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ORIGINAL PAPER

Soil respiration, N_2O, and CH_4 emissions from an Andisol under conventional-tillage and no-tillage cultivation for 4 years

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Abstract No-tillage (NT) management is a promising method to sequester soil C and mitigate global warming caused by agricultural activities. Here, we report 4 years of continuous soil respiration rates and weekly nitrous oxide (N_2O) and methane (CH_4) emissions in NT and conventional-tillage (CT) plots in a typical Japanese volcanic soil. Overall, the soil respiration, N_2O emission, and CH_4 uptake decreased significantly in the NT plot. A difference in soil respiration and N_2O emission between the two plots began after the tillage treatment and the incorporation of crop residues and fertilizers, whereas the CH_4 uptake did not vary significantly during the fallow period after the treatments. The N_2O emission was higher from the CT than from the NT plot during the fall. The overall lower CH_4 uptake in the NT than in the CT plot likely resulted from a combination of decreased soil gas diffusivity and higher mineral N content at the soil surface. Higher soil respiration and N_2O emission occurred in the NT plot in the summer of 2003 and were plausibly caused by an increase in the soil moisture content that resulted from lower temperatures during July and August; the higher soil moisture must have accelerated the decomposition of organic matter accumulated in the topsoil. These results indicate that NT management is generally effective for the mitigation of the total GWP by reducing soil respiration and N_2O emission in temperate regions; however, NT management may increase rather than decrease these emissions when fields experience cool summers with frequent rainfall.

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Introduction

The IPCC (2007) reported that the global average temperature has increased more than 0.5 °C since the Industrial Revolution as a result of an increased greenhouse effect caused by elevated concentrations of atmospheric gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). This panel expects global warming to accelerate because of the rapid socioeconomic growth of developing countries. To mitigate global warming, the anthropogenic emissions of greenhouse gases must be controlled, and uptake of the gases must be increased. This mitigation will require a commitment to develop more environmentally sustainable practices. Agriculture is no exception.

Soil contains much of the biosphere's C pool. During conversion from forest or natural grassland into agricultural land, the soil generally emits CO_2-C into the atmosphere (Koizumi et al. 1993; Lal 2001; Rasmussen and Collins 1991). However, certain cropping systems, such as no-tillage (NT), can increase the storage of soil organic C (Ball et al. 1999; Ellert and Janzen 1999; Huang et al. 2010; Oorts et al. 2007; Passianoto et al. 2003; Reicosky 1997; West et al. 2004); NT systems may even restore the soil organic C lost under conventional tillage (CT) and thus prevent soil erosion and water loss and reduce farm labor needs. However, the potential for mitigation of greenhouse gases by NT management is much more variable and complex than has previously been considered and depends on the soil type (Six et al. 2004).

The N_2O emissions under NT management have shown contradictory results, with emission increases in soils at high northern latitudes and in Australia (Baggs et al. 2003; Ball et al. 1999; Kassavalou et al. 1998) and no significant difference between NT and CT agricultural systems in New Zealand (Choudhary et al. 2002) and Canada (Elmi et al. 2003), whereas NT management in Brazil decreased N_2O emission (Passianoto et al. 2003). In the soils of relatively warm, wet areas, NT usually results in N_2O emissions similar to or lower than those of CT, but emissions may increase in relatively cold, dry areas, possibly because the denitrification responsible for N_2O production occurs at higher rates under NT than tillage management (Mummey et al. 1998). Generally, CH_4 uptake is higher under NT than tillage practices due to the higher microbial activity of the moister soils of NT management (Ball et al. 1999; Cochran et al. 1997; Six et al. 2004). In addition, tillage often disturbs microbial communities and reduces their activity (Hütsch 1998), and the addition of ammonium and nitrates hinders CH_4 uptake (e.g., Fender et al. 2012).

To investigate whether NT management increases the sequestration of soil organic C and affects the greenhouse gas emissions in Japanese agricultural fields, we have been monitoring soil respiration (CO_2 emission), N_2O emission, and CH_4 uptake within an NT plot that we established in October 2001. From 13 May 2002 to 13 May 2003, the annual soil respiration decreased by 23 % under the NT compared with CT conditions (Nouchi and Yonemura 2005). When organic matter was incorporated by plowing crop residues into the soil in an adjacent CT plot after harvest, both the soil respiration and N_2O emission rates increased rapidly. Most of the difference in annual soil respiration between the two plots (an increase of 648 g CO_2 m^{-2} $year^{-1}$ under CT) occurred primarily during fallow periods (an increase of 444 g CO_2 m^{-2} under CT). In addition, N_2O emission and CH_4 uptake were lower in the NT than in the tilled plot.

A long-term study is necessary to obtain consistent data on greenhouse gas emission as affected by NT management in a wet, temperate climate such as that of Japan because the meteorological conditions differ from year to year. Here, we report soil respiration and N_2O and CH_4 emissions measured in NT and CT plots during 4 years from January 2002 to December 2005.

Materials and methods

Field description, management, and soil analyses

In October 2001, we established two duplicates of NT and CT plots, each 10×20 m, in a field with Andisol soil at the National Institute for Agro-Environmental Sciences (NIAES; 36°01′N, 140°07′E) whose texture was light clay and pH (H_2O) was 6.7; plot details are provided by Nouchi and Yonemura (2005). However, we determined to use only one plot from each management for our analyses because long-term measurements were not done in all the duplicated plots. For the first 4 years, a double-cropping system based on the rotation of soybean (*Glycine max*) and barley (*Hordeum vulgare*; Table 1) was

Table 1 Summary of the cropping systems (crop, crop calendar, fertilizer, and harvesting amount) during the study period (2002–2005)

