Tillage-induced Soil Properties and Chamber Mixing Effects on Gas Exchange

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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) from tillage. This work evaluated effects of tillage-induced changes in soil properties on CO_2 and H_2O loss as measured by a portable dynamic chamber. Information was collected three times per second to characterise dynamic pressure at the soil surface and wind speed (measured 2 cm above the soil surface) with one or four chamber fans operating during the 30 s measurement period. A chamber was used to characterise CO_2 and H_2O losses from a 5.5 m-wide ploughed strip perpendicular to the prevailing wind. Fluxes of CO_2 were high immediately after mouldboard plough (MP) tillage and decreased with time. Short-term tillage-induced CO_2 losses measured with a large chamber using different air mixing rates independently verified turbulent mixing and pressure effects on CO_2 and H_2O losses. Fan number had greater effect on the CO_2 and H_2O fluxes from freshly tilled surfaces compared to surfaces not tilled (NT). Fluxes were lower with only one fan operating (press. = -0.39 Pa), compared to four fans (press. = –1.62 Pa) operating suggesting that increased negative dynamic pressure enhanced the flux. The magnitude of the increase was related to tillage-induced changes in soil properties. The results suggest caution when interpreting and extrapolating chamber-measured fluxes. While the absolute magnitude of the fluxes may be in question, the relative flux difference for different tillage treatments likely reflects the relative carbon (C) loss. Higher gas exchange occurred from MP versus NT when soil air permeability was more sensitive to convective pressure fluctuations. The tillage-induced change in soil properties led to short-term CO_2 losses that were higher than those from undisturbed soil. Changes in surface soil properties caused by tillage combined with the aerodynamic pressure forces associated with natural wind movement over the soil can result in substantial CO_2 loss. The large differences in CO_2 and H_2O loss between MP and NT treatments were likely caused by tillage in combination with wind speed effects in the chamber. The results demonstrated a need for better understanding of chamber effects, improved soil management and policies that favour less intensive conservation tillage to minimise C loss and increased C sequestration in agricultural production systems.

INTRODUCTION

Agriculture's role in sequestering carbon (C) is not clearly understood. There is a definite need for direct measurements to quantify carbon dioxide (CO_2) fluxes influenced by agricultural management practices (Houghton *et al.*, 1983). Understanding these processes will lead to enhanced soil management techniques and new technology for increased food production efficiency with a minimum impact on environmental quality and greenhouse gas emissions (Paustian et. al., 1997). Soil disturbance by tillage may alter environmental conditions and soil structure to enhance production of CO_2. Recent studies involving tillage methods indicate major gaseous losses of C immediately after tillage (Ellert and Janzen, 1999; Reicosky and Lindstrom, 1993; Rochette and Angers, 1999).

Chambers are commonly used to measure soil CO_2 fluxes and the exchange of these gases between the soil and the atmosphere. Chambers play a critical role in many aspects of research concerning traced gas exchange, so it is essential to understand how they function and how they perform as a tool for accurately measuring the exchange rates. Recent studies involving a dynamic chamber, various tillage methods and associated incorporation of residue in the field indicated large C losses immediately following tillage (Reicosky and Lindstrom, 1993). 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 NT having the least amount of CO_2 loss. Recent research evaluating flow and pressure effects on C losses suggests dynamic chambers have limitations that may affect natural CO_2 fluxes (Reicosky *et al.*, 1997; Denmead, 1979; Fang and Moncrieff, 1996; Gao and Yates, 1998a, b; Conen and Smith, 1998; Lund *et al.*, 1999; Hutchinson and Livingston, 2001, 2002; Takle *et al.*, 2003).

Because chamber-measured soil C emissions require concern for possible 'chamber effects' on soil gas fluxes, a study to evaluate tillage-induced CO_2 loss from a MP and NT surface using the portable dynamic chamber was conducted. One possible effect is related to chamber size suggesting a 'scale' effect related to change in soil properties, particularly occurring in freshly tilled soils. The objective of this work was to characterise the pressure distribution within the large portable chamber to quantify the effects of wind speed and turbulent mixing on measured gas fluxes.

METHODS AND MATERIALS

These studies used the large dynamic chamber described by Reicosky and Lindstrom (1993) with further modifications and improvements described by Wagner *et al.* (1997). Short-term, tillage-induced CO_2 release was measured with a large portable chamber (height = 1.22 m, area = 2.71 m^2) designed to measure canopy photosynthesis. The large area covered by the chamber helps cope with spatial variability encountered by smaller chambers.

