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Tillage-induced CO_2 emission from soil

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Abstract

The influence of agricultural production systems on greenhouse gas generation and emission is of interest as it may affect potential global climate change. Agricultural ecosystems can play a significant role in production and consumption of greenhouse gases, specifically, carbon dioxide. Information is needed on the mechanism and magnitude of gas generation and emission from agricultural soils with specific emphasis on tillage mechanisms. This work evaluated four different tillage methods on the short-term CO_2 and water vapor flux from a clay loam soil in the Northern Cornbelt of the USA. The four tillage methods were moldboard plow only, moldboard plow plus disk harrow twice, disk harrow and chisel plow using standard tillage equipment following a wheat (*Triticum aestivum* L.) crop compared with no tillage. The CO_2 flux was measured with a large portable chamber commonly used to measure crop canopy gas exchange initiated within 5 minutes after tillage and continued intermittently for 19 days. The moldboard plow treatment buried nearly all of the residue and left the soil in a rough, loose, open condition and resulted in maximum CO_2 loss. The carbon released as CO_2 during the 19 days following the moldboard plow, moldboard plow plus disk harrow, disk harrow, chisel plow and not tilled treatments would account for 134%, 70%, 58%, 54% and 27% respectively of the carbon in the current year's crop residue. The short-term carbon dioxide losses 5 hours after four conservation tillage tools was only 31% of that of the moldboard plow. The moldboard plow lost 13.8 times as much CO_2 as the soil area not tilled while different conservation tillage tools lost only 4.3 times. The smaller CO_2 loss following conservation tillage tools is significant and suggests progress in developing conservation tillage tools that can enhance soil carbon management. Conservation tillage reduces the extent, frequency and magnitude of mechanical disturbance caused by the moldboard plow and reduces the air-filled macropores and slows the rate of carbon oxidation. Any effort to decrease tillage intensity and maximize residue return should result in carbon sequestration for enhanced environmental quality.

Introduction

The management of crop residues and soil organic matter is of primary importance in maintaining soil fertility and productivity and for minimizing agricultural impact on environmental change. Soil is our most valuable resource for food and fiber production. A critically important component is soil organic matter or soil carbon. It is directly related to soil productivity and soil quality. Carbon (C) is the key element for the foundation of all life. Soil carbon gives our soils the dark color and is closely linked to soil physical, chemical and biological properties associated with enhanced soil productivity.

The possibility of global greenhouse warming due to a rapid increase of carbon dioxide, is receiving increased attention (Post et al., 1990; Wood, 1990). This concern is warranted because potential climatic changes could result in increased temperature and drought over present agricultural production areas (Wood, 1990). Thus, agriculture's role in the overall global carbon balance must be understood. We need

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direct measurements to quantify CO_2 flux as impacted by agricultural management practices (Houghton et al., 1983; Post et al., 1990). The crop root system can be used to sequester and redistribute carbon deeper in the soil profile where the carbon can become less susceptible to conversion to CO_2. Management practices need to be developed to optimize CO_2 utilization from soil and plants in photosynthesis to increase crop yields. There is a definite need for information on the impact of tillage on CO_2 from soil and how farming practices can be managed to minimize impact on global climate change.

Gliński & Stepniewski (1985) presented summary tables of long-term CO_2 flux from soil based on soil oxygen measurements and demand throughout the year. CO_2 evolved ranged from 1,800 to 47,200 kg CO_2 ha^{-1} yr^{-1} across various soils and climates. Daily respiration under field conditions ranged from 0 to 56 g CO_2 m^{-2} d^{-1} depending on soil type and time of year. These results show a wide range in CO_2 fluxes from various soils. Relatively small differences between bare and cropped soils due to root respiration have been observed (Pritchard & Brown, 1979). These studies do not consider the effect of tillage method on CO_2 flux from soil.

Information is needed on the short-term impacts of various tillage methods on carbon flow within an agricultural production system. Three experiments dealing with short-term tillage-induced CO_2 release were conducted. The objectives were; to measure the effect of different fall tillage methods on the CO_2 flux from soil; to characterize spatial variation of CO_2 flux across a glacial till landscape; and to evaluate the effect of conservation tillage tools on short-term CO_2 emissions.

Experiment 1

Materials and methods

This experiment was conducted in 1991 on a Hamerly clay loam (fine, loamy, frigid Aeric Calciaquoll) at the West Central Experiment Station of the University of Minnesota, Morris, Minnesota, (45° 35’ N. lat. 95° 55’ W. long.). The surface soil is characterized by 330 mm of black clay loam or silty clay loam and is nearly level (slope < 1 %) moderately well-drained, formed on a calcareous loam and clay loam ground moraine. The Ap horizon has a bulk density of about 1.30 Mg m^{-3} and the entire soil profile has available water holding capacity of 105 mm m^{-1} of soil.

Prior to the experiment, the study area was planted to spring wheat (*Triticum aestivum* L. cv. Marshall) on 22 April (DY 112), 1991, and harvested on 22 August (DY 224), 1991. During this period, seasonal rainfall was slightly above normal at 300 mm from planting to harvest. The average wheat yield was 2354 kg ha^{-1} with a normal amount of residue ($\approx$3500 kg ha^{-1}). Following grain harvest, the stubble was left at an average height about 0.18 m and the remaining residue was spread uniformly over the study area. Following harvest and prior to tillage (4 Sept. 1991, DY 247) the total rainfall was normal at 50 mm. In order to minimize the effect of weeds and volunteer wheat on CO_2 exchange rates, the area was sprayed with a herbicide, Ranger[1], (glyphosate) at 0.8 kg a.i. ha^{-1} on 30 August, 1991. After the tillage and subsequent rainfalls, additional herbicide was again applied to control weeds, and volunteer wheat as they emerged. Herbicide applications were made on 13 Sept., 17 Sept., and 20 Sept. at the rate of 0.8 kg ha^{-1} a.i. of glyphosate. The area was kept weed free so there was no CO_2 uptake by plants.