Crop	Crop calender		Fertilizer		Dry weight of whole plant at harvesting ($g\ m^{-2}$)		CN content	
	Sowing	Harvesting	Type	$g\ N\ m^{-2}$	No tillage	Conventional	C (%)	N (%)
					Ave. SD	Ave. SD		
Barley	16 November 2001	13 May 2002	8-8-8 (N-P-K)	6	917±126 (*n*=4)	970±111 (*n*=4)	43.3	0.75
Soybean	11 June 2002	9 October 2002	3-10-10 (N-P-K)	2	591±72 (*n*=4)	603±79 (*n*=4)	44.1	2.71
Barley	7 November 2002	14 May 2003	8-8-8 (N-P-K)	6	893±31 (*n*=4)	965±37 (*n*=4)	43.3	0.75
Soybean	18 June 2003	9 October 2003	3-10-10 (N-P-K)	2	667±66 (*n*=6)	612±77 (*n*=5)	45.4	2.96
Barley	7 November 2003	17 May 2004	8-8-8 (N-P-K)	6	1,041±60 (*n*=4)	996±60 (*n*=4	43.3	0.75
Soybean	17 June 2004	21 September 2004	3-10-10 (N-P-K)	2	820±33 (*n*=2)	899±57 (*n*=2)	44.8	2.46
Barley	5 November 2004	20 May 2005	8-8-8 (N-P-K)	6	956±75 (*n*=4)	1,198±144 (*n*=4)	34.7	0.60
Komatsuna	21 June 2005	29 July 2005	10-10-10 (N-P-K)	5	243±27 (*n*=4)	225±5 (*n*=4)	37.7	3.97
Komatsuna	1 September 2005	6 October 2005	10-10-10 (N-P-K)	5	178±15 (*n*=4)	143±16 (*n*=4)	37.6	3.96
Wheat	8 November 2005		8-8-8 (N-P-K)	4				

The fertilizer type shows gravimetric ratios (percentage) of soluble nitrogen, phosphate as P_2O_5, and potassium as K_2O. In the 8-8-8 and 10-10-10 fertilizers, the ammonium-N is included in the form of $(NH_4)_2SO_4$, $(NH_4)_2HPO_4$, and NH_4Cl, and the soluble phosphate-P in the form of $(NH_4)_2HPO_4$. In the 3-10-10 fertilizer, the ammonium-N is included in the form of $(NH_4)_2SO_4$, and the soluble phosphate-P in the form of $Ca(H_2PO_4)_2$. All the fertilizers include soluble K in the form of KCl. The fertilization date is the same as or 1 day before the sowing date. The NT and CT plots were set in October 2001 used. Between June and October 2005, komatsuna (*Brassica campestris* var. *perviridis*) was planted twice. In November 2005, wheat (*Triticum aestivum*) was planted instead of barley. The spacing between crop rows was 60 cm for all of the crops.

The soil was plowed twice to a depth of approximately 20 cm in the CT plot between the two yearly crops: immediately after harvest and about a week before sowing. In the NT plot, the aboveground parts of the crop residues were cut after harvest and left on the soil surface. The soil in the CT plot was compacted with a roller after the sowing of soybeans but not after the sowing of barley. Granular fertilizers were plowed into the soil in the CT plot and manually applied to the furrows where seeds were sown in the NT plot. During the summer, NIAES technical staff removed weeds from the field by hand every week or two. The weeds amounted to no more than a few percent of the mass of the crop residues, so weed residues most likely had a negligible effect on the C balance. Because the climate of the study area is generally wet, no irrigation was provided.

We determined the dry weight of the crops and the crop residues from three 1 × 1-m quadrats (two rows of the crop) in each treatment plot after harvest. The C and N contents of the soil and of the plant residue samples were analyzed using an NC analyzer (Sumigraph NC-22 F, Sumika Chemical Analysis Service Ltd., Tokyo, Japan). The initial soil C and N contents in November 2001 were 2.80 and 0.25 %, respectively; the initial total C and N amounts until 20 cm of soil depth were 3.8 and 0.33 kg m^{-2}, respectively.

Climate

As mentioned in the "Introduction" section, the climate influences the effects of NT management on gas emission and uptake. Our experimental site has a mild, wet, temperate climate, with a cold, dry winter under the influence of the Tibetan anticyclonic circulation; the precipitation is highest during the spring and fall because of the passage of cyclones and anticyclones coming from the west. The summer is hot and sunny under the influence of the Pacific anticyclonic circulation.

Data from a meteorological station located about 400 m from the two plots show that the annual mean temperature was approximately 14.5 °C from 2002 to 2005, and the total annual precipitation averaged approximately 1,200 mm (Fig. 1). The minimum and maximum mean monthly temperatures were 3 °C in January and 26 °C in July, respectively. However, the interannual variability was high. The temperature was 2.0 °C cooler on average in the summer of 2003 (June–August) than in the other years of the study.

Emission measurements

The basic experimental procedure used in this study was the same as that of Nouchi and Yonemura (2005). We used the open-flow chamber method (Nakadai et al. 2002; Yonemura et al. 1999) to measure soil respiration. The cylindrical chambers each consisted of two parts: a bottom section (21 cm in diameter and 7 cm high) made of stainless steel inserted 3 cm into the ground and a top section (21 cm in diameter and 9.5 cm high) made of grey polyvinyl chloride attached to the bottom section during the measurements. Each chamber had inlet and outlet tubes for air flow and a small hole to prevent a pressure imbalance from developing. During the measurements, each top section was loosely attached to the bottom of the chamber and covered with a sun shade consisting of a white conical funnel to avoid an excessive temperature increase. The CO_2 concentration was measured by an infrared CO_2 analyzer (Model ZRC, Fuji Electric Co., Ltd., Tokyo, Japan), which was calibrated every 3 h using a CO_2 standard (approximately 600 ppmv, Takachiho Kagaku Kogyo, Tokyo, Japan) provided from cylinders. The flow rate through the chambers was set at 1.5 L min^{-1}.

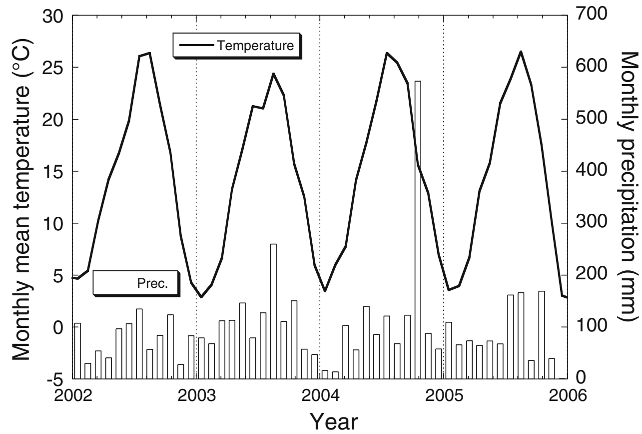


Fig. 1 Monthly mean temperature and monthly total precipitation from 2002 to 2005

Nine open-flow chambers were used in each plot. Three of them were monitored in a given week. In a subsequent week, three different chambers were monitored because continuous coverage of the soil by the chambers could create artificial chamber effects. Each measurement cycle (a total of six chambers from the two plots) lasted 30 to 60 min. The CO_2 emissions were calculated every hour using the difference in CO_2 concentration between the air from the chambers and the ambient air. The soil water content was measured at a depth of 5 cm using time domain reflectometry probes (CS615, Campbell Scientific, Inc., Utah, USA); the soil temperature was measured at depths of 5 and 20 cm by thermocouples.

