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Moldboard plow tillage depth and short-term carbon dioxide release☆

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Abstract

Agricultural ecosystems can play a significant role in the production and consumption of greenhouse gases, specifically, carbon dioxide (CO_2). Intensification of agricultural production is an important factor influencing greenhouse gas emission, particularly the relationship between intensive tillage and soil carbon (C) loss. Information is needed on the mechanism and magnitude of greenhouse gas generation and emission from agricultural soils with specific emphasis on tillage operations. The specific objective of this work was to evaluate the short-term effects of moldboard plowing depth on CO_2 loss from a Barnes loam (Udic Haploboroll, fine loamy, mixed) in west central Minnesota, U.S.A. Experimental treatments were weed-free replicated plots, moldboard plowed to depths of 0.102, 0.152, 0.203, and 0.280 m using two passes of a four-bottom conventional moldboard plow (MP) following harvest of a spring wheat (*Triticum aestivum* L.) crop that was compared with an undisturbed area (no-tillage). The CO_2 flux was measured immediately after the tillage with a large, portable chamber commonly used to measure crop canopy gas exchange and continued intermittently for several hours after the initial tillage and at 24 and 48 h and periodically to 500 h after tillage. To cope with the weather-induced temporal variability, the flux data at each tillage depth was fitted to the same two-part exponential function for smoothing temporal trends and statistical analysis. The CO_2 release immediately following tillage increased with plow depth, and in every case was substantially higher than that from the no-tillage treatment. Expressing the results relative to no till (NT) showed the relative cumulative CO_2 loss for plowed depths were 3.8, 6.7, 8.2, and 10.3 times larger than NT for the MP 0.102 m, MP 0.152 m, MP 0.203 m and MP 0.280 m, respectively. The smaller CO_2 loss with shallow tillage was significant and suggests progress is being made in understanding the effect of tillage intensity on soil C management. Any effort to decrease tillage depth and maximize crop residue return to the soil surface should result lower in fuel consumption and increase soil C sequestration for enhanced environmental quality.

Keywords: Soil carbon; Soil organic matter; Gas exchange; Carbon fluxes; Portable chamber

1. Introduction

World soils are an important pool of active carbon (C) and play a major role in the global C cycle and have contributed to the changes in concentration of greenhouse gases in the atmosphere. Agriculture is believed to cause some environmental problems, especially related to water contamination, soil erosion, and the greenhouse effect (Houghton et al., 1999; Schlesinger, 1985). Recent research results suggest that scientific agriculture can be a

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solution to environmental issues, in general, and to mitigating the greenhouse effect in particular. In fact, agricultural practices have the potential to store more C in the soil than farming emits through the use of land change and fossil fuel combustion (Lal et al., 1998).

The literature holds evidence that intensive tillage decreases soil C and supports increased adoption of new and improved forms of conservation tillage or direct seeding to preserve or increase soil organic matter (Lal et al., 1998; Paul et al., 1997; Reicosky et al., 1995). Based on the soil C losses with intensive agriculture, reversing the decreasing soil C trend with less tillage intensity should be beneficial to agriculture and the global population through better control of the global C balance. The environmental and economic benefits of less intensive tillage demand consideration in the development of improved management practices for sustainable agricultural production. Little work has been done characterizing the depth of moldboard plow tillage on carbon dioxide (CO_2) losses.

Studies involving a dynamic chamber, various tillage methods and associated incorporation of residue in the field indicated major C losses immediately following tillage (Reicosky and Lindstrom, 1993) with substantial variation across the landscape (Reicosky, 1995). The short-term impact of moldboard plow (MP) and various tillage methods on CO_2 loss from the soil was measured using a portable dynamic chamber designed to measure canopy photosynthesis and mounted on the front end of a 4-wheel drive forklift for portability. Reicosky and Lindstrom (1993) found that the MP had the roughest soil surface and the highest initial CO_2 flux and maintained the highest flux throughout the 19-day study. High initial CO_2 fluxes were more related to the depth of soil disturbance that resulted in a rougher surface and larger voids than to residue incorporation. Lower CO_2 fluxes were caused by tillage associated with low soil disturbance and small voids with no till (NT) having the least amount of CO_2 loss during 19 days. Ellert and Janzen (1999) and Rochette and Angers (1999) reported results for different soils and less intensive tillage methods. They concluded that short-term influence on tillage and soil C loss was small under semi-arid conditions in agreement with Roberts and Chan (1990) and Franzluebbers et al. (1995a,b). On the other hand, Reicosky and Lindstrom (1993) concluded that intensive tillage methods, especially MP to 0.25 m depth, affected this initial soil flux differently and suggested improved soil management techniques can minimize agricultural impact on global CO_2 increase. This interaction of soil and residue mixing enhances aerobic microbial decomposition of the incorporated residue to decrease soil organic C (Reicosky et al., 1995).

Much of the work on tillage depth has been related to eliminating soil compaction from ‘‘tillage pans’’ generated by previous tillage operations, genetic horizons with high soil penetration resistance, fragipans, and other physical and chemical properties that limit root depth. Moldboard plow (ranging from 0.15 to 0.20 m depth) has been the primary tillage tool in the central U.S.A. since intensive agriculture started more than 150 years ago. However, today some farmers are plowing at depths of 0.25–0.30 m to eliminate ‘‘plow pans.’’ Raper (2000) evaluated the effect of tillage depth of chisel and disc type implements on residue burial. Tillage depth for chisel plow had little effect on residue burial while the disk harrow buried more residue when operated at greater depths. Raper et al. (2000) reported that shallow in-row subsoilers pulled at 0.18 m usually required 50% of the draft and energy requirements of tillage at 0.33 m. Van Muysen et al. (2000) and St. Gerontidis et al. (2001) showed that tillage erosion or soil displacement distance and the associated changes in soil properties were larger with deep tillage. St. Gerontidis et al. (2001) showed a 50% reduction in plow depth reduced soil displacement by more than 75%. We are not aware of other reported moldboard plow tillage depth effects on soil properties or processes that affect environmental quality.

As farmers move to more conservation tillage, the number of moldboard plows used in the central U.S.A. has declined over the last 30 years (Reicosky and Allmaras, 2003). There is a need to understand the historical role of moldboard plows on the long-term soil C loss. The role of tillage depth on soil properties related to soil C loss and environmental quality has received little attention. Reicosky (1998) evaluated various methods of strip tillage on the tillage-induced CO_2 loss and found NT had the lowest CO_2 flux and MP had the highest flux. Other forms of strip tillage had an initial CO_2 flush related to tillage intensity that was intermediate between these extremes. The near linear relationship between the cumulative CO_2 loss for 24 h and the volume of soil disturbed in the tillage operation suggested that tillage depth with a MP may be varied for optimum or minimal soil CO_2 exchange. Reducing the volume of soil disturbed by decreasing MP tillage depth should enhance soil and air quality by decreasing soil C loss. Thus, the specific objective of this work was to determine the effect of MP tillage depth on the short-term tillage-induced CO_2 loss from a loam soil.

