnov-Grubbs' outlier test, $P < 0.01$). There were no significant differences in N_2O fluxes between the two methods, but CO_2 flux by the chamber method was higher than that by the gradient method. Since the gradient method could not measure the production, consumption and gas diffusion in the surface soil above the soil-air sampling tube (upper 0.05 m), the difference in extremely high N_2O and CO_2 fluxes between two methods resulted when the production and consumption of these gases were active in the soil above the installed location of soil-air sampling tube. Measurements of gas concentration and D/D_0 in the soil were required every measurement during the investigation period, because those values had a large seasonal variation. The measurement of CO_2 flux was more influenced by plant than that of N_2O. Therefore, it is necessary to consider the distance between the instruments (chambers and soil-air sampling tubes) and the plant. Our results suggest that the gradient method could lead to under or over estimation of CO_2 flux and of extremely high N_2O flux. On the other hand, the gradient method could be applied for N_2O flux measurement without extremely high flux, and for understanding the seasonal pattern of CO_2 flux. The gradient method is considered to be useful as it can estimate gas fluxes both in the soil and from soil to atmosphere at the same time.

Key words: carbon dioxide (CO_2), closed-chamber method, Fick's law, gas flux, gradient method, nitrous oxide (N_2O)

Introduction

An increase in nitrous oxide (N_2O) and carbon dioxide (CO_2) concentrations in the troposphere causes global warming (Prather *et al*. 2001). To increase the certainty in prediction of these gas increases, improvement in a mass balance accounting for sources and sinks of these gases is crucial (Lapitan *et al*. 1999). So far, the dominant method of measuring trace gas fluxes from the soil has been a closed-chamber method. The advantages of this method are that small fluxes can be measured; chambers are cheap, simple to construct, install and remove; and no extra equipment requiring electric supply is needed (FAO and IFA 2001). This method is more suitable for detecting trace gas fluxes such as CH_4 and N_2O (Lapitan *et al*. 1999). However, this method proves defective when, for instance, the soil is disturbed by the repeated actions of placing the chamber, when the atmospheric pressure on the soil surface is altered due to setting up of closed-chambers, when high gas concentrations inside the chamber may restrict gas diffusion from the soil, or when the presence of plants can create practical differences in the setting up and operation of the chambers (Granli and Bøckman 1994, FAO and IFA 2001). Therefore, an improper setting up of chambers on the experimental site may result in detrimental effects on gas flux measurement. Recently, the chamber deployment period was discussed by Nakano *et al.* (2004). Gas fluxes from soils could be measured by the simultaneous and continuous measurement system based on the automated closed-chamber method (Akiyama *et al.* 2000, Nishimura *et al.* 2005 a, b).

To estimate the soil depth of gas production and movement in the soil profile, it is necessary to measure gas fluxes within the soil profile. However, the closed-chamber method only measures the gas flux across the soil surface. Some studies measured N_2O and CO_2 concentrations in the soil profile to be used for the estimation of the depth of gas production in the soil (Mosier and Hutchinson 1981, Goodroad and Keeney 1985, Arah *et al.* 1991, Granli and Bøckman 1994, Li *et al*. 2002, Hashimoto and Suzuki 2002, Jacinthe and Lal 2004). The measurement of gas flux within the soil profile is required for more accurately estimating the gas movement in the soil profile (Hosen *et al.* 2000). The gas production in the soil profile and emission from the soil surface might be assessed by a combination of measuring the gas fluxes from soil surface and within the soil profile at the same time. Granli and Bøckman (1994) introduced a method of measuring gas fluxes within the soil profile based on the gas concentration gradient in the soil profile calculated from Fick's law, called a 'gradient method'. This method also demonstrates many disadvantages, such as the uncertainty in the value of the soil-gas diffusivity and gas concentration gradient of the soil profile and a large spatial variation (Rolston 1978, Granli and Bøckman 1994, Billings *et al*. 1998, Hutchinson and Livingston 2002). The effectiveness of this method seems to depend on soil conditions (Arah *et al*. 1991, Billings *et al*. 1998). There are very few studies comparing the N_2O fluxes measured by both the chamber and the gradient methods for more than one year and those measurement methods for N_2O and CO_2 fluxes (Maljanen *et al.* 2003). The purpose of this study is to compare the closed chamber and the gradient methods for measuring the fluxes of N_2O produced by denitrification and nitrification and CO_2 produced by the root respiration and decomposition of the organic matter on the Gray Lowland soil (onion field) and the Andosol (maize field).

