Carbon Dioxide and Nitrous Oxide Content in Soils under Corn and Soybean

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Agricultural practices affect the production and emission of CO_2 and N_2O from soil. The purpose of this 2-yr field study was to determine the effects of tillage (conventionally tilled [CT] and no-till [NT]) and fertilizer source (composted cattle manure and inorganic N–P–K fertilizer) on the CO_2 and N_2O content in soil profiles under corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. The mean CO_2 and N_2O gas contents (i.e., mass of gas per unit soil volume) in the soil profile were determined periodically during two field seasons by sampling the soil atmosphere using plastic tubes installed at three depths (10, 20, and 30 cm) within the crop row. The soil CO_2 content was greater in CT than NT soil and in manure-amended than inorganically fertilized plots during 1 yr of the study. The soil N_2O content was not affected by tillage practices or fertilizer sources. A significant autocorrelation between sampling dates in both years suggested that the CO_2 and N_2O contents in the soil profile were not erratic or random, but temporally dependent on site-specific factors. The peak CO_2 and N_2O levels were measured within 50 d after seeding, probably because soil moisture conditions slowed diffusive gas flux but were favorable for microbial activity. Fluctuations in soil CO_2 and N_2O contents were not related to the seasonal variation in soil temperature. At most sampling dates, there was a significant ($P < 0.05$) positive correlation between the CO_2 and N_2O content in the soil profile, suggesting similarity in the rate of gas accumulation and diffusive flux for CO_2 and N_2O in soils. The CO_2 and N_2O content in the soil profile appeared to be controlled more by soil moisture than soil temperature or agricultural practices.

Abbreviations: CT, conventionally tilled; DAS, days after seeding; NT, no-till; WFPS, water-filled pore space.

Rising greenhouse gas concentrations in the earth's atmosphere have the potential to affect global climate adversely. Agricultural emissions account for about 10 to 12% of the anthropogenic greenhouse gases emitted worldwide (Smith et al., 2007). The net flux of CO_2 between the atmosphere and agricultural lands is approximately balanced, but N_2O emissions from agriculture represent about 60% of global anthropogenic emissions (Smith et al., 2007). Reducing the amounts of CO_2 and N_2O released from agricultural soils into the atmosphere is possible by careful selection of agricultural practices. Subsurface processes affect the rates of CO_2 and N_2O production, transport, and emission from soils. It is relatively labor intensive to investigate in situ processes, but detailed characterization of soil gases is useful for two reasons: (i) it provides information about where CO_2 and N_2O are produced in the soil profile and when; and (ii) it allows more accurate prediction of feedbacks on the ecosystem-level C and N balances resulting from agricultural practices such as tillage, fertilizer applications, and cropping systems.

The activity of decomposer organisms is stimulated by tillage, which fragments and incorporates plant residues in the plow layer and disrupts soil aggregates, thus increasing the pool of readily mineralizable organic substrates (Adu and Oades, 1978; Reicosky and Lindstrom, 1993; Beare et al., 1994). The accelerated loss of soil C following tillage is also related to changes in soil porosity. Gregorich et al. (2006) concluded that the change in resource availability and soil environmental conditions induced by tillage had a profound effect on CO_2 and N_2O emissions, more so than any differences in the functional capacity of soil microbial communities in CT and NT systems. Soils under NT have larger and more anaerobic soil aggregates than plowed soils, microsites where denitrifying bacteria may be active (Grevers and de Jong, 1982; Aulakh et al., 1984). Doran (1980) found that denitrifier populations were 7.3 times larger in the profile of NT soils than CT soils, while Aulakh et al. (1984) reported denitrifier counts between 1.3 and 6.6

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times higher in NT soils than CT soils. Yet there is considerable variation in the N_2O production in agroecosystems, and many researchers have reported no difference in the N_2O fluxes from CT and NT systems (Kessavalou et al., 1998; Gregorich et al., 2005; Grandy et al., 2006; Parkin and Kaspar, 2006).

Fertilization increases the amount of N available for microbial processes such as organic matter decomposition, mineralization, nitrification, and denitrification and may increase CO_2 and N_2O fluxes in diverse ecosystems and climate zones (Brumme and Beese, 1992; Crill et al., 2000). Kowalenko et al. (1978) and Rochette and Gregorich (1998), however, reported no difference in CO_2 fluxes from N-fertilized soils and unfertilized soils, perhaps because N fertilizer additions do not stimulate decomposition unless fresh organic residues are present. In corn agroecosystems, Drury et al. (2006) found that CO_2 fluxes were unaffected by the depth of N fertilizer placement, but less N_2O was emitted with shallow fertilizer placement (2-cm depth) than deep placement (10 cm). Soil moisture increased with depth, which led to periodic anaerobic conditions that promoted the conversion of fertilizer N to N_2O through denitrification.

