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Net Global Warming Potential and Greenhouse Gas Intensity in Irrigated Cropping Systems in Northeastern Colorado

Arvin R. Mosier, Ardell D. Halvorson,* Curtis A. Reule, and Xuejun J. Liu

ABSTRACT

The impact of management on global warming potential (GWP), crop production, and greenhouse gas intensity (GHGI) in irrigated agriculture is not well documented. A no-till (NT) cropping systems study initiated in 1999 to evaluate soil organic carbon (SOC) sequestration potential in irrigated agriculture was used in this study to make trace gas flux measurements for 3 yr to facilitate a complete greenhouse gas accounting of GWP and GHGI. Fluxes of CO_2, CH_4, and N_2O were measured using static, vented chambers, one to three times per week, year round, from April 2002 through October 2004 within conventional-till continuous corn (CT-CC) and NT continuous corn (NT-CC) plots and in NT corn–soybean rotation (NT-CB) plots. Nitrogen fertilizer rates ranged from 0 to 224 kg N ha^{-1}. Methane fluxes were small and did not differ between tillage systems. Nitrous oxide fluxes increased linearly with increasing N fertilizer rate each year, but emission rates varied with years. Carbon dioxide efflux was higher in CT compared to NT in 2002 but was not different by tillage in 2003 or 2004. Based on soil respiration and residue C inputs, NT soils were net sinks of GWP when adequate fertilizer was added to maintain crop production. The CT soils were smaller net sinks for GWP than NT soils. The determinant for the net GWP relationship was a balance between soil respiration and N_2O emissions. Based on soil C sequestration, only NT soils were net sinks for GWP. Both estimates of GWP and GHGI indicate that when appropriate crop production levels are achieved, net CO_2 emissions are reduced. The results suggest that economic viability and environmental conservation can be achieved by minimizing tillage and utilizing appropriate levels of fertilizer.

Converting atmospheric CO_2 into stable organic carbon pools in the soil can sequester CO_2, while commonly used crop production practices generate CO_2 and N_2O and decrease the soil sink for atmospheric CH_4. The overall balance between the net exchange of these gases constitutes the net global warming potential (GWP) of a crop production system (Robertson and Grace, 2004). Typically agricultural soils vary from being minor emitters of CH_4 to small sinks for atmospheric CH_4 (Bronson and Mosier, 1993). Nitrous oxide, the principal non-CO_2 greenhouse gas emitted from soils, is produced naturally in the soil through nitrification and denitrification. Nitrogen fertilizer input to facilitate crop production augments this production. It is the relationship of soil C changes relative to N_2O emissions that typically regulates net GWP (Robertson et al., 2000).

Carbon dioxide emissions from fossil fuel combustion contribute approximately 50% of total GWP globally, while CH_4 (16%) and N_2O (5%) contribute about 20% to GWP from all sources (Intergovernmental Panel on Climate Change, 2001). Globally, anthropogenic sources of N_2O and CH_4 are dominated by agriculture and sum to 7.7 Pg CO_2 equivalents yr^{-1} (Robertson and Grace, 2004); this is close to the annual global atmospheric loading rate for CO_2 of 8.4 Pg CO_2 yr^{-1} (Intergovernmental Panel on Climate Change, 2001). In the United States, CO_2 emitted from farming (approximately 50 Tg), N_2O emitted in crop and livestock production (approximately 300 Tg), CH_4 emitted from livestock production (approximately 160 Tg), and increased soil C storage (approximately −60 Tg) sum to approximately 450 Tg of CO_2 equivalents annually (USEPA, 2002). The net emission of CO_2 equivalents from farming activities can potentially be decreased by changing management to increase soil organic matter content (Follett, 2001) and decrease N_2O emissions (Kroeze et al., 1999). Changing from CT to NT practices typically leads to increased soil organic carbon (SOC) content in the surface 7.5 cm of soil with little change observed below that depth (West and Post, 2002).

No-till management of soils has been promoted as a practice that off-sets the GWP from emissions of N_2O and CH_4 in crop production because of its ability to sequester carbon in the soil (Cole et al., 1997; Council for Agricultural Science and Technology, 2004). In a recent analysis of available field data, Six et al. (2004) found that systems that were recently converted to NT increased GWP relative to CT practices in both humid and dry climates. After more than 10 yr under NT, cumulative GWP was reduced in both humid and dry climates. Emissions of N_2O drive much of the trend in net GWP. The limited number of data sets that are available for such analyses, and the high uncertainty associated with the N_2O flux data, dictate a high uncertainty to the GWP data. The decrease in N_2O flux with time that a system has been in NT in the Six et al. (2004) analysis is attributed to increased soil aggregation and improved aeration status. During the first few years of NT, soil bulk density in the top 30 cm may increase, but as SOC accumulates over time, soil structure improves as more stable aggregates

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Abbreviations: CT, conventional-till; CT-CC, conventional-till continuous corn; GHGI, greenhouse gas intensity; GWP, global warming potential; NT, no-till; NT-CB, no-till corn–soybean rotation; NT-CC, no-till continuous corn; SOC, soil organic carbon.

develop, and soil aeration improves concomitantly (Six et al., 2004). The resulting effect is a decrease in net GWP over time in dry and humid climate soils.

A very different picture of the effect of time under NT on GWP is given in a modeling study. Using the DAYCENT ecosystem model, Del Grosso et al. (2002) observed that during the first few years of NT, the soil decreased net GWP. Over time, as the rate of increase in SOC declined and N_2O emissions increased because of increased N availability, the net GWP increased relative to CT soils. The increase in GWP could be minimized by decreasing N fertilizer input while maintaining yield. This simulation suggests that the impact of NT on net GWP decreases over time in a dry agroecosystem. During the first 12-yr period, the change in SOC is greatest and N_2O emissions are lowest (Del Grosso et al., 2002). Over time, the rate of C sequestration declines and N_2O emissions increase because the rate of immobilization of inorganic N declines. The model predicted that the small soil CH_4 sink declines under NT because of higher soil water content. Changes in CH_4 consumption are small, however, and have little impact on net GWP estimates as demonstrated by the Robertson et al. (2000) field study. The DAYCENT model does not account for changes in soil structure following conversion to NT but does allow uniform conditions for all comparisons.

The data used in the Six et al. (2004) evaluation are, in contrast, from a variety of studies that were likely conducted using a variety of methodologies. As a result, the relative importance of improved soil structure on decreasing N_2O emission suggested by the array of field studies and the DAYCENT model projection of increased N_2O emissions over time cannot be fully evaluated at this time.

Another concept for relating agricultural practices to GWP is greenhouse gas intensity (GHGI). This term relates GWP to crop yield and is calculated by dividing GWP by crop yield (grain yield for corn). A positive GHGI number indicates a net source of CO_2 equivalents per kg of yield and a negative value indicates net sinks of GHG to the soil. Little is known about the effects of tillage and crop rotation on GHGI.

We initiated studies in 2002 to provide data to assist in DAYCENT model verification. These studies were imposed on an existing tillage, N rate, and cropping system study that began in 1999 to examine the effects of these management variables on GWP and GHGI in irrigated cropping systems. The objectives were to obtain a multi-calendar year set of data that included crop production, climate, and trace gas flux data that could be used to support ecosystem process simulation modeling. This paper presents the full data set collected over the period of April 2002 through October 2004. Part of the April 2002–March 2003 data was presented in Mosier et al. (2005) and the N_2O flux data for 2003–2004 were discussed in Liu et al. (2005).

MATERIALS AND METHODS

Site Description

The tillage by N rate experiment was initiated in 1999 at the Agricultural Research Development and Education Center (ARDEC) in northeastern Colorado near the city of Fort Collins (40°39′ N, 104°59′ W; 1530 m above mean sea level). The region has a semiarid temperate climate with typical mean temperature of 10.6°C and rainfall of 382 mm yr^{-1} (the average of 1900–2003). Corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and barley (*Hordeum vulgare* L.) are the main crops in local agriculture. The soil is a Fort Collins clay loam classified as fine-loamy, mixed, superactive, mesic Aridic Haplustalfs. The field was in CT continuous corn for 6 yr before the experiment. Selected chemical and physical properties of the soil at a 0- to 15-cm depth, sampled in October 2002, are reported in Table 1.

Experimental Design and Management

A randomized factorial experimental block with three replicates was established, with two tillage systems (CT-CC, conventional-till continuous corn; NT-CC, no-till continuous corn; and NT-CB, no-till corn–soybean rotation) and three N rates: 0, 134, and 202 kg N ha^{-1} in 2002 and 0, 67, 134, and 224 kg N ha^{-1} in 2003 and 2004. Mechanical tillage was used in the CT-CC plots (stalk shredder, disk, moldboard plow, roller-mulcher [two passes], land leveler [two passes]) for seed bed preparation. The residue was left on the soil surface of the NT-CC and NT-CB plots after harvest without mechanical tillage. Fertilizer N as urea ammonium nitrate (UAN) solution (containing 32% N) was injected to about 5 cm below the soil surface in bands spaced 33 cm apart just before planting corn in late April each year. Besides basal N application, a subsurface band application of phosphorus (0–46–0) was applied at a rate of 56 kg P ha^{-1} before planting in 1999 and 28 kg P ha^{-1} in 2004 for both CT and NT systems. Liquid starter fertilizer containing P, K, and S was applied to the seed row at planting in 2000, 2002, 2003, and 2004. A lateral move sprinkler irrigation system was used to apply water. Herbicides were used for weed control in all treatments, resulting in the plots being essentially weed-free. Biomass samples were collected in mid- to late September each year for determination of crop residue production. Grain yields were measured at physiological maturity in late October to early November each year by hand harvesting two rows 7.6 m long per plot. Plot management details for the study are provided in Halvorson et al. (2004, 2006).

