

Effects of Conservation Tillage on Soil Organic Carbon Dynamics: Field Experiments in the U.S. Corn Belt

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ABSTRACT

The magnitude of greenhouse gas emissions from soil degradation depends on land use, cropping systems and tillage intensity. Information is needed on the mechanisms and magnitude of greenhouse gas emission from agricultural soils with specific emphasis on tillage. This work evaluates the impact of various conservation tillage tools and strip tillage on short-term tillage-induced CO₂ loss in west central Minnesota, USA. Maximum CO₂ loss followed the moldboard plow with various conservation tillage tools losing only 30% of that lost by the plow. No-till lost the least CO₂. Strip tillage decreased the amount of CO₂ loss relative to plowing. The CO₂ loss was related to volume of soil disturbed by the tillage operation. Additional data on CO₂ loss from the soil without using the portable chamber were collected to characterize the plume of CO₂ from a 5.5 m-wide plowed strip perpendicular to the prevailing wind, by measuring the concentration up and downwind. Concentration differences rapidly decreased with time after tillage and were as large as 140 $\mu\text{mol mol}^{-1}$ immediately after tillage, verifying tillage-induced losses without the chamber. The smaller CO₂ loss from conservation tillage tools is significant and suggests progress in developing conservation tillage tools that can lead to soil C enhancement. Reducing the volume of soil disturbed through strip tillage should enhance soil and air quality by increasing the labile C content and decreasing the tillage-induced CO₂ losses that may contribute to climate change. Enhanced soil and environmental quality benefits of less intensive tillage should be considered in soil management decisions.

INTRODUCTION

Soil carbon (C) reservoirs are of interest in global change and the greenhouse effect because soil can serve as a major source or sink for CO₂ depending on the level of management. Agriculture and intensive tillage have caused between a 30 and 50 % decrease in soil C since many soils were brought into cultivation over a 100 years ago (Schlesinger, 1986). Thus, there is a need for a better understanding of the tillage processes and the mechanisms

leading to C loss and how this C loss would link to soil productivity, soil quality and C sequestration.

Over the past two decades, conservation tillage has evolved primarily for erosion control. However, recent concern over global climate change re-emphasizes the importance of conservation tillage and how it may help reduce soil C losses. Conservation tillage has the potential for converting many soils from sources to sinks of atmospheric C in the U.S. (Kern and Johnson, 1993). Widespread implementation of conservation tillage practices in U.S. agriculture from the current one-fourth of the total cropland to three-fourths or more would substantially enlarge the soil C pool.

Recent tillage studies indicate major gaseous loss of C immediately following tillage (Reicosky and Lindstrom, 1993). They measured the effects of fall tillage method on CO₂ flux from a clay loam soil in the northern U.S. Corn Belt. Measurements of gas exchange taken with the large portable chamber immediately after tillage and continuing intermittently for 19 days showed differences in CO₂ losses related to tillage intensity that facilitated the movement of CO₂ out of and oxygen into the soil. Moldboard plow treatment buried nearly all the residue and left the soil in a rough, loose, and open condition and resulted in maximum CO₂ loss. The moldboard plow had two major effects: (1) loosening and inverting the soil to allowed rapid CO₂ loss and oxygen entry and (2) incorporation or mixing the residues enhanced microbial attack. The amounts released can be compared to the equivalent C in the tops and the roots of the previous wheat crop (Reicosky and Lindstrom, 1995) where the C loss following moldboard plowing exceeded that of the C input from the previous years' wheat crop.

The literature holds considerable evidence that intensive tillage decreases soil C and supports the increased adoption of new and improved forms of conservation tillage to preserve or increase soil organic matter (Reicosky et al., 1995). Based on the soil C losses with intensive agriculture, reversing the trend of decreased soil C with less tillage intensity should be beneficial to agriculture, as well as to the global population through increased global C management. Thus, the objectives of this work were (1) to evaluate the longer-term impact of various conservation tillage tools on CO₂ loss in the northern Corn Belt, USA, (2) to continue

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analysis of seasonal effects of strip tillage, and (3) to independently verify tillage-induced CO₂ loss without the portable chamber.