Organic fertilizers may also stimulate N_2O production by increasing the soil NO_3–N content and by providing soluble C that serves as an electron donor in the denitrification process (Bowman and Focht, 1974; Myrold and Tiedje, 1985). In addition, the decomposition of readily mineralizeable C substrates can deplete the soil O_2 supply, creating microsites favorable for denitrifying bacteria (Parkin, 1993; Flessa and Beese, 1995). Inorganic N fertilizer applications that increase the mineral N content in soil solution may enhance the production of N_2O from nitrification (Bowman and Focht, 1974) or denitrification when the soil water content is sufficiently high (Aulakh et al., 1984; Cates and Keeney, 1987; Sehy et al., 2003). In eastern Canada, Drury et al. (1998) found that twice as much N_2O was evolved from soils receiving 16.8 kg N ha^{-1} as NH_4NO_3 fertilizer than from unfertilized soils.

The annual and seasonal fluxes of CO_2 are affected by the amount, type, and timing of crop residue incorporation (Jacinthe et al., 2002). In their analysis of C sequestration rates using a global database of 67 long-term agricultural experiments, West and Post (2002) noted that the continuous corn system yielded more plant residue and hence a greater C input than corn–soybean rotations, but changing from continuous corn to a corn–soybean rotation did not change soil C sequestration, suggesting that more CO_2 was lost from the continuous corn system than the corn–soybean rotation. Leguminous plants such as soybean may induce higher levels of N_2O production in the soil directly, by rhizobia denitrification (O'Hara and Daniel, 1985), or indirectly, by increasing inputs of N to the soil and thereby increasing the substrate pool for nitrification and denitrification (Ta et al., 1986). Nitrous oxide production was greater in soils amended with leguminous plant residues than corn residue (McKenney et al., 1993); however, Rochette and Janzen (2005) determined that much of the increase in soil N_2O emissions in legume crops may be attributable to the N release from decomposition of crop residues after harvest rather than from biological N_2 fixation. In a 3-yr study in eastern Canada, Gregorich et al. (2008) found that annual N_2O emission from soil under soybean was lower than that from soil under corn, indicating that biological N_2 fixation does not appear to substantially contribute to the annual N_2O emission.

These studies illustrate that tillage, fertilization, and cropping system may or may not alter the CO_2 and N_2O emissions from soils, depending on local conditions. Less is known about how these agricultural practices affect the size and dynamics of CO_2 and N_2O pools in the soil profile. These pools represent the CO_2 and N_2O stored in soils, which should be considered with the plant canopy when calculating gas fluxes and net ecosystem exchange (Flechard et al., 2007). The objective of this study was to investigate the effects of tillage and fertilizer sources on CO_2 and N_2O content in the soil profile of corn and soybean agroecosystems during two growing seasons. Temporal variation in the CO_2 and N_2O content, related to temperature and moisture fluctuations in the soil profile, was also determined. The null hypothesis was that subsurface CO_2 and N_2O contents would not be affected by agricultural practices or soil conditions, but we expected that soil gas content would vary during the growing season.

MATERIALS AND METHODS

Research Site

The study was conducted at the Macdonald Research Farm of McGill University, located at Ste-Anne-de-Bellevue, Québec, from June 2002 to September 2003. The soil was a mixed, frigid Typic Endoaquent of the Courval series containing 700 g kg^{-1} of sand and 160 g kg^{-1} of clay with 15.4 g organic C kg^{-1} and a pH of 6.1 in the top 15 cm. The sandy loam layer (28-cm mean thickness) was underlain by sand (6-cm mean thickness) and clay starting at depths below 34 cm, on average.

Experimental Design

The plots selected for this study were part of a larger field experiment described by Whalen et al. (2003). Briefly, the experiment was laid out in a factorial (tillage × crop rotation) split-plot (fertilizer source) design in May 2000. The factorial main plots were 20 by 24 m, and were arranged in a randomized complete block design with four blocks. Each main plot was split into four 20- by 6-m subplots that received fertilizer treatments. Four factorial treatments were considered in this study, combinations of two tillage treatments (CT or NT) and two crop types (corn from a continuous corn system and soybean from a corn–soybean rotation). Two fertilizer treatments (inorganic N–P–K fertilizer and composted cattle manure) from the subplots were also included, for a total of 32 experimental plots.

The CT plots were tilled with a tandem disk (10-cm depth) each spring before seeding and with a moldboard plow (20-cm depth) each fall after harvest; there was no tillage disturbance in the NT plots. The split plots with the composted cattle manure treatment received a surface application of 45 Mg ha^{-1} (wet-weight basis) to supply 45 kg P ha^{-1}, which was incorporated in the CT treatment or left on the surface of the NT treatment before seeding. The compost contained, on average, 401 g total C kg^{-1}, 20.7 g total N kg^{-1} (Carlo Erba Flash EA NC Soils Analyzer, Milan, Italy), 2.3 g total P kg^{-1} (H_2SO_4–H_2O_2 digestion [Parkinson and Allen, 1975]), and 0.66 kg H_2O kg^{-1} (105°C for 48 h).