Tillage treatments covered a range of depths of tillage, estimated degree of soil disturbance, and estimated degree of residue incorporation with no-tillage (NT) as a check treatment. The four tillage treatments included moldboard plow (MP), using a 3-bottom plow, 0.46 m wide bottoms, to a depth of 0.25 m that resulted in complete inversion of the surface layer and nearly 100% incorporation of the residue. The second treatment was moldboard plow to the 0.25 m depth followed by a disk harrow twice (MP + D2X). This resulted in the same depth and degree of soil disturbance with smaller aggregates and a less porous surface. The third treatment was disk harrow (DH) that resulted in a shallow soil disruption (0.075 m) and partial incorporation of the residue. The chisel plow (CP) treatment used a standard chisel plow with 11 shanks on 0.30 m centers, 0.076 m twisted shovels staggered on three bars for complete soil disruption. The primary difference between DH and CP was the depth of soil disturbance to 0.15 m with CP compared to 0.075 m with DH. The disk and chisel tillage methods are commonly used for overwinter wind and water erosion control. The control treatment was no-tillage (NT) with soil and residue as left by harvest equipment from the preceding wheat crop.

The tillage equipment was pulled by a medium size farm tractor ($\approx$ 70 kW). Where the tillage imple-

[1] Names of products are included for the benefit of the reader and do not imply endorsement or preferential treatment by USDA.

ment was narrow, several adjacent passes were made to achieve the necessary plot width. The tillage plots were 6 m wide × 110 m long strips to allow the tillage implement to operate at the appropriate depth. Chamber measurements were made about 20 m from plot ends to minimize border effects. A 6-m alley allowed tractor movement between each plot and access from two directions.

Initial tillage was completed on 4 Sept. 1991 (DY 247) in the order MP, MP + D2X, DH, and CP. The tillage was done when the surface soil water potential was approximately - 45 kPa, a suitable water content for tillage of this soil.

The CO_2 flux from the tilled soil surfaces was measured using a large portable chamber described (Reicosky, 1990), Reicosky et al. (1990), Reicosky & Lindstrom (1993). Measurements for CO_2 flux were initiated within 5 min of the last tillage pass. Briefly, the chamber (volume of 3.25 m^3 covering a horizontal land area of 2.67 m^2) with mixing fans running was moved over the tilled surface until the chamber reference points aligned with plot reference stakes, lowered and data rapidly collected at 2-s intervals for a period of 80 s to determine the rate of CO_2 and water vapor increase. Data recorded included time, plot identification, solar radiation, photosynthetically active radiation, air temperature, wet bulb temperature, and the output of the infrared gas analyzer measuring CO_2 and water vapor concentration. After the appropriate lag times, data for a 30-s period was used to convert the volume concentration of water vapor and CO_2 to a mass basis then linearly regressed as a function of time as described by Reicosky et al. (1990). The slopes of these regression lines which reflect the rate of CO_2 and water vapor increase within the chamber are expressed on a unit horizontal land area basis. These measurements are presented on “land area” basis and differentiated from “exposed soil surface area” basis caused by the difference in surface roughness.

The total time for a single measurement required for the data collection and computation was about 2 minutes. Triplicate measurements were made on each tillage treatment before moving to the next plot. Initially, up to five replicated measurements per day were made on each treatment to provide limited data on the diurnal dynamics of CO_2 fluxes. When the fluxes on the tilled plots had decreased substantially, only two measurements per day were made.

Results and discussion

The short-term (55 hours after tillage) effect of tillage method on CO_2 flux is summarized in Figure 1. Each data point is the mean of three replicates error bars represent ±1 standard deviation. When error bars are not visible, the error bars are contained within the symbol. Positive values indicate CO_2 flux from the soil surface to the atmosphere. Relatively large initial fluxes (as large as 29 g CO_2 m^{-2} h^{-1}) from the moldboard plow surface were observed. CO_2 fluxes on the MP and the MP + D2X were largest immediately after tillage probably reflecting a “flush” of microbial CO_2 and CO_2 released from large voids generated by the tillage event (Blevins et al., 1984; Buyanovsky & Wagner, 1983; Buyanovsky et al. 1986; Hendrix et al., 1988). The rapid decrease in the CO_2 flux on MP from 29.1 g m^{-2} h^{-1} to 2 g m^{-2} h^{-1} 55 hours after tillage was noteworthy. Immediately after tillage, the MP + D2X treatment had a flux as large as 7 g m^{-2} h^{-1} that decreased to 2 g m^{-2} h^{-1} within 3 hr. The CP treatment showed a similar trend, but with lower initial flux. These tillage methods are compared with NT where there was little change in the CO_2 flux from 0.7 to 0.2 g m^{-2} h^{-1} during the same 55-hour period.

The initial CO_2 flux was largest for MP followed by the CP, apparently reflecting the depth of soil disturbance and increased void fraction in both tillage treatments. The third highest flux was MP + D2X, which also decreased rapidly during the first 55 hours that had the same depth of tillage but surface porosity was reduced by the two diskings. The DH had a relatively small CO_2 flux throughout the entire period and was only slightly larger than the NT plot. The cumulative CO_2 flux for the 55 h period in Figure 1 was estimated by calculating the area under the curves and resulted in 247, 78, 37, 88, and 22 g CO_2 m^{-2} for MP, MP + D2X, DH, CP and NT respectively.

Measurement of the CO_2 flux from the tillage surfaces was continued after a major rainfall event (3 day total of 49 mm) for up to 19 days after the initial tillage (Figure 2). During this period, the flux rates followed the earlier trends based on the tillage method. Throughout the remaining period, MP consistently had the highest CO_2 flux followed by MP + D2X. Both tillages completely incorporated surface residue. The DH and the CP had relatively low fluxes that were similar to NT during the remainder of the study. The results indicate that, for at least 19 days after tillage, MP caused more CO_2 to reenter the atmosphere compared to other treatments. The cumulative

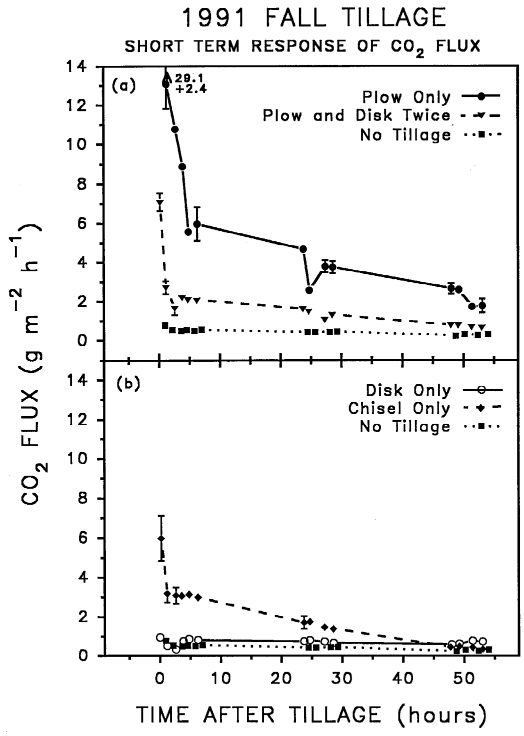

Figure 1. Short-term effect of fall tillage method on carbon dioxide flux versus time: **a**) Moldboard plow, moldboard plow plus disk twice and no tillage; **b**) Disk harrow, chisel plow and no till. Tillage done on 4 Sept. 1991 (DY 247).