Materials and Methods

Experimental site

The experimental sites were set up at an onion (*Allium cepa* L.) field (2.0×10^4 m^2) in Mikasa City (43° 14' N, 141° 50' E) and a maize (*Zea mays* L.) field (1.8×10^4 m^2) at the National Agricultural Research Center for Hokkaido Region, in Sapporo City (43° 00' N, 141° 24' E) located in central Hokkaido, Japan. The soil type in the onion field is humic Gray Lowland soil (Japanese Society of Pedology 2003). Chemical fertilizer was applied to the field at the rate of about 30 g N m^{-2} at the end of April; onion seedlings were transplanted at the beginning of May and harvesting was carried out in early and mid-September (Kusa *et al.* 2002). In the maize field, the soil type is Silandic Andosol (Japanese Society of Pedology 2003). Composted cattle manure was applied to the field at a rate of 3.0 g N m^{-2} (fresh weight 3.0 kg m^{-2}) each year in mid-May. After furrowing, chemical fertilizer was applied to each row at a rate of 13 g N m^{-2}. The row width was 75 cm and the inter-row width was 25 cm. Maize was sown in mid-May and harvested at the end of September. Monitoring of gas fluxes in the maize field was carried out only on the rows (Kusa *et al.* 2006). In general, these fields were monitored every week during the snow–free season (May–October) each year for 6 years in the Gray Lowland soil (1995–2000) and for 3 years in the Andosol (1998–2000).

Measurement of N_2O and CO_2 fluxes using the closed chamber method

Gas fluxes from the soil surface were measured using a closed-chamber technique. 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. The chamber positions are shown in Figure 1. During the measurement, the chamber was placed over the onion plants from 1995 to 1997 in the Gray Lowland soil, but the chamber was not placed over the plants from 1998 to 2000 in either soil. Fifteen minutes after placement of the chamber, the gas sample was taken from the enclosed atmosphere. Ambient air was collected at the soil surface and 2 m above the soil surface, and the mean of the two values was used as the background concentration in the calculation of gas emissions. The N_2O concentrations in the gas samples were measured using a gas chromatograph equipped with an electron capture detector (GC-14B; Shimadzu Corp., Kyoto, Japan). The CO_2 concentrations were analyzed using a portable infrared gas analyzer (ZFP-5; Fuji Electric Co., Ltd., Tokyo, Japan). The gas sampling method and the calculation of gas fluxes were described in detail in our previous papers (Kusa *et al.* 2002 and 2006). A positive value of the flux indicates gas emission, while a negative value indicates gas uptake. The mean gas fluxes of four replicates in the Gray Lowland soil and of two replicates in the Andosol were calculated. The cumulative gas fluxes for each year during the study period were calculated through linear interpolation.

Measurement of N_2O and CO_2 concentrations in the soil

After the polyvinyl chloride pipes (soil-air sampling tube: inside diameter was 0.013 m, 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 placement of the soil-air sampling tubes is shown in Figure 1. Twenty soil sampling tubes were installed at 0.05 m depth. A 0.01 L gas sample of the enclosed atmosphere in each soil-air sampling tube was taken out using a 0.01 L syringe, and all gas samples from the same depth were transferred into a 1 L Tedlar®Bag. The ambient air above the soil surface was also sampled to obtain the concentration at 0 m depth. The N_2O and CO_2 concentrations in the gas samples were measured using the same method as that for the chamber method.

Measurement of soil physical factors

Soil temperature was measured at a depth of 0.05 m with a digital thermometer. Intact soil samples (0–0.05 m depth) were collected using three 100 ml steel cylinders and these relative gas diffusion coefficients (D/D_0) were measured every time using the method proposed by Osozawa (1998).

Measurement of N_2O and CO_2 fluxes using the gradient method

The surface N_2O and CO_2 fluxes were calculated using the following equation based on Fick's law (gradient method; Granli and Bøckman 1994):

$$F_D = -D\frac{dC}{dz} = -\left(\frac{D}{D_0}\right) \times D_0 \times \left(\rho \times \frac{C_{0.05}\text{-}C_0}{0.05} \times \frac{273}{273+T}\right)$$

where F_D is the surface gas flux (mg m^{-2} s^{-1}) , D is the gas diffusion coefficient (m^2 s^{-1}), [dC/dz] is the gas concentration gradient (mg m^{-3} m^{-1}), D/D_0 is the relative gas diffusion coefficient from 0 to 0.05 m depth, D_0 is the N_2O or CO_2-air inter diffusion coefficient (m^2 s^{-1}), ρ is the gas density ($\rho CO_2 = \rho N_2O = 1.98 \times 10^6$ (mg m^{-3})), C_0 and $C_{0.05}$ are the gas concentrations at 0 and 0.05 m depth (m^3 m^{-3}), respectively, and T is the soil temperature at 0.05 m depth (°C). Values of D_0 under air pressure P (atm) and soil temperature T (°C) were calculated using the following equation:

$$D_S = D_0 \times \left(\frac{273}{273+T}\right)^{1.79} \times \left(\frac{P}{1}\right)$$

where D_S is the N_2O or CO_2-air inter diffusion coefficient under the standard condition (273 K, 1 atm) (m^2 s^{-1}). D_S (N_2O) and D_S (CO_2) (m^2 s^{-1}) represent 0.143×10^{-4} and 0.139×10^{-4}, respectively (Pritchard and Currie 1982). The air pressure was presumed to be 1 atm. The positive value of the F_D indicates gas emission while the negative value indicates gas uptake. The gas emission during the study period was calculated through a linear interpolation.