Methane, Carbon Dioxide, and Nitrous Oxide Flux Measurements

Measurement of the soil–atmosphere exchange of CH_4, CO_2, and N_2O began in April 2002 (Liu et al., 2005; Mosier et al., 2005). Measurements were made one to three times per week, year-round, midmorning of each sampling day. Ten-centimeter-high vented rectangular aluminum chambers were placed in a water channel that was welded onto anchors (78.6 × 39.3 ×

Table 1. Selected soil chemical and physical properties of the study site.

Treatment†	Bulk density	SOC‡	Total soil N	pH	EC§	Sand	Clay
	g cm^{-3}	g kg^{-1}	g kg^{-1}		mS cm^{-1}	— g kg^{-1} —	
CT-CC	1.36	11.9	1.47	7.7	1.00	402	334
NT-CC	1.28	12.8	1.52	7.7	0.95	402	334
NT-CB	1.47	13.8	1.37	7.8	0.91	402	334

† CT-CC, conventional-till continuous corn; NT-CB, no-till corn–soybean rotation; NT-CC, no-till continuous corn.

‡ Soil organic carbon.

§ Electrical conductivity.

10 cm that were inserted 10 cm into the soil) at each sampling. Anchors were set perpendicular to the corn row so that the corn row and inter-row were contained within each chamber. Anchors were removed for tillage and planting operations and reinstalled near the initial locations. Duplicate flux measurements were made within each replicate of each treatment plot for a total of six measurements per treatment. Gas samples from inside the chambers were collected by syringe at 0, 15, and 30 min after installation. Gas samples (25 mL to ensure over pressure of sample in the tubes) were then injected into 12-mL evacuated tubes that were sealed with butyl rubber septa and transported to the laboratory in Fort Collins for analysis by gas chromatography. The gas chromatograph used was a fully automated instrument (Model 3800; Varian, Palo Alto, CA) equipped with thermoconductivity, flame ionization, and electron capture detectors to quantify CO_2, CH_4, and N_2O, respectively (Mosier et al., 2005). Fluxes were calculated from the linear or nonlinear increase in concentration (selected according to the emission pattern) in the chamber headspace with time (Livingston and Hutchinson, 1995).

Ancillary Measurements

Soil water content and soil and air temperature were monitored continuously at selected sites and at each trace gas sampling event using time domain reflectrometry (TDR; Mosier et al., 2002) in 2002 and soil dielectric constant (Decagon Devices, Pullman, WA) in 2003 and 2004. Soil samples (0–15 cm) were collected several times during each corn growing season and were analyzed for mineral N (ammonium and nitrate) using a continuous flow analyzer (QuikChem FIA + 8000 Series; Lachat Instruments, Loveland, CO) after extraction with 1 *M* KCl (soil to solution ratio = 1:5). The total soil C was measured by dry combustion on 0- to 7.5-cm depth air-dried soils. Soil inorganic C was determined using the method of Sherrod et al. (2002). The difference between total soil C and soil inorganic C was the estimated SOC concentration. Soil bulk density was used to convert SOC concentration to a mass basis. The date and amount of precipitation and irrigation were also recorded at the site during the study period.

Statistical Analysis

Differences in gas fluxes by tillage, N rate, and year were determined statistically (ANOVA and GLM regressions) using MINITAB (Release 13 for Windows; Minitab, 2001) and Statistix 8.0 (Analytical Software, 2005). Significant differences are expressed at $P < 0.05$, unless otherwise stated.

RESULTS AND DISCUSSION

Temperature and Water

Averaged across the entire 30-mo observation period, soil temperature did not differ by tillage, N rate, or crop rotation. However, during March–July of each year, soil temperature was significantly ($P < 0.05$) higher (1–3°C) in CT soils compared to NT soils (Fig. 1B). The same amount of irrigation was applied to CT and NT treatments and we assume that precipitation was uniform across the experimental plots (Fig. 2A and 2B). Averaged across the three growing seasons, volumetric water content (Fig. 2C) was higher (1–5%) in NT soils compared to CT. No significant differences were observed with N rate or crop rotation within NT treatments.

Trace Gas Fluxes

Methane

Neither tillage nor N rate significantly influenced CH_4 flux ($P > 0.2$). Soils were typically small sinks or small sources of CH_4, depending on the timing of sampling relative to irrigation or precipitation, except during the first two to three months of the 2002 growing season. During this period surface soils (0–10 cm) were kept very wet in attempt to moisten the very dry soil profile below. Little precipitation was received during the autumn of 2001, and winter and early spring of 2002. During this time the soils of all plots served as small sources of CH_4 to the atmosphere (Fig. 3; Table 2).

During the 2002 growing season all plots were a net source of CH_4 to the atmosphere. Flux rates were not significantly different ($P > 0.2$) across tillage, N rate, or crop rotations. In 2003 and 2004 (Fig. 4A) most plots were small net sinks for atmospheric CH_4, with no significant differences ($P > 0.1$) observed with tillage, N rate, or crop rotation. During the fallow or non-cropped seasons (Fig. 4B), November–April 2002–2003 and 2003–2004, all plots acted as small net sinks of atmospheric CH_4. There were no significant differences across all treatments.

Intensification of agricultural practices in the shortgrass steppe decreased the soil sink for atmospheric CH_4 (Bronson and Mosier, 1993). Conversion of grassland and other native systems to agricultural uses has been shown to decrease the soil uptake of atmospheric CH_4 in a variety of other climate zones as well (Chan and Parkin, 2001; Kessavalou et al., 1998; Robertson et al., 2000). No-tillage cropping systems may have the potential to at least partially remediate crop production-related decreases in soil CH_4 consumption as Kessavalou et al. (1998), Hutsch (1998), and Robertson et al. (2000) found small increases in CH_4 consumption under NT. However, Chan and Parkin (2001) did not observe enhanced CH_4 consumption in NT soils compared to plowed soils. We also did not observe an enhancement of CH_4 consumption in NT soils. Possibly, the length of time that a field has been in NT influences the activity of the microbial populations responsible for CH_4 consumption. The soils in our study were converted from conventional moldboard plow cultivation to NT in 1999. The NT practices in the Robertson et al. (2000) and Kessavalou et al. (1998) studies were instituted more than 10 and 20 yr, respectively, before the gas flux measurements while the Hutsch (1998) soils had been in NT much longer.

Like the earlier observations (e.g., Bronson and Mosier, 1993; Chan and Parkin, 2001), cultivated fields can serve as small sinks or small sources of CH_4 depending on soil water conditions (Fig. 3 and 4; Table 2). Also, as observed earlier in cropped fields located near Fort Collins, application of N did not appear to have an inhibitory effect on CH_4 consumption (Bronson and Mosier, 1993; Delgado and Mosier, 1996). This is in contrast to the apparent decrease in CH_4 consumption in shortgrass steppe soils that had been N fertilized (Mosier et al., 1991). We also did not observe distinct seasonality in CH_4 consumption rates

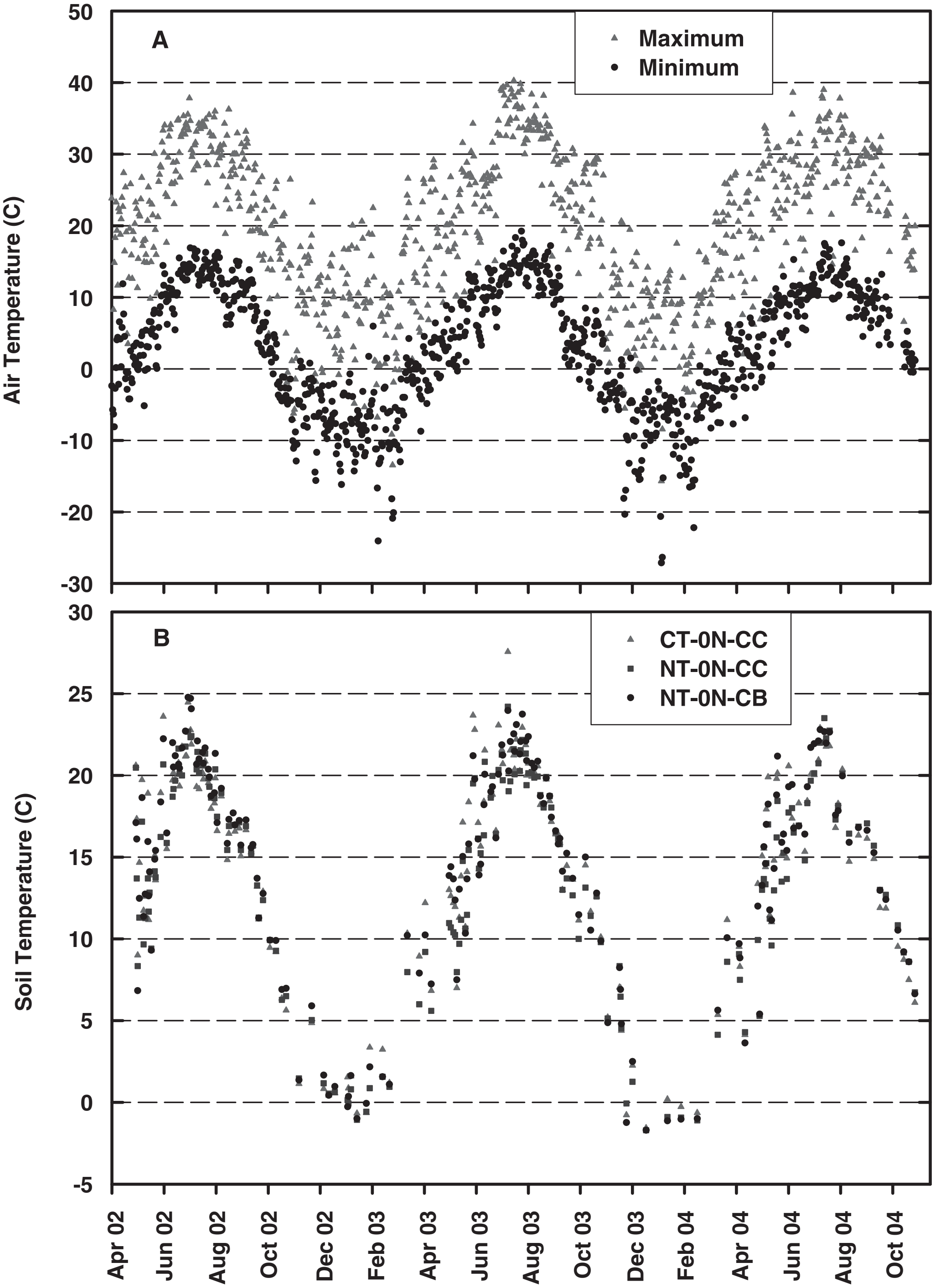

Fig. 1. (A) Daily minimum and maximum air temperature at the field site, April 2002–October 2004; and (B) soil temperature at a 5-cm depth, measured at the time of each gas flux measurement. Note the different temperature scales.