METHODS AND MATERIALS

The three experiments were conducted at the USDA-Agricultural Research Service, Swan Lake Research Farm, located in west central Minnesota, USA (45°41' 14" North Latitude and 95°47' 57" West Longitude). The soil selected was a relatively uniform Barnes loam (fine, loamy, mixed, superactive, frigid Calcic Hapludolls; National Cooperative Soil Survey, USA) formed on glacial till under tall grass prairie vegetation. The surface horizon is generally very dark with relatively high organic carbon (typically 2 to 3 g C kg⁻¹) and developed over subsoil high in calcium carbonate. The CO₂ flux from the tilled surfaces was measured using a large, portable chamber described by Reicosky and Lindstrom (1993) and Reicosky, (1997) and (1998). Emphasis was placed on measuring individual treatments sequentially to establish dynamic trends without complications of soil variability associated with treatment replication. Measurements of CO₂ flux were initiated within one minute after the tillage pass.

Conservation tillage tools, sometimes referred to as combination implements, encompass many types of tillage and planting techniques that maintain > 30 % residue cover after planting. The conservation tillage tools 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. Details of the equipment used in this study are provided in Reicosky (1997). The moldboard plow used was 6-bottom John Deere* model 2800 plow that was pulled at a speed of 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 second tillage tool was the Howard Paraplow (model 410B) was used as a deep tillage tool without soil inversion for the incorporation of nitrogen, also set to operate at 25 cm deep with the tines 51 cm apart. The third tillage tool was a White model 445 Conser-Till conservation chisel plow designed to leave variable amounts of residue on the soil surface after tillage. It consisted of a gang of coulters in the front designed to cut and partially incorporate the residue, followed by deep chisel points and a set of disc coulters that were used to smooth the surface. The fourth conservation tillage tool was a DMI 530 Eco-Tiger that consisted of an arrangement of discs in the front followed by subsoil shanks and smoothing discs. The Glencoe SS7400 Soil Saver consisted of a gang of 51 cm diameter coulters on 19 cm centers that helped break down and incorporate the residue followed by twisted shank tines that were set to till the soil to a depth of about 30 cm, followed by closing discs for leveling. The sixth conservation tillage tool was a John Deere model 510 Disc

Ripper which consisted of 61 cm diameter discs spaced about 28 cm apart to cut and mix residue into the soil. The subsoil shanks followed the first disc gang and went to a depth of about 46 cm followed by a gang of closing discs for smoothing the soil surface. All conservation tillage tools were compared to a surface that was not tilled referring to no soil disturbance. The term not tilled means no soil surface disturbance and does not reflect a true long-term no-till system, where soil organic matter had accumulated on the surface.

The strip tillage study, a continuation of that reported by Reicosky (1998), was conducted on plot area on the Barnes loam described above at selected times during the season. The soil surface was sprayed two weeks earlier with a contact herbicide to minimize the complications of photosynthesis and respiration after tillage. The tillage implement was a Yetter twin toolbar connected to a standard three-point hitch, 4-rows wide spaced at 76 cm. This tillage toolbar was modified to include a third beam of the same spacing for versatility and aligning additional tillage tools. Strip tillage tools and soil conditions are described by Reicosky (1998). The various tillage tools used were identified as no-tillage (NT) with only wheel traffic, residue managers (RM), L-128 fertilizer knife (LK), mole knife (MK), subsoil shanks (SS), and moldboard plow (MP).

The tractor with the tillage implement made a pass through the plot and within one minute the portable chamber was moved over the center two rows of the sample area and three successive measurements of gas exchange completed. The chamber followed the tillage implement to the next experimental area after the tillage tools had been changed. Another pass with a new tillage tool and the gas flux measured. This sequence of tillage and gas exchange measurements was repeated until all tillage tools were used. The gas exchange measurements were repeated on a regular cycle at least once an hour up to 6 hours after the initial tillage event. Intermittent measurements were made up at 24 and 48 hours to characterize the long-term effect of various strip tillage methods. The seasonal effects of strip tillage combined it with the early season data reported by Reicosky (1998) were evaluated in mid July and September 1997, to show the relative magnitude of the different forms of strip tillage.