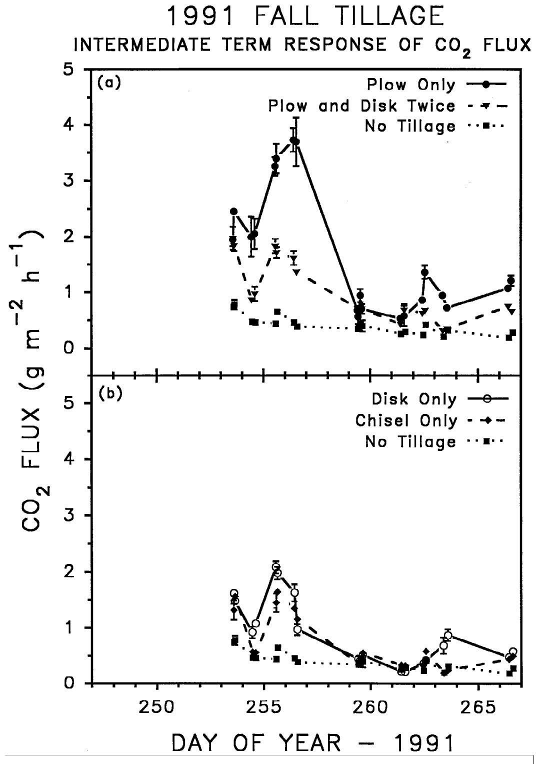

Figure 2. Intermittent-term effect of fall tillage method on carbon dioxide flux versus time following a major rainfall event: **a**) Moldboard plow, moldboard plow plus disk and no tillage; **b**) Disk harrow, chisel plow and no tillage. Note the change in scales from Figure 1.

CO_2 flux from each tillage surface for the 19 days after tillage was 913, 475, 391, 366, and 183 g m^{-2} for MP, MP+D2X, DH, CP, and NT, respectively.

Differences in the CO_2 flux within three days after tillage and between 3 and 19 days after tillage reflect the difference in the soil disturbance. The MP was the most disruptive tillage treatment with 100% residue incorporation, greatest surface roughness, largest soil surface area, and probably largest void fraction. This combination of factors all promoted CO_2 flux from the tilled surface. The MP+D2X, while tilled just as deep, had reduced surface roughness, but probably reduced void fraction that resulted in lower CO_2 flux. The primary difference between the MP and the MP+D2X was the difference in the surface roughness and void fraction that resulted in lower CO_2 flux after the soil clods had been broken down.

The amounts released during those 19 days can be compared with the equivalent C in tops and roots of the previous wheat crop in Figure 3 (Reicosky & Lindstrom, 1995; Reicosky et al., 1995). Accepting the common approximations that 45% of the wheat residue is carbon then the carbon equivalent of the 4.12 Mg of wheat residues ha^{-1} is about 1.85 Mg C ha^{-1}. With plowing only, the CO_2 loss was greater than the equivalent C input from the previous crop. The C released as CO_2 during the 19 days following moldboard plow, moldboard plow plus disk harrow, disk harrow, chisel plow and not tilled treatments would account for 134, 70, 58, 54, and 27%, respectively, of the C in the current year's crop residue. Considerably more C was lost as CO_2 from the plowed plots than from the area not tilled. The degree of residue incorporation on DH and the CP was essentially the same. Differences in CO_2 flux between these two treatments probably reflects the void fraction and surface roughness (tillage depth of disk only was approximately 75 mm while that for the chisel was over 150 mm). Given the short duration of the sampling, presumably, the wheat residue was only starting to decompose and did not contribute significantly to the intermediate-term CO_2 flux. The results suggest that the depth of soil disturbance was more important than residue incorporation in determining

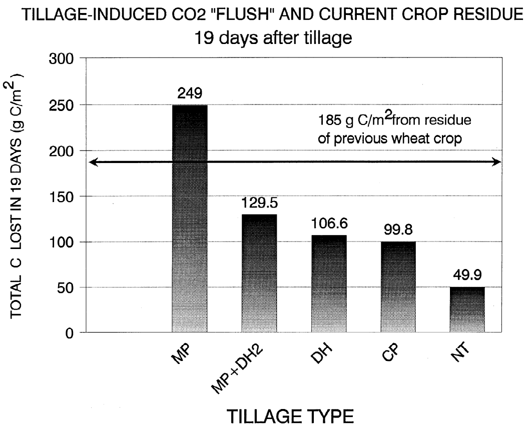

Figure 3. Cumulative carbon flux 19 days after tillage following different tillage methods related to carbon in previous crop residue (Reicosky & Lindstrom, 1993).

the magnitude of short-term CO_2 flux. These results are in general agreement with the work of Grabert (1968), who observed an increase in total respiration rate with increased plowing depth. The results contradict those of Richter (1974), who found higher CO_2 evolution in three soils at zero tillage than with rototillage; and those of Hendrix et al. (1988), who observed greater CO_2 output from no-tillage than conventional tilled soils. The timing in the short-term dynamics measured with field gas exchange techniques may not reflect the long-term carbon balance on soils because of soil surface changes such as crust formation that occur over periods of weeks and months may influence long-term dynamics.

In summary, fall tillage methods affected short and intermediate-term CO_2 flux rates from a harvested wheat field. Immediately after tillage moldboard plow had the largest rate > moldboard plow plus disk twice > chisel plow > disk > no-tillage. The cumulative CO_2 evolved for the 19 days of this study was in the order moldboard plow > moldboard plow plus disk twice > disk > chisel plow > no-tillage. Results suggest that high initial flux of CO_2 was more related to surface soil roughness and depth of soil disturbance than to residue incorporation. The CO_2 flux from all tillage plots showed small but consistent differences 19 days after tillage and 64 mm of rain. The rates were substantially lower following the rain due to soil re-consolidation. The data suggest lower short-term soil CO_2 fluxes are associated with tillage methods that limit soil disturbance. Differences in CO_2 flux among tillage methods suggest potential for improved soil management to minimize agriculture's contribution to global CO_2 increase. Tillage methods that minimize depth and extent of soil disturbances will have the least impact.