Dynamic pressure measurements inside the chamber were made on a two-dimensional grid through the plywood bottom of the chamber approximating the 'soil surface.' The pressure measurement locations (13-mm dia.) were drilled into a 13 mm thick piece of plywood on a 20 x 20 cm grid spacing referenced to the center of the chamber (177 cm long and 153 cm wide, nine rows of holes and eight columns of holes) that resulted in 72 locations for pressure and wind measurements. The holes not used for pressure or wind speed measurements were filled with a '00' rubber stopper flush with the upper surface.

Wind speed was measured using a hotwire anemometer TSI air velocity transducer (model number 8470-13E-V-STD-NC) with a range of 0 - 5.08 m s^{-1} and 0-5 V output. The shaft of the hotwire probe was inserted into a rubber stopper and carefully inserted through the bottom of the floor. The active portion of the sensor was placed 2 cm above the surface. The air pressure transducer was a Setra Model 264, a very low differential pressure measurement device. The 2.54 mm water column full scale corresponds to a +/- 25 Pa range with full-scale output 0 to 5 Volts DC for both uni-directional or bi-directional pressure measurements.

The output from the pressure transducer, the Viasala Model PTA427 barometric pressure sensor, and the air temperature sensor was collected at three times per second for a period of 30 seconds. The hotwire anemometer for wind speed was logged as a separate operation at the same frequency. The analog outputs were fed into a Hewlett Packard 3458 data acquisition system connected via HPIB (IEEE 488) to a laptop computer for rapid data acquisition.

The field work was conducted on a Barnes loam (Udic Haploboroll, fine-loamy, mixed) at the Barnes-Aastad Swan Lake Research Farm in west central Minnesota, USA (45°41'14' N latitude and 95°47'57' W longitude). The surface horizon is generally very dark with typically 28 to 32 g kg^{-1} C and developed over subsoil high in free calcium carbonate. More details can be obtained from Reicosky (1997). A strip of soil 50 to 60-m long was ploughed perpendicular to the prevailing wind direction using the 4-bottom MP (1.83 m wide) to give a total width of 3.7 (2 MP passes) to a depth of 0.25 m for four replicates. A corresponding strip adjacent to the ploughed plots was NT and chamber measurements completed. To minimise weed and volunteer wheat effects on the CO_2 exchange rate (CER), the entire study area was sprayed with a glyphosate herbicide.

Field data was collected on 5 and 6 August, 1998. Low and high negative pressures were selected to maximise information collection and to demonstrate temporal trends. Pressure and wind speed differences were accomplished by operating various combinations of the four fans inside the chamber. The smallest average negative pressure (-0.388 Pa) was achieved using only one fan (#4). The largest average negative pressure (-1.62 Pa) was achieved using all four fans. Preliminary measurements obtained without fans operating provided nonsense data due to the lack of uniform gas mixing inside the chamber. The sequence of gas exchange measurements was as follows. The first MP plot (rep 1) was tilled and within one min. four consecutive chamber measurements were made at the randomly selected pressure level (small or large) followed by the same sequence on the corresponding NT plot. Measurements were then repeated on the next MP plot (rep 2) and adjacent NT plot for all four replicates. Then, the other pressure level was selected and the measurement sequence repeated to complete both pressure levels. The measurement cycle was repeated twice over six hours the first day after tillage.

RESULTS AND DISCUSSION

The distribution of the dynamic pressure (measured at the surface of the plywood floor) and wind speed (measured 2 cm above the floor) are summarized in Figure 1. While the contour surface was not very smooth, the results likely reflect the turbulent mixing and show a few locations with a positive pressure. The majority of the locations showed variation that ranged from +1.83 to -3.49 Pa. The negative pressures may tend to cause CO_2 to be 'pulled or sucked' from the soil surface. The contour surface for the wind speed graph was approximately a mirror image of the pressure measurements with similar variation. The average wind speed 2 cm above the surface was 1.71 m s^{-1} with a minimum and maximum of 0.62 and 2.63 m s^{-1}, respectively.