Silage corn ('Cargill 2610') treated with fludioxinil [4-(2,2-difluoro-1,3-benzodioxol-4-yl)-1*H*-pyrrole-3-carbonitrile] and captan [3a,4,7,7a-tetrahydro-2-[(trichloromethyl)thio]-1*H*-isoindole-

1,3(2*H*)-dione] was planted at a rate of 75,000 seeds ha^{-1}. Soybean ('Cargill A086TR') treated with *Bradyrhizobium japonicum* was planted at a rate of 400,000 seeds ha^{-1}. All plots were seeded in the first week of June 2002 and 2003 with a John Deere 7100 MaxEmerge seeder (Deere & Co., Moline, IL). All corn plots received 50 kg N ha^{-1} of NH_4NO_3 banded at seeding. Plots receiving the inorganic N–P–K fertilizer treatments also had 45 kg P ha^{-1} from triple superphosphate banded at seeding; an additional 150 kg N ha^{-1} from NH_4NO_3 and 125 kg K ha^{-1} from potash was sidedressed at the four- to five-leaf stage (about 1 mo after seeding). We did not add NH_4NO_3 or KCl fertilizers to subplots with the compost treatment at this stage of corn development because we assumed that 25% of the N (about 150 kg N ha^{-1}) and at least 25% of the K (135 kg K ha^{-1}) in the compost was available for corn uptake during the growing season (Eghball et al., 2002). Soybean plots under compost treatment received 45 Mg ha^{-1} (wet weight) of composted cattle manure, while those grown in the split plots with the inorganic N–P–K fertilizer treatment received no NH_4NO_3 fertilizer. In the soybean plots, 45 kg P ha^{-1} from triple superphosphate was banded at seeding and 125 kg K ha^{-1} from potash was applied about 1 mo after seeding.

Soil Measurements

Soil bulk density was determined before gas sampling tube installation in June 2002 and after harvest in September 2003. Undisturbed soil cores (3 cm long by 5.5-cm i.d.) were collected from the 0- to 10-, 10- to 20-, and 20- to 30-cm depths in the planted row of eight plots selected randomly to represent each tillage × crop × fertilizer treatment. Bulk density was determined after drying cores at 105°C for 48 h. On average, bulk density in the soil profile (0–30 cm depth) was 1.27 g cm^{-3} in the CT plots and 1.29 g cm^{-3} in the NT plots. Porosity was calculated from the average bulk density, assuming a particle density of 2.65 g cm^{-3}.

Soil temperature and moisture were recorded on each gas sampling date from eight plots representing one replicate of each tillage × crop × fertilizer treatment. Temperature in the soil profile was measured using thermocouples installed at three depths (10, 20, and 30 cm) in the planted row. Soil cores (30-cm length, 3-cm i.d.) were collected from the eight plots described above, at three soil depths (0–10, 10–20, and 20–30 cm), and the moisture content was measured gravimetrically (105°C for 48 h). The average temperature and moisture in the soil profile (0–30-cm depth) was calculated; then we converted gravimetric water content to water-filled pore space (WFPS, m^3 m^{-3}), correcting for differences in soil bulk densities between treatments.

Gas Sampling

Polystyrene tubes (0.3-cm i.d.) were installed on 19 June 2002 and 23 June 2003 at three depths (10, 20, and 30 cm) in the planted rows of each experimental plot (3 tubes per plot × 32 plots = 96 tubes installed across the field site). The belowground end of the tube was covered with a plastic mesh (≤1 mm) to prevent soil from entering and blocking the tube. The aboveground portion of the tube was fitted with a one-way male slip stopcock (Cole-Parmer Instrument Co., Vernon Hills, IL). After removing the air in the headspace of tubes with a gas-tight syringe, 25 mL of air from the soil profile was transferred into previously evacuated 12-mL Exetainers (Labco, High Wycombe, UK). Gas samples were taken at 7- to 12-d intervals from June to September, for a total of 10 sampling dates in 2002 and nine sampling dates in 2003. Gas samples were analyzed with a gas chromatograph (Varian Model 3800, Walnut Creek, CA) equipped with automated valve injectors to simultaneously quantify CO_2, N_2O, and O_2 concentrations (expressed in μL L^{-1} units). A Haysep A column followed by a molecular sieve and He carrier at 46 mL min^{-1} were used to separate CO_2 from O_2, whereas N_2O was quantified on a Porapak Q column with Ar/CH_4 (90:10) carrier gas at 20 mL min^{-1} (Rochette and Hutchinson, 2005).