Experiment 2

Materials and methods

Experiment 2, described in more detail by Reicosky (1995), was conducted in the fall of 1993 at the USDA-Agriculture Research Service Swan Lake Research Farm located in west central Minnesota, (45°41'14" N and 95°47'57" W). A field was selected with four different soil types. The soils range from moderately-well to poorly drained; were formed on glacial till under tall prairie grass vegetation with properties presented in Table 1. The surface horizon is generally very dark with relatively high organic matter. Many of the soils are developed over subsoils with high calcium carbonate. The cropping history for 80 years was corn, soybean, and spring wheat with conventional tillage.

Two transects, each 195-m long were established (hereafter referred to as north and south transects), across an area where there was significant variation in the soil types as indicated by the soils map. The transects were 30 m apart in an east-west direction. The measurement locations were in the center of the soil-map unit on the respective transect. The soil series identification was confirmed by an NRCS soil scientist[2]. The name identification includes a sequential number at the end of the common name because the transects crossed the same soil-map unit more than once.

The study area was planted to spring wheat (*Triticum aestivum* L. cv. Marshall) on 21 April 1993 (Day 111) and harvested on 17 Aug. 1993 (Day 229). Seasonal rainfall was above normal with 524 mm from wheat planting to harvest. The last significant rain before plowing on Day 266 was 20 mm on Day 262 and 6 mm on Day 263.

To minimize weed and volunteer wheat effects on the CO_2 exchange rate, the entire field was sprayed with Ranger[1] (glyphosate) herbicide at 0.8 kg a.i. ha^{-1} on 27 August (Day 239) and 13 September (Day 256).

[2] The assistance of soil scientist, Gerry Gorton from the regional NRCS office at Fergus Falls, MN in describing the soil profiles is gratefully acknowledged.

Table 1. Summary of soil taxonomy and properties in the spatial variation study*

Soil Series (Taxonomy)	Drainage	Depth of A1 (m)	Bulk Density (kg m^{-3})	Soil Organic Matter (%OM)	Clay Content (%)	pH
Barnes loam (Udic Haploborolls, fine loamy, mixed)	Well	0.18	1.40-1.50	2-5	18-27	6.1-7.8
Hamerly loam (Aeric Calciaquolls, fine-loamy, frigid)	Mod. Well	0.20	1.20-1.60	4-7	18-27	6.6-8.4
Parnell silty clay loam (Typic Argiaquolls, fine Montmorillontic, frigid)	Very poor	0.56	1.20-1.30	6-10	27-40	6.1-7.8
Vallers silty clay loam (Typic Calciaquolls, fine; loamy, frigid)	Poor	0.30	1.20-1.35	5-8	28-35	7.4-8.4

*NRCS Data from soil interpretation records. Soils formed on glacial till under tall grass prairie.

Commercially available moldboard plows were used for tillage along the transects. In order to get the 2.74 m plowed width required for the chamber measurements two sets of plows were used. A four-bottom plow (0.46 m wide to a depth of 0.22 m) was pulled by the first tractor followed immediately with a two-bottom plow (same width and depth) pulled by a second tractor. Both sets of moldboard plows were each pulled by a medium-sized farm tractor (≈ 70 kW). Plowing resulted in nearly complete inversion of the surface layer and 100% incorporation of the residue. A no-till (NT) treatment used undisturbed soil with crop residues as left by the combine, it does not refer to a long-term "tillage system." Based on the soils map, the soil was a Parnell, located about 20 m north of plot 7 on the northern transect. The previous wheat crop was established using conventional tillage and planting equipment.

The CO_2 flux from plowed and no-till soil surfaces was measured using a large, portable closed chamber described earlier. After the appropriate lag and mixing times, data from a 30-s calculation-window was selected to convert volume concentration of water vapor and CO_2 to a mass basis and then regressed as a quadratic function of time to estimate gas fluxes (Wagner et al., 1996). These fluxes represent the rate of CO_2 and water vapor increase within the chamber and are expressed on unit horizontal land area basis. Occasional large holes around the perimeter of the chamber due to the rough-plowed surface were quickly filled with soil by hand to minimize leakage. No effects of significant leakage were observed once the holes were plugged. The convention of positive fluxes from the soil surface was selected for both CO_2 and water vapor.

The total time for a single measurement including both data collection and computation was about 2 min. Three sequential measurements were made at each site for replication as part of the routine measurement cycle before moving to the next site. Within a single day, four cycles along each transect were used to provide data on the temporal dynamics of CO_2 flux after plowing.

Due to the anticipated rapid decline in the CO_2 flux as a function of time after plowing, measurements were made with the portable chamber within 30 to 40 s after the pre-marked area was plowed. At each designated site the tractors pulled both sets of plows through the designated experimental site to a predetermined reference point. Then waited while the three successive measurements were taken. This was repeated until all seven pre-marked sites (on the transect) had been sampled. The measurement cycle was then repeated starting on the first site measured that day. The south transect was plowed from west to east and CO_2 flux evaluated on 23 September (Day 266) with the first chamber measurement at 0929 h. The north transect was plowed on 24 September 1993 (Day 267) from east to west with the first chamber measurements at 0953 h. Within any single day, four measurement cycles were completed on each transect. On Day 267, about 24 h after tillage on the south transect only, an additional cycle of measurements was completed. On both days, at the start of each measurement cycle, triplicate measurements were made on the NT site.

The cumulative amount of CO_2 evolved after plowing was calculated using numerical integration (trapezoid rule). This method assumes linear interpolation between the measured fluxes over the time interval. The areas for successive time intervals were summed to give a total amount of CO_2 evolved. The cumulative CO_2 flux following moldboard plowing was calculated for ≈3.5 h after tillage on both transects and for about 24 h after tillage on the south transect. The values for 24 h may be subject to error due to the long time between the last two measurements, however they represent a first approximation.