Concern for possible "chamber effects" on soil gas fluxes led to a third study to qualitatively evaluate tillage-induced CO₂ loss from a plowed line source without using the portable chamber. The research plots were in a remote rural area with minimal extraneous CO₂ from upwind vehicle exhaust either controlled or noted. A strip of soil 50 to 60 m long was plowed perpendicular to the prevailing wind direction using the 4-bottom plow (1.83 m wide) to give a total width of 3.7 or 5.5 m to a depth of 0.25 m. The total time required for 3 passes was typically 5 to 7 min plowing the soil upwind and leaving the dead furrow on the downwind edge of the tilled strip. The immediate upwind fetch area consisted of actively growing soybean and corn plots. To minimize weed and volunteer wheat effects on the CO₂ exchange rate, the entire plot area to be plowed was sprayed with RoundUp Ultra (glyphosate) herbicide at the

*Names are necessary to report factually on available data; however, 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.

rate of 0.8 kg ha⁻¹ (active ingredient) two weeks prior to tillage.

Ambient CO₂ concentration was measured on the upwind and downwind edges of the tilled strip using infrared gas analyzers (IRGA) operated from a portable generator. Two LiCor Model 6262 IRGAs and Model 670 Flow Controllers were located about 7 m apart and programmed to measure in absolute mode and calibrated for CO₂ concentration in the 0 to 1000 μmol mol⁻¹ range (0.4 μmol mol⁻¹ resolution). The shielded thermocouples for air temperature and intake for the gas samples were set at 0.2 m above the untilled soil surface. The upwind and downwind gas concentrations and air temperatures at the sampling height were recorded twice per second along with the output of the hotwire anemometer at 0.3 m on the downwind side using a Campbell 21X data logger. Data were collected for a 10 to 12 min. interval and then simultaneously downloaded to a laptop computer into spreadsheet files for further analysis.

A general outline for an experimental run was as follows. The equipment was set up so the alignment of the two IRGAs and sample intake was perpendicular to the wind direction at the time of tillage. Pre-tillage measurements (~ 1 h) were used to measure the CO₂ concentration of the intended "footprint" without any upwind contamination or tillage effect to determine the temporal variation in the undisturbed CO₂ flux. Just prior to tillage, one pass with the tractor and plow in the up position was made between the IRGAs, to test for exhaust from the tractor emitted 3 m above the soil (generally not detected). After ~1 h of pre-tillage data, the tractor was driven along the transect between the IRGAs and the area plowed. The tractor was then quickly returned to the end of the plot and a second pass made in the same direction, followed with the third pass if needed. Data collection continued for another hour after primary tillage. In summary, data collection consisted of two approximate 1-h periods, one prior to tillage with no soil disturbance, and one immediately after moldboard plowing. Even though data were collected twice per second, 1-min averages were used to smooth temporal variations and random noise. The standard deviation of the 120 concentration values was as large as ± 29 μmol mol⁻¹ immediately after plowing but declined to a range of ± 2 to 7 μmol mol⁻¹ 2 h after plowing. Before tillage, the standard deviation ranged from ± 1 to 2 μmol mol⁻¹ for both up and down wind on all days. The instantaneous concentrations were averaged for 1 min to calculate downwind minus upwind differences.

RESULTS AND DISCUSSION

The conservation tillage tools showed short-term CO₂ flux varied widely as a function of time following each of the different tillage methods. 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 CO₂ m⁻² h⁻¹ that decreased to about 7 g CO₂ 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 CO₂ m⁻² h⁻¹ and eventually decreased to about 3 to 4 g CO₂ m⁻² h⁻¹ at the end of 5 hours

(Reicosky, 1997). The flux decreased rapidly with time after tillage primarily due to soil drying and continued gas loss.

The cumulative CO₂ loss, shown as a percentage of moldboard plow, determined by calculating the area under the flux curves for the first 5 hours after tillage is summarized in Figure 1.