We used a closed-chamber method (Nishimura et al. 2005a) with rectangular chambers (40 × 40 cm and 10 cm high) to measure the soil N_2O and CH_4 emissions. Three chambers were established in each plot. No fans were used to avoid increasing the diffusivity at the soil–atmosphere interface due to the acceleration of the air stream. The gas was sampled in the morning on the same day of the week at 1, 31, and 61 min after closure of the chamber. The sampled gas was stored in 500-mL polyvinyl fluoride bags for direct transport to the laboratory and immediate analysis. CH_4 was measured by a flame ionization detector mounted on a GC-9A gas chromatograph (Shimadzu Co., Kyoto, Japan). N_2O was measured by an electron capture detector mounted on a GC-8A gas chromatograph (Shimadzu). The N_2O and CH_4 emissions were calculated from the change in the gas concentration per unit time in the chamber air, which was determined by linear regression.

Statistical analyses

We compared the gas emissions between the two tillage treatments using generalized linear models. Firstly, we assessed the treatment effect on gas emissions during the fallow periods. For the full model, we set the gas emission as the objective variable for each gas (CO_2, N_2O, and CH_4). As the explanatory variables, we chose the treatment (tillage regime), the crop year, the season (the postharvest periods for the summer and winter crops), and the interaction between the crop year and the season. We then performed stepwise model selection based on Akaike's information criterion (AIC; Akaike 1974; Sakamoto et al. 1986) for the full model.

Secondly, we assessed the treatment effect during the growing season for each crop. The full model used gas emission as the objective variable and the treatment, crop species, crop year, crop phase (the first 40 days after sowing or the period from 40 days to harvest), and the interaction between the crop species and the crop year as the explanatory variables. We divided the cropping season into the first 40-days after sowing and the period from 40 days after sowing until harvest because the degradation of the crop residues was active during the first 40 days (Nouchi and Yonemura 2005). In addition, we included the two-way interactions between the crop phase and each of the other explanatory variables and the three-way interactions among the crop phase, the treatment, and the crop species. We then performed stepwise model selection based on AIC for the full model. In this analysis, we used the data only from the soybean and barley because these crops provided multiple replicates for analysis.

As a result of this second process, the model with the interaction between the crop phase and the treatment was selected. Thus, we analyzed the effect of the treatment separately for each crop phase (during or after the first 40 days) to evaluate the significance of the tillage effect on gas emission. This means that we had to analyze the treatment effect for each crop phase (before or after the first 40 days) independently for the evaluation of the significance of the treatment effect on gas emission. The full model used in the analysis of each gas and each phase was analyzed by stepwise model selection based on AIC and included the treatment, the crop species, the crop year, and the two-way interactions of the crop species with the crop year and with the treatment as the explanatory variables.

Finally, we also evaluated the overall treatment effect on the gas emissions by averaging the emission data by year. The full model used the treatment and the year as the explanatory variables. We then performed stepwise model selection based on AIC for each gas.

The models selected by the stepwise model selection procedure that had different error distributions (normal or log-normal) were further selected by AIC. We then used the likelihood ratio test for the final selected model to evaluate the significance of the treatment effect. This procedure was conducted for all of the aforementioned analyses, which were performed with version 2.6.2 of R software (R Development Core Team 2011).

Additionally, we compared the total dry matter of the harvested crops between the CT and NT treatments using generalized linear models and used these parameters in each case to estimate the C balance. For the full model, we set the dry matter of the harvested crop in each plot and each year as the objective variable. As the explanatory variables, we chose the treatment (tillage regime), the crop species, the crop year, and the interaction between the crop species and the crop year. We defined the day of sowing of the summer crops as the start of the crop year. Therefore, our data included a total of five crop years. We then performed stepwise selection for the full model using AIC as the basis for the selection.

Results

Figures 2, 3, and 4, respectively, show the time series from 2002 to 2005 for the soil respiration (CO_2 emissions) and temperature in the NT plot, for the N_2O emissions and soil moisture in both tillage plots, and for the CH_4 emissions and soil temperature in the both tillage plots. To describe the general pattern of the emissions, the mean monthly values from 2002 to 2005 are shown in Fig. 5. To focus on each phase of the annual agricultural calendar, Table 2 presents the soil respiration data and N_2O and CH_4 emissions for each crop averaged over the study years during each of four seasonal phases, Table 3 shows the soil respiration and the change in C input from the crop residues for each year, and Table 4 shows the N_2O and CH_4 emissions for each year. In Table 2, the values were averaged separately for the 40-day period after sowing (to account for the short-term effects of tillage and fertilizer application) and for the period from 40 days after sowing until harvest because the active degradation of the crop residues occurred during the initial period (Nouchi and Yonemura 2005). Table 5 shows the model selected by the stepwise procedure for each analysis using AIC. The case numbers (C1-C12) in Table 5 correspond to