Results

The coefficient of variation (CV) values of D/D_0 at 0-0.05 m depth was around 50% and D/D_0 had a large seasonal variation (Table 1). Similarly, N_2O and CO_2 concentrations at 0.05 m and these fluxes by both methods had large CV values (Table 1, Figs. 2 and 3). Especially, CV values of N_2O were larger than those of CO_2.

In both soils, the seasonal patterns of surface N_2O fluxes by the chamber method were similar to those by the gradient method (Figs. 2 and 3). These fluxes significantly increased around the harvesting season. Except for extremely high N_2O fluxes (outlier; greater than 0.63 mg N m^{-2} h^{-1}, Smirnov-Grubbs' outlier test, $P < 0.01$), a positive significant correlation was found between N_2O fluxes by both the chamber and gradient methods (Fig. 5). There was no uniform relationship between extremely high N_2O fluxes by the two methods (Fig. 5). The difference in N_2O fluxes between the chamber method and the gradient method was not significant (paired t-test: $|t| = 0.15$, $P = 0.88$, $n = 120$). The above-ground onion parts were included in the chamber from 1995 to 1997 in the Gray Lowland soil and the chamber was installed closer to the crops compared to the soil-air sampling tube in both soils (Fig. 1). These conditions did not make any impact on N_2O fluxes using the chamber and the gradient methods (Figs. 2 and 3). However, in the Gray Lowland soil, the N_2O fluxes by the gradient method tended to be higher than those by the chamber method in 1996 and lower in 2000 (Fig. 2).

In both soils, seasonal patterns of the surface CO_2 fluxes by the chamber method were similar to those by the gradient method (Figs. 3 and 4). Significant positive correlations were found between both chamber and gradient methods for both N_2O ($P < 0.01$, r = 0.54, n = 104) and CO_2 ($P < 0.01$, r = 0.52, n = 43 (1995−1997), $P < 0.01$, r = 0.49, n = 77 (1998−2000) fluxes (Fig. 5). The CO_2 fluxes by the chamber method were significantly higher than those by the gradient method (paired t-test: $|t| = 4.2$, $P < 0.01$, $n = 43$ for the Gray Lowland soil from 1995 to 1997, $|t| = 5.4$, $P < 0.01$, $n = 78$ from 1998 to 2000). In the Gray Lowland soil, the above-ground onion parts were included in the chamber from 1995 to 1997, therefore the CO_2 fluxes using the chamber method from 1995 to 1997 were markedly higher than those from 1998 to 2000 (Fig. 4). Since the chamber was installed closer to the crops than the soil-air sampling tube in both soils (Fig. 1), the chamber method resulted in detection of more root respiration than the gradient method. This result indicated that onion and maize respiration might increase the CO_2

fluxes that were obtained using the chamber method.

The ranges of N_2O emission from the Gray Lowland soil during the study period were 310 – 1190 mg N m^{-2} and 353 – 835 mg N m^{-2} and those in the Andosol were 634 – 1980 mg N m^{-2} and 683 – 2570 mg N m^{-2} using the chamber and gradient methods, respectively (Table 2). The difference in N_2O emissions between the chamber and gradient methods during the study period was not significant (paired *t*-test: $|t| = 0.033$, $P = 0.98$, $n = 9$). The ranges of the CO_2 emission from the Gray Lowland soil were 356 – 480 g C m^{-2} and 218 – 271 g C m^{-2} and those in the Andosol were 337 – 539 g C m^{-2} and 225 – 435 g C m^{-2} using the chamber and gradient methods during the study period, respectively (Table 3). The CO_2 emissions by the chamber method from 1998 to 2000 were significantly higher than those by the gradient method in both soils (paired *t*-test: $|t| = 3.1$, $P < 0.05$, $n = 6$).

Discussion

Comparison between the chamber method and the gradient method

Our results suggest that the gradient method would be useful in estimating N_2O fluxes from the soil surface when the fluxes were not extremely high (> 0.63 mg N m^{-2} h^{-1}) (Figs. 2, 3 and 5). Similarly, the usefulness of the gradient method for estimating N_2O fluxes from the soil surface was reported by Dunfield *et al.* (1995) and Maljanen *et al.* (2003). However, N_2O fluxes by the gradient method did not completely correspond to those by the chamber method, especially when the fluxes were extremely high (Figs. 2, 3 and 5). These results caused the difference in the N_2O emissions between these two methods during the study period (Table 2).