2. Methods and materials

The experiments were conducted during the 1998 growing season at the USDA-Agricultural Research Service, Swan Lake Research Farm in West Central Minnesota, U.S.A. (45°41′14″N Lat. and 95°47′57″W Long.) on soils high in soil organic C (Reicosky and Lindstrom, 1993, 1995; Reicosky, 1997, 1998). The soil selected was a relatively uniform Barnes loam (fine, loamy, mixed, Udic Haploborolls) formed on a glacial till under tall grass prairie vegetation. The cropping history for the last 80 years has been corn (*Zea mays* L.), soybean (*Glycine max* L.) and spring wheat (*Triticum aestivum* L.) with conventional tillage and has transitioned to a corn and soybean rotation in the last 30 years. The experimental site was selected near the center of the soil map unit in an attempt to have soil uniformity across all replicates. The surface horizon is generally very dark with relatively high organic C (typically 20–30 g C kg^{-1}) and developed over subsoil high in free calcium carbonate. The preceding crop was spring wheat (*Triticum aestivum* L. cv. Marshall). Both plowed and adjacent no-till plots had surface residue from the previously harvested wheat crop that yielded 3360 kg ha^{-1} grain and an estimated 4370 kg residue ha^{-1} returned. To minimize weed and volunteer wheat effects on the CO_2 exchange rate, the entire field was sprayed with RoundUp Ultra[2] (glyphosate–isopropylamine salt of *N*-(phosphonomethyl)glycine, $C_3H_8NO_5P$) herbicide at the rate of 0.8 kg ai ha^{-1} as needed.

Moldboard plow tillage was accomplished with a conventional 0.46-m wide four-bottom Case[2] plow (Model 500) pulled at preset depths of 0.102, 0.152, 0.203, and 0.280 m below the untilled soil surface. These depths are approximate but represent substantial differences in the depth of tillage as could be adjusted on the MP. The MP was pulled with an 80-kW tractor at about 7–8 km h^{-1} to mimic large field operations. The shallowest depth was that at which the plow operation resulted in complete inversion and nearly complete incorporation of the crop residue. All measurement areas for the four replicates were in the same soil type and located within 30 m of each other in an attempt to reflect the same soil conditions. With only one chamber for flux measurements, replicates were selected as different days to evaluate all four MP tillage depths each day.

[2] Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

The MP treatments required two passes using the four-bottom plow that resulted in a total tillage width of 5.1 m. The length of the tilled area was approximately 30 m to allow sufficient area for plow penetration to the prescribed depth where the gas exchange was measured. The first pass enabled the second pass to get a more uniform depth of tillage as a result of having the plow depth control wheel in the furrow on the second pass. All the measurements were made with the chamber covering most of the second pass for uniform soil depth considerations and for timing of the measurements to make them as rapid as possible after tillage.

The CO_2 flux from the tilled surfaces in these studies was measured using a large, portable chamber described by Reicosky and Lindstrom (1993) and Reicosky (1997, 1998). Measurements of CO_2 flux were generally initiated within 1 min after the second tillage pass and continued at various times to 21 days after tillage. Briefly, the chamber with the mixing fans running was placed over the tilled surface or the NT surface, the chamber lowered and data collected for 1-s intervals for a total of 60 s to determine the rate of CO_2 and water vapor increase inside the chamber. The chamber was then raised, calculations completed and the results stored on computer diskette. After the appropriate lag and mixing times, data for a 30-s calculation window was selected to convert the volume concentrations of water vapor and CO_2 to a mass basis, then regressed as a function of time using linear and quadratic equations to estimate the gas fluxes (Wagner et al., 1997). These fluxes represent the rate of CO_2 and water vapor increase within the chamber from a unit horizontal land area as differentiated from soil surface basis caused by differences in soil roughness. Only treatment differences with respect to tillage depth or experimental objectives will be described in the results. Soil CO_2 fluxes at each depth were integrated using the smooth function in order to estimated total soil respiration during the entire measurement period in this study.

A word of clarification is needed to understand and interpret these results in view of a recently identified "chamber effect." The present data set was collected before a portable chamber bias or artifact was identified. The measured fluxes after tillage were unreasonably large relative to other long-term measurements of soil C loss. Subsequent work identified a small net negative differential pressure (−1.5 Pa) measured at the soil surface inside the chamber. Turbulent mixing required to obtain a representative gas sample for the infrared gas analyzer caused aerodynamic pressure forces. These types of pressure forces in chambers have been identified by others (Rochette et al., 1992; Lund et al., 1999; Conen and Smith, 1998; Fang and Moncrieff, 1996; Welles et al., 2001). Wind generated pressure differences caused negative pressure fluctuations that led to overestimates of the CO_2 flux due to the ‘‘venturi effect.’’ This negative pressure associated with the airflow in this chamber design apparently enhances the rate of CO_2 loss from the loosened soil. Further work with this chamber by Reicosky (2000), Denmead and Reicosky (2003) and Reicosky (2003) demonstrated differences in the wind conditions inside and outside the chamber impacted the chamber measured flux. Quantification of the ‘‘venturi effect’’ to understand the negative pressures and their influence on chamber measured fluxes will require a sophisticated and expensive soil calibration system and meteorological measurements. Thus, caution is needed in interpreting the analysis of absolute fluxes, while treatment differences on a relative basis are more meaningful. However, we believe the relative fluxes measured for the different tillage depth treatments can be compared because the differential pressure was constant across all tillage depth treatments. Recognizing the limitations of the absolute flux values, we chose to continue with the analysis in the hopes of learning more about the role of tillage depth on CO_2 loss based on a comparison of cumulated relative fluxes.