(Fig. 4A and 4B). Fluxes typically ranged between +2 and −2 μg CH_4–C m^{-2} h^{-1} in both summer and winter.

Carbon Dioxide

During the soybean phase of the NT-CB rotation (2003) the soybeans were not removed from the gas flux measurement area because we wanted to measure the effect of growing soybeans on N_2O emissions. As a result, plant respiration was included in the CO_2 flux measurements during the growing season (Fig. 5A and 5C). During the corn growing season in 2002, corn plants were maintained within the flux chamber area until August. In 2003 and 2004 corn plants were removed by cutting the plants off at the soil surface and removing them from the flux measurement area in early July (Fig. 5A, 5B, and 5C). Soil respiration typically closely follows changes in soil temperature with maximum fluxes during

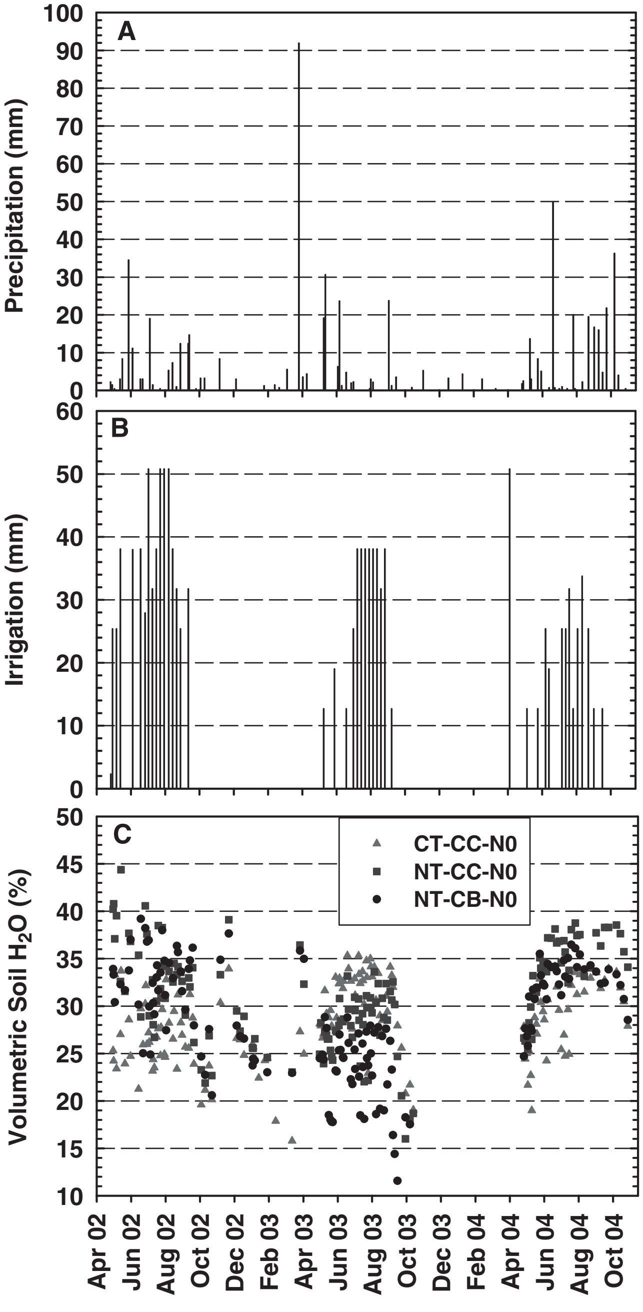

Fig. 2. (A) Precipitation and (B) irrigation at the field site, and (C) volumetric soil water content measured at the time of each gas flux measurement.

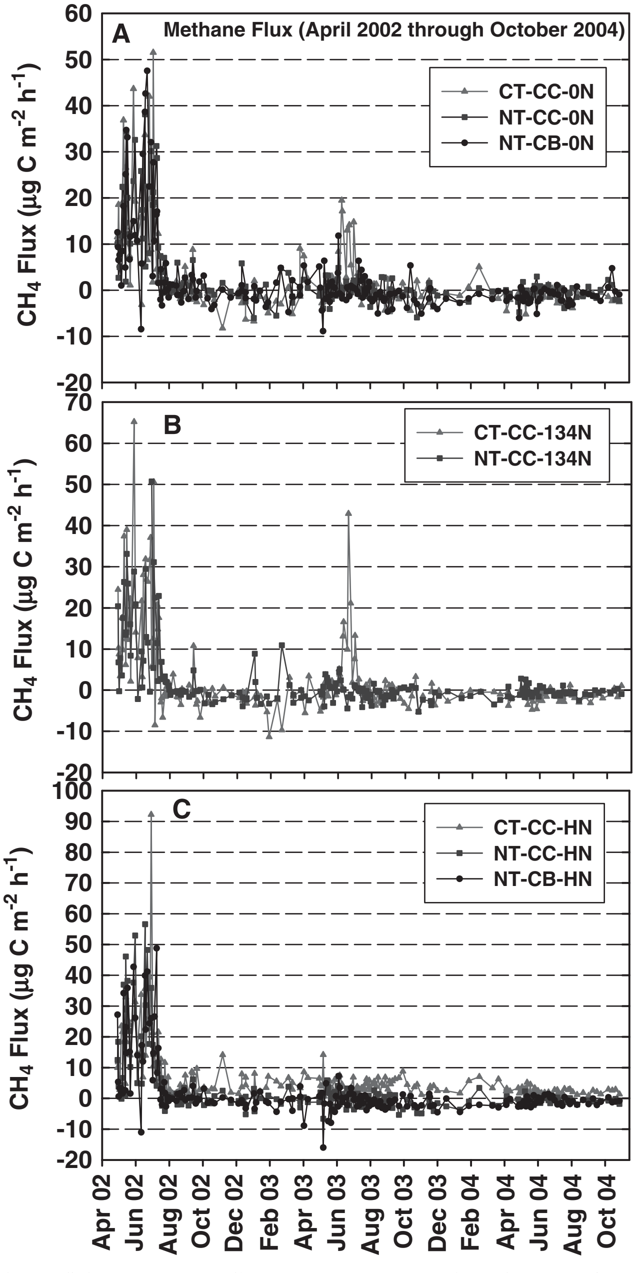

Fig. 3. Soil–atmosphere CH_4 exchange observations from 28 Apr. 2002 until 28 Oct. 2004 in (A) plots to which no fertilizer N was applied, (B) plots to which 134 kg N ha^{-1} fertilizer N was applied, and (C) plots fertilized with 202 kg N ha^{-1} in 2002 and 224 kg N ha^{-1} in 2003 and 2004. Note the different scales for CH_4 flux.

the warmest part of the year and minimum fluxes during the coldest parts of the year. Even when soil temperature was below 0°C, CO_2 fluxes were measurable.

The CO_2 exchange rates can be directly compared for CT-CC and NT-CC across all three years, but in NT-CB only during the 2002 and 2004 growing seasons when corn was growing and during the fallow periods, because soybeans were not removed from the gas measurement area during the 2003 growing season (Fig. 5A; Table 2). During 2002, CO_2 flux rates were significantly greater from CT soils than NT soils ($P < 0.01$) (Fig. 6A). There were no significant differences with N rate. Within the NT treatments CO_2 fluxes did not differ with crop rotation ($P > 0.2$). Although CO_2 fluxes tended to be higher in 2002 than in 2003 or 2004, within the NT treatment they were not significantly different across years ($P > 0.1$). Growing season CO_2 fluxes averaged slightly higher from NT soils than the CT soils in both 2003 (not statistically significant, $P = 0.29$) and 2004 ($P = 0.026$) (Fig. 6A).