Gas Content in the Soil Profile

To correct for differences in porosity and water content between treatments, gas concentrations were converted to volumetric concentration in the total soil volume. This conversion assumes that the gases in the air and liquid phases are in equilibrium at the time of sampling. Calculations to convert soil gas concentrations (μL L^{-1}) to gas content (mg m^{-3}) in the 0- to 30-cm soil profile were adapted from Christian and Cranston (1997). The number of moles in the gaseous state of the soil volume (n_g) was calculated from the ideal gas equation, while the number of moles of gas (n_w) in the dissolved phase was defined as

$$n_w = 10^{-6}\frac{C_g P \beta V_w}{RT_1} \quad [1]$$

where C_g is the gas concentration (μL L^{-1}) from the gas chromatograph, P is the atmospheric pressure at which gas samples are analyzed (~1 atm), β is the Bunsen coefficient accounting for the solubility of the gas in soil water, V_w is the volume of water (L) in the soil sample, which varied due to changes in the soil moisture content, R is the ideal gas constant (0.082 L atm mol^{-1} K^{-1}), and T_1 (K) is the temperature in the soil profile. The Bunsen coefficients of CO_2, N_2O, and O_2 were a function of soil temperature, which accounts for gases dissolved in soil water (Glinski and Stepniewski, 1985; Tiedje, 1994). The gas content per unit volume of soil (mg m^{-3}) in the profile (0–30 cm) was calculated with correction for differences in air-filled pore space between CT and NT plots.

Statistical Analysis

Owing to the sequential nature of gas sampling from the field site, repeated measures analysis was conducted using the PROC MIXED feature of the SAS statistical software package (SAS System 9.1, SAS Institute, Cary, NC). The general procedure for mixed models was outlined by Littell et al. (1998). Covariance structures were compared objectively using the Bayesian information criterion and the Akaike information criterion, and we determined that the autoregressive AR (1) covariance structure provided the best fit for our model with the least complexity. This analysis yielded estimates of autocorrelation coefficients between sampling dates. Treatment effects (tillage, crops, and fertilizer) on CO_2 and N_2O content in the soil profile were then evaluated and tested for significance at the 95% confidence level using the Tukey–Kramer test (Steel et al., 1997). The PROC CORR function of SAS was used to determine the Pearson correlation coefficients (r) between CO_2, O_2, and N_2O content in the soil profile at each sampling date at significance levels of $P < 0.05$, 0.01, and 0.001.

RESULTS AND DISCUSSION

Carbon Dioxide and Nitrous Oxide Content in the Soil Profile: Temporal Variation

The 2002 season was characterized by a cool, wet spring followed by relatively hot and dry conditions in August and September, while the 2003 season was more like the 30-yr average for this region (Table 1). Soil water content ranged from 46 to 67% WFPS during the first month of 2002, but never

Table 1. Monthly averages for temperature and precipitation at the Pierre Elliott Trudeau International Airport climate station during the 2002 and 2003 field seasons. Long-term averages (1971–2000) for precipitation and temperature are also provided (Environment Canada, 2004).

Month	Monthly precipitation			Daily average air temperature		
	2002	2003	30-yr avg.	2002	2003	30-yr avg.
	mm			°C		
June	106.0	70.0	87.5	17.5	18.8	19.3
July	55.0	54.0	106.2	22.1	21.6	22.3
August	11.0	79.0	100.6	21.8	21.6	20.8
September	86.5	104.0	100.8	18.3	17.7	15.7
Total	258.5	307	395.1			

exceeded 50% WFPS during 2003 (Fig. 1). As expected, the CO_2 and N_2O content in the soil profile varied during the growing seasons, with higher contents during the first month of gas sampling for both 2002 and 2003 (Fig. 1 and 2). The mean CO_2 content in the soil profile was about 1.4 times greater and the mean N_2O content in the soil profile was about 11 times greater during the 2002 season than the 2003 season (Fig. 1 and 2).

The effect of soil water content on CO_2 in soil profiles was described by Skopp et al. (1990) as a delicate balance between having sufficient water for substrate diffusion and microbial requirements and adequate O_2 for respiration. Microbial respiration reaches a maximum when WFPS is between 50 and 75% (Linn and Doran, 1984). Soil water content is a key controller of microbially mediated gaseous N production because it affects microbial metabolism as well as the solubility and availability of substrates (organic C, NH_4, and NO_3) used in nitrification and denitrification reactions (Weitz et al., 2001). Production of N_2O declines rapidly when soil water content falls below 60% WFPS, as denitrification activity decreases with increasing O_2 availability (Linn and Doran, 1984; Davidson, 1991).

Soil temperature ranged from 14 to 25°C during the periods studied (Fig. 1), but fluctuations in the gas content of the soil profile were not related to soil temperature. One peak in CO_2 content that occurred 60 days after seeding (DAS) in the 2002 season appeared to correspond with an increase in soil temperature (Fig. 1 and 2) but was not different from the CO_2 content in the soil profile at the sampling events immediately preceding or following this peak. No peak in N_2O production coincided with an increase in soil temperature (Fig. 1 and 3). During the growing season, the effect of temperature on gas content in the soil profile is often negligible unless substrates are abundant and the soil water content is optimal for microbial processes (Rochette and Gregorich, 1998; Akiyama and Tsuruta, 2003).

