63 Soil Variability and Carbon Dioxide Loss After Moldboard Plowing

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Soil variability in the field is partly due to natural differences in soil properties and can be impacted by past management. Soil spatial variability within fields has widely been demonstrated by soil testing results and crop yield differences. Because landscapes and soils vary greatly, land use and soil management must be tailored to fit the specific soil properties to enhance their utilization and maintain their long-term sustainability. Numerous reasons for variation in soil characteristics include soil forming factors, farming practices, and wind and water erosion. Because irregular soilscape units do not match well with symmetrically-shaped legal boundaries, several landscape units are usually managed in the same way. Larson and Robert (1991) discuss "farming by soil" practices that develop a management perspective for the application of fertilizer and herbicides based on soil-specific information. The "farming by soil" technology is one of the major breakthroughs in soil management in a decade or more. The importance of soil C in nutrient supply through mobilization–immobilization and the global C budget requires information on soil C levels and maintenance for the long-term.

Man's activities in agriculture production associated with tillage can have a significant influence on the atmospheric composition. Research on global warming and the greenhouse effect has highlighted the linkage between gas composition, atmosphere and the world weather patterns (Wood 1990; Post et al., 1990). Many natural factors as well as human activities influence atmospheric composition by merely contributing or removing gases and involving chemical reactions. Minimizing agriculture's impact on global increase in atmospheric CO_2 requires that we sequester C and maintain high levels of soil organic matter. Maintaining or even increasing soil organic matter levels for specific soils to maintain economic crop production may require both reduced tillage and crop rotations that maximize residue produced and returned to the soil surface.

The effect of landscape position on soil respiration has been reported by DeJong (1981) who observed a two-fold increase in soil respiration at the foot

of the hill as compared to the top of the hill. The highest CO_2 evolution rate was for grassland, intermediate for cereals, and lowest under fallow conditions. Even on uniform-level soils, spatial variability in soil properties can be large. Dugas (1993) made soil chamber CO_2 measurements sequentially at nine positions in a 5 ha field on a Houston Black clay (fine, montmorillonitic, thermic Udic Pellusterts). The coefficient of variation of chamber CO_2 fluxes across the nine positions averaged 40% throughout the d, indicating the need for a large number of chamber measurements to obtain a representative CO_2 flux measurement. Rochette et al. (1991) found spatial variability in soil respiration, described by the coefficient of variation for each series of measurement, was highest in May at 69% and decreased to 25% toward the end of the season. The number of measurements required to estimate soil respiration within 10% of the mean at a 0.05 probability level was 190 before crop emergence and 30 after 70 days.

Reliable averages of soil and vegetation CO_2 evolution are important measurements related to C cycling. The spatial variability associated with flux of CO_2 from soil needs to be addressed to obtain reliable averages, but has only received limited attention. Speir et al. (1984) found that spatial variability of soil biochemical properties including soil respiration was significantly greater than that of chemical properties. Robertson et al. (1988) determined that spatial variability of soil respiration was random with no spatial correlation at scales of 1 to 80 m. The results may appear random due to temporal variations in soil temperature and water content (Singh & Gupta 1977).

Aiken et al. (1991) reported variation in the soil CO_2 efflux was attributed to positional trends, spatial correlation and random effects in a wheat crop under wet and dry soil conditions. Spatial homogeneity for CO_2 efflux was not found in four of the five data sets evaluated. Positional trends accounted for spatial structure in these cases. Residual variability after removing the positional trends was isotropic and randomly distributed. No spatial correlation was observed after removal of the positional trends. They noted, however, that spatial correlation may have been apparent had the positional trends not been removed. The spatial structure was affected by soil water content under wheat. They further concluded that defining spatial structure for soil respiration required the determination of many environmental factors that are dynamically changing as a function of time as well as with position in the landscape.

Recently, Reicosky and Lindstrom (1993, 1995) showed that tillage, particularly moldboard plowing, resulted in a "flush" of CO_2 when gas exchange measurements were made within 5 min. after tillage. Significant amounts of gaseous C were lost as CO_2; comparable to C in the crop residue plowed under. Reicosky and Lindstrom (1994) assumed 4120 kg ha^{-1} of wheat residue contained 45% C. The cumulative CO_2 released from the soil surface during 19 d after moldboard plowing was the same as 134% of the C in the previous crop residue. This analogy does not imply the CO_2 came from the residue, but does provide perspective on loss of CO_2. The relative rate of gaseous C loss as measured relative to C in the current crop suggests that moldboard plowing can result in enough short-term C loss equivalent to the C in the current crop within 14 d.