The MP tillage was accomplished on 12, 13, 17 and 18 August 1998 (JD, Julian Day 224, 225, 229, and 230) and started between 09:00 and 10:00 h each day. Each tillage day was treated as one replicate with all four tillage depths completed within that day. The sequence of events was to do primary MP tillage at the prescribed shallow depth and immediately make gas exchange measurements. Upon completion of the initial gas exchange measurements, the plow depth was adjusted and the tillage repeated at the next lower depth. This sequence was continued until all depth treatments were plowed. Within 30 s of the last tillage pass for a given depth, the first set of gas exchange measurements was completed. The gas exchange measurements were continued rotating through all tillage depths and no-till plots for the first 5 h after tillage and at 24 and 48 h and then intermittently out to 21 days. The gas exchange measurements on the plowed plots were then compared with a no-till area with and without the same amount of traffic to characterize the day-to-day variation in the soil, climate and soil water content on the gas flux. Soil water content (0–0.20 m) data were collected just prior to tillage (Table 1). Weather data collected within 300 m of the experimental site to characterize environmental conditions are summarized in Table 2. The last two rain events prior to tillage were 2.8 and 1.0 mm on 2 and 8 August, respectively. Two significant rains occurred after tillage during the measurement period. One was on 19 August of 5.9 mm and the other on 22 August of 52.6 mm. Wet, soft soil conditions immediately after the rain precluded any flux measurements. Both rain events resulted in an increase in respiration rate measured a few days after the rain. Similar climate conditions were experienced on the day of tillage for reps 1, 2, and 3 with rep 4 reflecting the different conditions on 18 August when air temperatures were cooler and the soil slightly drier associated with a passing cold front.

The use of only one chamber and large spatial, temporal within a day and rep-to-rep variation as a result of replications being selected for tillage on different dates provided unique analytical challenges. No significant correlations of soil CO_2 flux with either soil temperature or water content were noted within the data set. The wide range in fluxes within a treatment from immediately after tillage to 21 days later contributed to the complexity. To explain the results in view of the large spatial and temporal variation in the CO_2 flux, some form of data smoothing or curve fitting was required. A meaningful comparison between the plow depths can only be performed with long-term averages that include all the variation. Numerous attempts to fit the CO_2 flux data versus time to simple regression equations did not result in the same significant model for all plow depths. The raw data suggested two distinct periods based on the CO_2 fluxes. The initial rapid decline in CO_2 flux followed by a more slowly changing flux required the use of a two-part function with a break point. The general equation relating CO_2 flux to time after tillage was estimated with the CO_2 flux ($g\,CO_2\,m^{-2}\,h^{-1}$) defined as carbon dioxide exchange rate (CER) using the following

Table 1
Summary of water content data

Soil depth (m)	12 August 1998 JD 224	13 August 1998 JD 225	17 August 1998 JD 229	18 August 1998 JD 230
0–0.102	.3132 (.0043)	.3009 (.0070)	.3017 (.0103)	.2341 (.0149)
0.102–0.204	.3388 (.0056)	.3237 (.0130)	.3438 (.0068)	.2611 (.0173)
0.204–0.408	.3241 (.0187)	.3015 (.0124)	.2894 (.0214)	.2570 (.0282)

Average gravimetric water content (kg H_2O kg soil^{-1}) and (S.E.); All water contents are the average of 5 reps except 12 August 1998 which is the average of 4 reps.

Table 2
Summary of weather station data

Sensor location	12 August 1998 JD 224	13 August 1998 JD 225	17 August 1998 JD 229	18 August 1998 JD 230
T (air) 2 m (C)	18.2–24.8	16.4–27.0	17.1–23.8	15.8–20.5
Relative humidity 2 m (%)	64–83	63–92	60–84	82–92
T (bare soil) 0.05 m (C)	22.0–28.5	21.5–30.8	21.8–29.4	21.4–24.0
T (grass) 0.05 m (C)	21.4–22.5	21.2–23.0	21.4–22.5	20.9–21.2
RI 2 m (kWh/m^2)	0.119–0.787	0.102–0.785	0.105–0.881	0.036–0.332
HF 0.05 m bare (Wh/m^2)	−26 to 113	−26 to 161	−39 to 148	−32 to 47
HF 0.10 m bare (Wh/m^2)	−35 to 71	−33 to 106	−39 to 93	−33 to 23
HF 0.05 m grass (Wh/m^2)	−12 to 49	−13 to 80	−18 to 51	−13 to 17
HF 0.10 m grass (Wh/m^2)	−13 to 32	−12 to 58	−13 to 37	−13 to 7
RN 1 m bare (kWh/m^2)	0.052–0.531	0.056–0.543	0.034–0.542	0.020–0.230
RN 1 m grass (kWh/m^2)	0.050–0.526	0.056–0.558	0.034–0.565	0.022–0.227
Wind speed 2 m (m/s)	1.73–3.84	0.45–2.75	1.66–3.23	3.16–4.49
Wind direction 2 m (degrees)	159.0–175.9	165.2–225.9	32.1–63.8	115.5–131.2
Wind direction S.D.	14.0–18.8	14.0–25.9	10.3–24.3	15.4–18.5

Ranges from the weather station are from hourly averages between 07:00 and 13:00 CST when the tillage and gas exchange measurements were completed. Symbols used are: *T*, temperature; RI, incoming radiation; RN, net radiation; HF, heat flux; S.D., standard deviation of wind direction.

function:

$$\mathrm{CER} = a_0 + (1-\delta)b_0\,\mathrm{e}^{-k_0 t} + \delta(b_0+b_1)\mathrm{e}^{-(k_0+k_1)t}$$

where t is the time after tillage (h), δ switch point or break point in the function at $t_0 = 0.22$ h based on visual inspection, with $\delta = 1$ for $t < t_0$, $\delta = 0$ for $t \geq t_0$. a_0 = lower limit of CER as $t \to \infty$ (g CO_2 m^{-2} h^{-1}); b_0, maximum CER of the slowly changing portion ($t \geq t_0$) of the two-part function (g CO_2 m^{-2} h^{-1}); b_1, incremental increase in the initial CER at $t = 0$ for the rapid decline portion ($t < t_0$) of the two-part function over the slowly changing portion. *Note*: $b_0 + b_1$ represents the maximum CER at $t = 0$ (g CO_2 m^{-2} h^{-1}); k_0, rate of decline of CER for the slowly changing portion ($t \geq t_0$) of the two-part function (g CO_2 m^{-2} h^{-2}); k_1, incremental increase in the rate of decline of CER for the rapid decline portion ($t < t_0$) of the two-part function over the slowly changing portion. *Note*: $k_0 + k_1$ represents the rate of decline for the rapid decline portion (g CO_2 m^{-2} h^{-2}).

The NT area showed no trend with time, so CER for the NT treatment was estimated by the mean of the observations as:

$$\mathrm{CER} = a_0.$$

In order to ensure continuity of the function at the breakpoint, the following restriction was imposed for the regression analysis:

$$b_0 + b_1 = b_0\,\mathrm{e}^{0.22k_1}$$

which gives:

$$\mathrm{CER} = a_0 + (1-\delta)b_0\,\mathrm{e}^{k_0 t} + \delta b_0\,\mathrm{e}^{-(k_0+k_1)t+0.22k_1}$$

The model was estimated separately using 220 data points for each MP tillage depth using the SAS MODEL procedure (SAS Institute Inc., 1988).