In our study sites, N_2O fluxes significantly increased during the pluvial period and after heavy rainfall (Kusa *et al.* 2002 and 2006). The ratio of N_2 to N_2O in gases emitted from soil usually depends on soil moisture (Bouwman 1990, Granli and Bøckman 1994). Smith *et al.* (2003) reported that N_2O emission was not detectable under flood conditions, because any N_2O produced during denitrification might be completely reduced to N_2. The N_2O production could be enhanced by water surplus in the soil (Scholes *et al.* 1997, Kusa *et al.* 2002 and 2006); however, the N_2O was reduced to N_2 in the soil with significantly high water content. Arah *et al.* (1991) reported that the shape of N_2O concentration profile in soil (0–0.05 m depth) indicated significant N_2O consumption in the upper 0.05 m layer. Hutchinson and Livingston (2002) pointed out that the uncertainty in the gas flux by the gradient method was caused by the imprecision in determining the soil gas diffusion coefficient and the gas concentration gradient, because these parameters could not be measured over the infinitesimally small distance. This uncertainty is likely to remain high, especially if sources or sinks of the target gas are non-uniformly distributed or located near the soil surface. Fierer *et al.* (2005) suggested that Fick's law approaches tend to underestimate CO_2 production in surface soil layers because the CO_2 concentration gradient in the surface soil (around 0.1 m depth) could be underestimated due to the high rate of CO_2 transport from soil to the atmosphere and the production of CO_2 in shallower depth compared to the depth of the soil-air sampling tube. If N_2O production or reduction in the surface soil (above the location of soil-air sampling tube: upper 0.05 m) was enhanced by water surplus in the soil after rain, the concentration gradient would not have reflected the real N_2O production in the surface soil. Therefore, the accurate N_2O flux could not be obtained by the gradient method when production and consumption of N_2O was active in the soil above the installed location of soil-air sampling tube.

Additionally, several studies also reported a spatial variation in N_2O fluxes from soils (Rolston 1978, Maljanen *et al.* 2002, Yanai *et al.* 2003). The immense variability of soil structure (such as aggregated soil) and N_2O that is both produced and consumed in the soil caused variation in the gas diffusion coefficient (D/D_0) and concentration gradient, respectively. Accordingly, the gradient method is likely to be more successful in physically greater homogeneous soils (e.g. snow overlying the soil surface) (Arah *et al.* 1991, Hutchinson and Livingston 2002). Although set up locations of the chamber were in the vicinity of the soil-air sampling tubes, the chambers and soil-air sampling tubes were apart from each other (Fig. 1). The difference in N_2O fluxes between the two methods might be associated with the spatial variation in the N_2O flux, as also pointed out by Maljanen *et al.* (2003).

Some studies demonstrated the usefulness of the gradient method for CO_2 flux measurement (Sakata *et al.* 1994, Billings *et al.* 1998, Osozawa 1998, Fierer *et al.* 2005). On the other hand, Fujikawa *et al.* (2007) reported that there was no relationship between CO_2 fluxes by those two methods. They pointed out that the gradient method could not detect root respiration in the soil above the soil-air sampling tube (depth 0.05 m). In this study, the gradient method could be used to determine the seasonal pattern of the CO_2 flux for both types of soil. However, the gradient method underestimated the CO_2 emission compared to the chamber method in our study (Figs. 3, 4 and 5, Table 3). A similar result was reported by Fierer *et al.* (2005). The gradient method underestimated the CO_2 production in the surface soil and detected less root respiration compared to the chamber method because the distance between the chamber and the plant was less than in the case of the soil-air sampling tube (Fig. 1). Consequently, CO_2 flux by the chamber method was significantly higher to that by the gradient method.

Arah *et al.* (1991) reported that the N_2O fluxes by the chamber and the gradient methods were different because of the considerable N_2O consumption in the surface soil (upper 0.05 m) and the use of average values of D/D_0 and air-filled porosities during the whole study period. In our study, the values of D/D_0 and the concentrations of N_2O and CO_2 in the soil had a large seasonal variation (Table 1) and we measured D/D_0 and gas concentrations every measurement during the investigation period. This indicates the need to measure D/D_0 and gas concentrations at the same time to make the gradient method applicable to gas flux measurement.