Soil CO_2 flux was significantly greater ($P < 0.01$) in CT than in NT during the 2002–2003 fallow season (Fig. 6B). The CT soils were plowed in early January 2003, and CO_2 fluxes increased greatly immediately

Table 2. Annual trace gas exchange as affected by tillage, N fertilization, and crop rotation.†

	CH_4		N_2O		CO_2	
Treatment‡	**Average**	**SD**	**Average**	**SD**	**Average**	**SD**
	–g C ha^{-1} yr^{-1}–		–g N ha^{-1} yr^{-1}–		–kg C ha^{-1} yr^{-1}–	
			2002			
CT-CC-0	267	84	375	75	4864	368
CT-CC-134	299	180	970	190	4815	236
CT-CC-202	392	116	1298	230	4513	574
NT-CC-0	344	86	233	67	3440	281
NT-CC-134	223	120	698	72	3647	356
NT-CC-202	370	140	940	395	3601	558
NT-CB-0	289	107	611	91	3682	483
NT-CB-202	335	177	1605	483	3563	353
			2003			
CT-CC-0	49	207	247	61	3548	317
CT-CC-134	−33	234	2616	1257	3730	816
CT-CC-224	−151	59	3563	667	3661	681
NT-CC-0	−27	59	209	28	3188	261
NT-CC-134	−56	91	1374	281	3520	542
NT-CC-224	−88	51	2984	1822	3534	645
NT-CB-0	−53	52	228	67	§	§
NT-CB-56	−105	101	599	237	§	§
			2004			
CT-CC-0	−87	56	460	130	3572	545
CT-CC-134	−111	85	864	272	3252	752
CT-CC-224	−96	86	1461	320	2876	455
NT-CC-0	−64	15	223	88	3369	321
NT-CC-134	−95	46	1201	616	3890	568
NT-CC-224	−94	21	1451	739	3399	719
NT-CB-0	−106	57	846	411	3770	773
NT-CB-224	−128	81	2137	640	3619	750

† Annual estimates were made from linear interpolation between measured points in time and summing daily calculated values for the entire year. Standard deviations are for six measurement replicates of yearly totals.

‡ CT-CC, conventional-till continuous corn; NT-CB, no-till corn–soybean rotation; NT-CC, no-till continuous corn. The number refers to fertilizer rate (kg N ha^{-1}).

§ Values are not presented because soybean plants were kept within chamber areas during the entire growing season and are not comparable to other respiration values.

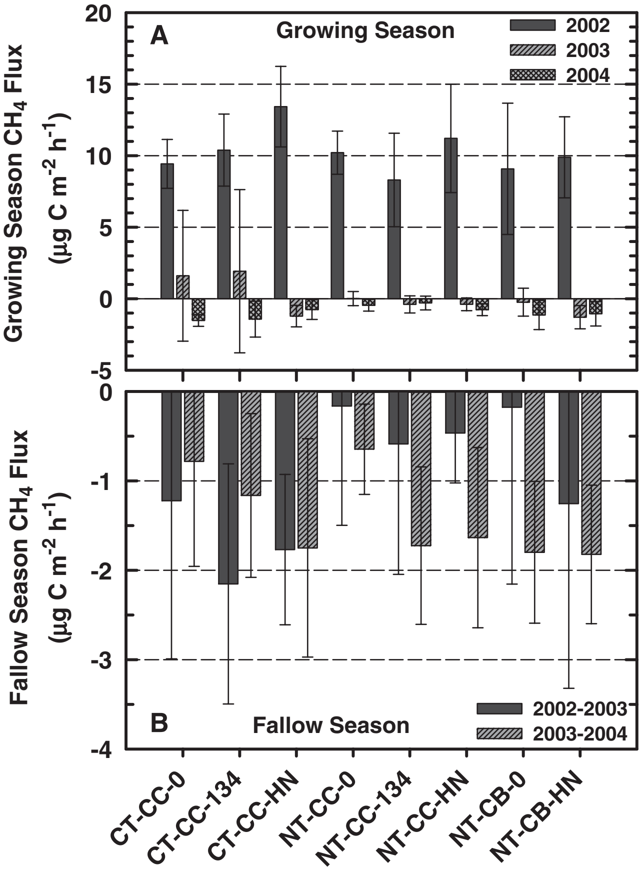

Fig. 4. Average soil–atmosphere exchange rates of CH_4 during (A) the 2002, 2003, and 2004 growing seasons; and (B) during the fallow seasons, November–April of 2002–2004. Note the different scales for CH_4 flux.

following plowing and remained higher than fluxes from NT soils until crop planting at the end of April (Fig. 5). During 2003–2004 fallow season, crop rotation did not measurably affect CO_2 emissions in NT soils. The CO_2 flux rates tended to be lower in CT soils in 2003–2004 than in 2002–2003 ($P < 0.01$) while the reverse was the case for all NT treatments. The reason for this apparent reversal of trends in CO_2 emissions during the fallow seasons is unknown. One possibility is that the NT soils are approaching a steady state relative to changes in SOC content. As SOC accrual decreases, CO_2 emissions would tend to increase relative to CT soils. The CO_2 exchange rates were not influenced by differences in fertilizer N rates ($P > 0.2$).

Carbon dioxide flux from the soil is largely due to biological processes, although inorganic processes such as dissolution of carbonates due to soil acidification can also serve as a source of atmospheric CO_2 (Robertson et al., 2000). Typically, CO_2 flux from soil is recognized as the result of two processes: root respiration and decomposition of organic materials by soil micro- and macrofauna. Decomposition of organic matter is performed by the soil biota, and predominately by soil microorganisms. The main factors controlling soil microbial activity include temperature, water, oxygen content, substrate availability, and substrate quality. The contributions of these factors are influenced by factors such as location in the landscape, vegetation type, soil texture, and management.

Root respiration results in the release of CO_2 from the metabolism of plant root cells, although because of methodological problems, it is difficult to determine root cell derived CO_2 from the CO_2 derived from decomposition of root exudates in the rhizosphere. Thus, these two processes are often not distinguished in discussions of root respiration (Wiant, 1967). The contribution of root respiration to total soil respiration is dependant on vegetation type, growing patterns, season, soil, climate, and management conditions. Rochette et al. (1999) reported that for maize in eastern Canada, root respiration was zero over the first 30 d from planting, but during the next 30 d of plant growth the contribution of root respiration increased linearly to a maximum of 45% where it remained constant until plant senescence. Total soil CO_2 flux during the 160-d period from planting to harvest was 5.5 Mg CO_2–C ha^{-1}, with root respiration accounting for 28.7% of this total seasonal soil respiration (Rochette et al., 1999). We used a root respiration contribution of 30% of the total growing season CO_2 efflux in our estimates of CO_2 efflux from soil respiration (Tables 2 and 4).

Seasonal changes in CO_2 flux have been reported to follow seasonal temperature trends (Anderson, 1973;

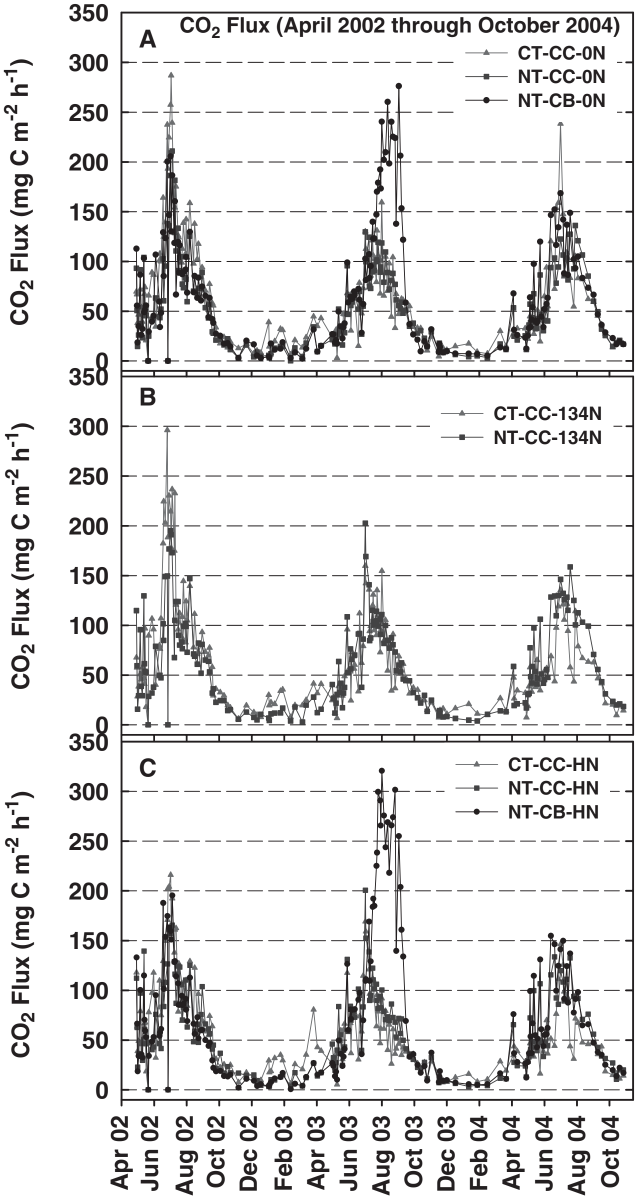

Fig. 5. Soil–atmosphere exchange of CO_2 from (A) unfertilized conventional-till continuous corn (CT-CC), no-till continuous corn (NT-CC), and no-till corn–soybean rotation (NT-CB) plots; (B) CT-CC and NT-CC plots fertilized with 134 kg N ha^{-1}; and (C) CT-CC and NT-CC plots fertilized with 202 kg N ha^{-1} in 2002 and 224 kg N ha^{-1} in 2003 and 2004, and NT-CB plots fertilized with 202, 56, and 224 kg N ha^{-1} in 2002 (corn year), 2003 (soybean year), and 2004 (corn year), respectively.

Buyanovsky et al., 1987; Franzluebbers et al., 2002; Raich and Tufekcioglu, 2000; Rochette et al., 1991). On a shorter time scale, diurnal changes in soil CO_2 flux generally follow soil temperature (Akinremi et al., 1999; Parkin and Kaspar, 2003), with maximum CO_2 fluxes occurring in the mid-afternoon, and minimum fluxes occurring in the early morning.

In long-term experiments it has been generally observed that as C inputs to soil increase, soil organic matter increases (Jenkins, 1991; Paustian et al., 1995). Substrate availability is not only a function of C inputs, but is also related to accessibility. Carbon accessibility in soil is influenced by three mechanisms: (i) physical protection, (ii) chemical stabilization, and (iii) biochemical resistance (Christensen, 1996). Physically protected C is material trapped inside of soil aggregates that is not accessible to microbial action (Tisdall and Oades, 1982; Elliott, 1986; Beare et al., 1994; Jastrow and Miller, 1997). Chemically stabilized C is in the form of organic matter bound to soil, especially clays (Tisdall, 1996; Christensen, 1996). Biochemical availability relates to the susceptibility of organic materials to enzymatic attack (Paul and Clark, 1989).