Theoretically, the two-part function might represent the initial physical release or degassing of soil CO_2 caused directly by the tillage, followed by a somewhat slower rate of release of CO_2 due to aerobic microbial activity. The slower declining rate may have been due to soil reconsolidation following tillage, depletion of microbial energy sources, soil drying or several other causes not addressed.

Cumulative CER at 500 h after tillage was estimated from the CER regression functions from each MP tillage depth. Relative cumulative CER values and relative tillage depths were calculated as a proportion of the 0.280 m-tillage depth. Regression analysis was conducted using SigmaPlot (Systat Software Inc., 2004) with both a linear function and the sigmoidal function:

$$\mathrm{CCER} = \frac{a}{(1+\mathrm{e}^{-((d-d_0)/b)})}$$

where CCER is the relative cumulative CER, d the relative tillage depth, d_0 the relative tillage depth at which the slope of the function switches from increasing to decreasing, a the maximum relative cumulative CER and b is the rate parameter.

3. Results and discussion

The soil water content, C content and minimum/maximum temperatures and wind speeds on the days of tillage are summarized in Tables 1 and 2. The water content profiles were also slightly drier on 18 August. In general, there was reasonable agreement in the solar radiation and minimum and maximum air temperatures for 3 days of the study, but the fourth day (18 August) had somewhat lower solar radiation (cloud cover) and air temperatures and higher winds and as a result, somewhat lower CO_2 fluxes. The soil type was uniform based on visual parameters, but could include some soil variation across landscape as the new areas of tillage were completed. It is assumed the spatial soil variation was small within each day and that gas flux differences were attributed to tillage depths.

Estimated model parameters and standard errors from the regression analysis are shown in Fig. 1a–e. Adjusted R^2 values for each tillage depth ranged from 0.76 to 0.89 ($n = 220$). All of the regression parameters were significant ($\alpha = 0.05$). Fig. 1a–c show apparent trends in the a_0, b_0 and b_1 parameters with each parameter increasing with tillage depth. While it is not possible to assign any physical meaning to the coefficients, it is interesting to note that a_0, b_0 and b_1 increased with tillage depth and k_0 and k_1 showed a tenfold difference and parallel trends with depth. These trends indicate that both initial CO_2 fluxes and long-term CO_2 fluxes increase with tillage depth.

The CO_2 fluxes as a function of time for the first day after tillage are summarized in Fig. 2. Fig. 2a–d show the first part of the two-part exponential function fit for each tillage depth in the initial 5 h after tillage. Note the rapid decline in the flux during the first few minutes with the break at 0.22 h after tillage that reflected tillage-induced degassing of the soil, followed by a

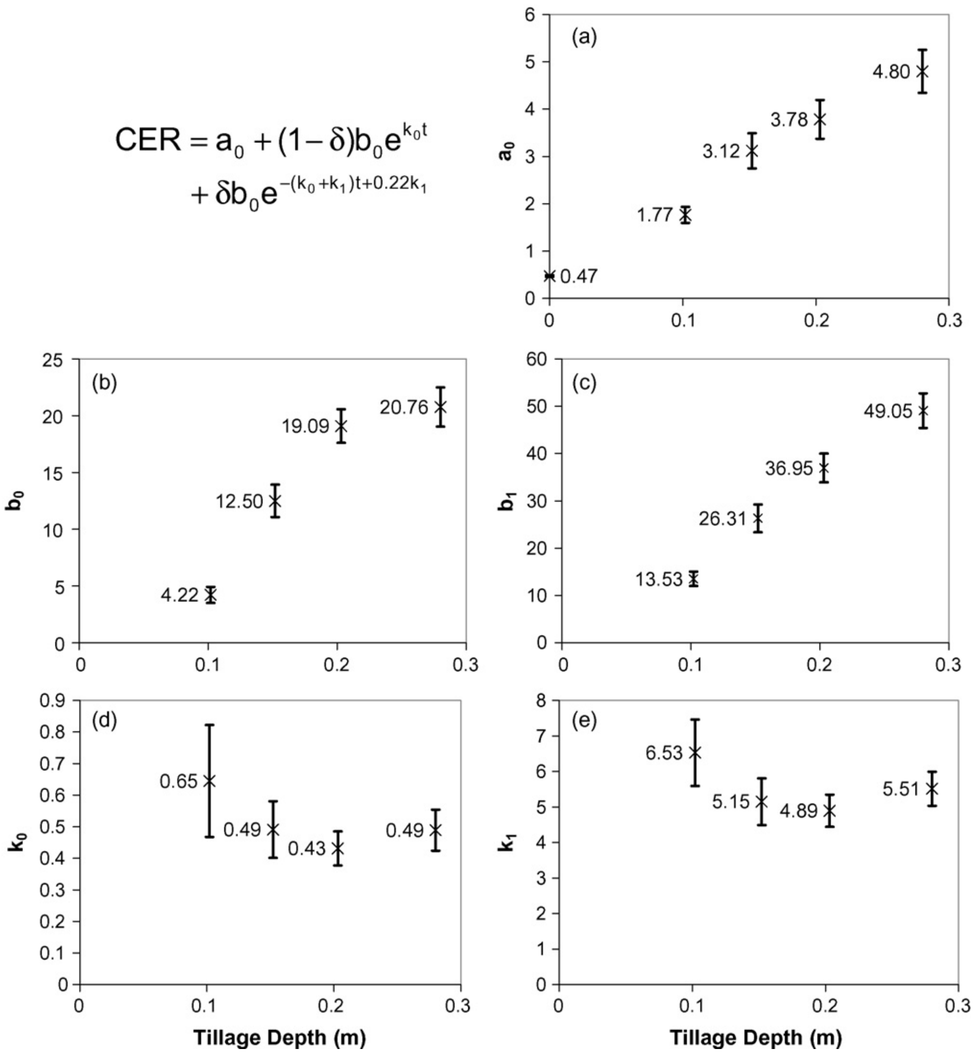

Fig. 1. Estimated model parameters for each tillage depth. See the text for model parameter definitions. Error bars represent approximate standard errors.