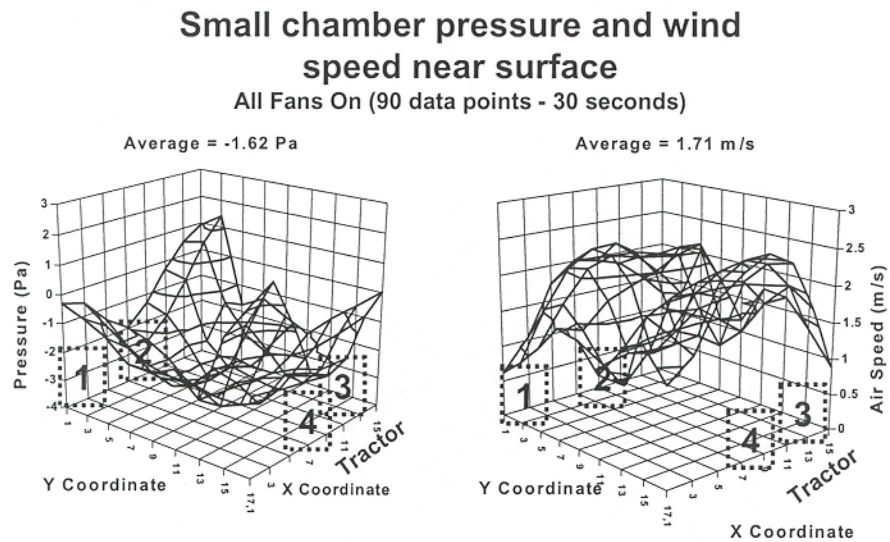

Figure 1. Dynamic pressures and wind speeds in the chamber near the 'soil surface' with all four fans operating

The rate of CO_2 loss from both MP and NT treatments was affected by the number of fans operating and average pressure as shown in Figure 2. The rapid decline in loss of CO_2 reflects loss from the soil pores and associated drying of moist soil. The MP treatment consistently had a higher flux with all four fans operating (average pressure of -1.62 Pa), than with only fan #4 operating (average pressure of -0.388 Pa). The parallel relationship in the temporal trends extends to six hours after the initial tillage. The consistent difference between these two treatments suggest the magnitude of the negative pressure developed as a result of turbulent mixing contributes to exaggerate the flux of CO_2 from the MP soil. The average flux from MP treatment measured on 5 August with all four fans operating was 89% higher than the average flux obtained from only one fan (#4). In contrast, the difference in the rate of CO_2 loss for the NT treatment was negligible with only the four fans operating and was 7% higher than with only fan #4. On 6 August (data not shown), the average flux measured on MP treatments with all four fans operating was 76% higher than the average flux obtained from only one fan (#4). In contrast, the rate of CO_2 loss for the NT treatment was 17% higher with four fans operating compared to only fan #4. The reasonable agreement from two days of data collection suggest that an interaction between the turbulent mixing within the chamber and soil loosening from tillage contributed to the net CO_2 loss.

The effect of a number of fans operating on evaporation (ET) or water loss is summarized in Figure 3. Evaporation from the MP plots increased with time related to increased radiation and air temperature in typical diurnal fashion related to increasing potential evaporation. Both ET and CO_2 losses were highest from the MP plots when all four fans were operating. The ET measured with all four fans operating was 25% higher than ET measured with only fan #4. The ET from the NT treatments was lower than from MP.

The ET on NT with four fans operating was only slightly, but consistently higher than with only fan #4. The average ET increase with all four fans operating versus only fan #4 operating for the NT treatment was 32 %. In contrast to a large increase from the MP treatment where moist soil was brought to the surface, ET from NT only showed a slight tendency to increase with time. On 6 August, the ET flux magnitudes and trends were similar to those on 5 August. The average ET measured on MP treatments with all four fans operating was 24% higher than that with only fan #4. In contrast, the difference in the ET for the NT treatment was similar with only the four fans operating at 32% higher than fan #4 alone. Results from the MP treatment showed that tillage and chamber mixing rates affected the CO_2 fluxes more than ET suggesting CO_2 is drawn through the loosened soil by pressure fluctuations.