Repeated measures analysis of the time-series data collected during this study revealed significant autocorrelation in time (Box and Jenkins, 1976). For a lag time of 2 wk, we observed autocorrelations of 0.64 and 0.47 for successive measures of CO_2 and N_2O, respectively, in 2002, while in 2003 the autocorrelations were 0.91 for CO_2 and 0.90 for N_2O contained in the soil profile. The autocorrelation values were lower in 2002 because there was greater variation in soil moisture content during the 2002 season than the 2003 season (Fig. 1). Autocorrelation indicates that variation in CO_2 and N_2O content in the soil profile was not erratic or random, but depended on site-specific factors. Hence, a sampling location with conditions that stimulated gas production (e.g., high resource availability, active soil microbial community, and favorable soil environment) at any sampling date continued to be a "hot spot" for gas production for the next 2-wk sampling interval. It may be possible to reduce the number of replicate gas samples during the crop growing period without compromising the reliability of the results, thus allowing researchers to intensifying sampling efforts earlier in the season when soil water content is highest. This possibility should be investigated using longer lag times.

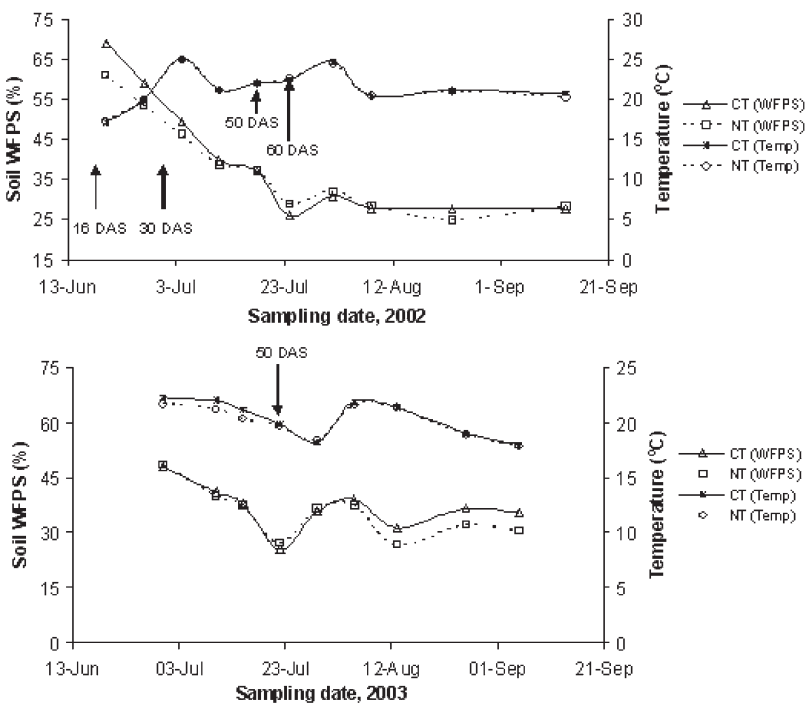

Fig. 1. Temperature (Temp) and water-filled pore space (WFPS) in the soil profile (0–30 cm) of conventionally tilled (CT) and no-till (NT) plots during the 2002 and 2003 growing seasons. Arrows point to specific days after seeding (DAS).

Carbon Dioxide and Nitrous Oxide Content in the Soil Profile: Correlation with Oxygen Content

The CO_2 and O_2 content in the soil profile were negatively correlated ($P < 0.05$) on 9 of 10 sampling dates in 2002 and all sampling dates in 2003 (Table 2). This suggests that aerobic respiration depleted the O_2 in the soil profile. The strength of the correlation may indicate the amount of O_2 depleted during aerobic respiration, but may also be related to the fact that CO_2 is more soluble than O_2 in soil water (Glinski and Stepniewski, 1985), which creates an imperfect stochiometry between the gases. Soils were not saturated at any sampling date during this study, which would favor O_2 diffusion in the air-filled pore space of the soil profile.