Results and discussion

The change in CO_2 flux as a function of time after plowing is illustrated in Figure 4 for the Parnell2 soil. This represents the change in the CO_2 flux from 1 min. to ≈3.5 h after plowing. The time of the first measurement after plowing was consistent within 30 to 40 s on all sites and was rounded to the nearest minute after plowing for simplicity. The ≈3.5-h time after plowing in the last series of measurements varied slightly due to chamber travel time between sites and is considered approximate. The actual times ranged from 3.40 to 3.62 h. The CO_2 flux in Figure 4 decreased from a high of 114 to 48 g CO_2 m^{-2} h^{-1} within 8 min. to about 8 g CO_2 m^{-2} h^{-1} after 3.5 h. All of these fluxes were larger than the no-till site average of 0.38 g CO_2 m^{-2} h^{-1}. The decrease in the CO_2 flux as a function of time after plowing was fitted to a reciprocal linear function and a modified exponential function programmed in SAS (1988). The coefficients for the equations for Parnell2 soil are summarized in Figure 4. Analysis of the other data sets showed the reciprocal linear function had the lowest-residual-mean square in 12 of 14 data sets. This curve type fit all the data sets reasonably well and allows a Y intercept and a gradual linear decline in the flux as a function of time after tillage. However, the data is limited to the ≈3.5 h time interval.

There was a substantial difference in the CO_2 fluxes between the plowed areas and the no-till after 24 h on the south transect that indicated significant CO_2 was lost overnight. The change in CO_2 flux from 3.5 h to 24 h after plowing ranged from 1.1 g CO_2 m^{-2} h^{-1} on the Hamerly5 soil to 4.4 m^{-2} h^{-1} on the Vallers3 soil. The fluxes after 24 h were still 6 to 10 times larger than the 0.18 g CO_2 m^{-2} h^{-1} from the no-till site on the morning of Day 267. The decreasing trends in the plowed sites should continue until the next perturbation, i.e.. another tillage event or rainstorm that could cause surface sealing or cold temperatures or drier soils that could decrease the CO_2 flux (Reicosky & Lindstrom, 1993).

The CO_2 fluxes on three different soils in the north transect as a function of time after plowing are illustrated in Figure 5, representing the lowest, middle and highest initial fluxes on Day 267. The time trends were similar for all three soils. The data were fitted using the inverse linear function as described previously. The good fit suggests this function may be used to approximate the initial flush of CO_2, at least for 3.5 h after plowing. The coefficients were extremely variable across all soils and within the same soil series and have limited physical meaning. These data and other appropriate functions require further analysis before empirically derived coefficients can be related to soil physical properties and processes.

The cumulative CO_2 loss from 1 min. to ≈3.5 h after plowing is summarized in Figure 6 and 7 for the north and south transects, respectively. The cumulative CO_2 loss along the north transect ranged from 67 g CO_2 m^{-2} for Parnell2 to 26 g CO_2 m^{-2} for Barnes1. The cumulative flux for the 3.5-h period shows differences with respect to soil series and with position along the transect for the same series. These values were 30 to 80 times larger than the no-till value of 0.78 g CO_2 m^{-2} for the same period illustrating significant loss of CO_2 in the initial flush immediately after plowing.

The cumulative flux for the first 3.5-h after plowing on the south transect ranged from 60 g CO_2 m^{-2} for Vallers3 to a low of 20 g CO_2 m^{-2} for Barnes2 (Figure 7). However, the initial measurements on Barnes2 were not made until 8 min. after plowing due to operator error and may not be a representative. More realistic is Barnes3 that had 35 g CO_2 m^{-2} evolve during the 3.5-h period after plowing. These cumulative fluxes illustrate substantial variation due to soils and their location within the landscape. All cumulative fluxes were larger than no-till at 0.58 g CO_2 m^{-2} for the same period.

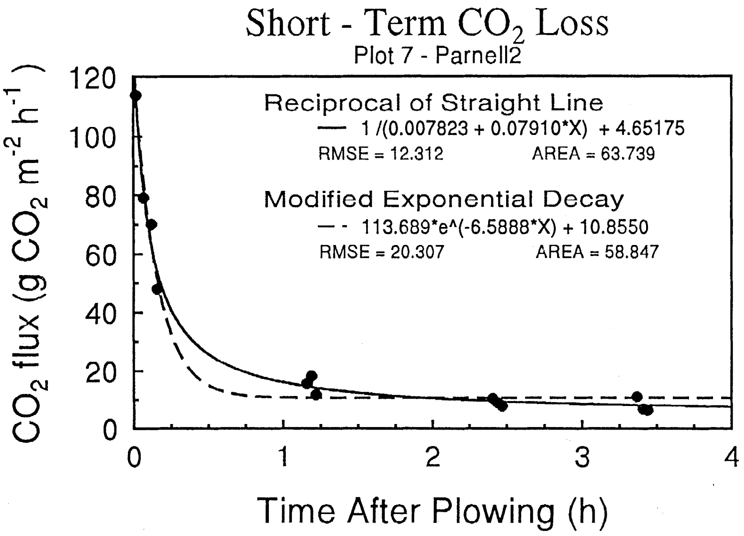

Figure 4. The CO_2 flux as a function of time after plowing for Parnell2 soil on the north transect. Coefficients are for fitted reciprocal linear and modified exponential curves.

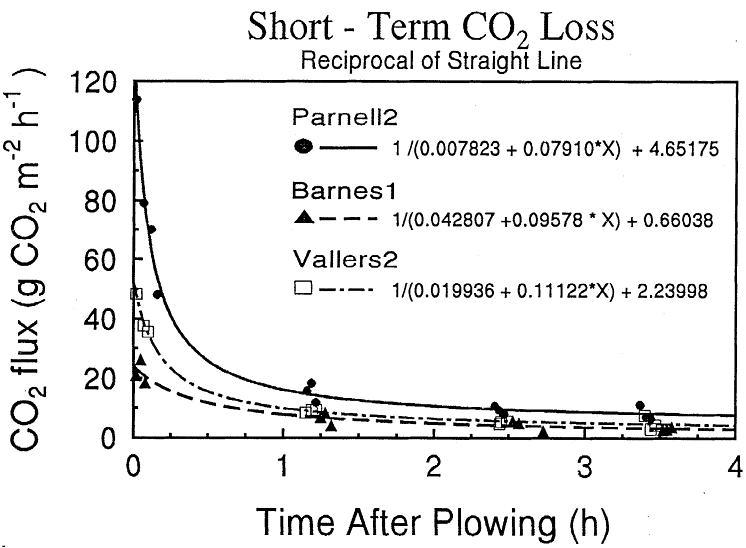

Figure 5. The CO_2 flux as a function of time after plowing for three different soil series on the north transect that represent low, median, and high fluxes measured on Day 267.