There is ample evidence that cropping and associated tillage decreases soil organic matter in the long term (Peck 1989, Wagner 1989). The mechanisms for these losses are not clear, however. The magnitude of gaseous C loss after plowing explains much of the sustained C loss in many of agricultural systems (Reicosky & Lindstrom 1994). Moldboard plowing is one of the most disruptive types of tillage, and now appears to have two major effects: (i) to invert and loosen the soil sufficient to allow rapid CO_2 loss and O_2 entry and (ii) to incorporate–mix the crop residues for enhanced microbial attack. Tillage perturbs the soil system and causes a shift in the gaseous equilibrium by enhancing soil-atmospheric exchange of CO_2 and O_2 that enhances oxidation of soil C and organic matter loss. Conservation tillage limits soil disruption and leaves crop residue on the surface thereby limiting contact with the soil and associated microorganisms reducing residue decomposition rates.

The significant flush of CO_2 immediately after tillage reported by Reicosky and Lindstrom (1993, 1994) confirms the role of tillage affecting C flow within agricultural production systems. There is a need for more information on the variation and magnitude of this CO_2 flush based on the interaction of tillage on different soil types within the landscape. The specific objective of this work was to quantify the variation in CO_2 loss immediately after fall plowing on several soil types previously cropped to wheat. A field was selected with four different soil types and transects established across the soils to follow the CO_2 loss immediately after moldboard plowing.

METHODS AND MATERIALS

The experiment 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). The soils selected in this field (Table 63–1) range from moderately-well to poorly drained; were formed on glacial till under tall prairie grass vegetation. 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.

The study area was selected by establishing two transects, each 195-m long, across an area where there was significant variation in the soil types as indicated by the soils map, hereafter referred to as north and south transects. Two parallel transects 30 m apart were established in an east-west straight line in anticipation of moldboard plowing along the transects. The measurement locations or sites were selected to be in the center of the soil-map unit on the respective transect. The soil series identification was confirmed by an SCS soil scientist[1]. The soil names and relative location are shown schematically in Fig. 63–1.The name identification includes a sequential number because the transects crossed the same soil map unit more than once.

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

Table 63–1[2]. Summary of soil taxonomy and properties in the spatial variation study.

SOIL SERIES (Taxonomy)	DRAINAGE	DEPTH of Al	BULK DENSITY	SOIL ORGANIC MATTER	CLAY CONTENT	PH
		(m)	(kg/m^3)	(%OM)	(%)	(-)
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, montmorillonitic, 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

[2]SCS DATA from soil interpretation records. Soils formed on glacial till under tall grass prairie.

