Soil Sequestration and Gas Emissions of Carbon after 3 Decades of Tillage Systems for Corn and Soybean Production in Indiana

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ABSTRACT

Few researchers have assessed the possibly interacting effects of long-term tillage and rotation practices on organic carbon (OC) sequestration in soil to depths well beyond the maximum depth of tillage operations while also studying carbon dioxide (CO_2) emissions from the soil surface of those same experiments. This study was conducted from 2003 to 2005 on tillage and rotation experiments initiated 30 yrs ago in West-Central Indiana on a dark prairie soil with silty clay loam texture.. Our objectives were to determine how tillage systems such as moldboard plow (MP), chisel (CP), and no-till affected OC retention and surface soil CO_2 emissions. These tillage systems were investigated in continuous corn and corn-soybean rotations. Soil OC distribution was determined from soil cores in multiple increments to a 1.0 m depth in late 2003 and early 2004. Gas fluxes from the soil surface were measured at weekly or biweekly intervals for up to 14 weeks in the corn growing seasons of 2004 and 2005. The increase in soil OC with no-till relative to moldboard plow averaged just 8 t/ha (or 5% on an equivalent mass basis) in both rotations. Rotation systems had little impact on OC; continuous corn was not superior to the soybean-corn rotation in either no-till or moldboard plow systems. While no-till clearly resulted in more OC and N accumulation in the surface 15 cm than moldboard plow, the relative no-till advantage declined sharply with depth. Indeed, moldboard plowing resulted in substantially more OC, relative to no-till, in the 30-50 cm depth interval despite moldboard plowing consistently to less than a 25 cm depth. Growing season CO_2 emissions were significantly affected by rotation but not by tillage treatments. . CO_2 emission was higher under continuous corn than with corn following soybean. Our results suggest that conclusions about soil OC gains under long-term no-till are highly dependent on sampling depth and, therefore, tillage comparisons should be based on samples taken much deeper than the deepest depth of direct soil disturbance by tillage implements. After 3 decades of consistent tillage and crop rotation management, tillage system impacts on overall soil OC retention and seasonal CO_2 emissions were less than expected. Continuous corn did not store more soil OC than rotation corn, perhaps because continuous corn emitted more CO_2 from the soil surface than corn-soybean rotation systems.

Keywords: Soil organic carbon, Carbon dioxide emission, continuous corn, rotation corn, tillage systems, no-till.

1. Introduction

Soil management practices are one of the major factors that can significantly influence soil-atmosphere exchange of greenhouse gases (IPCC, 1996) that are believed to be an important contributory factor to global climate change (Bouwman, 1990). Measurements of soil gas fluxes for different tillage treatments and cropping systems are, therefore, important for identifying management practices that can impact positively the global C balance (Post et al., 1990, Reicosky et al., 1997) and decrease greenhouse gas emission. However, the magnitude of gas emission is affected by cropping systems (Drury et al., 2002; Verma et al., 2005).

In recent studies in Minnesota and Iowa, respectively, Reicosky et al. (2005) and Al-Kaisi and Yin (2005) found a relatively higher CO_2 emission for soils under moldboard than chisel, strip- and deep-ripped, and no-till in corn and corn-soybean rotation systems. In contrast, La Scala et al. (2005) found that CO_2 emission was highest under chisel relative to moldboard and no-till shortly after tillage.

Relatively fewer studies have been conducted to evaluate long-term effects of tillage and rotation systems on greenhouse gas emissions. However, Curtin et al. (2000) found that CO_2 emission with no-till was significantly less than for conventional tillage, although tillage system differences were higher under continuous wheat than in wheat-fallow systems. Similarly, Dao (1998) reported a significantly lower CO_2 flux no-till than for moldboard plow and that gas flux was almost doubled within 60 days when crop residues were buried with moldboard plowing. In a 3-yr study where emission was measured all year round, Kessavalou et al. (1998) found higher CO_2 emission in native grasses (sod) relative to wheat-fallow rotation and higher annual emission for MP relative to NT. Similarly, in a 2-year multiple weeks study, Bauer et al. (2005) reported a lower CO_2 emission for no-till relative to conventional tillage (disc harrow followed by S-tined harrow smoothing).