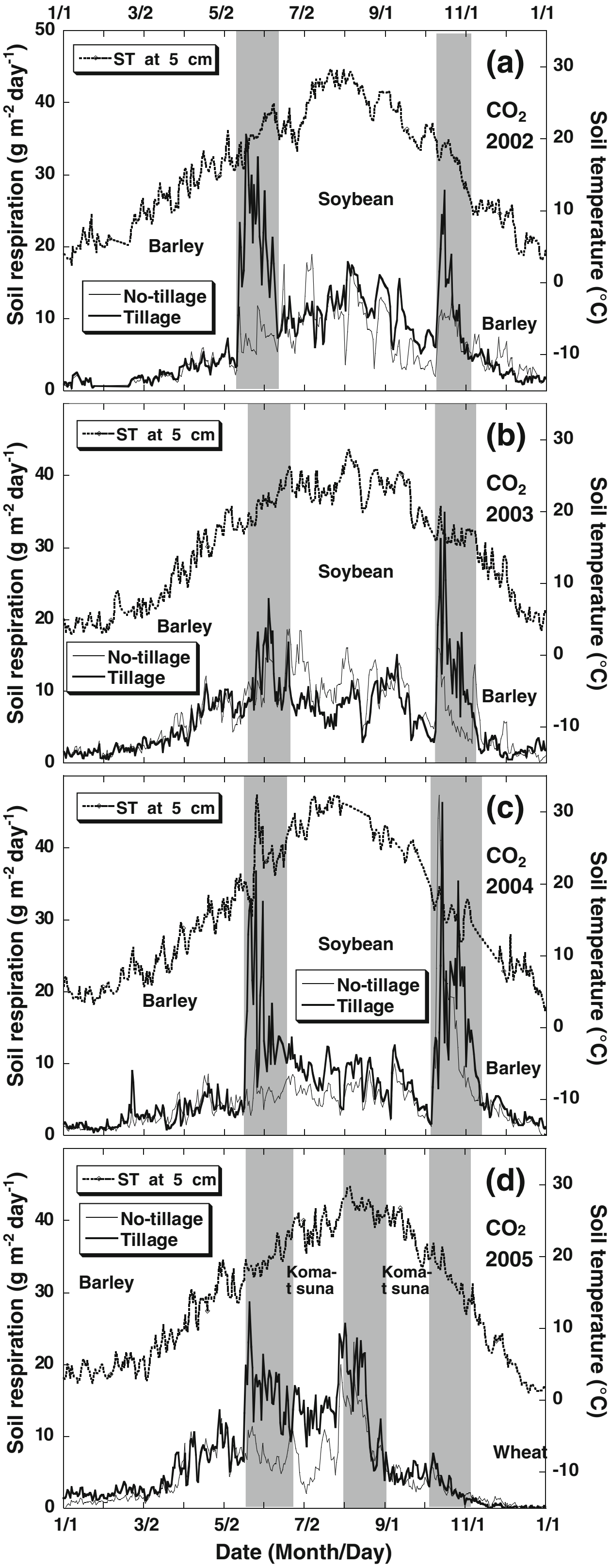


Fig. 2 Daily soil respiration and soil temperature (ST) at a depth of 5 cm from 2002 to 2005 in the no-tillage (NT) and conventional-tillage (CT) plots. *Shaded areas* represent the fallow periods. ST was recorded in the NT plot

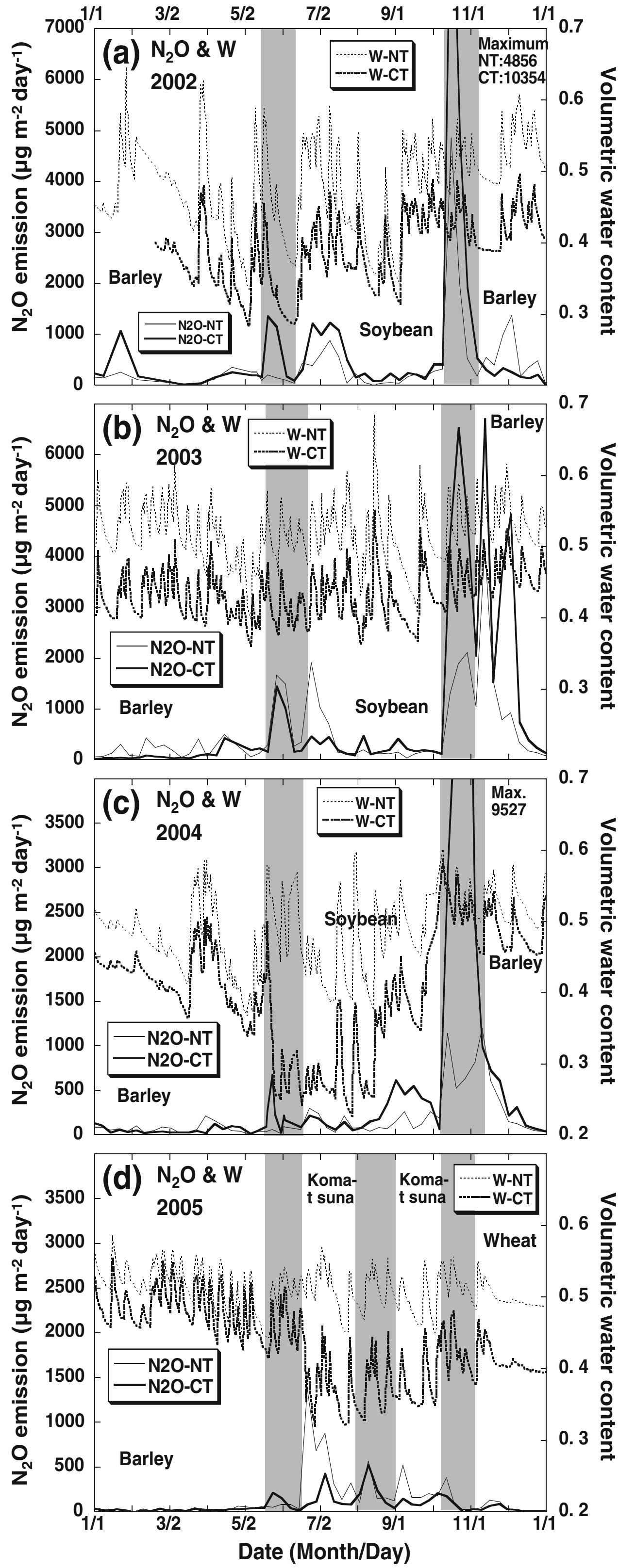


Fig. 3 N_2O emission and soil moisture (W) at a depth of 5 cm from 2002 to 2005 in the NT and CT plots. *Shaded areas* represent fallow periods. W was recorded in the NT plot