Due to the concern for the chamber effect on soil gas fluxes, the different methods of tillage were related to moldboard plow as a percentage. The cumulative CO₂ loss for 5 hours after tillage was 81 g CO₂ m⁻² for the moldboard plow and the smallest treatment area not tilled at 6 g CO₂ m⁻². Paraplow had the second highest CO₂ loss with the remaining conservation tillage tools intermediate during the 5-hour period. All conservation tillage tools produced more CO₂ than the not tilled treatment, but substantially less than the moldboard plow. The mean short-term cumulative loss for the four conservation tillage tools was only 31 % of the moldboard plow. The moldboard plow treatment lost 13.8 times more CO₂ as the soil area not tilled compared to the mean of the four different conservation tillage tools that only lost 4.3 times as much CO₂. The smaller CO₂ loss following the conservation tillage tools is a significant secondary benefit.

The average CO₂ fluxes relative to moldboard plow 28 days after tillage are summarized in Figure 2. These data represent the average of six or eight measurements over a brief period and reflect conditions at the time of the measurement. Variation between tillage methods from one day to the next was a result of a complex interaction of the previous rainfall and the degrees of soil drying affected by the tillage method. Even at 28 days after tillage, the moldboard plow had the largest CO₂ flux. The Paraplow had decreased to nearly half that of the moldboard plow, while the other conservation tillage tools had lower values closely related to not tilled. These differences suggest the effect of moldboard plowing exists for at least 28 days after tillage and the interactions between the residue incorporation and soil mixing that affects biological oxidation and drying would affect the CO₂ flux. While designed to leave crop residue on the surface for erosion control, these conservation tillage tools cause lower CO₂ loss, suggesting progress is being made in developing conservation tillage tools that can further enhance soil C management.

The short-term CO₂ flux in the strip tillage study was generally the largest for the moldboard plow and the not tilled treatment the least CO₂ loss. Other forms of strip tillage were intermediate and only a relatively small amount of CO₂ was detected immediately after tillage with limited soil disturbance. All tillage methods declined toward the not tilled values as the soil dried. The 5-hour cumulative CO₂ fluxes following strip tillage for 3 days in 1997 are summarized in Fig. 3 for early, mid-season and late season tillage events.

Only two tillage passes were used. Both upwind and downwind concentrations (1 min averages) were about 375 μmol mol⁻¹ and declined to 340 μmol mol⁻¹ at tillage when the downwind concentration increased to 360 μmol mol⁻¹ after the first pass and then to 403 μmol mol⁻¹ after the second pass. With no further tillage, the downwind concentration decreased rapidly to approach the upwind

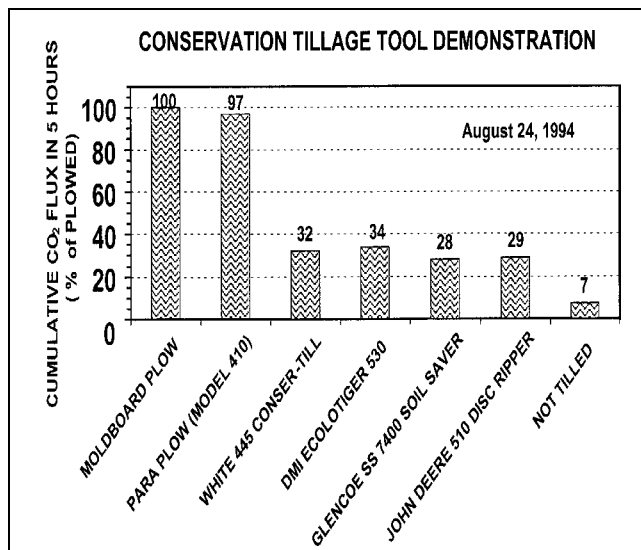


Figure 1. Cumulative CO₂ loss for 5 hours from conservation tillage tools as a percentage of the moldboard plow.

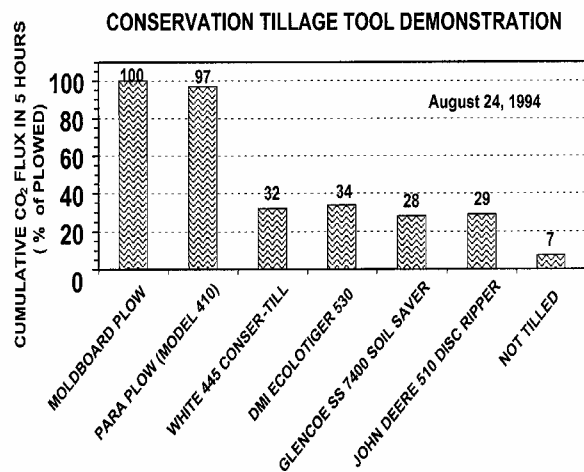


Figure 2. Average CO₂ flux following conservation tillage tools 28 days after tillage relative to moldboard plow.

value 1 h later. The upwind concentration showed a continued gradual diurnal decline to 330 $\mu\text{mol mol}^{-1}$ as a result of active crop photosynthesis upwind of the test area.