In the Midwestern USA where corn-soybean rotation is the dominant cropping system, conservation tillage (no-till) accounts for more than 22% of production from all cropland area, and conventional tillage systems are used in more than 35% of cropland area (Conservation Technology Information Center, 2003). About 20.8 x 10^6 hectares of poorly drained agricultural lands in the Midwest are tile drained (USDA, 1987). However, while some information is available for short-term CO_2 emission (Al Kaisi and Yin, 2005; Reicosky, 1997; Reicosky et al. 1997), there is a complete lack of data to assess effects of long-term tillage and rotation systems, and their interactions, on long-term CO_2 for this important agricultural region. The specific objective of this research was to assess the temporal variability in CO_2 fluxes from the soil surface during a crop growing season, and how these emissions are related to tillage, rotation and their interactions in the long-term.

2. Materials and Methods

2.1 Site Description and Agronomic Practices

This research was conducted in long-term tillage and crop rotation experimental plots located at the Purdue University Agronomy Center for Research and Education near West Lafayette, Indiana (40^o 28' N Lat.). The experiments were established in 1975 with the initial goal to determine long-term yield potential of different tillage systems in various crop rotations, and to determine changes in soil characteristics and crop growth that could be associated with yield differences. Since time of establishment in 1975, moldboard plow, chisel, ridge, and no-till systems were compared in continuous corn, corn-soybean, soybean-corn, and continuous soybean rotations. The soil was developed under prairie vegetation, has less than 2 % slope, and is a poorly drained Chalmers silty clay loam (fine, silty, mixed, mesic Typic Endoaquoll) but tile drained at 20-m intervals.

Cultural practices have been relatively consistent since the study began. No-till planting was done with a single coulter to cut through the residues and loosen the soil ahead of standard planter units. Since 1997, tined row cleaners have been used in place of no-till coulters in front of the standard seed disk openers. Lime (2.0 Mg/ha) was applied periodically to maintain soil favorable pH. Starter N fertilizer was routinely applied at the rate of at 37 kg N ha^{-1} when corn was planted. Since 2001 nitrogen was side-dress applied in June at the rate of 222 kg N ha^{-1} using 28% Urea Ammonium Nitrate (UAN). Phosphorus and potassium fertilizers were periodically broadcast applied (either alone or in combination) before fall primary tillage operations to maintain adequate to high soil-test levels for these nutrients. Corn and soybean yield results from the rotation and tillage treatments have been reported previously (Vyn et al., 2000). Essentially, corn yields have been similar for moldboard and chisel plowing; no-till corn yields have averaged 2 or 3% less than those after moldboard and chisel when corn follows soybean, but 14% less when corn follows corn.

2.2 Experimental Treatments

This study included no-till (NT), chisel (CH), and moldboard (MB) plow treatments in continuous corn (CC) and corn following soybean (rotation corn, RC). The experimental layout was a randomized complete block in a split-plot design with rotations as the main treatments and tillage as the subunits (randomized in rotations) with three replications. Each replicate consisted of plots that were 9 m wide, 45 m long (0.04 ha). Following spring tillage operations in 2005, soil surface residue cover was 3% in MP and 31% in CP versus 93 % in the undisturbed NT system. Starter nitrogen fertilizer (34-0-0) placement was applied at a rate of 37 kg N ha^{-1} and N was also side-dress applied to all plots on June 6, 2005 at a rate of 222 kg N ha^{-1} in the form of urea-ammonium nitrate.

2.3 Organic Carbon Measurements:

Soil probe samples were predominantly taken before spring tillage and planting operations in 2003. The sampling procedures for the 6 depth increments (0-5cm, 5-15cm, 15-30cm, 30-50cm, 50-75cm and 75-100cm) were identical to those outlined in a companion study on the same research station (Omonode et al., 2006). Careful measurements of soil bulk density at the same time as obtaining these samples enabled us to calculate soil OC in terms of mass per unit equivalent soil mass for all tillage and rotation systems.