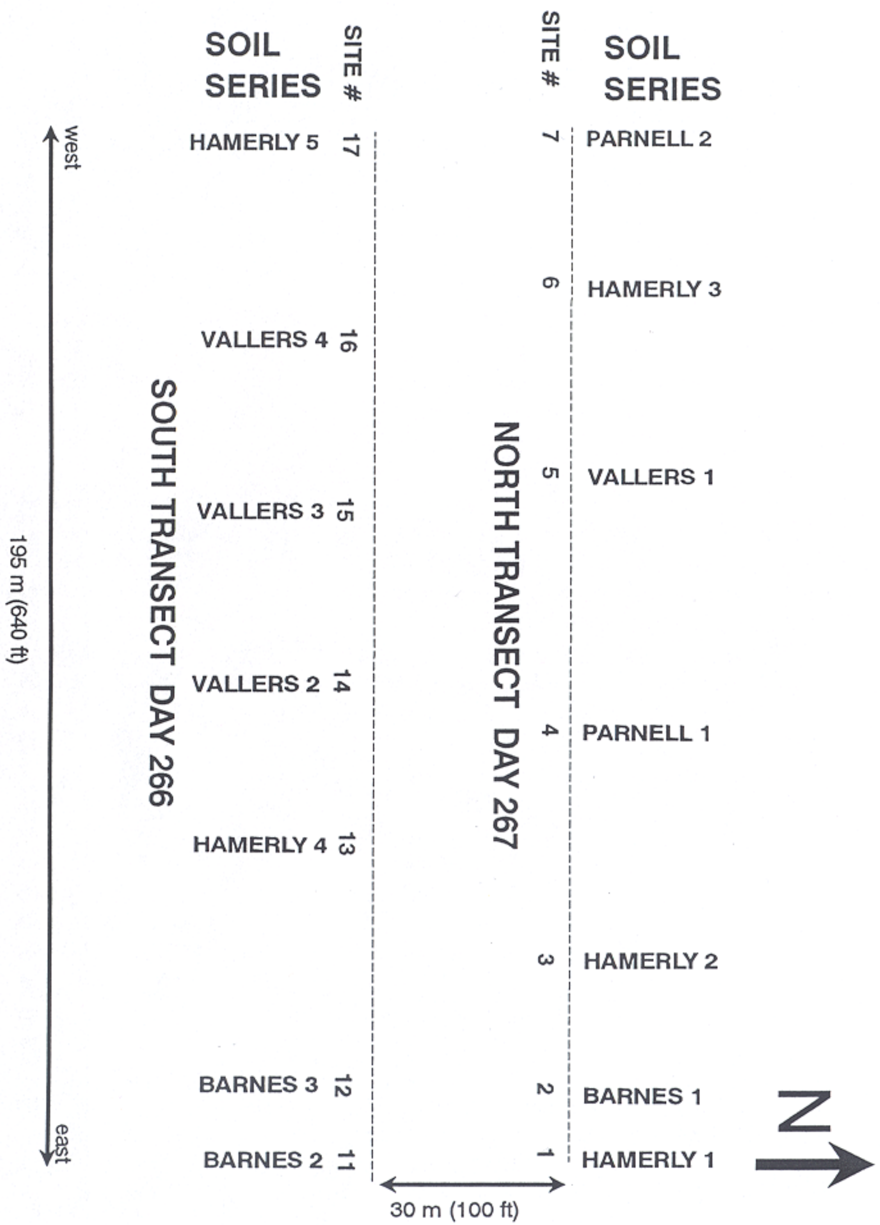

Fig. 63–1. Schematic representation of soil site location within the north and south transects. Soil series and site numbers indicate position in the landscape.

The study area was planted to spring wheat (*Triticum aestivum* L. cv. Marshall) on 21 April 1993 (D 111) and harvested on 17 Aug. 1993 (D 229). Seasonal rainfall was above normal with 524 mm from wheat planting to harvest. The last significant rain before plowing on D 266 was 20 mm on D 262 and 6 mm on D 263. Variation in yield along the transects was measured by harvesting four swaths of a 1.52-m plot combine with 6.09-m lengths over each of the pre-marked measurement sites. The four replicates were averaged to represent grain yield at that site. The average yield for the wheat over the larger field was 1480 kg ha^{-1} while grain yield measured at each of the pre-marked soil sites ranged from 253 kg ha^{-1} to 2655 kg ha^{-1}. Low yields on the transects were related to excess water in low areas.

To minimize weed and volunteer wheat effects on the CO_2 exchange rate, the entire field was sprayed with Ranger[3] (glyphosate) herbicide at 0.8 kg a.i. ha^{-1} on 27 August (D 239) and 13 September (D 256).

Commercially available moldboard plows were used for tillage along the transects. The necessary plowed width for gas exchange measurements was accomplished using two sets of plows. A four bottom plow (0.46 m wide to a depth of 0.22 m) was pulled by the first tractor. A second two bottom plow (same width and depth) pulled by another tractor immediately behind the first was required to get the necessary 2.74-m width for the chamber measurements. 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) site was selected for gas exchange measurements over undisturbed soil with crop residues as left by the combine. The NT designation only implies no soil disturbance after wheat harvest and does not refer to a long term "tillage system." 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 by Reicosky (1990) and Reicosky, et al. (1990) in the same manner as Reicosky and Lindstrom (1993). Briefly, the chamber (volume = 3.25 m^3 covering land area = 2.67 m^2) with mixing fans running, was moved over the plowed surface until the chamber reference points aligned with site reference stakes, lowered and data collected at 1 s intervals for a period of 80 s to determine the rate of CO_2 and water vapor increase. The chamber was then raised, calculations completed and results stored on computer diskette. Data included time, plot identification, solar radiation, photosynthetically active radiation, air temperature, wet bulb temperature and the output of a LI-COR Model 6262 infrared-gas analyzer measuring CO_2 and water vapor concentrations in the same air stream. 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

[3]Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products that may be suitable.

as a quadratic function of time to estimate gas fluxes (Wagner et al., 1994). These fluxes represent the rate of CO_2 and water vapor increase within the chamber and are expressed on unit horizontal land area basis as differentiated from an exposed soil area surface basis resulting from surface roughness. The rough-plowed surface caused occasional large holes around the perimeter of the chamber that did not allow the base of the chamber to form a good seal. These 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 d, 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 (Reicosky & Lindstrom 1993), measurements were made with the portable chamber within 30 to 40 s after the pre-marked area was plowed. The sequence of events was as follows: the tractors pulling both sets of plows tilled through the designated experimental site to a pre-determined reference point, then stopped and waited while the chamber was quickly moved over the site and three successive measurements taken. Upon completion of the three measurements, the plows tilled through the next designated experimental site to the next pre-marked location and the chamber moved over the pre-marked area to repeat another series of three measurements. The sequence was repeated across the different soils on the transect until all seven pre-marked sites had been measured. 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 (D 266). The north transect was plowed on 24 September 1993 (D 267) from east to west. Chamber measurements were made facing into the wind. Within any single d, four measurement cycles were completed on each transect. On D 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 no-till site that had surface residue as left by the field combine. Based on the soils map, the soil was a Parnell, located about 20 m north of plot 7 on the north transect.

The very high flux within 30 s after moldboard plowing caused the CO_2 channel of the infrared gas analyzer to over-range on D 266 that required modification on the calculation method. The majority of the measurements used the standard 30 s calculation window (30 data points) as described by Reicosky and Lindstrom (1993) with the quadratic regression (Wagner et al. 1994). For those data sets where the CO_2 concentration exceeded 500 μ mol mol^{-1}, however, the data were screened to determine the valid range over which the CO_2 concentration was increasing. The calculation procedures were the same as described previously; only the number of data points (the width of the calculation window) was varied by determining initial and final valid data points.