The relative magnitudes of the cumulative CO₂ flux were essentially the same, with the exception that the 24 September data showed moldboard plow flux was slightly lower than the subsoil treatment. The cause for the low value of moldboard plow on this day is not known.

Relative differences between other methods of strip tillage on all three dates were comparable with largest absolute fluxes during mid-season, when soil temperatures and day length were near maximums. The relatively large amounts of strip tillage-induced CO₂ emitted mid season suggest a strong association with biological activity directly related to the water content and soil temperatures at the time of tillage. The relative magnitude of the flux on each day appears to be directly related to the volume of soil disturbed by each of the strip tillage implements (Reicosky, 1998). These data

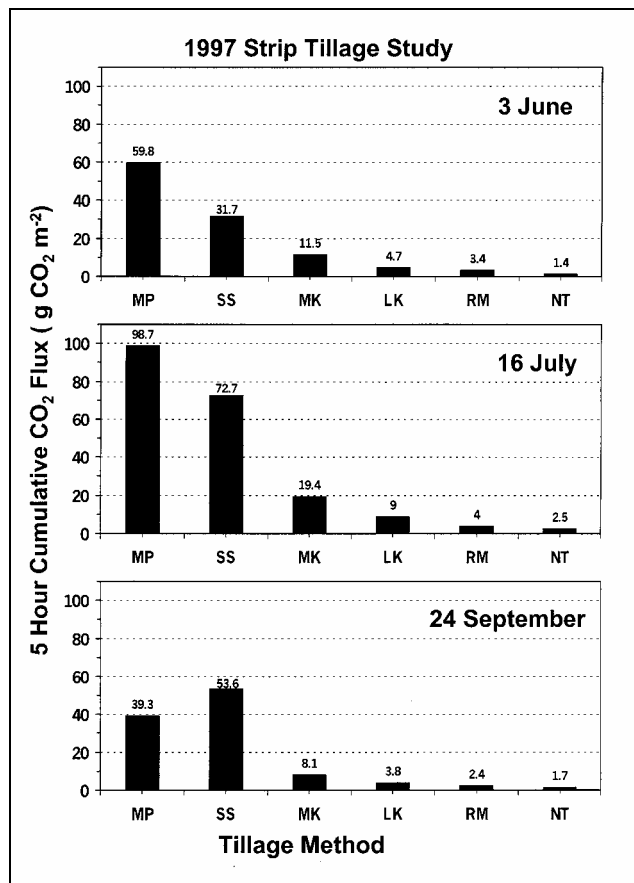


Figure 3. Cumulative CO₂ loss following various strip tillage tools during early, mid and late season in 1997.

showed seasonal variation directly related to a given set of soil water and temperature conditions.

The tillage-induced plume of CO₂ from a plowed strip perpendicular to the prevailing wind was demonstrated in several experimental runs and illustrated with selected examples in Figures 4 and 5. Instantaneous CO₂ concentration differences decreased with time after tillage and were as large as 140 $\mu\text{mol mol}^{-1}$ immediately after tillage. On 26 June, data collection started at 0800 with tillage 90 min later (Fig. 4).

A second example of tillage-induced CO₂ loss is illustrated on 15 July in Fig. 5 with 3 tillage passes. Prior to tillage, the 1-min-average CO₂ concentrations on 15 July decreased from 345 to 332 $\mu\text{mol mol}^{-1}$, reflecting the diurnal change in CO₂ concentration caused by actively growing crops upwind of the study site. Immediately after three tillage passes the downwind concentration increased to 383 $\mu\text{mol mol}^{-1}$ or a 51 $\mu\text{mol mol}^{-1}$ increase over the upwind concentration and then gradually declined to 10 $\mu\text{mol mol}^{-1}$ difference about 1 h after tillage. Each of the three tillage passes, spaced 5 to 7 min apart in this example, showed an increased CO₂ that rapidly declined as the ambient concentration was diluted by the upwind air. Measurements of the upwind and downwind CO₂ concentration differences support the effect of intensive tillage on gaseous carbon loss first identified with the portable chamber (Reicosky and Lindstrom, 1993). The

rapid increase in the downwind concentration after tillage confirms the tillage-induced CO₂ loss and illustrates the dynamic nature of soil gas exchange.