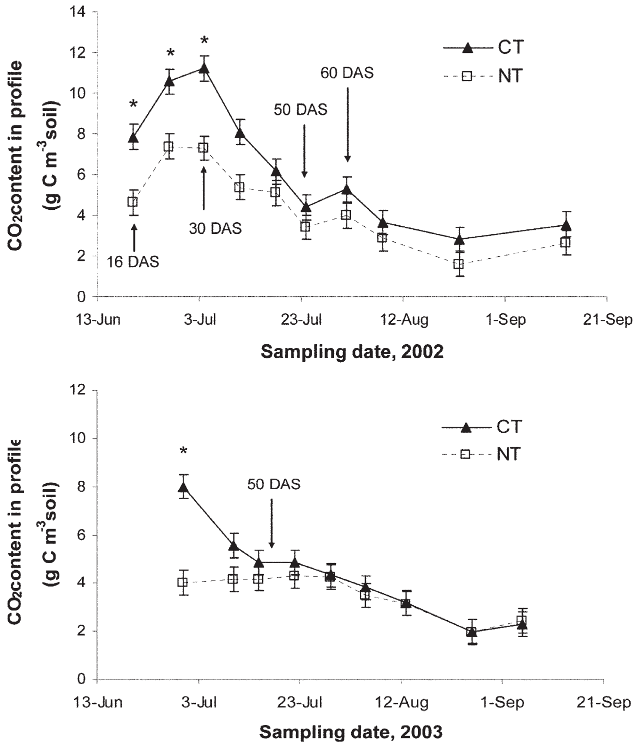

Fig. 2. Variation in CO_2 content in the soil profile (0–30 cm) of conventionally tilled (CT) and no-till (NT) plots during the 2002 and 2003 growing seasons. Vertical bars represent standard errors. Arrows point to specific days after seeding (DAS). *Significantly different at $P < 0.05$.

The N_2O and O_2 contents in the soil profile were negatively correlated ($P < 0.05$) on half of the sampling dates (five in 2002, four in 2003), and more often on sampling dates early in the growing season (Table 2). No relationship was observed, however, between N_2O and O_2 on 16 DAS in the 2002 season, possibly because soil moisture content >60% WFPS may favor denitrification to N_2 rather than N_2O gas (Kiese and Butterbach-Bahl, 2002). The negative correlation between N_2O and O_2 content in the soil profile suggests that anaerobic conditions favoring denitrification existed until 44 DAS in the 2002 season and 49 DAS in the 2003 season. Fertilizer inputs before seeding and about 1 mo after seeding could supply NO_3–N for denitrification, while the C source could be from root exudates or decomposing organic matter. The soil environment was generally drier and hotter in the later part of both growing seasons, and it could be that N_2O production in the soil profile came from nitrification, an aerobic process (Davidson, 1991). Further work is needed to clarify the relationship between N_2O and O_2 content in the soil profile.

Finally, the CO_2 and N_2O contents in the soil profile were positively correlated throughout the 2002 season and on five of nine sampling dates in the 2003 season (Table 2). These results may suggest that diffusional constraints in the soil profile control the accumulation of these gaseous products of microbial metabolism. Nitrogen mineralization and subsequent nitrification may be responsible for some portion of the N_2O in the soil profile (in dry soils during the later part of both growing seasons). Aerobic respiration and denitrification may occur simultaneously in aerobic upland soils within

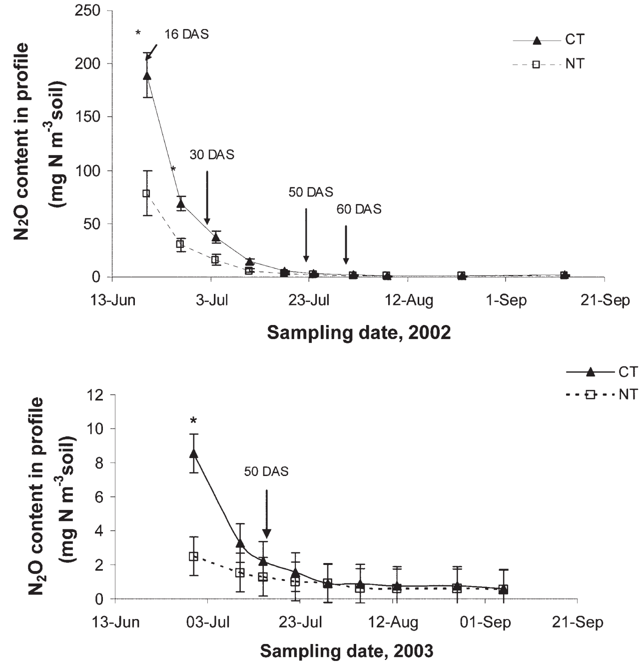

Fig. 3. Variation in N_2O content in the soil profile (0–30 cm) of conventionally tilled (CT) and no-till (NT) plots during the 2002 and 2003 growing seasons. Vertical bars represent standard errors. Arrows point to specific days after seeding (DAS). *Significantly different at $P < 0.05$.

Table 2. Pearson correlation coefficients (r) between CO_2, N_2O, and O_2 content in the soil profile (0–30-cm depth) of corn and soybean agroecosystems in Quebec, Canada (n = 32). Data were collected during the 2002 and 2003 growing seasons.