2.4 Carbon Dioxide Measurements

Tillage-induced soil surface CO_2 was simultaneously measured by the vented flux chamber method (Mosier et al., 1991). In each measurement plot, duplicate gas chamber anchors were driven about 10 cm into the soil and about 10 m apart from each other in the plot. A carpenter's level was used to ensure that the anchors were level.

Gas fluxes were measured by placing the chambers (chamber volume = 2433 cm^3) over the anchors to cover the soil surface. To ensure that there was no gas exchange between chamber and the atmosphere during sampling, chambers were made air-tight by sealing all spaces between anchor and chamber with water before sampling was begun. Samples were then collected from the chambers through a rubber septum at regular intervals of 0, 5, 10, and 15 min after deployment using a 20 mL polypropylene syringe and pressurized into pre-evacuated vials (12 mL Exetainer, Labco, High Wycombe, UK).

In the 2004 growing season, gas sampling was carried in 7 measurement periods beginning in June (approximately 8 weeks after secondary tillage and 6 weeks after planting) and ending September.. During the 2005 growing season, sampling was carried out for 14 weeks beginning on April 8 (1 week before secondary tillage) and continued through September 13. Unfortunately, however, due to inclement weather conditions, sampling was not done in the month of July.

Anchors were kept in the same positions through the course of the experiment and all sampling were carried out between 10 a.m. and 12 noon of each sampling date. Soil moisture was determined using a TRIME-TDR and soil temperature recorded with a thermometer to 7 cm soil depth at time of gas sampling for each chamber position.

The concentrations of CO_2 in the samples were determined using a gas chromatograph (Varian 3800 GC, Mississauga, Canada) equipped with an automatic Combi-Pal injection system (Varian, Mississauga, Canada) that was described in detail by Drury et al. (2004). Gas fluxes were calculated from the rate of change in chamber concentration, chamber volume, and soil surface area using the formulation of Hutchinson and Mosier (1981). Chamber gas concentration was converted from molar mixing ratio unit of parts per million (ppm) determined by GC analysis to mass per volume units assuming ideal gas relations (Venterea et al., 2005).

3. Results

3.1 Soil Organic Carbon

In general, tillage treatments had more impact on both OC and bulk density of the soil than crop rotation treatments. Interactions of rotation × tillage were consistently insignificant for soil OC and bulk density (data not reported).

On a mass per unit area basis, about 65% higher OC accumulated in no-till in the 0-5 cm depth compared to plow: the latter differences were highly significant (Figure 1). Tillage effects on OC were also highly significant in the 5-15 cm depth increment on a mass basis (30% higher in no-till). In the 15-30 cm depth, tillage effects on mass per unit area basis were again significant (13% higher in no-till for OC). However, the tillage system trends reversed dramatically below 30 cm. In the 30-50 cm depth, plow had 32% higher OC than no-till (Fig. 1). Tillage system effects on soil OC mass were not significant below the 50cm depth. However, on a cumulative basis to the 1.0m sampling depth, no-till stored 8.02 t/ha (5%) more O
The mass of OC was somewhat higher for continuous corn than for soybean-corn rotation at depths to 75 cm (Fig. 2). However, rotation system differences in OC were not significant at any depth interval except 75-100cm. Grain corn yields averaged over 10.5 t/ha while soybean seed yields averaged over 3.4 t/ha during that period. For the first 25 years of this experiment, continuous corn resulted in 5% less grain yield than rotation corn in the plow treatment, but 19% less grain yield than rotation corn in the no-till system (Vyn et al., 2000). Although there were no statistically significant differences between continuous corn and soybean-corn rotation systems in cumulative OC storage to a depth of 1 m , continuous corn had 4.31 t/ha (3%) more OC than the soybean-corn rotation. More details about the relative OC as well as total nitrogen sequestration by these tillage systems, and the impacts of tillage and rotation on soil bulk density and aggregate stability, are available in a recent thesis by Gal (2005).