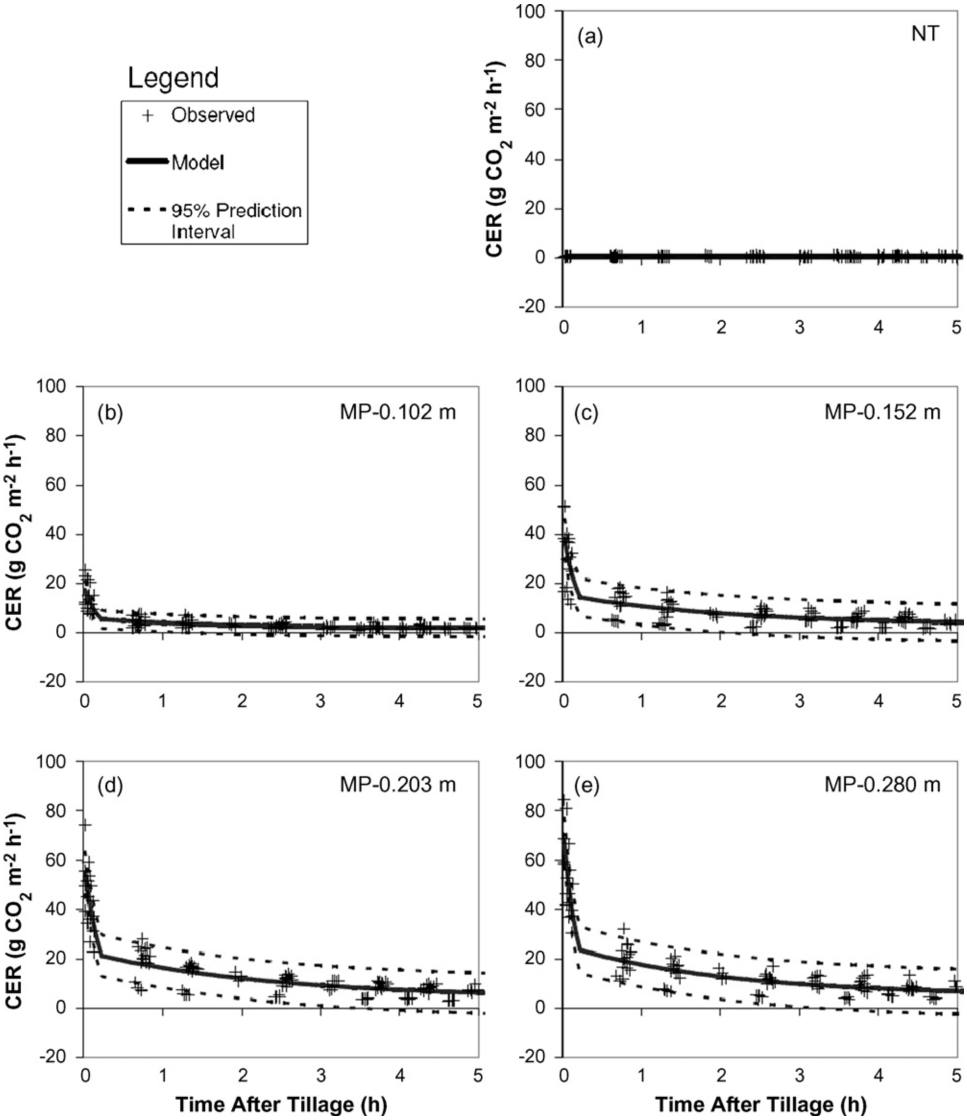

Fig. 2. The short-term instantaneous data and smoothed CO_2 flux (solid line) versus time to 5 h after MP tillage at four depths. The dashed lines represent the 95% confidence bands.

more gradual decline over the first 5 h. The data show the initial flux was largest for the maximum tillage depth on 3 of the 4 days. The maximum initial flux for the maximum depth ranged from a low of 60 g CO_2 m^{-2} h^{-1} to a high of 85 g CO_2 m^{-2} h^{-1}. For the shallowest plow depth, the initial CO_2 flux ranged from 10 g CO_2 m^{-2} h^{-1} to as high as 22 g CO_2 m^{-2} h^{-1}. In all cases there was a rapid initial decline followed by a more gradual decline in the CO_2 flux out to 5 h after tillage. Although the 95% confidence bands expanded with depth of tillage, the relative differences between the fluxes for each MP depth remained the same with the greatest depth showing the largest CO_2 loss at the end of 5 h and the shallowest depth showing the least. All MP depths showed more CO_2 loss than from the NT areas on both a relative and an absolute basis. Noteworthy is the clustering of the points in Fig. 2c–e below the smoothed line near the lower 95% confidence limit. This grouping of data points is from rep 4 reflecting the different environmental conditions on 18 August when air temperatures were cooler, wind speeds were higher, and the soil slightly drier. The sensitivity of CO_2 fluxes to daily environmental conditions on different days only increases the difficulty of interpreting treatment effects.

The CO_2 flux measurements were continued at 24 h and intermittently thereafter to 21 days after the initial tillage with results summarized in Fig. 3. Fig. 3a–e