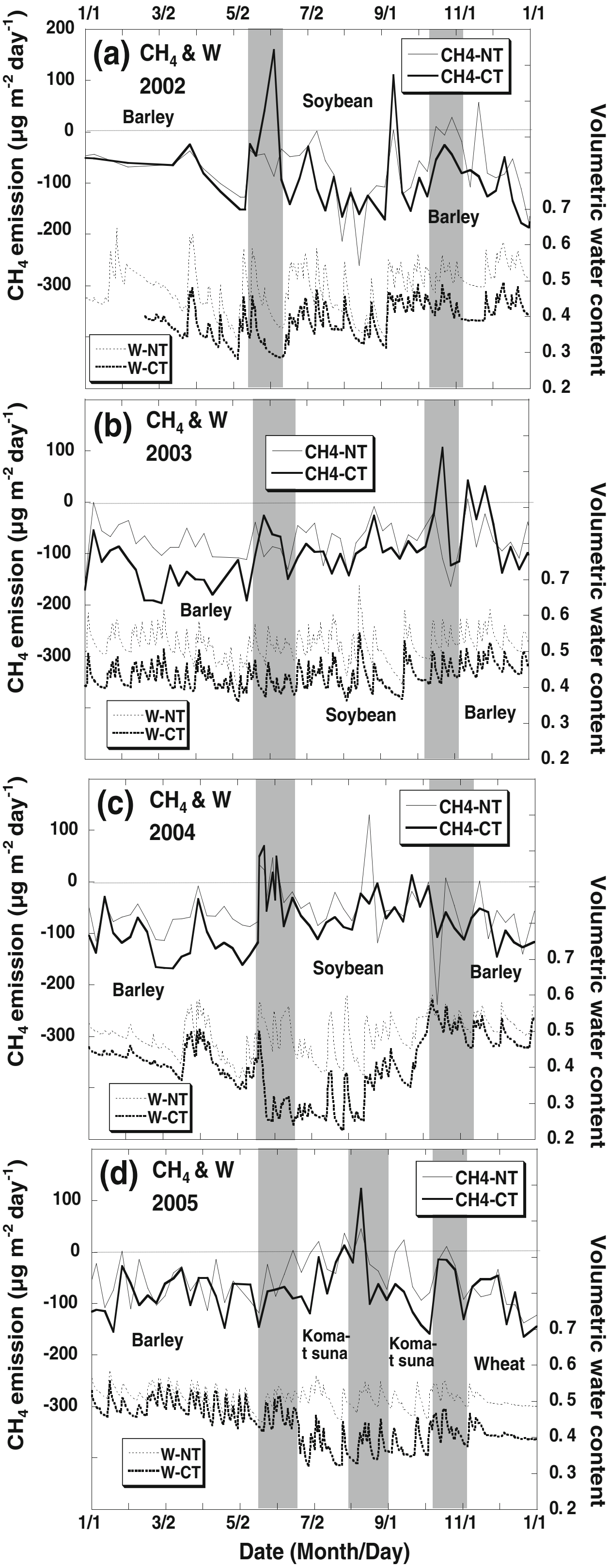
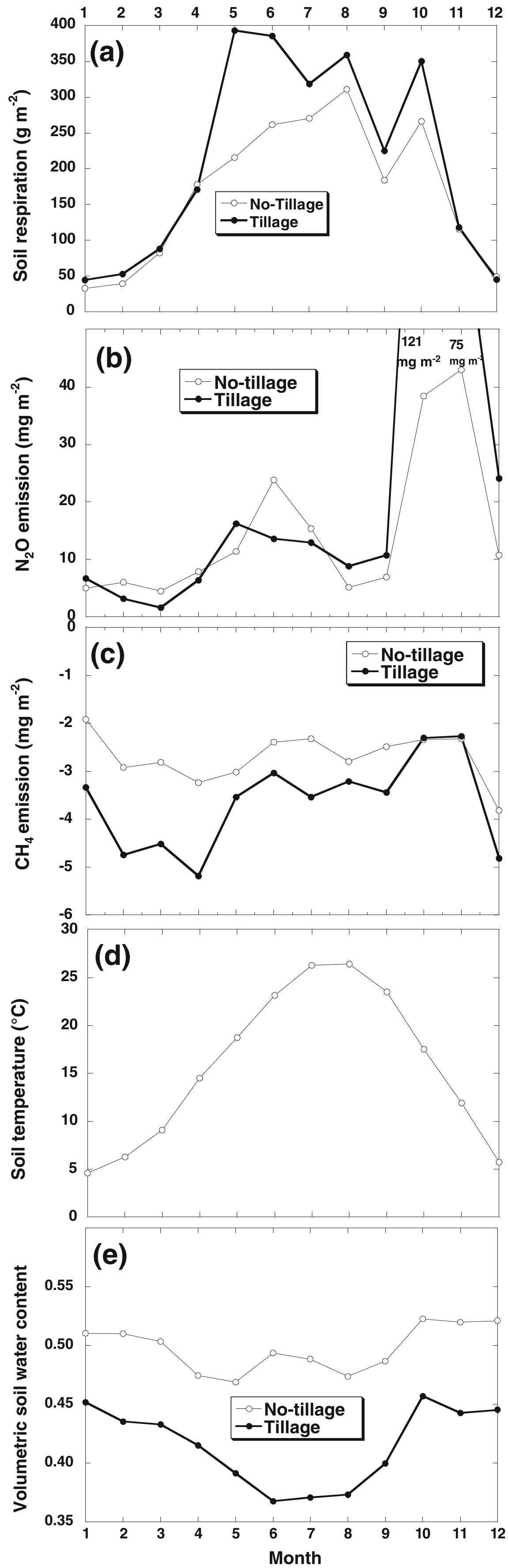


Fig. 4 CH_4 emissions and soil moisture (W) at a depth of 5 cm from 2002 to 2005 in the NT and CT plots. *Shaded areas* represent fallow periods. W was recorded in the NT plot



◀ **Fig. 5** Monthly average **a** soil respiration, **b** N_2O, and **c** CH_4 emissions, **d** changes in soil temperature at a depth of 5 cm in the NT plot, and **e** changes in the volumetric soil water content at a depth of 5 cm from 2002 to 2005

the case numbers given in the results section. For each selected model, we evaluated the significance of the treatment effect using the likelihood ratio test (see below).

Soil respiration (CO_2 emissions)

The soil respiration displayed many peaks, most of which were associated with variations in the soil temperature and moisture (Fig. 2). Except for transient increases during the fallow periods, the soil respiration varied seasonally in both plots, with maximal and minimal values in the summer and winter, respectively, associated with seasonal variation in the soil temperature (Fig. 5a, d).

Marked increases in the soil respiration were observed in the CT plot during the fallow periods after the first tillage that followed the harvest and incorporation of the crop residues. The soil respiration was 54.2 % (ranging from 49.5 to 58.5 %) lower in the NT plot than in the CT plot (χ^2=55.68, df=1, P<0.0001) during the fallow periods (C1). For the analysis of soil respiration during the 40 days after sowing, the treatment effect was not included in the selected model (C2). However, the soil respiration in the NT plot for the period from 40 days after sowing until the harvest of soybean or barley was 13.6 % (ranging from 7.3 to 19.4 %) lower than that in the CT plot (χ^2=5.01, df=1, P<0.025; C3). The increases in soil respiration after the second tillage at the end of the fallow period and sowing were lower than those that occurred during the fallow periods but were still higher in the CT than in the NT treatment.