Fig. 1. Organic carbon mass per unit area for two tillage systems at multiple depth increments to a 1 m sampling depth

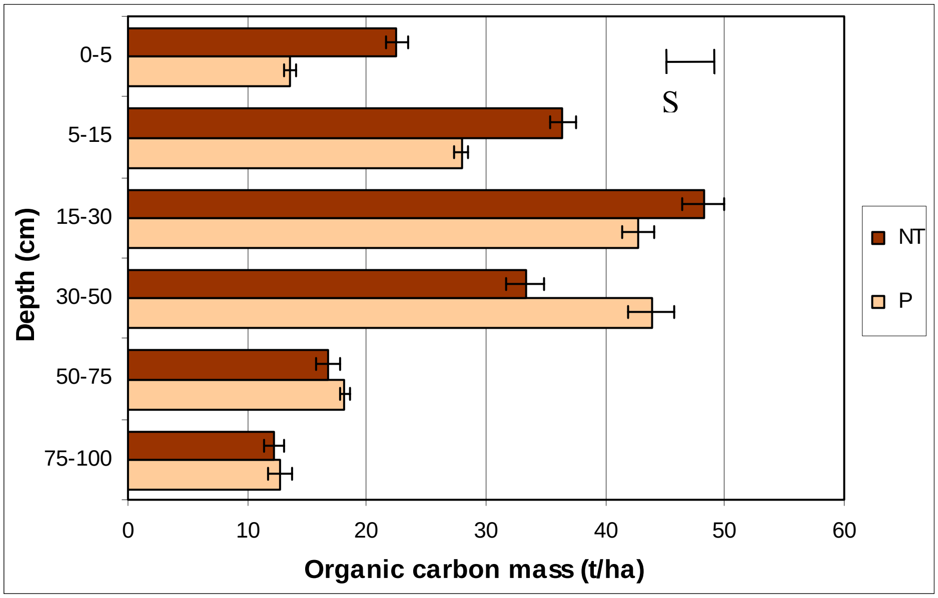
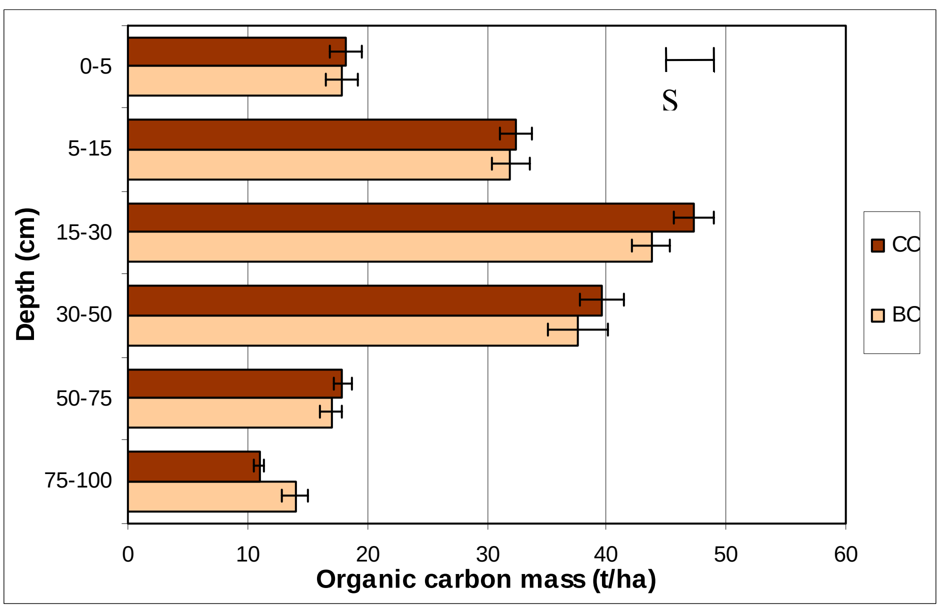


Fig. 2. Organic carbon mass per unit area for two rotation systems at multiple depth increments to a 1 m sampling depth



3.2 Caron Dioxide Flux

Long-term CO_2 emission in the 2004 and 2005 growing seasons were highly variable among treatments and with time, but was not significantly affected by tillage (Figures 3 and 4). However, rotation effect on CO2 fluxes was statistically significant (2004: $P < 0.0206$; 2005 $P < 0.0108$). Although tillage differences were generally insignificant, mean emissions were higher from chisel plow than from moldboard plow and no-till systems in both years (Fig. 3). Average