With the extremely high fluxes, the minimum number of data points in any one of the 18 data sets where the CO_2 concentration exceeded 500 μ mol mol^{-1} was 13. In view of this problem, the maximum CO_2 range on the infrared gas analyzer was set to 1,000 μ mol mol^{-1} for the measurements on D 267. The accuracy of using fewer data points may restrict the interpretation of the results on D 266. The trends were reasonable, however, and the results should be as valid as when 30 data points were used.

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.

Microclimate data was collected from a standard weather station located ≈200 m from the edge of the experimental area. Measurements included air temperature at 2 m, solar radiation, wind speed, wind direction, relative humidity, and photosynthetically active radiation collected at one-min. intervals and averaged hourly. The change in air temperature and solar radiation may have resulted in differences in the initial flux measured immediately after plowing as the soil temperature may have tended to increase slightly with increase in air temperature. The impact of radiation and air temperature on soil respiration immediately after plowing, however, was not determined by direct measurement.

RESULTS AND DISCUSSION

Microclimate data for two days of this study showed seasonal solar radiation indicative of clear skies during both days. The air temperature went from a minimum of 0.6°C to a maximum to 17°C on D 266 and from a minimum of 2°C to a maximum of 20°C on Day 267 with typical diurnal fluctuations. The relative humidity reached a maximum of 100% during the night and decreased to a low of 40% on D 266 and 42% on D 267. Wind speeds were nominal ranging as high as 4.3 m s^{-1} with variable wind direction from the south, southwest and northwest on both days. Some of the variation in initial CO_2 flux on each soil may be related to the increase in air temperature as a function of time during the day and after plowing. The increase in air temperature from 0900 to 1000 h was 3.0 and 3.1 °C for D 266 and 267, respectively. In this analysis, air temperature was assumed to have little effect on the initial flush of CO_2 .

The grain yield from the pre-marked sites is summarized in Fig. 63–2. The average yields are low due to the cooler and wetter than normal climate experienced in the 1993-growing season. The field-average yield across the remainder of the 24-ha field was 1480 kg ha^{-1}. The yield from each of the sites ranged from 253 to 2345 kg ha^{-1} on the north transect and from 1822 to 2655

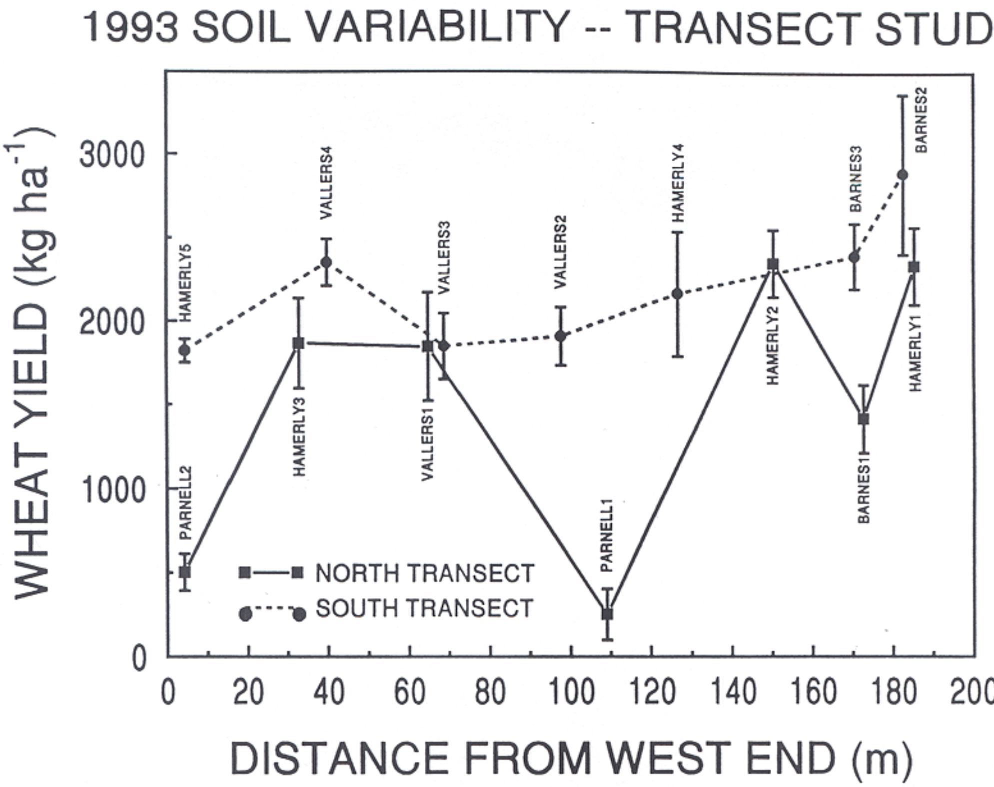

Fig. 63–2. Spatial variation in wheat yield from measurement sites in north and south transects. Error bars represent ± 1 standard error of the mean of 4 replicates.