In the annual analysis (Table 3), the soil respiration values from the NT plot were 21.7 % (ranging from 17.2 to 25.9 %) lower than those from the CT plot (χ^2=17.14, df=1, P<0.0001; C4). The summer of 2003 was unusual, in that this summer was colder and wetter than those of the other years (Fig. 1). The increase in soil respiration in the NT plot during the spring fallow (May and June) period in 2003 was less striking than that in the CT plot. During the spring fallow (May and June) period, both the increase and the temporal variation in soil respiration were similar in both plots (Fig. 2b). The increase in soil respiration after the second tillage in the spring of 2003 was higher in the NT than in the CT plot. Even the total annual soil respiration in 2003 did not differ significantly between the two plots (Table 3).

The seasonal variation in soil respiration followed a similar pattern in both plots (Fig. 5a). However, the monthly average soil respiration in the NT plot was lower than that in the CT plot from May to October, a period when the difference in soil moisture between the two plots was higher than at any other time of year (Fig. 5e).

N_2O emissions

The N_2O emissions showed higher peaks after the fertilization that followed sowing in 2002 and 2004 as well as during the fallow periods (Fig. 3), as was shown previously (Nouchi and Yonemura 2005). The N_2O emissions from the NT plot during the fallow periods were one third (ranging from 29.0 to 37.9 %) of those in the CT plot (χ^2=68.96, df=1, P<0.0001; Table 2; C5). The N_2O emissions from the NT plot during the 40-day period after sowing (or the second tillage) were 47.5 % (ranging from 36.2 to 56.8 %) lower than those from the CT plot (χ^2=13.67, df=1, P=0.0002; C6).

Table 2 Periodically accumulated soil respiration and N_2O and CH_4 emissions in no-tillage (NT) and conventional-tillage (CT) plots after dividing the annual agricultural calendar into four periods (spring fallow, soybean cropping, fall fallow, and barley cropping)

	Soil respiration (g CO_2 m^{-2})		N_2O emission (mg m^{-2})		CH_4 emission (mg m^{-2})	
	NT	CT	NT	CT	NT	CT
	Ave.±SD	Ave.±SD	Ave.±SD	Ave.±SD	Ave.±SD	Ave.±SD
Spring fallow (4 years)	993±31	2,083±228	34.1±10.0	41.0±8.4	−6.79±1.03	−6.49±3.81
Soybean (3 years)						
During 40 days after sowing	1,168±56	1,122±211	61.5±23.7	55.9±13.8	−6.17±0.55	−15.82±8.91
From 40 days until harvesting	1,707±212	1,950±235	26.7±1.5	52.8±11.9	−16.53±1.09	−19.01±2.28
Fall fallow (3 years)	1,029±268	1,393±345	120.4±9.4	378.3±8.1	−5.41±2.46	−5.06±0.39
Barley (4 years)						
During 40 days after sowing	461±34	427±53	110.2±44.8	173.0±77.7	−7.09±1.03	−8.07±3.08
From 40 days until harvesting	1,776±287	1,939±83	59.8±4.4	41.8±4.8	−38.57±2.82	−58.28±7.97

Soybean cropping and barley cropping are each divided into two sub-periods (first 40 days after sowing and from 40 days after sowing until harvest). Each periodically accumulated value is a 3- or 4-year average

Ave. average value of three duplicates over the relevant entire period, *SD* standard deviation value of three duplicates over the relevant entire period

Table 3 Annual soil respiration, crop dry weight, and estimated C input in no-tillage (NT) and conventional-tillage (CT) plots

Year	Soil respiration ($g CO_2$-C m^{-2})		Dry weight of crop and crop residue (g C m^{-2})		C input (g C m^{-2})		Difference in C input (g C m^{-2})
	NT sum.±SD	CT sum.±SD	NT sum.	CT sum.	NT	CT	
2002	546±6	630±121	704	675	158	45	112
2003	663±87	628±2	510	507	−153	−121	−32
2004	513±92	622±57	607	556	94	−66	160
2005	478±58	543±73	372	330	−106	−213	107
Total	2,200±140	2,423±153	2,192	2,068	−8	−355	347

C input = crop dry weight−soil respiration, difference in C input between NT and CT=C input in NT−C input in CT

For the period from 40 days after sowing until harvest, the model that included the interaction between the crop species and the treatment was selected (result not shown); therefore, we analyzed the N_2O emissions for the soybeans and barley separately. For the soybeans, the emission of N_2O was 8.7 mg m^{-2} (ranging from 6.8 to 10.7 mg m^{-2}) lower in the NT than in the CT plot during this period (χ^2=14.70, *df*=1, *P*=0.0001; C7). However, for the barley, the emission of N_2O was 66.4 % (ranging from 45.3 to 90.5 %) higher in the NT than in the CT plot from 40 days after sowing until the barley harvest (χ^2=14.71, *df*=1, *P*=0.0001; C8). Extremely high N_2O emissions were observed during the 2002, 2003, and 2004 fall fallow periods (Figs. 2b–d, 3a–d, and 4a, b) after the application of soybean residues, including the seeds, especially in the CT plot. These sizable increases in the N_2O emission during the fall fallow periods were not observed in 2005 (Fig. 5), when the komatsuna residues were incorporated into the soil. Furthermore, when soil moisture was high after precipitation, a sporadic increase in N_2O emission was observed (Fig. 3).

The N_2O emissions during the spring fallow (May and June) period in 2003 were slightly higher in the NT than in the CT plot, and this increase continued and was combined with the increases that occurred after the application of fertilizers (Fig. 3b). The N_2O emissions after the spring and summer fallow periods in 2005 were also higher in the NT plot and showed a similar pattern. For the annual data (Table 4), the N_2O emissions from the NT plot were 42.5 % (ranging from 37.3 to 47.3 %) lower than those from the CT plot (χ^2=30.14, *df*=1, *P*<0.0001; C9). The monthly average N_2O emission in the NT plot (Fig. 5b) was lower than that in the CT plot during the fall. However, the emission was greater in the NT plot in June and July during Japan's rainy season, when the difference in soil moisture between the two plots was greater than at any other time of year (Fig. 5e).