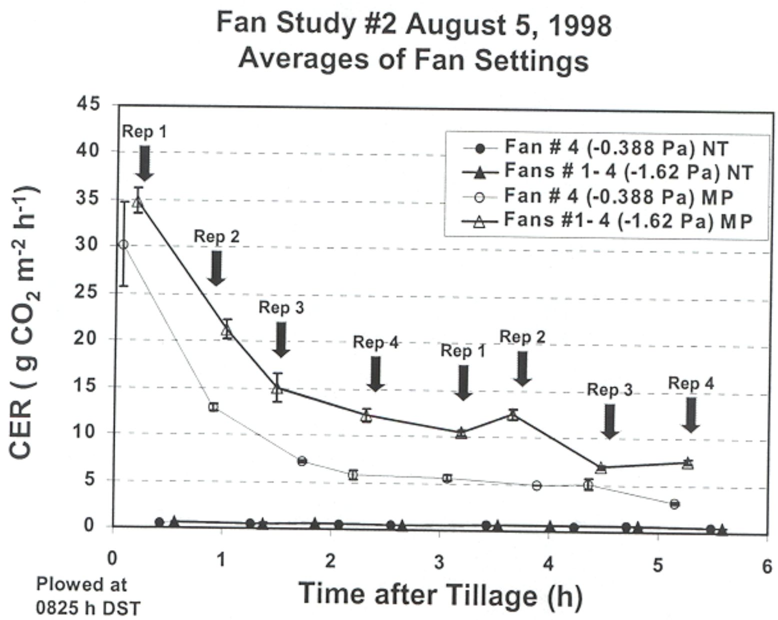

Figure 2. Short-term CO_2 flux (CER) as a function of time after MP and NT treatments. Note: Each data point is the average of 4 repeated measurements (+/- standard error) at the same time in each measurement sequence.

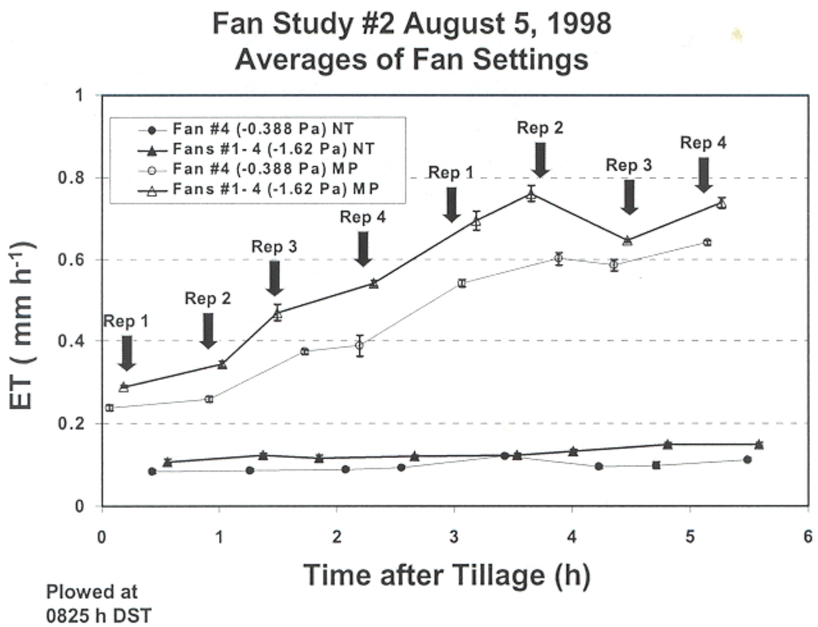

Figure 3. Evapotranspiration (ET) as affected by wind and pressure over MP and NT treatments

In summary, the results indicate gas fluxes measured by the dynamic chamber tend to increase with increasing mixing intensity or wind speed within the chamber. The magnitude of the increase was related to tillage-induced change in soil properties. The results suggest using caution when interpreting and extrapolating chamber measured fluxes. While the absolute magnitude of the fluxes may be in question, the relative flux difference for different tillage treatments likely reflected the relative C loss. Fluxes were likely exaggerated by the combination of soil loosened by tillage and the net negative pressures generated by turbulent mixing within the dynamic chamber. While chamber data may not reflect the true CO_2 loss due to the turbulent-induced negative pressures, tillage-induced CO_2 loss is confounded by natural aerodynamic forces that enhance diffusion and convection loss which results from changes in soil porosity, bulk density and associated soil air permeability. Tillage also breaks up soil aggregates and exposes 'fresh' surfaces for enhanced gas exchange from the interior that may have had a higher CO_2 concentration. Thus, changing the surface soil properties by tillage combined with the aerodynamic pressure forces associated with natural wind movement over the soil can result in substantial CO_2 loss. The real question is how the wind and mixing effects inside the chamber are different from the wind and mixing effects outside the chamber. Further work is needed to identify and quantify the aerodynamic forces involved in chamber measured soil gas exchange, especially CO_2 and H_2O, when surface soil properties are drastically changed by intensive tillage.

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