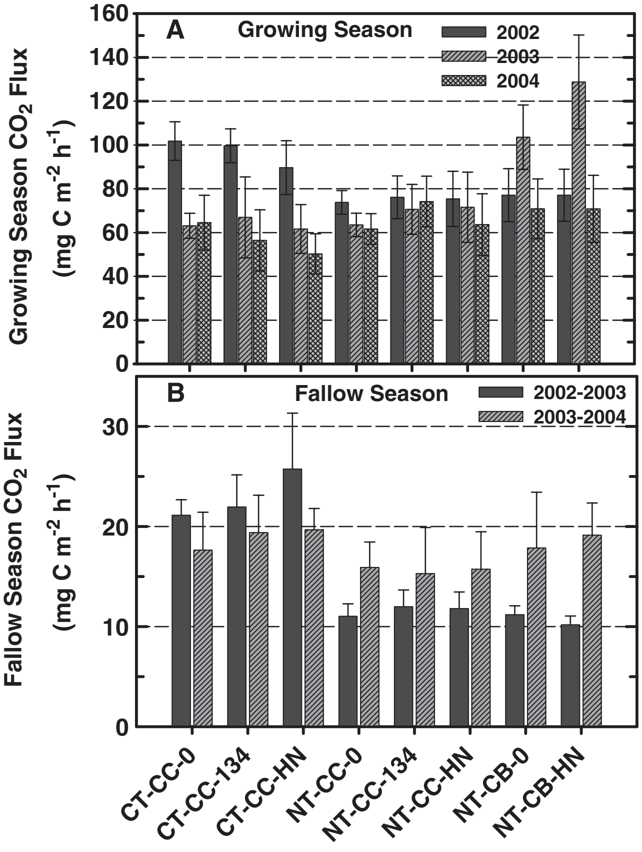

Fig. 6. Soil–atmosphere exchange of CO_2 during (A) the 2002, 2003, and 2004 growing seasons (May–October); and (B) during the fallow seasons (November–April) 2002–2003 and 2003–2004. Note the different scales for seasonal CO_2 flux.

Soil Carbon Change

While terrestrial systems represent a major source of CO_2 to the atmosphere, measurements of soil CO_2 fluxes alone are not necessarily indicative of atmospheric loadings. Net CO_2 flux to the atmosphere from terrestrial systems represents the balance between C inputs by autotrophic fixation and outputs by heterotrophic oxidation of organic material. Measurement of soil CO_2 flux will not distinguish net CO_2 flux to the atmosphere. Net CO_2 flux to the atmosphere can be determined from changes in storage. However, small annual changes coupled with high spatial variability usually restrict such measurements to long-term monitoring. Total C input is difficult to measure as well because of the difficulty in quantifying root biomass in the field.

Rochette et al. (1999) observed that soil CO_2 fluxes varied between approximately 2 and 6 g CO_2–C m^{-2} d^{-1} during the growing season in a corn field located near Ottawa, Ontario, Canada. Parkin and Kaspar (2003) observed similar CO_2 emissions from the soil from a corn field located near Boone, Iowa, during Days 63–158 of the year. The CO_2 flux rates from both CT and NT soils during the growing season were of similar magnitude (Fig. 5) in our study to those reported by Rochette et al. (1999) and Parkin and Kaspar (2003). The soil–atmosphere exchange of CO_2 that we observed followed the same seasonal temperature patterns, with the highest fluxes typically associated with the highest temperatures (Fig. 1 and 5). During the 2002 growing season CO_2 flux was greater than in 2003 and 2004 from CT soils, and was greater from CT than NT soils in 2002. During the following two growing seasons, there were no significant differences between CT and NT soil CO_2 emissions (Fig. 6A; Table 2).

During the two fallow seasons, CO_2 flux was generally higher from CT than NT soils (Fig. 6B). Fluxes from CT tended to be higher during the 2002–2003 fallow season than during the following years. For all NT soils, the reverse trend was the case. Reasons for the reverse trend by year and tillage are not clear. Possibly the NT soil C accumulation is slowing with time after conversion from CT to NT. If the NT soils are approaching a steady state of SOC content after 4 to 5 yr of NT then CO_2 emissions would tend to be progressively more similar to those from CT. The CENTURY model predicts such trends for NT systems as they mature (Del Grosso et al., 2002).

Nitrous Oxide

Nitrous oxide fluxes quickly increased each year, days to weeks following N fertilization. Fluxes were highest the month following fertilization then declined to background levels in early autumn (Fig. 7). Differences of flux intensity between years is evident, with 2002 and 2004 being lower than 2003 (Fig. 7; Table 2).

Year

In CT-CC soils, N_2O fluxes were significantly higher from all N-fertilized plots during 2003 than in 2002 or 2004 ($P < 0.01$) (Table 2). The N_2O flux rates from NT-CC fertilized plots were significantly higher ($P < 0.05$) in 2003 than in 2002 but were not different between 2002 and 2004. In CT-CC and NT-CC unfertilized plots, N_2O emission rates did not differ across years, while N_2O fluxes from the NT-CB unfertilized plots were significantly lower during 2003, the soybean phase of the rotation, than in 2002 or 2004, the corn phase of the crop rotation (Fig. 8A).

Tillage

Nitrous oxide fluxes from unfertilized CT-CC soils were small, yet were significantly greater ($P < 0.05$) than from NT-CC soils during all three growing seasons. During 2002, N_2O fluxes trended higher in CT-CC soils fertilized at the same rate compared to NT-CC treatments and were significantly higher in 2003 ($P < 0.01$) (Tables 2 and 3). In 2004, N_2O flux rates trended higher, but not significantly in the NT-CC fertilized plots compared to the CT-CC fertilized plots. Tillage effects were different each of the three growing seasons of the study. In 2002, N_2O emissions from CT-CC plots averaged higher, but not significantly, than from NT-CC plots, while in 2003, emissions were statistically higher from the CT-CC plots. In 2004, N_2O emissions were higher from the NT-CC plots compared to the CT-CC treatments ($P < 0.1$). Averaged over the whole three

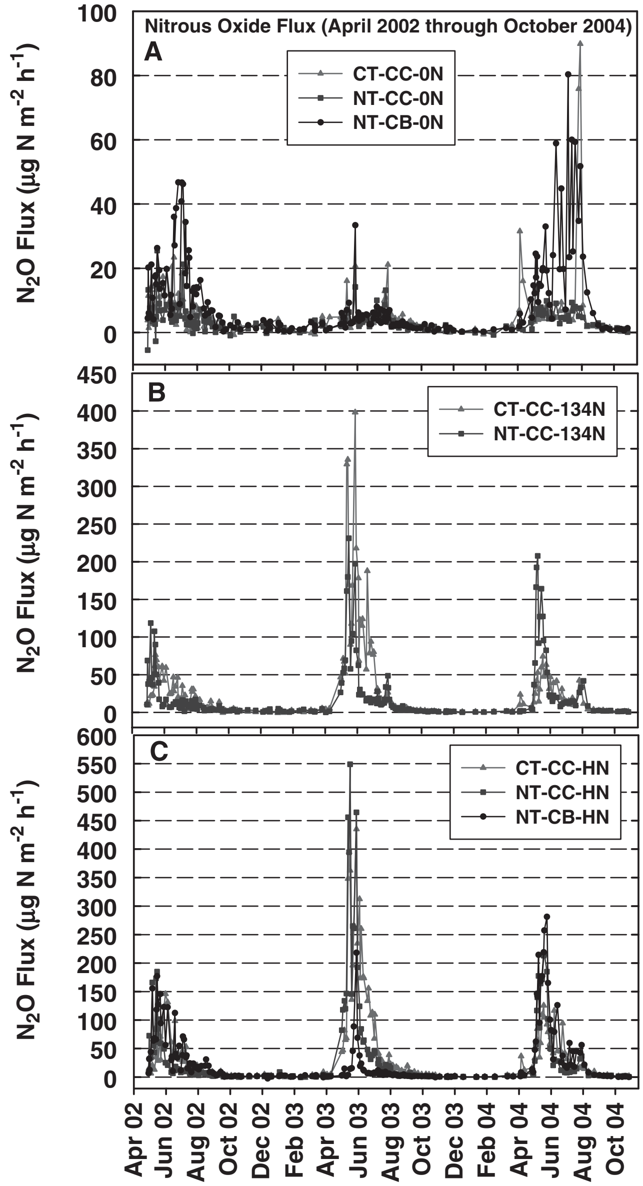

Fig. 7. Nitrous oxide flux rate observations made during 28 Apr. 2002 through 28 Oct. 2004 from (A) unfertilized conventional-till continuous corn (CT-CC), no-till continuous corn (NT-CC), and no-till corn–soybean rotation (NT-CB) plots; (B) CT-CC and NT-CC plots fertilized with 134 kg N ha^{-1} yr^{-1}; and (C) CT-CC and NT-CC plots fertilized with 202, 224, and 224 kg N ha^{-1} in 2002, 2003, and 2004, respectively, and NT-CB plots fertilized with 202, 56, and 224 kg N ha^{-1} in 2002 (corn year), 2003 (soybean year), and 2004 (corn year), respectively. Note the different scales.