Comparison between the fluxes of nitrous oxide and carbon dioxide

In the Gray Lowland soil, although CO_2 fluxes by the chamber method that included the onion plants were significantly higher than those without onion plants and those by the gradient method (Fig. 4), N_2O fluxes were not affected by the existence of onion plants inside the chamber (Fig. 2). In addition, the chamber method might have detected more root respiration than the gradient method because the set up location of the chamber was closer to the crops compared to the soil-air sampling tube (Fig. 1). CO_2 fluxes resulted from respiration in soil and vegetation (Smith *et al.* 2003); therefore, CO_2 fluxes increased near the root and the aerial part. N_2O is generally produced by denitrifying and nitrifying bacteria (Bouwman 1990). Plants provide an input of degradable organic material to soil and remove NH_4^+ and NO_3^- from soil. Increase in N_2O flux occurs when plants are removed or damaged and the roots remain in the soil (Granli and Bøckman 1994). In our study sites, the N_2O flux significantly increased about a month before and after the harvesting season (Figs. 2 and 3, Kusa *et al.* 2002 and 2006). The degradable organic matter provided by onion and maize might have influenced on the seasonal pattern of N_2O flux from the soil, however, the N_2O flux did not vary greatly in spite of the difference in distance between the chamber, or the soil-air sampling tube, and the plants (Figs. 1, 2 and 3). Some plants, notably rice, have internal gas channels through which N_2O produced in the soil may escape to the atmosphere (Mosier *et al.* 1990), but our results indicate that the released N_2O through onion plants from the soil might be considerably small. It suggests that the sites for setting up the chamber and the soil-air sampling tube were more important for measuring CO_2 flux than N_2O flux.

Conclusions

Although extremely high N_2O and CO_2 fluxes by the gradient method were under or over estimated compared to those by the chamber method, the gradient method can be used to measure the N_2O flux when the emission values are not extremely high and to figure out the seasonal pattern of the CO_2 flux. The gradient method could not detect the production and consumption of N_2O and CO_2 in the surface soil above the soil-air sampling tube (upper 0.05 m). Since the chamber method can not measure the gas flux in the soil profile, the gradient method is considered to be useful as it can simultaneously estimate gas fluxes both in the soil and from soil to atmosphere. The measurement of CO_2 flux was more influenced by the distance between the plants and the instruments (chamber and soil-air sampling tube) used compared to N_2O.

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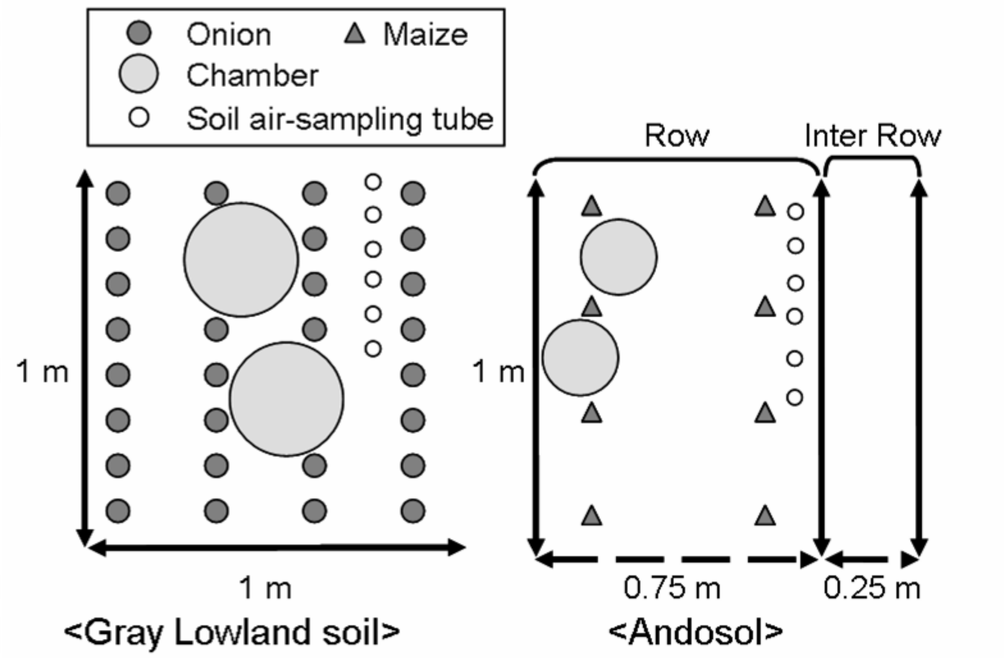

Figure 1 Schematic diagram of the setting up of chambers and soil-air sampling tubes. Chambers were placed over the onion plants from 1995 to 1997 in the Gray Lowland soil but were not placed over the plants from 1998 to 2000 in either soil.