Days after seeding	CO_2 vs. N_2O	CO_2 vs. O_2	N_2O vs. O_2
	2002		
16	0.46**	−0.85***	−0.33 NS
23	0.56***	−0.90***	−0.58***
30	0.64***	−0.95***	−0.74***
37	0.78***	−0.93***	−0.74***
44	0.77***	−0.90***	−0.66***
50	0.59***	−0.70***	−0.08 NS
58	0.60***	−0.05 NS	−0.16 NS
65	0.60***	−0.63***	−0.32 NS
80	0.61***	−0.83***	−0.46*
101	0.63***	−0.47**	−0.23 NS
	2003		
27	0.66**	−0.77***	−0.94***
37	0.86***	−0.84***	−0.74**
42	0.83***	−0.84***	−0.57*
49	0.74***	−0.93***	−0.64**
56	−0.29 NS	−0.76***	0.03 NS
63	0.53*	−0.69**	−0.14 NS
71	0.45 NS	−0.80***	−0.21 NS
84	0.45 NS	−0.76***	−0.17 NS
94	0.30 NS	−0.62**	−0.05 NS

* Significance at the $P < 0.05$ level. NS = not significant.

** Significant at the $P < 0.01$ level.

*** Significant at the $P < 0.001$ level.

Table 3. Analysis of variance for sampling date and main-plot (tillage and crop) and subplot (fertilizer) effects on CO_2 and N_2O content in the soil profile (0–30-cm depth). Data were collected from corn and soybean agroecosystems in Quebec, Canada, during the 2002 and 2003 growing seasons.

Effect	2002					2003				
	df	CO_2		N_2O		df	CO_2		N_2O	
		F	$P > F$	F	$P > F$		F	$P > F$	F	$P > F$
Date	9	22.18	<0.0001	10.93	<0.0001	8	24.08	<0.0001	10.43	<0.0001
Tillage	1	14.38	0.0006	1.34	0.2799	1	1.49	0.2436	0.63	0.4393
Crop	1	0.01	0.9313	0.47	0.5121	1	3.88	0.0701	0.10	0.7534
Fertilizer	1	18.35	0.0002	2.19	0.1631	1	2.27	0.1563	0.00	0.9455

anaerobic microsites (Parkin, 1993; Abbasi and Adams, 1998; Drury et al., 1998; Gregorich et al., 2006).

Carbon Dioxide and Nitrous Oxide Content in the Soil Profile: Effect of Tillage, Crop, and Fertilizer

The ANOVA describing the significance of sampling date, tillage, crop, and fertilizer treatments on the CO_2 and N_2O contents in the soil profile is shown in Table 3. The CO_2 and N_2O contents in the soil profile were affected by the sampling date ($P < 0.0001$), as presented in Fig. 2 and 3 and discussed above. We found that tillage, fertilizer treatment, and the tillage × crop interaction ($P = 0.0216$) all had a significant ($P < 0.05$) effect on the CO_2 content in the soil profile during 2002 (Table 3). There was a marginal crop effect ($P = 0.0701$) on the CO_2 content in the soil profile during 2003, but agricultural practices (singly or interactively) did not affect the N_2O content in the soil profile during either season (Table 3).

There was more CO_2 in the CT soil profiles than in NT soil profiles during 2002, especially during the first month after seeding (Fig. 2). We also observed significantly ($P < 0.05$) more CO_2 in the soil profile at the first sampling event in 2003 (Fig. 2). These results point to tillage-induced C mineralization and loss of C from soil organic matter and crop residues shortly after the spring tillage event. This is consistent with Franzluebbers et al. (1995), who reported 9 to 12% greater CO_2 emissions in CT plots than NT plots under a soybean–corn–wheat (*Triticum aestivum* L.) rotation. The physical process of tillage incorporates plant residues and manure into the soil, and also makes previously protected organic materials more accessible to the decomposers.

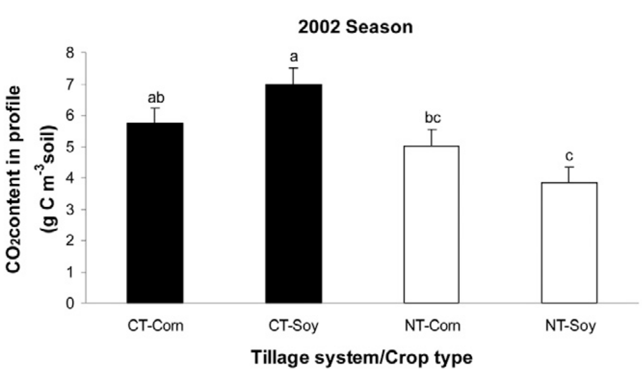

Fig. 4. The average CO_2 content in the soil profile (0–30) of corn and soybean plots under two tillage systems (conventionally tilled [CT] and no-till [NT]) during the 2002 growing season. Vertical bars represent standard errors and bars with the same letter were not significantly different ($P < 0.05$, Tukey's test).