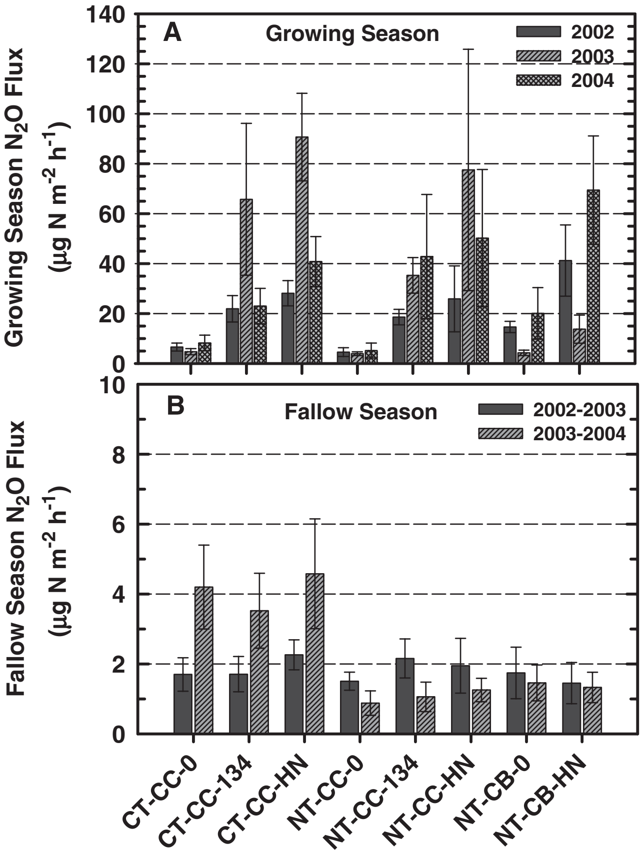

Fig. 8. Seasonal averaged N_2O fluxes during (A) the 2002, 2003, and 2004 growing seasons from plots fertilized at the rates of 0, 134, and 202 or 224 kg N ha^{-1} in conventional-till continuous corn (CT-CC) and no-till continuous corn (NT-CC) plots and 0 and 202, 0 and 56, and 0 and 224 kg N ha^{-1} in no-till corn–soybean rotation (NT-CB) plots in 2002 (corn year), 2003 (soybean year), and 2004 (corn year), respectively; and (B) the November through April 2002–2003 and 2003–2004 fallow seasons. Note the different scales.

years, growing season emission rates were similar, but significantly ($P < 0.1$) higher in CT-CC because of the large difference between the fluxes in 2003.

Crop Rotation

During the corn phase of the corn–soybean rotation (NT-CB-0, 2002, and 2004) the apparent N input from the previous year soybean production raised background N_2O emissions by approximately 90% compared to CT-CC-0 and more than 300% compared to NT-CC-0. The N_2O fluxes from both the no-N and high N fertilizer rate plots were significantly greater ($P < 0.05$) than from the NT-CC plots that were fertilized at the same rates (Fig. 8A; Tables 2 and 3). Enhanced N_2O flux rates averaged approximately 15 µg N m^{-2} h^{-1} when no fertilizer N was added and 15 to 20 µg N m^{-2} h^{-1} during the growing season when the highest rates of N were added.

During the fallow seasons, N_2O fluxes were not affected by N fertilization from the previous spring N application in either CT or NT soils (Fig. 8B). There were also no differences between the different tillage treatments during the 2002–2003 fallow season. During the 2003–2004 fallow season, N_2O flux rates from CT soils were approximately double those from NT soils. In the NT plots N_2O flux rates trended higher in 2002–2003.

Nitrogen Rate

Nitrous oxide production and emissions from soil are regulated, mainly, by substrate availability, soil water content, and temperature (Dobbie et al., 1999). The influence of each of these factors on the microbial processes of nitrification and denitrification, by which N_2O is produced, is generally, individually, well known. It is the interaction of these factors with physical conditions such as soils, management, and timing of weather events that influence, not only production, but also diffusion of N_2O through and out of the soil that is not yet well understood. Year-to-year variability of N_2O emissions from fields that were managed the same way each year can be high (Dobbie et al., 1999). This was the case for our study as well (Fig. 7, 8, and 9).

Although the slope varied, the N_2O flux rates were linearly proportional to N fertilizer rates (Fig. 9A, 9B, and 9C). The CT-CC response to N was 1.1, 3.9, and 1.5 µg N_2O-N m^{-2} compared to 1.0, 3.2, and 2.0 µg N_2O-N m^{-2} in NT-CC for 2002, 2003, and 2004, respectively (Fig. 9A, 9B, and 9C). The annual N_2O emissions from N-fertilized NT and CT plots were 1.9 to 3.2 times greater in 2003 than in 2002 (Tables 2 and 3). In 2004, total N_2O annual emissions were 0.9 to 1.2 times higher than in 2002 from CT plots and 1.6 to 1.8 times greater in NT plots (Tables 2 and 3). The variability in annual N_2O emission was reflected in significant tillage-by-year and N rate-by-year interactions (Table 3). In 2002 tillage did not significantly affect N_2O flux, while in 2003 N_2O fluxes were significantly greater from CT plots compared to NT plots ($P < 0.05$). In 2004, N_2O emissions were marginally greater ($P < 0.1$) from NT than from CT soils (Table 3). During the corn phase of the corn–soybean rotation N_2O fluxes were significantly greater from NT-CB than from NT-CC plots for both zero and 202/224 kg N ha^{-1} treated plots in 2002 and 2004, respectively. Apparently residual N from the soybean grown the previous year became available and was utilized by N_2O-producing organisms to increase growing season N_2O flux by about 15 µg N_2O-N m^{-2} h^{-1}. During the soybean phase of the rotation, N_2O emissions were only a few µg N_2O-N m^{-2} h^{-1} higher than comparably fertilized NT-CC soils ($P < 0.1$) (Fig. 8 and 9).

Nitrous oxide fluxes were higher in NT than in CT in the studies in England and Canada, discussed in Six et al. (2004), but were not different in the Nebraska (Kessavalou et al., 1998) and Michigan (Robertson et al., 2000) studies. Soil moisture was likely continually higher at the sites where N_2O emissions were higher in NT, but the fields in England and Canada had been converted to NT less than 10 yr before the studies were conducted. Tillage had little effect on soil CH_4 consumption or N_2O emissions in the semiarid wheat–fallow system in Nebraska or the crop rotation studies in more humid Michigan. The Nebraska and Michigan sites had been converted to NT 20 and 10 yr, respectively, before the gas flux measurements were made.

Table 3. Nitrous oxide flux rate response to fertilizer addition.

	Treatment†						
	CT-CC		NT-CC		NT-CB		
Year	Slope	Intercept	Slope	Intercept	Slope	Intercept	Figure
	μg N_2O-N h^{-1} g^{-1} N m^{-2}	μg N_2O-N m^{-2}	μg N_2O-N h^{-1} g^{-1} N m^{-2}	μg N_2O-N m^{-2}	μg N_2O-N h^{-1} g^{-1} N m^{-2}	μg N_2O-N m^{-2}	
2002	1.07	6.8	1.02	4.4	1.31	14.6	9A
2003	3.93	6.2	3.24	0.2	1.69	4.3	9B
2004	1.49	5.3	2.02	11.2	2.2	20.1	9C
3-yr average	2.17	6.9	2.14	4.3	1.76	13.0	9D
2003–2004 average	2.71	5.8	2.63	5.7	1.83	12.2	
3 yr all data	2.23	6.3	2.15	6.4	2.08	10.5	9E

Statistical analyses

	Tillage (T)	N rate (N)	Year (Y)	T × N	T × Y	N × Y	T × N × Y
2002	NS‡	**		NS			
2003	*	**		NS			
2004	§	**		NS			
2003 and 2004	NS	**	**	NS	**	**	*
2002–2004	§	**	**	NS	*	**	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† CT-CC, conventional-till continuous corn; NT-CB, no-till corn–soybean rotation; NT-CC, no-till continuous corn.
‡ Not significant.
§ Significant at the 0.1 probability level.

Net Global Warming Potential and Greenhouse Gas Intensity Estimates

The overall balance between the net exchange of CO_2, CH_4, and N_2O constitutes the net global warming potential (GWP) of a cropping system. Storage of atmospheric CO_2 into stable organic carbon pools in the soil can sequester CO_2, while commonly used irrigated crop production practices generate CO_2 and N_2O and decrease the soil sink for atmospheric CH_4. Typically, agricultural soils are minor emitters of CH_4 and generally small sinks for atmospheric CH_4 (Bronson and Mosier, 1993). Nitrous oxide, the principal non-CO_2 greenhouse gas emitted from soils, is produced naturally in the soil through nitrification and denitrification (Robertson et al., 2000). Nitrogen fertilizer input to facilitate crop production augments this production. It is the relationship of soil C changes to N_2O emissions that typically regulates net GWP (Robertson et al., 2000). In addition to the fluxes of greenhouse gases, the energy used to pump irrigation water; for farm operations such as plowing, planting, and harvesting; and for producing fertilizer are included in the GWP estimate (Robertson et al., 2000; Mosier et al., 2005). We relate GWP to crop production by dividing net GWP by crop produced on an area basis to estimate the greenhouse gas intensity (GHGI) of a production system.