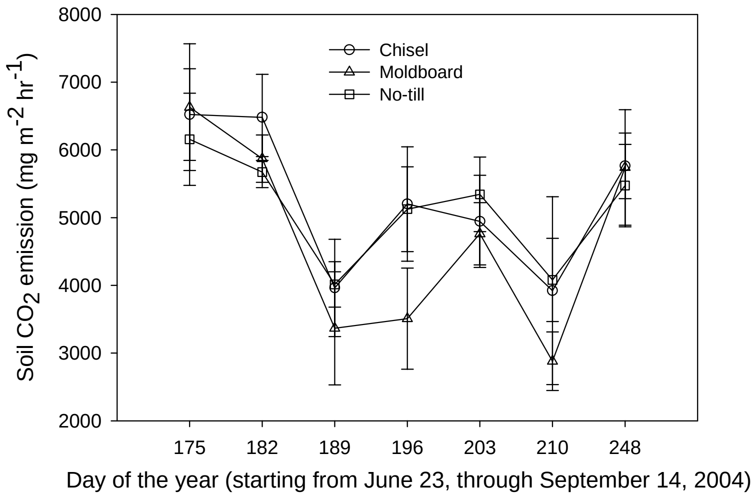
CO_2 emission for the 2004 growing season was highest for chisel (5258 mg m^{-2} hr^{-1}) relative to no-till (5124 mg m^{-2} hr^{-1}) and moldboard (5265.1 mg m^{-2} hr^{-1}). In 2005 emissions with chisel and moldboard were about 11 and 7.8% , respectively, higher than for no-till (average emission was 3479, 3356 and 3093 mg m^{-2} hr^{-1} for chisel, moldboard, and no-till, respectively). Soil CO_2 emission peaked in June of both years, perhaps due to higher mineralization of OC..

Averaged over tillage treatments, CO_2 emission was significantly higher under continuous corn than for rotation corn in both 2004 and 2005 growing seasons (Fig. 4). In general, average emission was about 14% higher for continuous corn than for rotation corn in both 2004 and 2005 growing seasons (2004: continuous corn = 5394, rotation corn = 4648 mg m^{-2} hr^{-1}; 2005: continuous corn = 3594, rotation corn = 3071 mg m^{-2} hr^{-1}). Barber et al. (1979) , in a 7-year study with continuous corn and annual moldboard plowing on the same research station, observed that the quantity of corn residues returned to soil was a major factor affecting soil C concentration. Estimated corn plant biomass returned to soil is higher in rotation corn than in continuous corn when both treatments are in corn (i.e. every second year), but overall crop biomass returned to soil is likely lower from rotation corn than continuous corn because soybeans have returned much smaller crop biomass to soil (based on their mean 3.3 Mg ha-1 grain yields; data not presented). Drury et al (1998) and Tan et al. (2002) also reported increased corn yield and soil organic matter in rotation corn relative to monoculture corn.

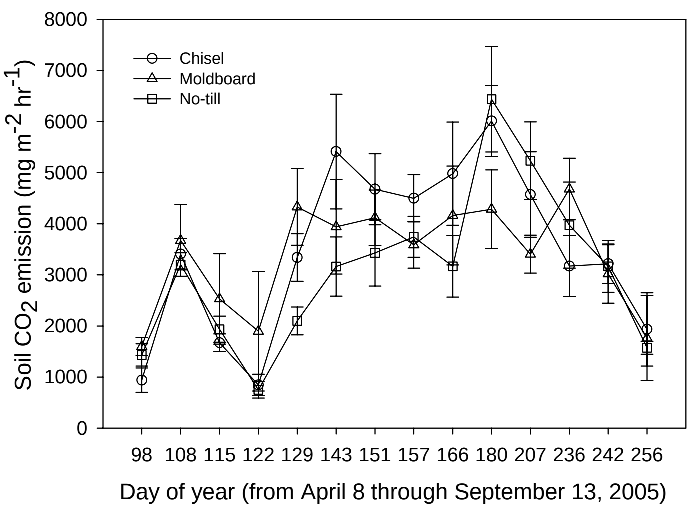
Our rather unique emission results with the CP system were not unexpected. In these plots we observed significantly more organic C accumulation (24% higher organic C) in the 30-50 cm depth interval of moldboard plowed plots than for no-till (Fig. 1), and a higher organic C in continuous corn relative to rotation corn in the soil profile to a 75 cm depth (Fig. 2). In another nearby field on the same research station, Omonode et al. (2006) reported higher soil organic C in soils that were subjected to intermittent chisel plow or no-till for 5-7 years after 17 years of moldboard plowing relative to soils that were under continuous chisel plow treatment for the same 24-year period. In this study, Omonode et al. (2006) concluded that long-term chisel treatment could be more detrimental to soil organic C sequestration than MP. Yang and Kay (2001) also reported a trend where less organic C was found in the 10-20 cm depth of chisel-plowed than moldboard-plowed soils in Canada.