A clearer understanding of tillage interactions and residual soil organic matter and how it is maintained and/or increased is unfolding. Intensive tillage, particularly moldboard plowing, causes large losses of CO₂, whether measured by a chamber or meteorological technique. Present data support increased adoption of new and improved forms of conservation tillage equipment and offers significant potential to preserve or increase soil C levels. Reversing soil C loss will be beneficial to agriculture, as well as the global population, through better control of global C balance. Strip tillage minimizes the impact of tillage on soil, water and air quality. Results suggest we must minimize the volume of soil disturbed, by tilling just the soil volume necessary to achieve an effective seedbed and leaving the remainder of the soil residue cover undisturbed to conserve water and C, to minimize soil erosion and CO₂ loss. The lower CO₂ loss (more carbon in the soil) will also limit environmental impact, and do much to improve environmental quality, increase infiltration, and minimize runoff and the greenhouse effect. Results suggest environmental benefits of strip tillage and conservation tillage as opposed to broad area tillage need to be considered when making soil management decisions. The energy savings represent an additional economic benefit associated with less soil disturbance. The data suggest potential for use of soil as a sink for soil C through improved soil tillage and management for enhanced environmental quality.

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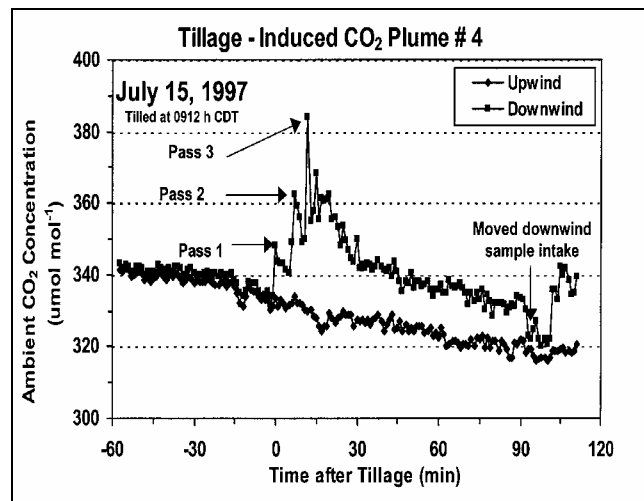


Figure 4. Ambient CO₂ concentrations upwind and downwind of a plowed strip (3.67 m wide) as affected by tillage on 26 June 1997.

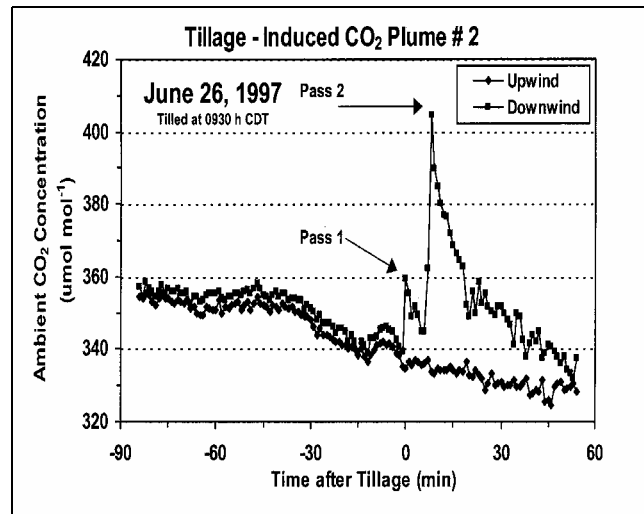


Figure 5. Ambient CO₂ concentrations upwind and downwind of a plowed strip (5.5 m wide) as affected by tillage on 15 July 1997.