CH_4 emissions

During the fallow period, the treatment effect on CH_4 emissions was not included in the selected model (C10). However, the CH_4 uptake during the 40 days after the sowing of soybean and barley in the NT plot was 1.80 mg m^{-2} (ranging from 1.03 to 2.58 mg m^{-2}) lower than that in the CT plot (χ^2=5.36, *df*=1, *P*<0.020) (C11). For the period from 40-days after sowing until harvest, the model that included the interaction between the crop species and the treatment was selected (result not shown). Therefore, we analyzed the CH_4 emissions during this period separately for soybeans and

Table 4 Annually accumulated N_2O and CH_4 emissions in no-tillage (NT) and conventional-tillage (CT) plots

Year	N_2O emission (mg m^{-2})		CH_4 emission (mg m^{-2})		GWP (N_2O, CH_4)	
	NT Sum. (GWP)±SD	CT Sum. (GWP)±SD	NT Sum. (GWP)±SD	CT Sum. (GWP)±SD	NT	CT
2002	169 (50.4)±21	282 (84.0)±8	−26.5 (−1.8)±2.7	−32.1 (−2.2)±7.1	48.5	81.8
2003	202 (60.0)±45	326 (97.1)±50	−26.6 (−1.8)±5.7	−35.5 (−2.4)±2.5	58.2	94.7
2004	65 (19.3)±9	196 (58.4)±47	−22.3 (−1.5)±1.9	−36.6 (−2.5)±5.2	17.8	55.9
2005	56 (16.5)±10	30 (8.9)±6	−18.4 (−1.3)±4.7	−27.1 (−1.9)±3.3	15.3	7.0
Total	491 (146.3)±73	834 (248.4)±76	−94 (−27.9)±10.0	−131 (−39.1)±41	118.4	209.3

The time horizon for the GWP (equivalent to grams of CO_2 per square meter) was set at 100 years. The GWP (N_2O, CH_4) shows GWP for N_2O + GWP for CH_4 in the NT and CT plots

Table 5 Statistical information

Case	Targe variable	Error distribution	Explanatory variable
C1	Dry matter	Log normal	Treatment + Crop_name + Term + Crop_name:Term
C2	Soil respiration	Log normal	Treatment + Term + Season + Term:Season
C3	Soil respiration	Log normal	Treatment + Crop_name + Term + Crop_name:Term + Crop_name:Treatment
C4	Soil respiration	Log normal	Treatment + Year
C5	N2O emission	Log normal	Treatment + Term + Season + Term:Season
C6	N2O emission	Log normal	Treatment + Crop_name + Term + Crop_name:Term + Crop_name:Treatment
C7	N2O emission	Log normal	Treatment + Term
C8	N2O emission	Log normal	Treatment + Term
C9	N2O emission	Log normal	Treatment + Year
C10	CH4 emission	Normal	Treatment + Crop_name + Term + Crop_name:Term + Crop_name:Treatment
C11	CH4 emission	Normal	Treatment + Term
C12	CH4 emission	Normal	Treatment + Year

Treatment refers to NT or CT. Term refers to the period between the sowing of successive crops. Season refers to the period between the sowing of the summer and winter crops or the sowing of the winter and summer crops. Year refers a period of 365 days. Crop_name refers to soybean, barley, komatsuna, or wheat. Crop_phase is the period lasting for 40 days after sowing t or the period from 40 days after sowing until harvest

barley. For soybeans, the treatment effect was not included in the selected model (C12). For barley, the CH_4 uptake in the NT plot was 4.93 mg m^{-2} (ranging from 3.64 to 6.21 mg m^{-2}) lower (about 50 %) than that in the CT plot (χ^2=13.67, *df*=1, *P*=0.0002; C13). In the annual analysis (Table 4), the yearly average CH_4 uptake was 9.36 mg m^{-2} (ranging from 7.53 to 11.19 mg m^{-2}) lower from the NT than from the CT plot (χ^2=20.80, *df*=1, *P*<0.0001; C14). The difference in CH_4 uptake between the two plots was high in 2004 and low in 2002 (Table 4).

The monthly average CH_4 uptake in the NT plot was lower than that in the CT plot, except in October and November (the fall fallow period), when the values were similar (Fig. 5c). CH_4 uptake was at its maximum between December and April, and the difference between the two plots was greater during this period than at any other time of year. In June and July (the spring fallow period), the CH_4 uptake decreased in both plots.

Discussion

Soil respiration and carbon balance

The magnitude and seasonal variations of soil respiration in the present study generally agree with the results (<30 g m^{-2}-day^{-1}) of previous studies conducted in upland fields at the NIAES (e.g., Koizumi et al. 1993; Yonemura et al. 1999). The high soil respiration from the CT plot during the fall fallow period can be attributed to the degradation of the easily decomposable soybean residues; the N content of soybean residues (1.8 %) is higher than that of barley (0.75 %) and wheat (0.95 %), and this difference is the main reason for the high soybean degradability. In contrast, the lower soil respiration from the NT plot during the spring fallow period can be attributed to the more degradation-resistant organic matter from barley and wheat whose residues have higher silicate contents (e.g., Hodson et al. 2005; Guntzer et al. 2012).

The higher soil respiration in the NT plot in the summer of 2003 can be attributed to lower soil temperatures (Fig. 2b) and higher soil moisture (Fig. 3b) during July and August, which may have led to a higher moisture content in the organic matter that accumulated in the top layer of the soil in the NT plot as a result of reduced evaporation. This moisture, in turn, may have resulted in more rapid decomposition of the organic matter in this layer, which was usually under dry conditions that limit the rate of decomposition in the NT plot. As Nouchi and Yonemura (2005) noted, the C input of the NT plot calculated using the soil respiration and the dry weight of the crop and crop residue was generally higher than that of the tilled plot (i.e., the net C sequestration due to the NT practices; Table 3). However, 2003 was an exception.