Many researchers reported that the soil environment is more conducive to denitrification in NT than CT systems due to factors such as increased substrate availability and higher water content, which result in more anaerobic microsites (Grevers and de Jong, 1982; Aulakh et al., 1984; Lal, 1989). Only at the first sampling date of 2003 did we observe a significant ($P < 0.05$) difference in the N_2O content of the soil profile due to tillage, and it was the CT soils that had a greater N_2O content than the NT soils (Fig. 2). This observation is consistent with that of Gregorich et al. (2006), who observed higher N_2O fluxes on CT than NT soils after addition of a labile C substrate. Soil aggregation was greater in NT soil than CT soil in the first and second year after plot establishment (Whalen et al., 2003), which led to slightly greater bulk density and less air-filled pore space in the NT system, but this did not seem to affect the N_2O content in the soil profile. While some NT soils may be susceptible to O_2 depletion after rainfall and when decomposers are very active, it is less likely in coarse-textured soils and those recently converted to NT (Six et al., 2004; Gregorich et al., 2005; Grandy et al., 2006; Parkin and Kaspar, 2006). This study was established on a sandy loam soil and had only been under NT management for 2 to 3 yr at the time of this study; additional years of study would be necessary to examine how the N_2O content in the soil profile is affected as physical characteristics change in the NT soils.

Overall, the specific crop did not affect the CO_2 and N_2O content in the soil profile except that corn plots tended to have a greater CO_2 content ($P = 0.0701$) than soybean during 2003 (Table 3). All plots were under corn production the previous year (2002), with similar yields and residue input (Whalen et al., 2007), so differences in the soil CO_2 content were attributed to the crops grown in 2003. The soil profile under corn probably had greater root biomass and more rhizodeposition than that under soybean (Kogel-Knabner, 2002; Johnson et al., 2006). We expected more respiration (from roots and decomposers) in the soil profile of corn plots than soybean plots, but these crop-specific rhizosphere effects may have been obscured by the presence of weeds in all plots.

There was a significant ($P < 0.05$) tillage × crop interaction in 2002, where CT soils under soybean production had a greater mean CO_2 content in the soil profile than NT soils (Fig. 4). We found that the lack of seedbed preparation in the NT soil impeded soybean root growth and led to a significantly ($P < 0.05$) lower yield in the NT system than the CT system in 2002, but corn growth and yield was not affected by the tillage system in 2002 (Whalen et al., 2007). This is further evidence that crop roots may influence the CO_2 content in the soil profile, but this needs to be confirmed with additional field studies.

Finally, the CO_2 content in the soil profile was greater in plots receiving organic fertilizer (composted cattle manure) than inorganic fertilizer in the first month of the 2002 season (Fig. 5). This may be related to the presence of readily decomposable C from organic fertilizer (Rochette and Gregorich, 1998; Rochette et al., 2006). Increasing the labile organic C pool can also stimulate denitrification and generate more N_2O when there is sufficient NO_3–N and anaerobic conditions (Drury et al., 1998). Fertilizer treatments did not affect the N_2O content in the soil profile (Table 3), suggesting that the quantities of organic C, NO_3–N, and other nutrients supplied by the fertilizer sources were not sufficient to deplete the O_2 content, stimulate denitrification, and thereby increase the soil N_2O content.

CONCLUSIONS

The temporal pattern in CO_2 and N_2O storage within soils at this site was probably controlled by soil moisture; other factors affecting the subsurface CO_2 and N_2O storage at this site remain to be identified. The CO_2 and N_2O levels peaked during the first 50 DAS, probably because soil moisture conditions slowed diffusive gas flux but were favorable for microbial activity. Soil temperature did not have much effect on subsurface processes that caused CO_2 and N_2O to be produced and retained in the soil profile during the growing season. Further research is needed to distinguish the contribution of nitrification and denitrification processes to the soil N_2O pool. The agricultural practices established 2 to 3 yr earlier at this site did not consistently affect the CO_2 and N_2O content in the soil profile. How long it would take to alter the CO_2 and N_2O storage in soils at this site by adopting recommended practices such as NT in order to control gas fluxes and mitigate greenhouse gas emissions remains to be determined.

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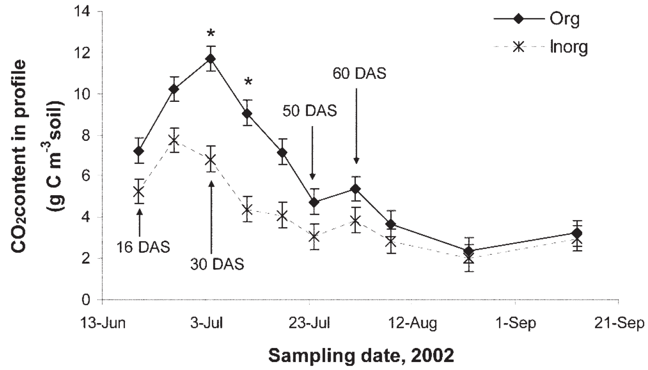

Fig. 5. Variation in CO_2 content in the soil profile (0–30 cm) of plots receiving compost (Org) and inorganic fertilizer (Inorg) during the 2002 growing season. Vertical bars represent standard errors. Arrows point to specific days after seeding (DAS). *Significantly different at $P < 0.05$.

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