Fig. 3. Long-term weekly soil carbon dioxide emission as affected by tillage treatments in (a) 2004, (b) 2005, and (c) average of 2004 and 2005 growing seasons.

(a)



(b)



(c)

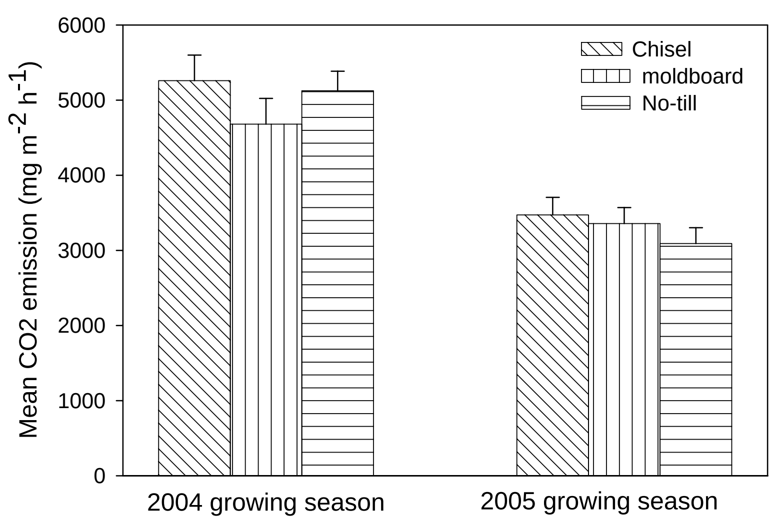
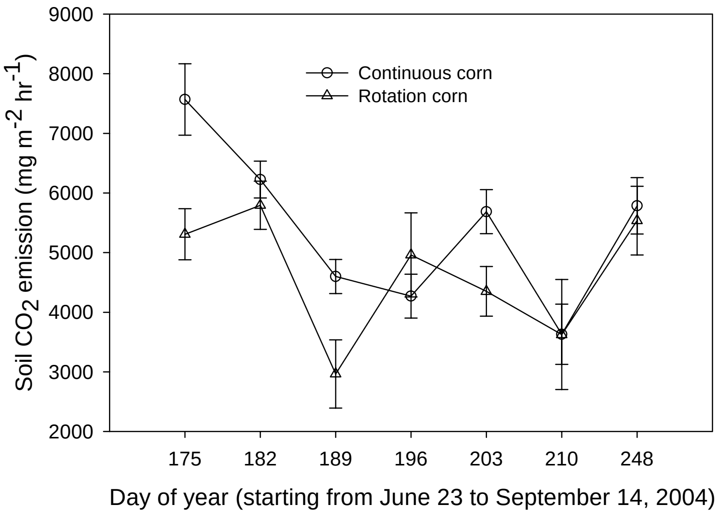
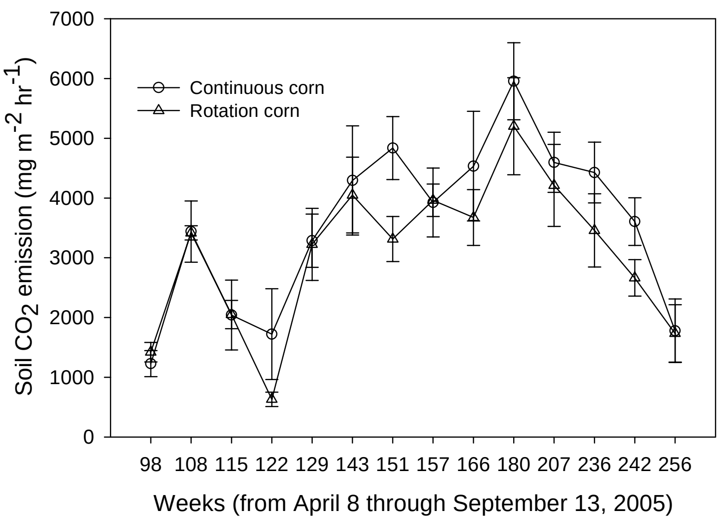