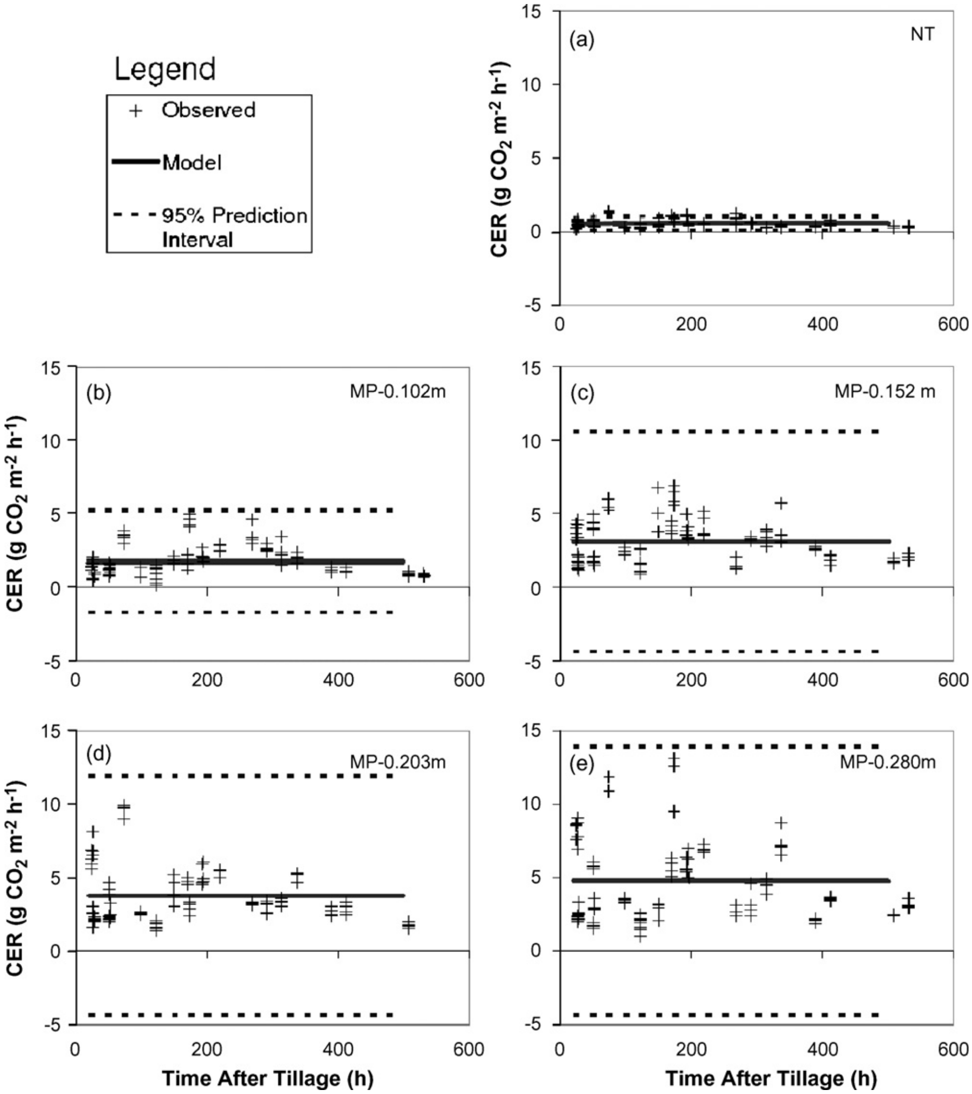

Fig. 3. The long-term instantaneous data and smoothed CO_2 flux (solid line) versus time to 500 h after MP tillage at four depths. The dashed lines represent the 95% confidence bands.

shows the smoothed fit for the flux versus time and the considerable variation in the individual data points reflecting several factors affecting the flux. The smoothed flux was essentially constant over time after the initial 5 h. Again, the variability increased with MP tillage depth as the 95% confidence bands expanded with depth of tillage, the relative differences between the fluxes for each MP depth remained the same. The large scatter in the data points with the maximum tillage depth reflects the complex interaction of several physical, chemical and biological factors that control the CO_2 flux. Despite the data scatter and temporal variation, the smoothed long-term CO_2 flux showed essentially the same relative trends with respect to tillage depth as observed in Fig. 2. The greatest depth of tillage had the largest flux, even with two rainfall events and under slightly different climatic conditions.

Noteworthy were the relatively small temporal changes in the flux after the initial rain-induced soil consolidation (on 22 August, 96 h after last tillage) that was likely related to temperature and water regime during the measurements. Some of the variation was smoothed by the function; however, each tillage depth was individually smoothed with the same general function to enable analytical comparisons. Typically, the NT plot had the lowest flux and the 0.280-m depth always had the highest flux throughout the study. The results suggest that the tillage-depth effects extend beyond the short-term and were noticeable up to at least 21 days after tillage. In other studies, Reicosky (2002) reported that tillage-induced CO_2 differences between MP and NT were observed for as long as 87 days with the differences decreasing with time.

There was an increase in CO_2 lost to the atmosphere as the MP depth increased. Fig. 4a and b show the smoothed cumulative CO_2 flux increased with MP tillage depth, approaching a plateau as tillage depth increases. Because the cumulative flux is a nonlinear function of the instantaneous flux, the standard errors were calculated from the flux regression model estimates using the delta method (Bender, 1996). The general decrease with time reflects natural soil reconsolidation or compaction and the effect of raindrop impact from two intensive rainfall events. The general increase in CO_2 lost with MP tillage depth likely reflects a larger volume soil disturbed and higher late-summer soil CO_2 concentrations at the 0.3 m-depth in the profile (Reicosky, 2002).

Looking at the 24- and 500-h periods summarized in Fig. 4b, the average soil C emissions during the 24-h interval ranged from 11 g CO_2 m^{-2} with NT and 50 g CO_2 m^{-2} with MP to 0.102 m to a high of 162 g CO_2 m^{-2} for MP at 0.280 m. The temporal and spatial variation in these data are not reflected in the cumulative loss from the smoothed function for each replica at 24 h where the maximum depth ranged from a low of 111 g CO_2 m^{-2} on 18 August (cool day) to 170–182 g CO_2 m^{-2} for the remaining 3 days. The large difference reflects the lower fluxes experienced on 18 August as a result of cooler air temperatures and somewhat drier conditions. With the exception of 17 August, the maximum tillage depth always had the highest 24-h cumulative flux compared to the other depths (see Fig. 5). The NT plots always had the smallest amount of CO_2 lost as a result of no soil disturbance. The total soil CO_2 emissions during the 21-day interval ranged from 237 g CO_2 m^{-2} with NT and 891 g CO_2 m^{-2} with MP tillage to 0.102 m to a high of 2445 g CO_2 m^{-2} for MP tillage at 0.280 m. The relationship shows the gradual decline in CO_2 loss as the tillage depth decreased from 0.280 to 0.102 m, which was the shallowest depth that soil could be inverted. The decline in the cumulative CO_2 loss as a function of tillage depth is in general agreement with the earlier observations of Reicosky (1998), which showed that the tillage-induced CO_2 loss was related to the volume of soil disturbed. Expressing the data on a soil volume basis would suggest that the same phenomenon was observed here in that the CO_2 loss from MP tillage was proportional to the tillage depth or volume of soil disturbed. Expressing the smoothed results relative to NT showed the relative cumulative CO_2 loss for plowed depths were 3.8, 6.7, 8.2, and 10.3 times larger than NT for the MP 0.102 m, MP 0.152 m, MP 0.203 m and MP 0.280 m, respectively, over this period.