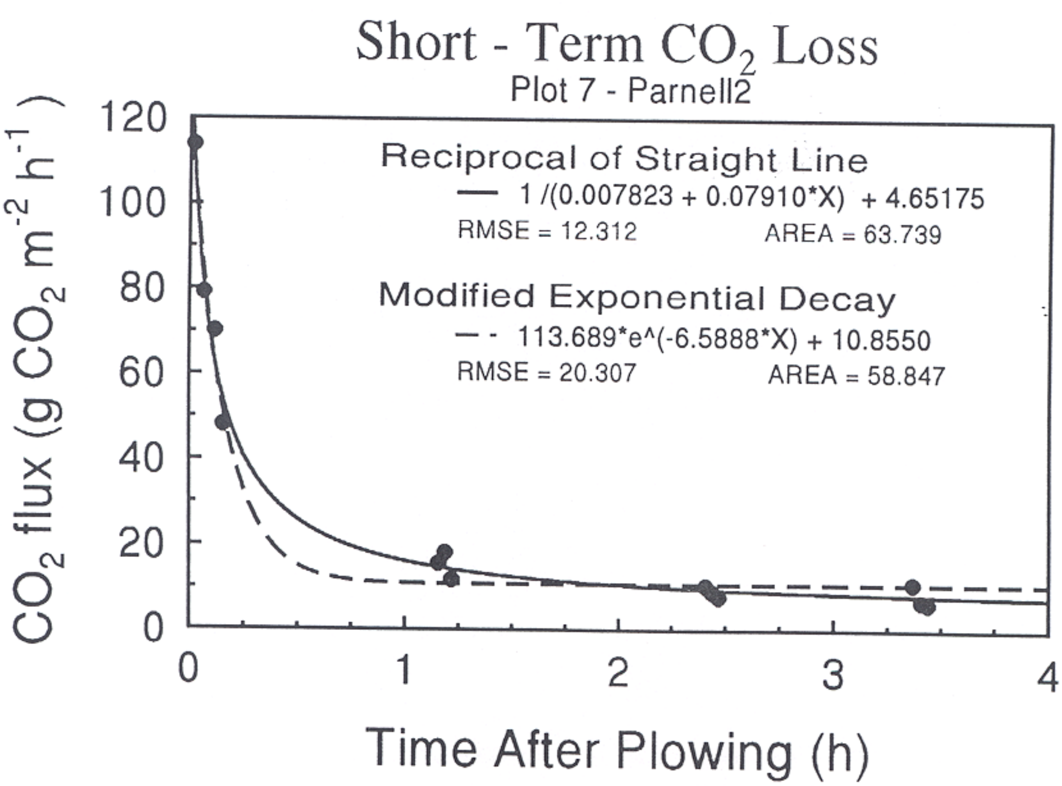

Fig. 63–3. The CO_2 flux as a function of time after plowing for Parnell2 soil on the north transect. Coefficients are for fitted reciprocal linear and modified exponential curves.

kg ha^{-1} on the south transect. Most of the low yields were from low lying poorly drained areas that retained runoff. The Parnell soils had the lowest yields related to their drainage. Yields within the same soil series were variable and ranged from a low of 1822 kg ha^{-1} for Hamerly5 to a high of 2345 kg ha^{-1} for Hamerly2. Similar differences were observed for Vallers and Barnes soils. The results show substantial yield variation related to soil series and position within the landscape that need to be considered in soil management plans.

The change in CO_2 flux as a function of time after plowing is illustrated in Fig. 63–3 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 Fig. 63–3 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 are summarized in Fig. 63–3. Analysis of the 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. The data is limited, however, to the ≈3.5 h time interval.

There was a significant 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 g 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 D 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.

The CO_2 fluxes on three different soils in the north transect as a function of time after plowing are illustrated in Fig. 63–4, representing the lowest, middle and highest initial fluxes on D 267. The time trends were similar for all three soils. The data were fitted using the inverse linear function as described previously. The reasonably 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 no physical meaning. These data and other appropriate functions require further analysis.

The spatial relationship in the CO_2 flux immediately after plowing was of interest. The flux at one min. and ≈3.5 h after tillage for both north and south transect is summarized in Fig. 63–5 and 63–6 as a function of distance from the west end of the transect. The CO_2 fluxes are different for each of the soils and show maximum values at 1 min. after tillage that ranged from a high of 114 g