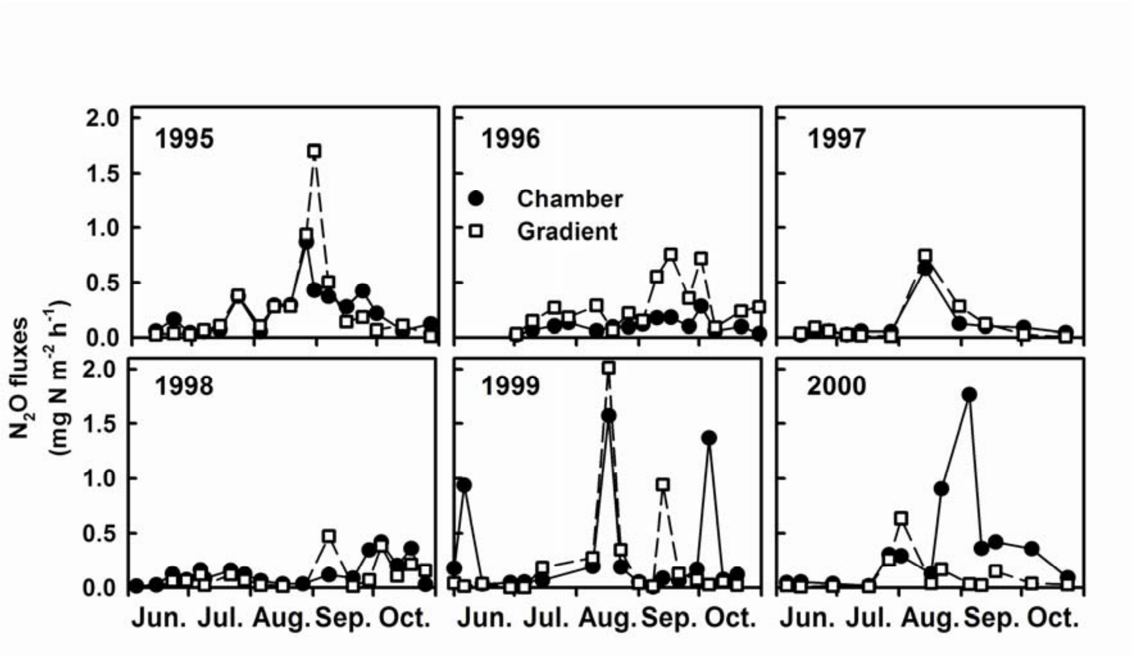

Figure 2 Seasonal patterns of N_2O fluxes from the soil surface by the chamber and gradient methods on Gray Lowland soils from 1995 to 2000. Closed circles and open squares denote the N_2O fluxes using the chamber and gradient methods, respectively. Chemical fertilizer was applied at the end of April and onion was harvested in early and mid-September.

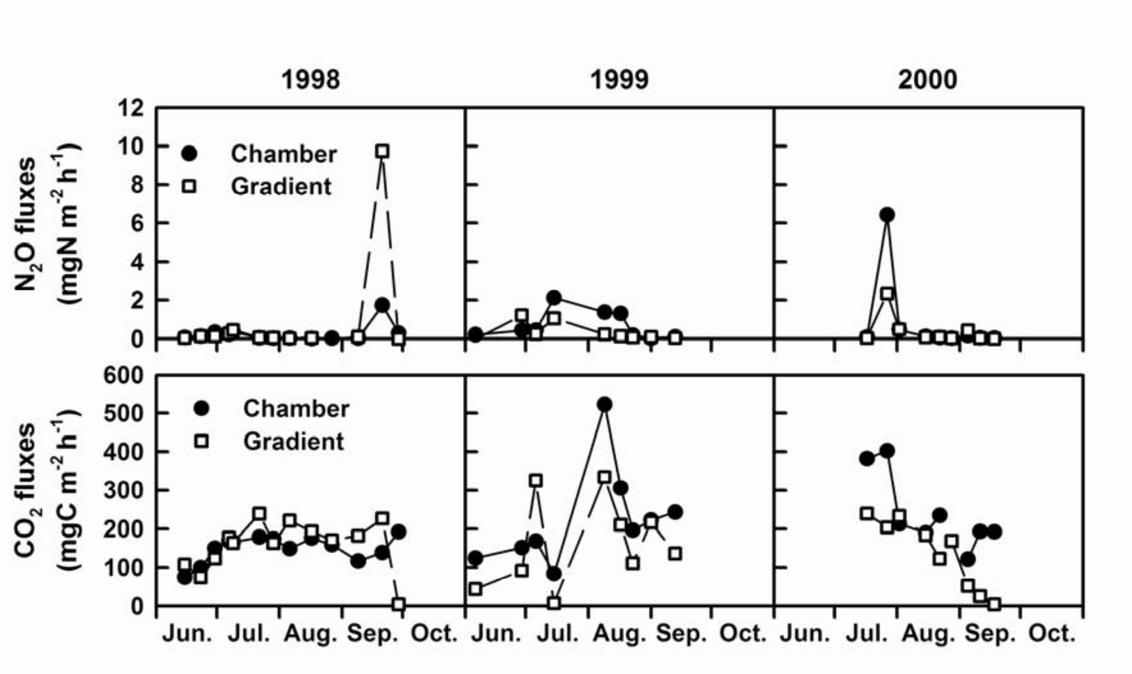

Figure 3 Seasonal patterns of N_2O and CO_2 fluxes from the soil surface by the chamber and gradient methods on Andosol from 1998 to 2000. Closed circles and open squares denote the gas fluxes using the chamber and gradient methods, respectively. Manure and chemical fertilizer were applied in mid-May and maize was harvested at the end of September.