The same method was used to calculate the 24-h cumulative CO_2 loss for sites on the south transect where a measurement cycle was made on the morning of Day 267. These data were taken approximately 24 h after plowing on Day 266 and can be used to approximate the cumulative CO_2 loss for 1 day. The cumulative CO_2 fluxes values ranged from a high of 143 g CO_2 m^{-2} to a low of 77 g CO_2 m^{-2}. The cumulative CO_2 fluxes for 24- h along the south transect were 108, 101, 143, 106, 125, 90, and 77 g CO_2 m^{-2}, respectively for the Hamerly5, Vallers4, Vallers3, Vallers2, Hamerly4, Barnes3 and Barnes2 soils. These values can be compared with the no-till site which lost 6.66 g CO_2 m^{-2} during the same period. The average CO_2 fluxes at the end of the 24-h period after plowing were larger than from no-till. This is in agreement with observations of Reicosky & Lindstrom (1993), where moldboard plowing showed higher fluxes as long as 3 days after

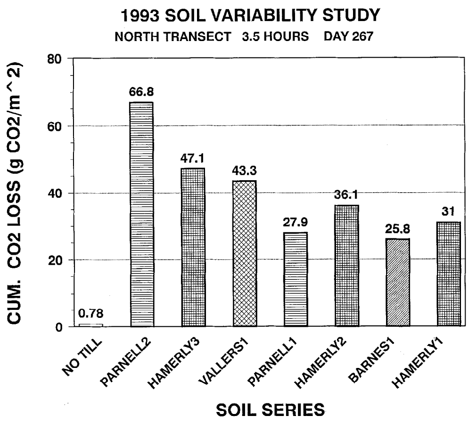

Figure 6. The cumulative CO_2 loss for the first 3.5 hours after plowing for soils on north transect (Day 267) using the trapezoid rule for numerical integration.

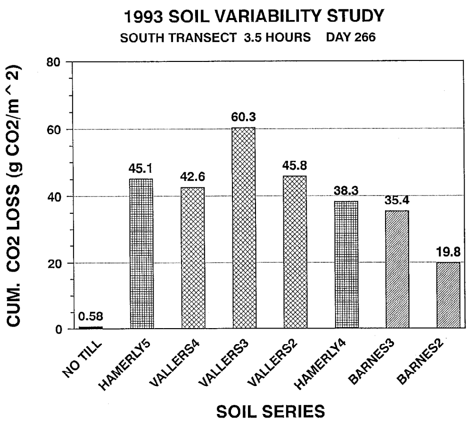

Figure 7. The cumulative CO_2 loss for the first 3.5 hours after plowing for soils on south transect (Day 266) using the trapezoid rule for numerical integration.

tillage before a 49-mm rainfall event. These results however, need to be interpreted with caution due to the long interval with no data points during the night.

The distribution of soil properties over space is an important source of variability in a field experiment that has long been recognized. In this work, the rate of CO_2 loss was partially dependent on soil position within the landscape. Temporal variation in factors that control associated processes are complex and difficult to quantify. Critically important is the dynamic temporal variation from perturbation of the soil system when it is moldboard plowed. The temporal trends superimposed on the spatial variation in landscapes only further complicate the analysis.

In summary, these results show a large loss of CO_2 immediately following moldboard plowing. Measurements within 1 min. after plowing as opposed to 5 min. after plowing showed the maximum initial CO_2 flux was nearly threefold what has previously been measured. Enhanced loss of CO_2 and the subsequent entry of oxygen into the soil could shift the gaseous equilibrium and result in enhanced long-term organic matter decomposition. These results help explain the long-term decrease in soil organic matter as a result of plowing on agricultural soils. There was significant spatial variation along the transects that was partly related to soil type, and probably related to soil organic C and water content at the time of tillage.

Experiment 3

Materials and methods

Conservation tillage and "no-till" are currently being recommended for erosion control. Conventional methods using moldboard plow are declining due to energy cost and potential to cause soil erosion. Conservation tillage tools are primarily designed for residue management and to meet conservation compliance. There is little information on how the degree and extent of soil mixing by these tools may affect soil carbon.

The study was conducted August 24, 1994 on a Barnes loam described in Table 1 in spring wheat residue (variety Marshall) and weed mix that had been killed with Roundup[1] (glyphosate 0.8 kg a.i. ha^{-1}) two weeks before tillage. The amount of wheat straw residue was less than that for a normal wheat crop. The grassy weeds contributed to residue cover, however no measurement of weeds were made. The herbicide prevented any re-growth of germinated wheat and weeds that may affect the gas exchange measurements. The residue was cut to two heights, a short residue that was approximately 5 cm tall and another area where the residue was about 30 cm tall so that tillage equipment could operate in both short and tall residues and to see if there were some differences in the way the residue was incorporated. The soil surface ($\approx$2.5 cm deep) was fairly wet due to 3 mm of rain the previous night which resulted in higher carbon dioxide fluxes than anticipated on the not tilled area. However, the remainder of the soil depth was only slightly more moist than typical for fall tillage. These conditions may have been ideal for some of the tillage equipment that performs better under dry conditions.

Description of equipment and settings

Conservation tillage tools, also referred to as combination implements, encompass many types of tillage and planting techniques that maintain at least 30% or greater residue cover after planting. They consist of a wide variety of basic components, commonly found as part of other tillage implements mounted on toolbars, that are adjustable to vary residue cover left after tillage to fit the definition of conservation tillage. Combination implements are often used for one pass tillage and chemical incorporation. Most operate in heavy residue without clogging and often require larger horsepower available in modern tractors. Because of the wide variety of these combination implements, the specific equipment used in this study will be briefly described.

The moldboard plow, used in this study for reference, was a John Deere[1] Model 2800 that consisted of six 46 cm-wide bottom plows pulled by a 142 kW tractor at about 8 km h^{-1}. The plows were set to go 25 cm deep representing the maximum depth normally encountered with moldboard plowing that left the soil in a loose friable condition. The plow left between 7 and 9% residue cover under these conditions.

The Howard Paraplow[1] (model 410B) has been used as a research tool for deep tillage without inversion and for incorporation of nitrogen. It is designed to lift the soil in place and set it back down with minimal inversion. This specific model had four plows that were set to 25 cm deep spaced 51 cm apart. This tool was pulled by a 104-kW tractor at about 8 km h^{-1} and resulted in 76 to 84% residue cover left on the soil surface.