Fig. 4. Long-term weekly soil carbon dioxide emission as affected by crop rotation treatments in (a) 2004, (b) 2005, and (c) average of 2004 and 2005 growing seasons.

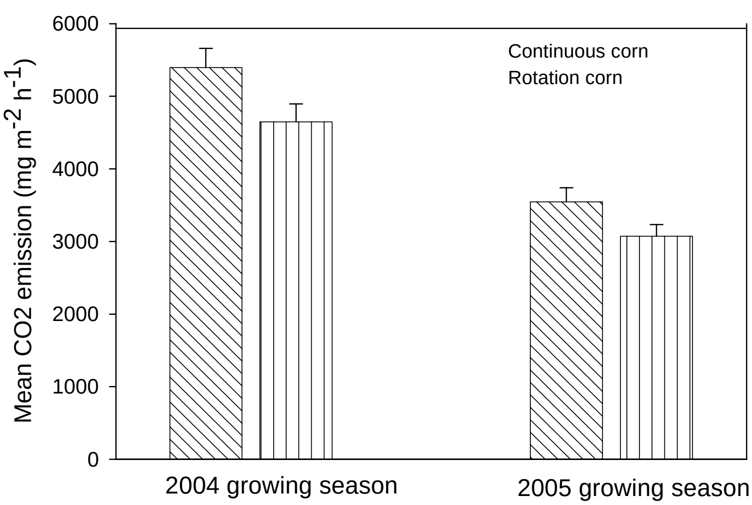
(a)



(b)



(c)



4. Conclusions

There is insufficient experimental data to accurately assess the effects of long-term tillage and rotation systems on soil OC storage at depth, and on greenhouse gas fluxes in the Midwest Corn Belt. This research was initiated to determine both OC sequestration and long-term fluxes of CO_2 in soils that have been uniformly managed using moldboard, chisel, and no-till practices in continuous corn and corn-soybean rotations for the last 3 decades.

Our results from the comparison of continuous (annual) moldboard plowing versus continuous no-till on a Chalmers silty clay loam confirmed that no-till resulted in a substantial gain of OC at the 0-5 and 5-15 cm depth intervals, a generally equal OC status at the intermediate depth of 15-30 cm, but a substantial reduction, relative to the plow system, in the 30-50 cm depth interval. These two tillage systems had similar soil OC concentrations at 50-100 cm depth. Calculations based on soil OC content increases solely from the upper 30 cm in no-till would have suggested that no-till resulted in 23 t/ha more OC than plow. However, calculations based on soil OC to the full 1 m depth suggested that no-till resulted in an overall gain of just 8 t/ha. Clearly, carbon sequestration assumptions about tillage systems based on shallow sampling depths would have been highly inaccurate for this soil.

CO_2 emission during the growing season was significantly affected by rotation (continuous corn higher than corn-soybean), but not by tillage systems. However, among tillage systems CO_2 emission was numerically in the order: no-till < moldboard< chisel. The higher CO_2 flux from continuous corn than for rotation corn was not differentially affected by tillage practices. Our results suggested that rotation system (and thereby meaning the amount and quality of above-ground and below-ground crop materials and associated microbial activity) seemed to be a more important factor determining the dynamics of long-term gas fluxes from the soil surface.

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