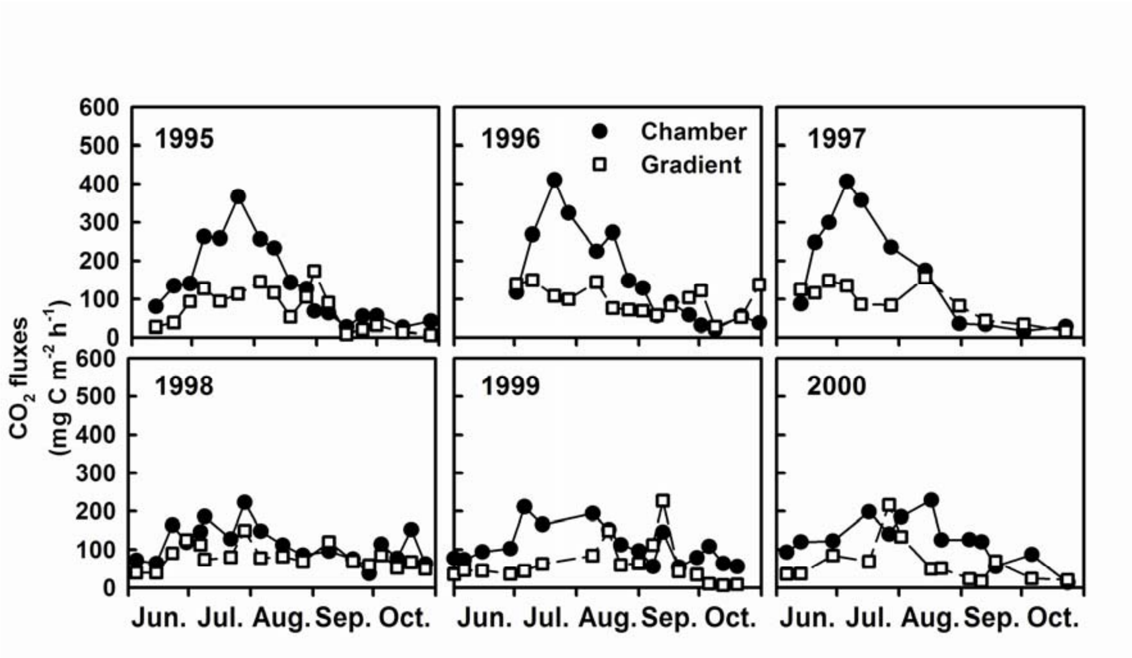

Figure 4 Seasonal patterns of CO_2 fluxes from the soil surface by the chamber and gradient methods on Gray Lowland soils from 1995 to 2000. Closed circles and open squares denote the CO_2 fluxes using the chamber and gradient methods, respectively. Chambers were placed over the onion plants from 1995 to 1997 but were not placed over the plants from 1998 to 2000.