Global Warming Potential

Measurement of the change of SOC is the typical way in which CO_2 exchange is estimated (Robertson et al., 2000). An estimate of net GWP for the April 2002–March 2003 period using estimates of SOC from soil C measurements for CT-CC and NT-CC plots indicated that all NT-CC plots were net sinks of GWP and all CT-CC plots were net sources (Mosier et al., 2005). The soil estimate did not distinguish differences in SOC changes between N rates, even though biomass production was about 1.5 times greater when 134 or 224 kg N ha^{-1} was added compared to the no-N plots. The SOC values were calculated as the annual loss (or gain) in soil organic C content in the 0- to 7.5-cm depth estimated by linear regression of all CT-CC or NT-CC plots between 1999 and 2002 (Mosier et al., 2005). Using those SOC estimates, the zero-N plots showed the greatest net gain in GWP (smallest values) within tillage treatments. The data presented in Table 4 contain SOC data that are based on linear regression of CT-CC or NT-CC plot SOC measurements made between 1999 and 2004 for the specified N fertilizer rates. As expected for NT soils, SOC is increasing with increasing N rate because crop residue production increased with N rate each year. Soil SOC changes were estimated the same way for CT soils and observed changes were smaller than in NT, and the changes do not readily reflect fertilizer N input rates. Using the SOC method for calculating net GWP, the CT soils were always net sources of CO_2 while NT soils were always net sinks (Fig. 10A; Table 4). The NT-CB rotation was a net source of GWP during the corn phase of the corn–bean rotation and a small net sink of GWP during the bean part of the rotation (Table 4).

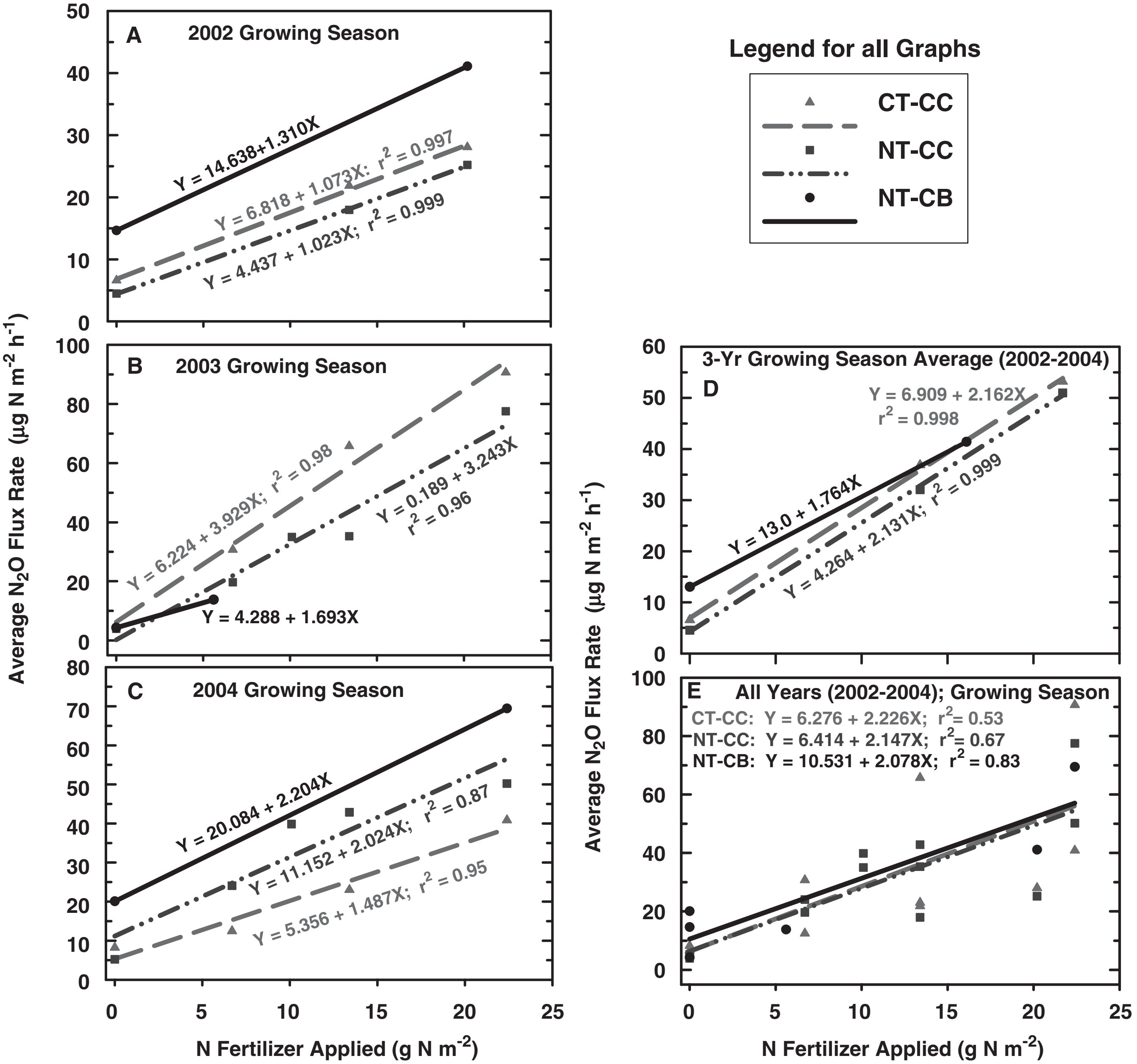

Fig. 9. Effect of N fertilizer rate on growing season N_2O emissions in (A) 2002, (B) 2003, (C) 2004, (D) three-year average, and (E) all three years of data. Note the different scales.

During the corn part of the CB rotation N_2O emissions were higher than from continuous corn plots.

We present a second method of estimating net GWP (Fig. 10B; Table 4) where we calculate net CO_2 exchange by using measured soil respiration values and aboveground crop residue input (Hanson et al., 2000; Rochette et al., 1999). The seasonal and yearly CO_2 emission totals were calculated by linear interpolation between measured values, and summing the total of daily CO_2 flux estimates. We estimated the amount of CO_2 evolved from soil organic matter and crop residue decomposition during the growing season by multiplying growing season CO_2 emission by 0.7 to remove the contribution of total CO_2 evolution due to root respiration (Rochette et al., 1999), then subtracting this value from the crop residue input from the previous year. For example, for 2002, we used the amount of crop residue that was returned to the soil at harvest in November 2001 (Table 4). The 2001 residue production was large and total C from residue generally exceeded total CO_2 emission from the decomposition of soil organic matter and plant residue in 2002. As noted in the discussion of the CO_2 flux data above, measured soil respiration rates did not differ with N rate, even though considerably more crop residue (Halvorson et al., 2006) was returned to the soil the year before in N-fertilized plots compared to where no N fertilizer was applied. Differences in root residues may have influenced these measurements, but no data are available to quantitatively measure their impact at any given time. The same

Table 4. Net global warming potential (GWP) and greenhouse gas intensity (GHGI) in irrigated corn near Fort Collins, CO. Effect of tillage, N rate, and crop rotation for 2002, 2003, and 2004.

Treatment†	Irrigation‡	Farm operations§	N fertilizer¶	N_2O#	CH_4#	Soil respiration#	Crop residue††	SOC‡‡	Net GWP respiration§§	Net GWP soil C¶¶	Grain##	GHGI respiration†††	GHGI soil C†††
		kg CO_2 equivalents ha^{-1} yr^{-1}									kg ha^{-1}	kg CO_2 kg^{-1} grain kg	
							2002						
CT-CC-0	227	273	0	150	20	14900	12200	370	3400	70	6570	0.50	0.01
CT-CC-134	227	273	448	420	21	14700	16700	60	−600	1100	12550	−0.05	0.09
CT-CC-202	227	273	653	570	29	14200	18700	120	−2700	1400	12370	−0.22	0.11
NT-CC-0	227	114	0	110	30	10100	14500	460	−3900	−200	5460	−0.72	−0.04
NT-CC-134	227	114	448	310	24	10500	19100	1550	−7500	−700	9520	−0.79	−0.07
NT-CC-202	227	114	653	410	32	10400	19100	2490	−7300	−1300	11160	−0.66	−0.11
NT-CB-0	227	114	0	280	22	13500	5400	420	8750	229	6346	1.38	0.36
NT-CB-202	227	114	653	750	25	13100	4690	1420	10200	343	10206	1.00	0.03
							2003						
CT-CC-0	185	273	0	150	1.02	9900	10100	370	430	60	6990	0.06	0.01
CT-CC-134	185	273	448	1190	0.99	10600	15100	60	−2400	1800	10850	−0.22	0.17
CT-CC-224	185	273	724	1640	−3.9	10100	14700	120	−1700	2500	11670	−0.15	0.22
NT-CC-0	185	114	0	90	−0.9	9700	10100	460	0	−260	4690	−0.10	−0.05
NT-CC-134	185	114	448	600	−2.9	10400	14100	1550	−2400	−390	9890	−0.24	−0.04
NT-CC-224	185	114	724	1290	−2.7	10600	15800	2490	−2900	−360	10630	−0.27	−0.03
NT-CB-0	179	114	0	110	−1.8	–	10700	420	–	−21	2398	–	−0.01
NT-CB-56	179	114	187	280	−3.6	–	13000	1420	–	−670	3415	–	−0.20
							2004						
CT-CC-0	125	273	0	210	−3.4	10400	9000	370	2030	110	6920	0.29	0.02
CT-CC-134	125	273	448	400	−4.2	9700	12000	60	−1100	1100	11310	−0.00	0.09
CT-CC-224	125	273	724	660	−3.3	9400	12000	120	−830	1500	12440	−0.07	0.12
NT-CC-0	125	114	0	100	−1.1	9200	8100	460	1400	−240	4220	0.33	−0.06
NT-CC-134	125	114	448	550	−2	10500	10800	1550	930	−430	9030	0.10	−0.05
NT-CC-224	125	114	724	670	−2.5	9300	13700	2490	−2 700	−980	11390	−0.24	−0.09
NT-CB-0	125	114	0	390	−2.2	13800	4200	420	10 240	210	7853	1.30	0.03
NT-CB-224	125	114	724	990	−2.7	13200	5900	1420	9260	530	12658	0.73	0.04

† CT-CC, conventional-till continuous corn; NT-CB, no-till corn–soybean rotation; NT-CC, no-till continuous corn. The number refers to fertilizer rate (kg N ha^{-1}).