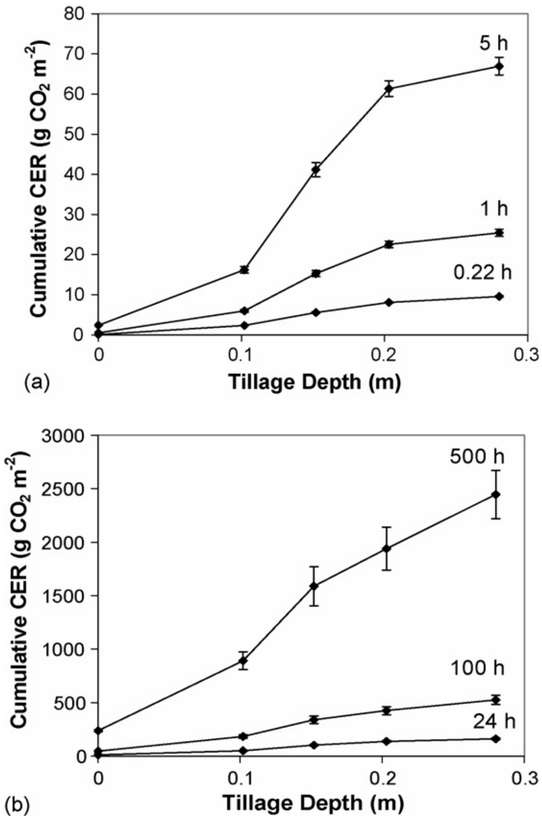

Fig. 4. The relationship between smoothed cumulative CO_2 flux and MP tillage depth, (a) at 0.22, 1 and 5 h after tillage and (b) at 24, 100, and 500 h after tillage. Error bars represent approximate standard errors.

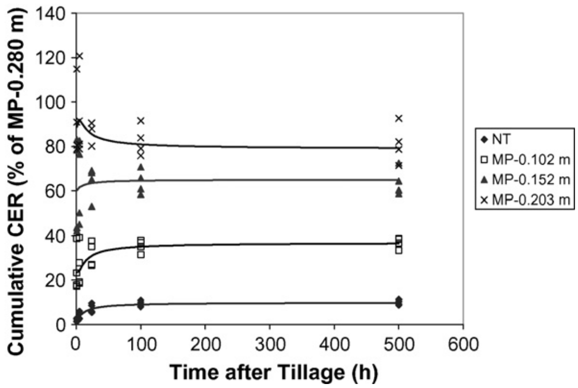

Fig. 5. Cumulative CO_2 loss at different tillage depths relative to MP tillage at 0.280 m as a function of time after tillage.

Another way to illustrate the effects of the MP tillage depth on the cumulative CO_2 loss is summarized in Fig. 5. The cumulative CER for each depth of tillage over the cumulative CER at 0.280 m is plotted as a function of time after tillage. The ratio is expressed as a percentage of the cumulative CER value for MP depth at 0.280 m. The data points at each time were taken from the smooth values for each replicate. The NT treatment was typically less than 10% of the MP treatment at 0.280 m. The remaining tillage depths were intermediate showing a progressive increase in CO_2 losses with tillage depth of 35, 65 and 81% of the MP treatment at 0.280 m for the 0.102, 0.152 and 0.203 m-tillage depths, respectively. The results show the relative effect of MP tillage depth on the cumulative CO_2 lost. The incremental increases in the ratio reflect the increase in cumulative CO_2 lost at the maximum depth in Fig. 4a and b.

Due to the day-to-day differences in climate and soil moisture across the four soil locations and the chamber pressure affect, the CO_2 loss relative to that at 0.280 m was plotted versus the relative tillage depth to adjust for the climatic differences between the different days of the study. The results show a slight sigmoidal or near linear relationship in Fig. 6 indicating that cumulative CO_2 loss increased with tillage depth. Regression analysis showed the sigmoid curve had a slightly higher R^2 suggesting CER tends to approach a plateau at the maximum depth. From a practical view, the simpler linear relation is easier to comprehend, but is unclear how it contributes to a theoretical understanding of factors controlling gas fluxes. These results illustrate cumulative CO_2 loss is related to depth of MP tillage and is proportional to the volume of soil disturbed in the tillage operation.

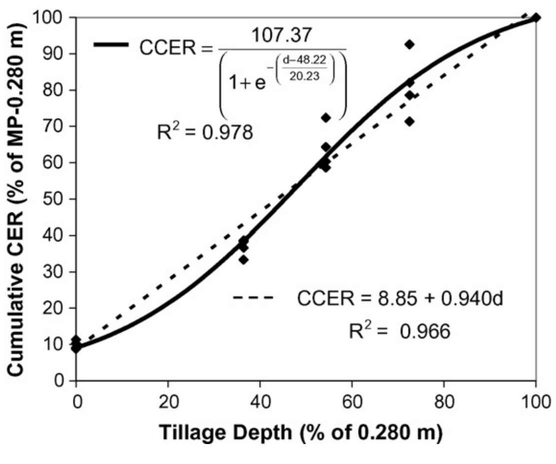

Fig. 6. Relative CO_2 loss over 500 h vs. depth of soil disturbed by MP tillage. Fluxes at the maximum depth of 0.280 m were assumed the largest.

Both the data in Fig. 4a and b and Fig. 6 may reflect the CO_2 concentration profile with depth. Measurements in other nearby studies showed the CO_2 concentration near the surface was low and showed a gradual increase to about 0.200 m (Reicosky, 2002). From 0.200 to 0.700 m, the CO_2 concentration profile was approximately constant with depth. As a result, the MP tillage depth of 0.102 and 0.152 m reflect smaller CO_2 loss due to the smaller soil volume disturbed and lower CO_2 concentration than the 0.203 and 0.280 m depths. The near soil surface CO_2 concentrations are typically lower due to drier soil and the steep concentration gradient for diffusion and gas exchange to the atmosphere. The drier surface soil, the steep concentration gradient and the combined diffusive and convective transport to the atmosphere contributed to pre-tillage gas exchange and as a result lower surface CO_2 concentrations and lower subsequent loss with shallow MP tillage. Deep tillage releases gas from a larger soil volume and a higher concentration of CO_2 during the initial soil degassing. The soil at 0.28 m-depth readily exposed to more oxygen contributes to enhance biological oxidation and long-term CO_2 losses.

Short-term evaporation was not significantly correlated with depth of tillage due to similar water content profiles and potential evaporative demand during the measurements. The only significant difference in water loss was between NT and all MP tillage depths shown in the cumulative evaporation for the first 5 h after tillage in Fig. 7. The higher evaporation was likely due higher water content and exposed surface area of the MP treatments. Cumulative evaporation was consistent for the first 5 h after tillage at all tillage depths suggesting that there was little difference in the initial water content profile (also Table 1). The shallowest MP tillage did lose 0.1–0.3 mm less water during the 5 h after tillage than the deeper tillages. The water content data for the 0–0.102 m depth was only 0.020–0.030 kg H_2O kg soil^{-1} lower than the water content for the 0.102–0.204 m and 0.204–0.408 m water contents. Therefore, the shallowest tillage (0.102 m) did expose a slightly drier soil layer than the maximum tillage depth. The effects of climate differences between the days of tillage and gas flux measurements are also illustrated in the evaporation differences. Noteworthy is 18 August when the passing cold front lowered the evaporation rate relative to the other 3 days in the study as a result of lower potential evaporation, lower radiation and air temperatures and stronger winds (Table 2). Cumulative evaporation from the NT