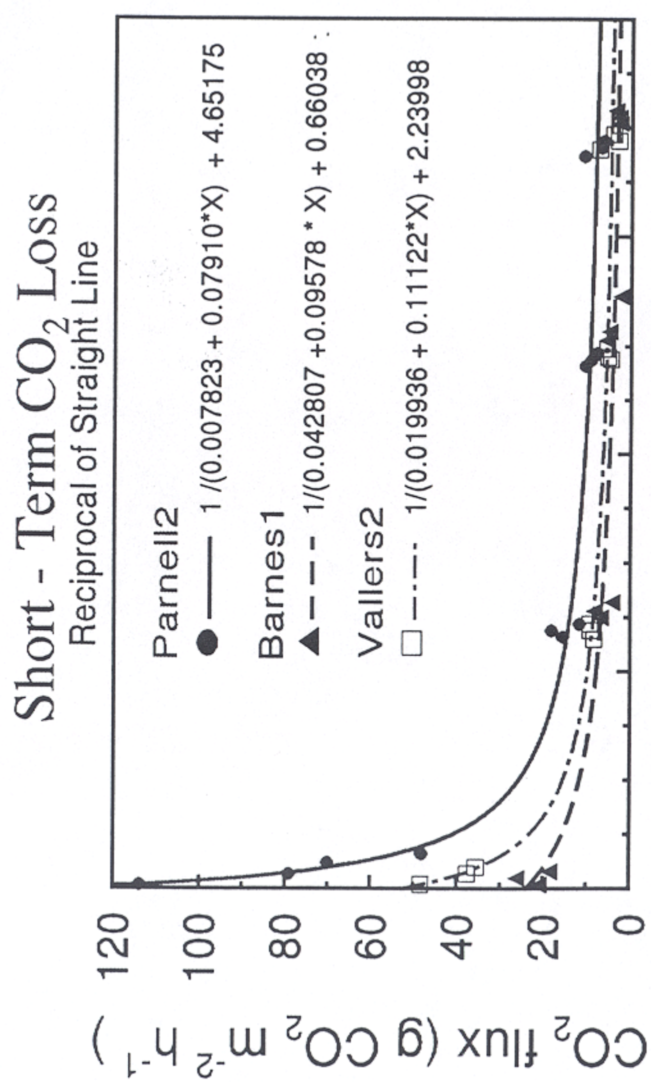

Fig. 63–4. The CO_2 flux as a function of time after plowing for three different soil series on the north transect that represent low, median, and high fluxes measured on D 267.

CO_2 m^{-2} h^{-1} to a low of 50 g CO_2 m^{-2} h^{-1} on the north transect, and a high of 80 g CO_2 m^{-2} h^{-1} to a low of 30 g CO_2 m^{-2} h^{-1} on the south transect. The values at ≈3.5 h after plowing were substantially lower and ranged from 4 to 7 g CO_2 m^{-2} h^{-1} on both transects. The magnitude of initial fluxes and rapid decline in CO_2 flux immediately following plowing suggest significant gaseous C loss, depending on soil type and location within the landscape.

The cumulative CO_2 loss from 1 min. to ≈3.5 h after plowing is summarized in Fig. 63–7 and 63–8 for the north and the 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 (Fig. 63–8). The initial measurements on Barnes2, however, 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.

The same method was used to calculate the cumulative CO_2 loss for sites on the south transect where a measurement cycle was made on the morning of Day 2 before starting on the north transect. These data were taken ≈24 h after plowing on D 266 and can be used to approximate the cumulative CO_2 loss for 1 d. 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 cumulative CO_2 losses during the 24-h-period after plowing were larger than from no-till with substantial soil differences. These results show lingering effects of plow perturbation, however, need to be interpreted with caution due to the long interval with no data points during the night. This is in agreement with observations of Reicosky and Lindstrom (1993), where moldboard plowing showed higher fluxes as long as 3 days after tillage before a 49-mm-rainfall event.

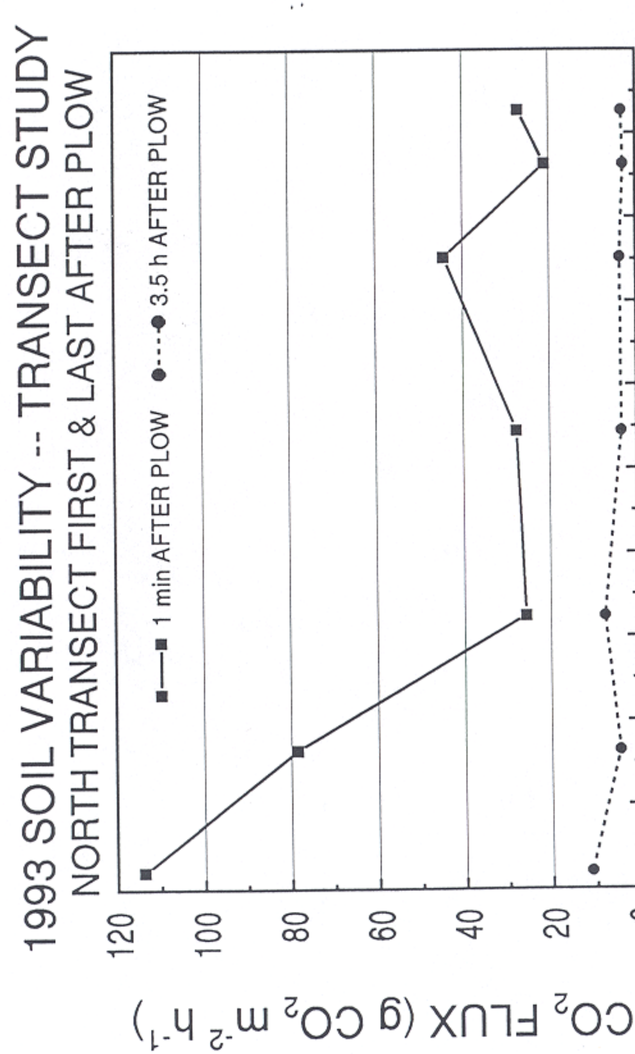

Fig. 63–5. The CO_2 flux at one minute and 3.5 hours after plowing on the north transect as a function of landscape position (distance from the west end).