‡ West and Marland (2002) estimate of 598 kg C ha^{-1} m^{-1} H_2O applied (applied 0.48 m H_2O). We estimated actual electricity use rather than using the West and Marland values. The water table depth averaged 7.5 m and required approximately 14.8 kilowatt hours to pump 1 cm of water ha^{-1}, or the equivalent of 1.29 kg CO_2–C to pump 1 cm of water across 1 ha.

§ Shredding corn stalks, disking, moldboard plowing, roller-mulching (twice), land leveling (twice), planting, herbicide application, and harvesting for CT; and planting, herbicide application, and harvesting only for NT.

¶ N fertilizer production = 45.5 kg CO_2 ha^{-1} for application + 3.0 kg CO_2 kg^{-1} N applied (Follett, 2001).

N_2O, CH_4, and CO_2 = gas flux from linear interpolation of flux measurements for each calendar year. The time period January–April 2002 used the average of the same time period for 2003 and 2004. The time period November–December 2004 used the average of the same time period for the 2002 and 2003 calendar years. 1 kg N_2O ha^{-1} = 296 kg CO_2 ha^{-1} (Intergovernmental Panel on Climate Change, 2001); 1 kg CH_4 ha^{-1} = 23 kg CO_2 ha^{-1}.

†† Aboveground crop residue returned to the field at harvest of the previous year.

‡‡ Soil organic carbon sequestration estimated from the linear regression of change in SOC (0- to 7.5-cm depth) between 1999 and 2004 for each N rate.

§§ Sum of CO_2 equivalents from irrigation, farm operations, N fertilizer production, N_2O emissions, CH_4 exchange, and net respiration (CO_2 respired − crop residue C returned). Negative sign indicates that the system is removing CO_2 from the air and a positive sign indicates that the system is emitting CO_2 to the air.

¶¶ Sum of CO_2 equivalents from irrigation, farm operations, N fertilizer production, N_2O emissions, CH_4 exchange minus the annual increase in SOC determined by the linear regression of change in SOC (0- to 7.5-cm depth) between 1999 and 2004 for each N rate. Negative sign indicates that the system is removing CO_2 from the air and a positive sign indicates that the system is emitting CO_2 to the air.

Corn grain production during the year indicated (Halvorson et al., 2006).

††† Net GWP calculated either from soil respiration or SOC divided by the grain yield.

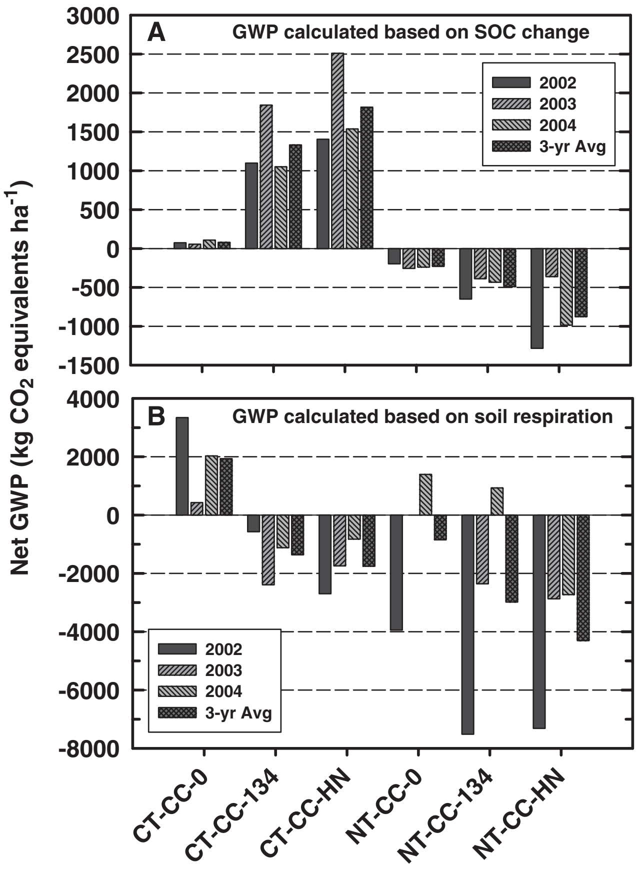

Fig. 10. Net global warming potential calculated (A) from changes in soil organic carbon (SOC) from 1999 to 2004; and (B) from soil respiration and crop residue input data for the conventional-till continuous corn (CT-CC) and no-till continuous corn (NT-CC) 0, 134, and high N (HN) kg N ha^{-1} N rate treatments. Note the different scales.

amount of irrigation water was applied to all plots for a particular year and the same energy estimate by tillage was used across years, so across tillage and N rate the variables of importance that changed were energy used to manufacture N fertilizer, N_2O emissions, and crop residue input. Soil respiration was greater in CT plots than from NT plots in 2002, but was not different across treatments or years in 2003 and 2004. Residue input exceeded respiration output in all NT plots in 2002, in only the N-fertilized plots in 2003, and in only the plots fertilized with 224 kg N ha^{-1} in 2004. Unfertilized CT soils were a net source of CO_2 in all years while increased residue production in fertilized soils offset the increased N_2O emissions. The result was a small net sink of GWP in CT soils in both 2003 and 2004. In 2003 and 2004 net GWP was greater in soils fertilized with the highest N rate, because crop residue production was the same in both 134 and 224 kg N ha^{-1} plots, while N_2O emissions were much greater with the highest N rate. The NT plots were a net source of GWP when no N was added because of the low levels of biomass production. The 224 kg N ha^{-1} plots were net GWP sinks in all three years while the 134 kg N ha^{-1} plots were net GWP sources in 2004 because of the low biomass production in 2003 and relatively high N_2O production (Tables 3 and 4). For the NT-CB plots during the 2002 and 2004 corn part of the rotation, net GWP is much larger than in the NT-CC and CT-CC plots because the bean residue input from the year before is much smaller than the corn residue. As a result, the NT-CB plots were calculated to be a large source for GWP.

The two methods for estimating net GWP provide different views. The SOC technique is based on SOC measurements. These values are subject to error due to spatial variability and interference from inorganic C, even though repeatability of analyses on the same soil samples is very good (±1% of the same soil sample). The soil respiration measurements also suffer from spatial as well as temporal variability problems. In making the respiration estimate we assume that day-to-day and hour-by-hour variability in CO_2 evolution from soils is captured in our measurements, as Rochette et al. (1999) suggest. The results from the 2002 respiration technique calculation suggest that soils were a much larger sink for CO_2 than estimated by the SOC technique, and that N-fertilized CT soils were net CO_2 sinks as well (Table 4). In 2004, the respiration data suggest that the soil C accrual rate in NT was slowing, relative to 2002 and 2003, in the 0 and 134 N rates. These observations coincide with other changes, such as a tendency for higher N_2O emission rates from NT compared to CT in 2004 and lower CO_2 soil–atmosphere exchange rates in CT in 2004 compared to NT.

Greenhouse Gas Intensity

The GHGI relates GWP to crop production. As with GWP, positive values expressed as kg CO_2 equivalents per kg of corn grain produced indicate a net source of GHGs to the atmosphere while negative values indicate net sinks of GHG to the soil. Using the SOC estimates to calculate GHGI resulted in all NT systems being a net sink for CO_2 and all CT soils being a net source, as with GWP. Using the soil respiration estimates in 2002, only the high N rate of CT-CC plots decreased atmospheric CO_2 per unit of corn produced, while all NT plots were CO_2 sinks (Tables 4 and 5). In 2003, both the CT-134 and

Table 5. Statistical analysis of global warming potential (GWP) and greenhouse gas intensity (GHGI) data from Table 4. Effect of tillage, N rate, and year on GWP and GHGI.

Year	Tillage (T)	N rate (N)	T × N	Year (Y)	T × Y	N × Y	T × N × Y
				2002			
GWP	***	***	**	NA†	NA	NA	NA
GHGI	***	***	***	NA	NA	NA	NA
				2003			
GWP	*	**	NS	NA	NA	NA	NA
GHGI	*	**	NS	NA	NA	NA	NA
				2004			
GWP	**	***	**	NA	NA	NA	NA
GHGI	**	***	**	NA	NA	NA	NA
				2002–2004			
GWP	***	**	***	***	***	***	***
GHGI	***	***	***	**	***	***	***

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Analysis not applicable.

CT-224 N rates were small consumers of GHGs (0.1 to 0.15 kg CO_2 equivalents per kg of corn produced). This was similar to the NT sink size. In 2004, the GHGI in the N-fertilized CT plots was not significantly different from zero while the 134 N rate of the NT plots was a net CO_2 source. The highest NT-N rate, because of the higher corn yield, was a net GHGI sink. These estimates for both GWP and GHGI indicate that when appropriate crop production levels are achieved, net CO_2 emissions are reduced. The results suggest that economic viability and environmental conservation can be achieved by the utilization of appropriate levels of fertilizer.

CONCLUSIONS

These multi-year data suggest that there is year-to-year variability in trace gas exchange, as demonstrated by Dobbie et al. (1999) in other systems and inter-annual variability in SOC exchange as well. The data also suggest the possibility of two trends in the NT-CC system. First, the N_2O flux rates relative to CT-CC may be changing, from tending to be lower in NT-CC to higher. Second, measured CO_2 respiration rates were higher in CT in 2002 but were not measurably different in either 2003 or 2004. Both the N_2O and CO_2 flux trends suggest that the rate of SOC accumulation in the NT plots is slowing and that the system is approaching steady state as predicted for NT by DAYCENT simulations (Del Grosso et al., 2002). Although the trends in GWP appear to be best described by DAYCENT simulations rather than the Six et al. (2004) projections, further confirmation of long-term trends is needed. This data need may be addressed either by continuing to make observations for several years or by initiating a multiple year set of observations after the site has been under no-till for at least 10 years.

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