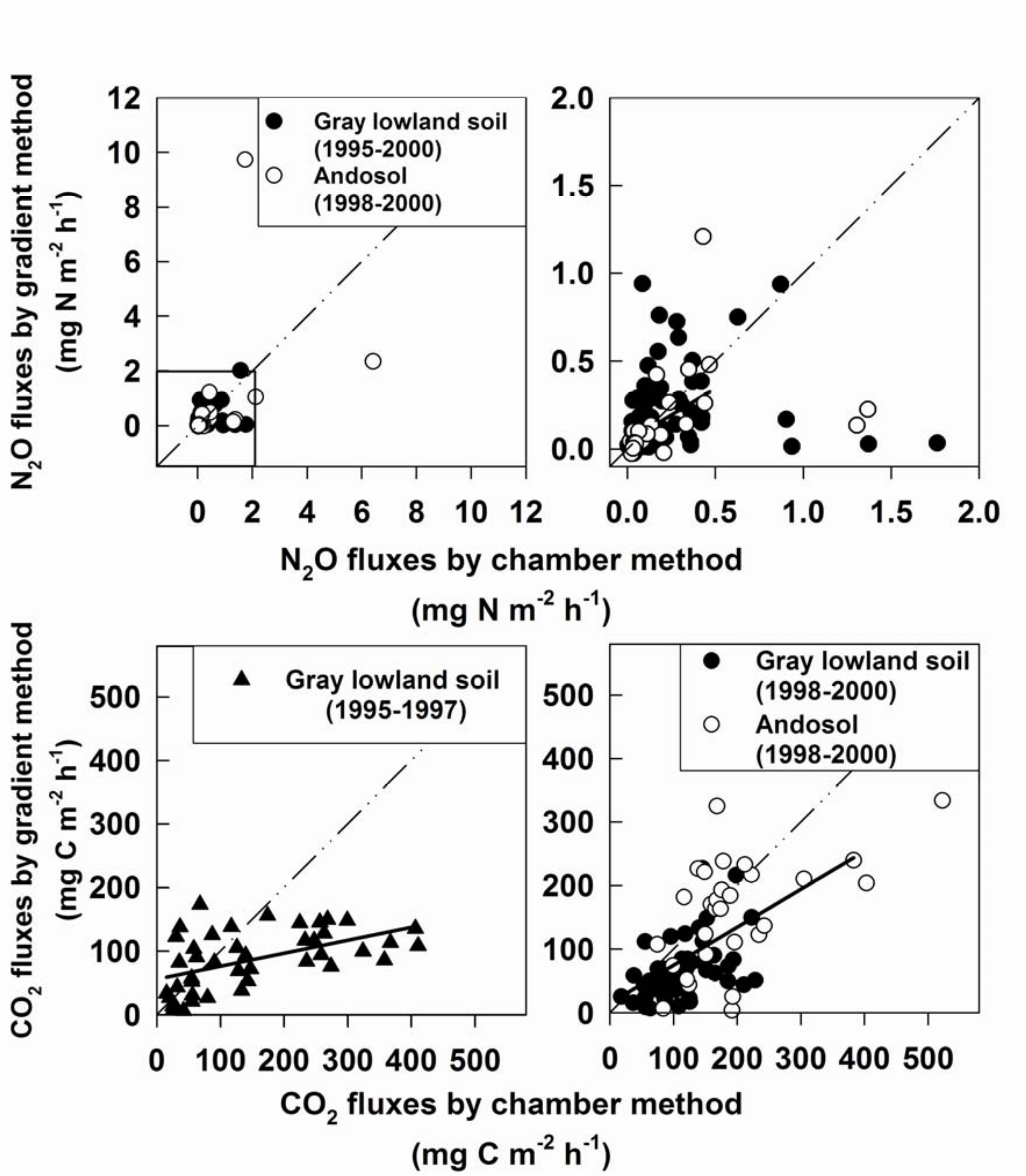

Figure 5 Comparison in gas fluxes between the chamber and gradient methods. The solid line denotes the regression line and dash-dotted line denote the 1:1 line. The outlier value (Smirnov-Grubbs' outlier test, $P < 0.01$) was excluded for calculating regression lines. The obtained regression model for N_2O is y = 0.610x + 0.0416, p < 0.01, r = 0.542, n = 104 and that for CO_2 is y = 0.204x + 55.6, $P < 0.01$, r = 0.519, n = 43 (1995–1997), y = 0.623x + 12.4, $P < 0.01$, r = 0.487, n = 77 (1998–2000).

Table 1 Summary of N_2O and CO_2 concentrations and soil relative gas diffusion coefficient (D/D_0) values.

Soil	(Unit)	Gray Lowland Soil				Andosol			
		Average	Range	CV (%)	*n*	Average	Range	CV (%)	*n*
D/D_0 at 0–0.05 m depth		0.106	0.002–0.219	48	115	0.122	0.000–0.256	56	61
N_2O concentration at 0.05 m	(10^{-6} m^3 m^{-3})	2.21	0.084–21.3	140	96	8.31	0.104–92.5	260	35
CO_2 concentration at 0.05 m	(10^{-6} m^3 m^{-3})	2060	780–10800	69	96	3410	910–9140	56	36

The study periods for the Gray Lowland soil and the Andosol were 1995–2000 and 1998–2000, respectively. CV, coefficient of variation.

Table 2 N_2O emission during the study period using the chamber and gradient methods.

Year	Study period	N_2O emission (g N m^{-2})			
		Chamber	Gradient	Chamber	Gradient
		Gray Lowland soil		Andosol	
1995	6/13–10/28	756	835	ND	ND
1996	7/2–10/31	310	823	ND	ND
1997	6/13–10/23	450	507	ND	ND
1998	6/23–10/27	433	366	634	2570
1999	5/26–10/20	928	818	1980	1070
2000	5/30–10/24	1190	353	1430	683
	Average	678	617	1350	1440

ND, no data.

Table 3 CO_2 emission during the study period using the chamber and gradient methods.

Year	Study period	CO_2 emission (g C m^{-2})			
		Chamber	Gradient	Chamber	Gradient
		Gray Lowland soil		Andosol	
1995	6/13–10/28	457	233	ND	ND
1996	7/2–10/31	468	271	ND	ND
1997	6/13–10/23	480	269	ND	ND
1998	6/23–10/27	356	258	381	435
1999	5/26–10/20	414	220	539	372
2000	5/30–10/24	432	218	337	225
	Average	435	245	419	344

ND, no data.