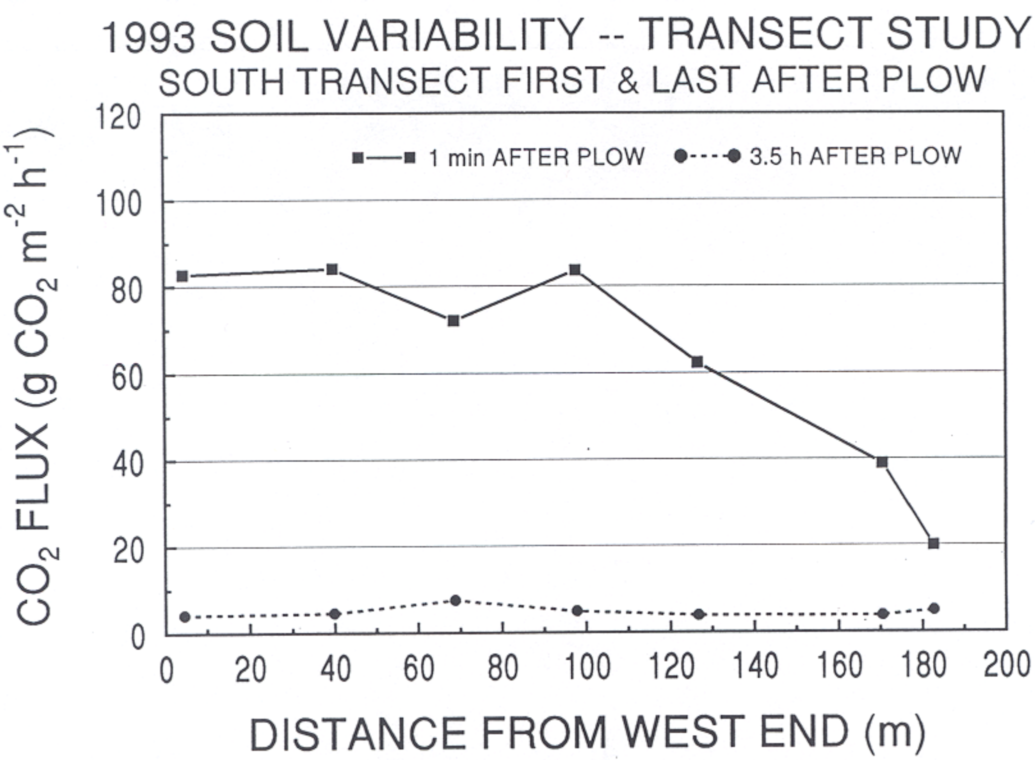

Fig. 63–6. The CO_2 flux at one minute and 3.5 hours after plowing on the south transect as a function of landscape position (distance from the west end).