The White[1] model 445 Conser-Till conservation chisel plow is designed to leave variable amounts of residue on the soil surface after tillage. The White[1] model 445 Conser-Till consists of a gang of either ripple coulters or disk coulters in the front, designed to cut or partially incorporate residue to a depth of 10 cm. The front gang of coulters is followed by a gang of chisel points (twisted shovels or straight shovels) set to a depth of 25 cm and then followed by deep till subsoil shanks that till the soil to 41 cm. The subsoil shanks were at a 76 cm spacing. Disk coulters are individually mounted and spaced at 30 cm, they may be raised or lowered hydraulically to obtain desired residue coverage. Deep till shanks are optional on the rear bar and may be set at a depth of 5 to 15 cm below the depth of the standard shanks. The equipment was 5.2 m wide and pulled by a 224-kW 8 wheel drive tractor at a speed of about 9.7 km h^{-1} and left 31 to 35% residue cover after tillage.

The DMI[1] 530 Ecolo-Tiger consisted of an “X” disk frame of nine concave disks 56 cm in diameter individually spring loaded on 38 cm centers. The “X” frame is independently and hydraulically controlled to vary residue management. The disk gangs are followed by 5 subsoil shanks at a 76 cm spacing to go 41 cm deep. Five lead shanks are mounted ahead and between regular shanks to take out the middles and provide up to 10% more fracturing. These lead shanks run at a depth 10 cm shallower than the regular shanks. The subsoil shanks are followed by a gang of disk levelers, operated hydraulically and independently, for leaving a smoother soil surface. The equipment was 3.8 m wide and was pulled by a 186-kW 8 wheel drive tractor at about 9.7 km h^{-1} and left 29 to 43% residue cover after tillage.

The Glencoe[1] SS 7400 Soil Saver consisted of a gang of 51-cm-diameter coulters on 19 cm centers. The gang of coulters is followed by several gangs of deep till chisel plows at 38 cm spacings with 10 cm twisted shovels and no harrows or levelers at the rear. The twisted shovels were set to till the soil to a depth of 30 cm and left 32 to 36% residue cover after tillage. The operating width was 4.1 m and was pulled by a 127-kW tractor at 9.7 km h^{-1}. There are a variety of straight chisels, twisted chisels or sweeps available to cover as much as 75% or as little as 20% of the residue. The machine can be set up with either of two shank patterns (location on the frame) to leave the soil highly ridged (best for quick soil warm up and erosion control) or relatively flat for smoother subsequent passes across the field.

The John Deere[1] 510 Disk Ripper consisted of a disk gang with disks 61 cm in diameter and spaced 28 cm apart at a fixed 20 degree angle for aggressive disking to cut residue and mix it into the soil. It is followed by a gang of ripper shanks or deep subsoil shanks on a 76 cm spacing that were set to loosen the soil to 38 cm deep. The subsoil shanks were then followed by an additional gang of disks set at the opposite angle to level or smooth the soil surface that left between 24 and 34% residue cover after tillage. The rear gang angle can be set at 16 degrees for aggressive disking in heavy residue. For use in lighter soils and low residue levels, the rear gang can be set at 14 degrees. The equipment was 3.8 m wide and was pulled by a 186-kW 8 wheel drive tractor at 9.7 km h^{-1}.

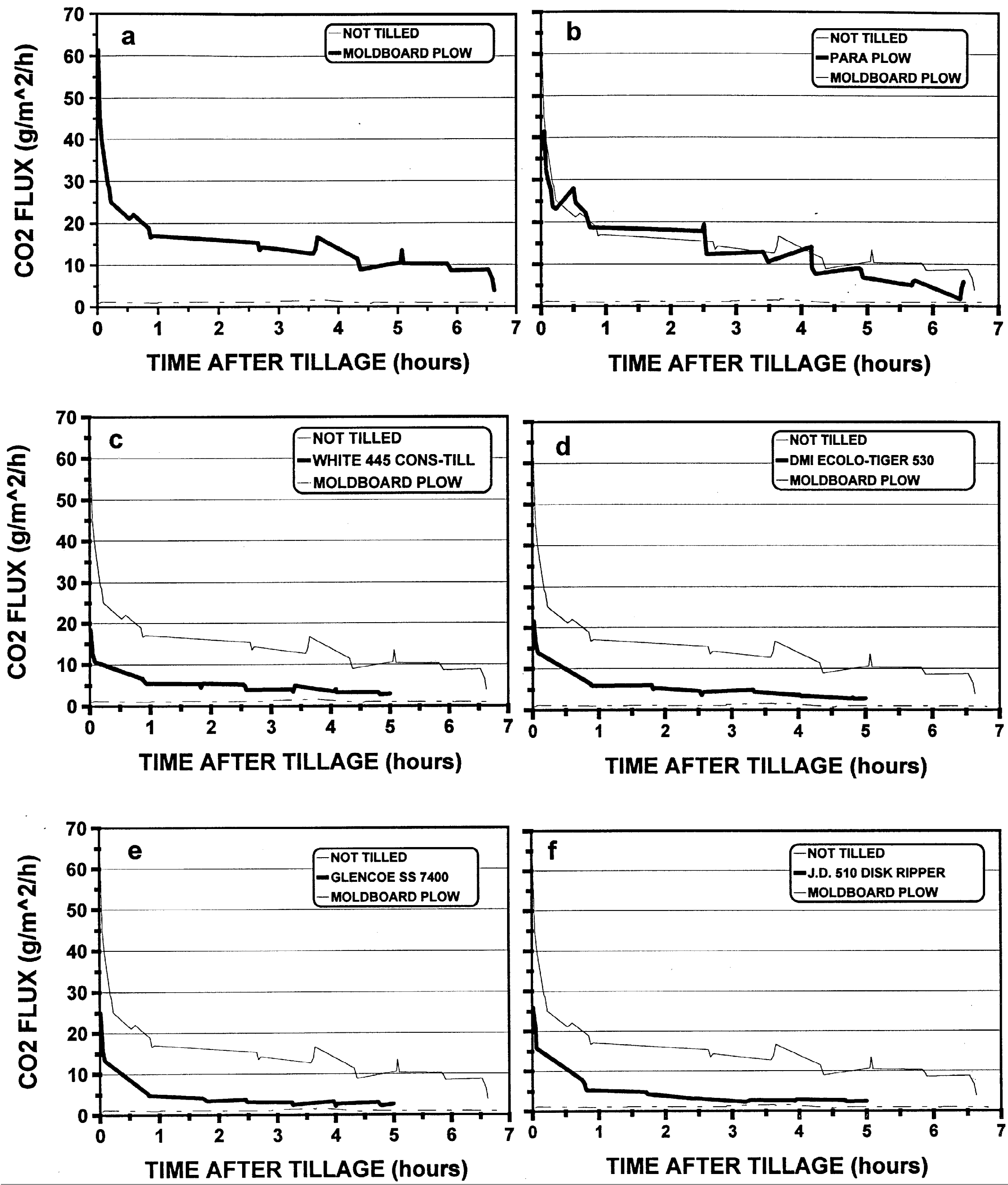

Figure 8. The CO_2 flux versus time after tillage for different conservation tillage tools relative to moldboard plow and an area not tilled.