To properly interpret the soil respiration values, it is important to consider the amount of crop residue that was scattered over the soil surface in the NT plot or that was incorporated into the soil in the CT plot because these values reflect the growth of the previous crop (Table 1) and are an important C input into the soils of agroecosystems. Over the years, the dry matter production in the NT plot was 7.9 % (with a standard error ranging from 5.7 to 10.0 %) lower than that in the CT plot (χ^2=13.74, *df*=1, *p*=0.0002; C15). The NT practices are effective in keeping soil moisture at higher levels throughout the year (Fig. 5e). However, the higher dry matter production in the CT plot in approximately half of the years (Table 1) may be due to the generally adequate soil moisture conditions under the wet and temperate climate of the study area. Furthermore, the soybean production was considerably higher in the NT plot in the summer 2003 crop. This higher dry matter production might be linked to the unusually cold conditions in 2003. The higher dry matter production by komatsuna in the NT plot in late 2005 can be explained by field observations that the higher soil moisture in the NT plot promoted initial root development because of dry weather during this period (Fig. 1).

If we account for the C added to the soil in the crop residues (Table 3), the NT plot appears to sequester more C than the CT plot. However, the soil C content was not significantly greater in the NT plots (Fig. 2 of Togami et al. 2009). The estimated values for the increase in soil carbon were less than 5 Mt/ha, which is within the error range of the soil C content measurements by Togami et al. (2009). Thus, additional, longer-term measurements are necessary to clarify this important point.

N_2O emission

As has been reported in many previous studies (e.g., Akiyama and Tsuruta 2003; Ni et al. 2012), N_2O was emitted after the crop residues were tilled into the soil and after the application of N fertilizer. The N_2O emission was observed for 40 days after sowing in many cases, as was reported previously in the same field (Nouchi and Yonemura 2005). The increased N_2O emission during the fallow periods after the first tillage can be attributed to the decomposition of crop residues; the increased emission after the second tillage might be attributable to the fertilizer. Surprisingly high N_2O emissions were observed during the fall fallow periods between 2002 and 2004 because the soybean seeds whose N content is as high as 4.8 % and whose C/N ratio is 10 were incorporated into the soil during the first tillage (Table 1). However, this result would be uncommon under actual agricultural management (because the goal is to harvest these seeds), although the plowing of the entire soybean crop into the soil may occasionally be conducted to improve soil quality. Except for the high N_2O emissions during the fall fallow and the subsequent periods, the N_2O emissions generally ranged within low levels and were comparable to those in other soybean fields with Andisol soil (Yazaki et al. 2011) or were lower than those from soybean fields with Gray Lowland soil (Nishimura et al. 2005a). The N_2O emissions from February to April, in June, and in July were generally higher in the NT plots (Fig. 5b), and the significantly higher N_2O emissions more than 40 days after the sowing of barley can be attributed to the sustained higher soil moisture content in the NT plot (Fig. 5e), as was shown in previous studies (e.g., Ball et al. 1999).

The absence of differences in N_2O emission between the two plots during the spring fallow period in 2003 and the higher N_2O emissions from the NT plot after the fallow period are similar to the soil respiration pattern at this time. This similarity indicates that the enhanced N_2O emission during these periods is closely related to the decomposition of organic matter placed on the soil surface. Several previous studies (e.g., Nishimura et al. 2005b) also showed similar enhancement of N_2O emission related to organic matter application. Despite variation among the crops, years, and times of year, the overall N_2O emission was significantly lower in the NT plot, which is a clear advantage of this approach from the perspective of mitigating greenhouse gas emissions (Table 4).

CH_4 uptake

The CH_4 uptake was much lower than that previously observed in another field at the NIAES (approximately 1000 μg of CH_4 m^{-2} day^{-1}; Yonemura et al. 2000a), which can be partly attributed to the higher soil moisture content in our study field (Fig. 5e). The CH_4 uptake was significantly higher in the CT plot for the study as a whole (by 37 mg m^{-2}, Table 4). The significantly higher CH_4 uptake in the CT plot during certain of the crop growth periods (<40 days after the sowing of soybeans and >40 days after the sowing of barley) may have been mainly caused by increased CH_4 absorption into the soil because of a higher gas diffusivity of the plowed soil layer and/or greater CH_4 oxidation because of a lower N content in the topmost soil layer.

The accumulated mineral N in the uppermost soil layer in the NT plot may have reduced the CH_4 oxidation activities, especially during the winter seasons (Nishimura et al. 2005b; Fender et al. 2012) because the topsoil is responsible for most of the CH_4 uptake. At the same time, the sustained higher soil moisture and the greater compaction in the NT plot reduce the soil gas diffusivity that drives CH_4 transfer from the atmosphere into the deeper soil. Yonemura et al. (2009) estimated that excluding rainy days, the soil gas diffusivity in the same NT plot was about one fourth of that in the CT plot, indicating that the CH_4 uptake rate was approximately half that expected from the diffusion calculation (Yonemura et al. 2000b).

The lower CH_4 uptake in the NT plot is a potential disadvantage of this approach from the perspective of the mitigation of greenhouse gas emissions. However, this disadvantage can be neglected because CH_4 uptake is low even after accounting for the net global warming potential (IPCC 2007; Table 4). Overall, the patterns of soil respiration, N_2O emission, and CH_4 uptake in our study indicated that the CH_4 uptake and the N_2O emission both decreased significantly in the NT plot and were similar to those obtained in a wetter midlatitude climate (Alvarez et al. 1998) and in a tropical climate (Matsumoto et al. 2008; Mosier et al. 1998).

Conclusions

We investigated 4 years of emissions of three greenhouse gases (CO_2, N_2O, and CH_4) in NT and CT plots set in a typical Japanese field with volcanic soil under a wet temperate climate. Our results indicate that NT management is generally effective for the mitigation of the total GWP through reduced soil respiration and N_2O emission in temperate regions. The N_2O emission decreased significantly in the NT plot (Fig. 2), although the CH_4 uptake also decreased significantly in this plot (Fig. 3; Tables 2 and 4). The decreased N_2O emission is a clear advantage of this approach from the perspective of mitigating greenhouse gas emissions (Table 4). Soil respiration (CO_2 emission) was significantly lower in the NT plot (Fig. 2, Tables 2 and 3), suggesting that NT practices could cause the fields to act as a C sink even though the dry matter production in the NT plot was often significantly lower than that in the CT plot (Tables 1 and 3).

In wetter weather, the NT benefits of reduced soil respiration and N_2O emission may be limited or nonexistent, as in the summer of 2003. In the long term, unusually high soil moisture, as in the summer of 2003, may cause sudden increases in soil respiration and releases of C from NT fields from C stored in the topsoil, which normally contains less moisture. These increased emissions under cool, wet conditions demonstrate the importance of drainage whenever NT is practiced in wet regions.

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