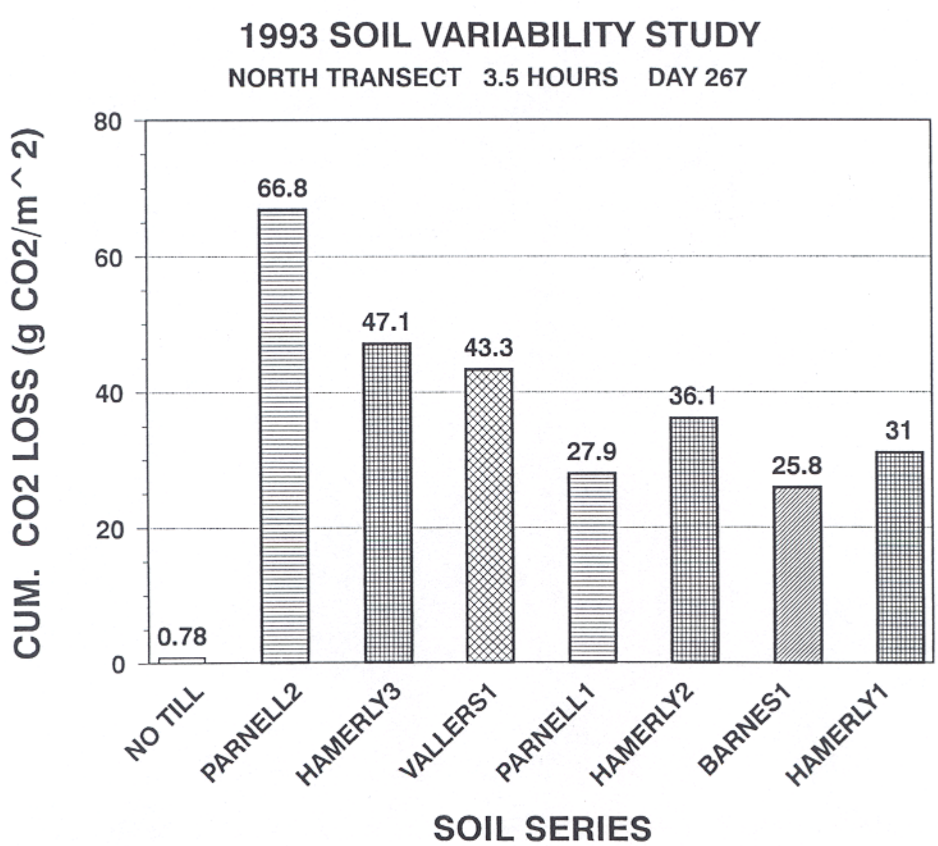

Fig. 63–7. The cumulative CO_2 loss for the first 3.5 hours after plowing for soils on north transect (D 267) using the trapezoid rule for numerical integration.

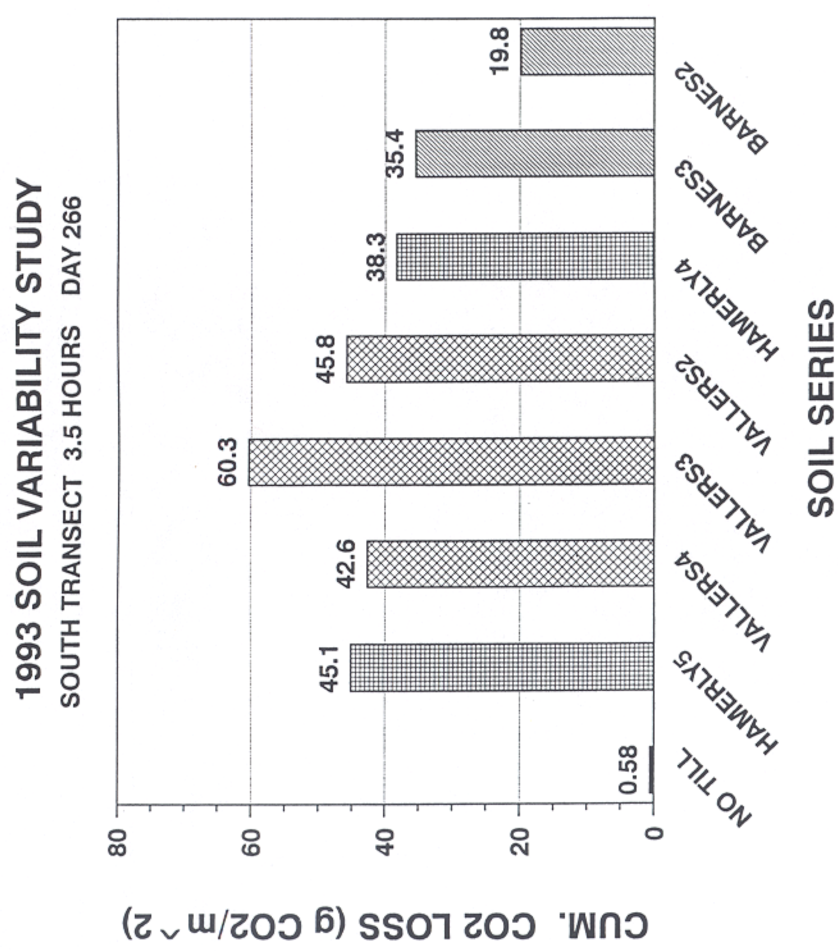

Fig. 63–8. The cumulative CO_2 loss for the first 3.5 hours after plowing for soils on south transect (D 266) using the trapezoid rule for numerical integration.

In summary, these results show a large loss of CO_2 immediately following moldboard plowing that agrees with earlier results of Reicosky and Lindstrom (1993). Measurements within 1 min. after plowing as opposed to 5 min. after plowing increased the maximum initial CO_2 flux nearly three-fold. Enhanced loss of CO_2 and the subsequent entry of oxygen into the soil could shift the gaseous equilibrium and result in enhanced 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.

The distribution of soil properties over space is an important source of variability in field experiments that has long been recognized. In this work, the rate of CO_2 loss was partially dependent on soil position within the landscape. The ability to characterize this spatial variability can be critical in field studies where properties under investigation are not uniformly distributed. 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.

Quantifying CO_2 emission from soil as a function of tillage is complex and will require specific information on each soil type, particularly water content and organic C level at time of tillage. The data show positional differences in initial CO_2 flux that ranged from 114 to 35 g CO_2 m^{-2} h^{-1} immediately after plowing and a cumulative CO_2 loss for 3.5 h that varied from 26 to 67 g CO_2 m^{-2}. Quantifying positional trends for a spatially distributed parameter will require further work to provide policy makers with quantitative data for environmental quality decisions.

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