Results and discussion

The CO_2 flux as a function of time after tillage is summarized in Figure 8a through 8f. Figure 8a shows the results for the moldboard plow and the area not tilled. These same data are plotted for reference on each of the graphs for each conservation tillage tool in Figure 8b through 8f. The moldboard plow and Paraplow had the highest initial fluxes with the other conservation tillage tools intermediate between moldboard plow and the area not tilled. The average initial flux for the moldboard plow was 49 g CO_2 m^{-2} h^{-1} that decreased to about 7 g CO_2 m^{-2} h^{-1}. The Paraplow was next highest with the four other conservation tillage tools having initial fluxes that ranged from 14 to 21 g CO_2 m^{-2} ha^{-1} and eventually decreased to about 3 to 4 g CO_2 m^{-2} h^{-1} at the end of 5 hours. The flux decreased rapidly with time after tillage primarily due to soil drying and continued gas loss.

The cumulative carbon dioxide flux was determined by calculating the area under the curves in Figure 8 using numerical integration and is summarized in Figure 9. It represents the total amount of carbon dioxide lost during the first 5 hours after tillage, which was the longest period common to all tillage equipment. The cumulative carbon dioxide loss for 5 hours after tillage was 81g CO_2 m^{-2} for the moldboard plow and the smallest on treatment area not tilled at 6 g CO_2 m^{-2}. The Paraplow was second at 79 g CO_2 m^{-2} with the other remaining conservation tillage tools intermediate ranging from 23 to 28 g CO_2 m^{-2}. All conservation tillage tools produced more CO_2 than the NT treatment, but significantly less than the moldboard plow.

Most conservation tillage tools are designed to leave residue on the surface to meet conservation compliance regulations. The average cumulative short-term CO_2 loss (5 hours) for four conservation tillages was only 31% of the moldboard plow and is a further benefit. The moldboard plow treatment lost 13.8 times as much CO_2 as the soil area not tilled, compared to the average of 4 different conservation tillage tools that lost only 4.3 times. The smaller CO_2 loss following conservation tillage tools is significant. While primarily designed to leave crop residue on the surface, these conservation tillage tools can have a second beneficial effect that results in less CO_2 loss. These preliminary results suggest that progress is being made in developing conservation tillage tools that can further enhance soil C management.

Conclusions

A clearer understanding of the residual soil organic matter and how it is maintained and/or increased is unfolding. Intensive tillage, particularly moldboard plowing, can cause large gaseous losses of carbon. The data suggest potential for using the soil as a sink for C through improved soil and tillage management. The soil C levels are controlled by many factors that can be summarized by simple C mass balance:

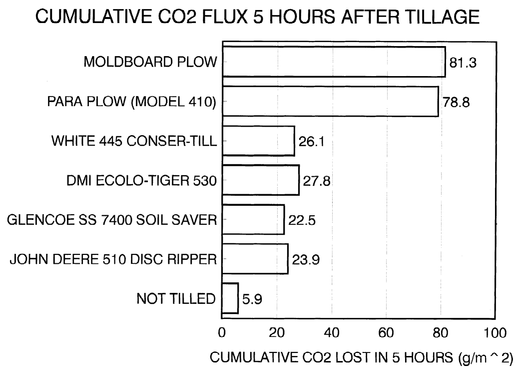

Figure 9. Cumulative CO_2 loss after conservation tillage tools for the first five hours after tillage.

$$\text{carbon input - carbon output = net carbon gain} \quad (1)$$

Carbon input is controlled by the level of residue input. This is largely determined by crop choice, fertilization and climate. Management can control the crop selection, rotation system and the fertilization. While the managers cannot control the climate, they can decide planting dates, harvesting dates and in some cases can irrigate to achieve the needed biomass. The amount of C leaving the system is controlled by the crop grain and residue removal, the rate of biological oxidation and soil erosion. These latter two mechanisms of soil C loss are substantially reduced if tillage is reduced or eliminated. The large losses of CO_2 following moldboard plowing compared to the relatively small losses with no-till or conservation tillage illustrates why crop production systems involving moldboard plowing have decreased soil C and why no-till systems are reversing this trend.

Keeping crop residues on the soil surface and reducing tillage intensity not only reduces erosion but also reduces physical release of CO_2 and possibly the biological oxidation of soil C which is less obvious but usually the greater cause of organic matter depletion in the soils. The magnitude of the CO_2 loss after moldboard plowing explains why C loss continues in agricultural systems with conventional tillage. The moldboard plow not only fractures, inverts and opens the soils which allow rapid CO_2 and oxygen exchange, but also incorporates residue into the soil which feeds a microbial population explosion. With conservation tillage, most crop residues are left on the soil surface, but only a small portion is in intimate contact with the soil moisture and available to the microorganisms. As a result, the residues decompose more slowly. Improved management practices need to be developed to control the rate of biological oxidation necessary to maintain the optimum soil processes and properties for sustained crop production.

In conclusion, soil carbon levels are affected by agricultural management practices through a complex interaction of processes determined by C inputs and decomposition rates. The data from long-term field experiments leads to two key management factors affecting soil C: 1) the quantity and quality of C added as residues to soils and; 2) the type and intensity of tillage used. Intensive tillage, such as moldboard plowing, that disturbs the soil to depths and leaves the soil surface very rough can result in substantial carbon loss. Current changes in agricultural management practices, e.g. increased use of crop rotations, cover cropping, decreased fallow frequency and increased use of conservation tillage or no-tillage, provide an opportunity to reverse the decrease in C loss from agricultural soils, changing them from sources to sinks for CO_2. Significant spatial variation in CO_2 emissions after tillage across the landscape presents challenges to the management of these complex systems. Present data supports increased adoption of new and improved forms of conservation tillage equipment and offers a significant potential to preserve or to increase soil C levels. Reversing this trend will be beneficial to agriculture as well as to the global population through better control of the global carbon balance. Accomplishing these objectives requires new research to provide a detailed understanding of the interactions of soil manipulation and disturbance as they affect biological oxidation and tillage-induced gaseous losses as part of total soil C loss.

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