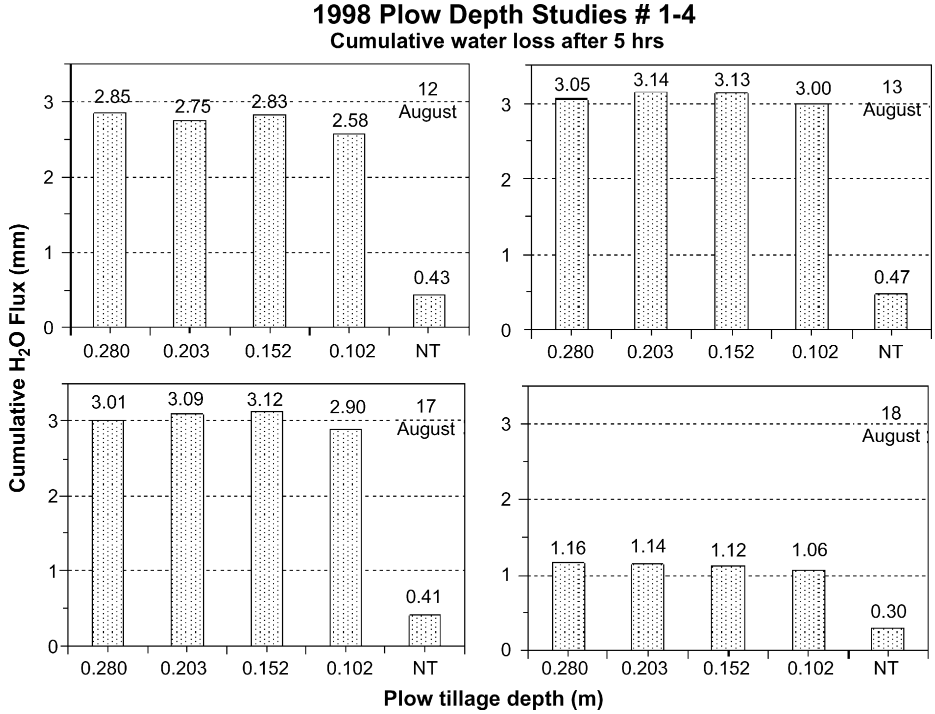

Fig. 7. Cumulative water loss for the first 5 h after MP tillage at four depths and NT on 4 days of measurement.

treatment ranged from 14 to 15% of that from the plowed treatments in the first 3 days of the study. Only on 18 August was the cumulative evaporation from the NT as high as 27% of the MP treatments. Decreased evaporation was in general agreement with the decreased CO_2 loss as a result of cooler temperatures on that day.

The practical implication of this work comes into play when we consider ways to minimize greenhouse gas emissions from agricultural sources. Agriculture plays a critical role in conserving energy used in tillage and minimizing CO_2 emissions back to the atmosphere. Previous work in strip tillage has demonstrated that the tillage-induced CO_2 loss was directly proportional to the volume of soil disturbed in the tillage operation (Reicosky, 1998). This study shows a similar trend (Fig. 4b) with the smoothed cumulative CO_2 loss for 21 days after tillage of 237, 891, 1588, 1939 and 2445 g CO_2 m^{-2} for the NT, MP 0.102 m, MP 0.152 m, MP 0.203 m and MP 0.280 m depths, respectively. We estimated the CO_2 released from the burning of fossil fuel associated with primary tillage. Fuel use was estimated for MP at different depths following the procedures developed by the ASAE (American Society of Agricultural Engineers, 2003a,b), and was converted to CO_2 emissions using a standard conversion factor (Energy Information Administration, 2004). Fuel consumption estimates were made for the tractor and moldboard plow actually used in the experiment, assuming (1) the 80 kW PTO rating accurately reflected the maximum PTO power of the tractor, (2) a medium soil texture, (3) a firm tractive condition at the time of tillage, and (4) an operating speed of 7.5 km h^{-1}. As expected, the amount of CO_2 released increased nonlinearly with increased tillage depth reflecting increased energy requirement. The CO_2 released from fossil fuels ranged from zero for the NT, to 4.7, 5.6, 7.1, and 11.5 g CO_2 m^{-2} for the MP 0.102 m, MP 0.152 m, MP 0.203 m and MP 0.280 m depths, respectively. The results suggest that decreasing the CO_2 emissions associated with tillage requires decreasing the volume of soil disturbed which is more important than lowering fossil fuel consumption. The economics associated with fuel savings are relatively straight forward; however, the economics of environmental concerns are more complex.

4. Summary and conclusions

In summary, the relative cumulative tillage-induced CO_2 losses were directly related to depth of plowing. The impact of MP tillage depth on the CO_2 loss was largest at the maximum tillage depth and declined as tillage depth decreased. Despite the uncertainty in the absolute fluxes measured by the chamber, the relative fluxes showed increased CO_2 loss with tillage depth. Depth of tillage was related to the volume of soil disturbed and supports earlier work on the short-term tillage-induced CO_2 loss from different methods of strip tillage. This trend continued for nearly 21 days after MP tillage under different initial weather conditions for each replicate and included two rainfall events. These results showed CO_2 loss due to tillage-induced soil properties changed with MP depth and ultimately led to a net C loss from the soil. The smoothed fluxes relative to NT showed the relative cumulative CO_2 loss for plowed depths were 3.8, 6.7, 8.2, and 10.3 times larger than NT for the MP 0.102 m, MP 0.152 m, MP 0.203 m and MP 0.280 m, respectively, in this study. Soil CO_2 was lost to the atmosphere and presumably oxygen entered the soil through large voids to enhance microbial activity. This effect was exacerbated with MP tillage depth with more CO_2 lost with maximum tillage depth, at least to 0.280 m in this study. Intensive tillage also breaks up the soil clods and aggregates to expose fresh surfaces for enhanced gas exchange from the interior where the aggregate interior may have a higher CO_2 concentration. This effect is amplified with the depth of tillage where the soil CO_2 concentration is likely higher. Changing the surface soil properties by MP tillage depth combined with aerodynamic forces associated with natural wind movement over the soil can result in substantial CO_2 loss and oxygen entry. A host of other factors play a role in determining the magnitude of the CO_2 flux, but are difficult to isolate and quantify the specific effects under dynamic field conditions. Further work is needed to quantify the types of tillage and depths on soil gas exchange when surface soil properties are changed with tillage. Any effort to decrease MP tillage depth should result in improved management practices for sustainable production and enhanced environmental quality.

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