

# Tillage Effects on Carbon Fluxes in Continuous Wheat and Fallow–Wheat Rotations

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## ABSTRACT

The traditional cropping system in semiarid regions of the Canadian prairies involves frequent summer fallowing with several tillage operations to control weeds during the fallow period. Recently, there has been a trend toward reduced tillage and more intensive cropping, but the impact of this shift in management on sequestration of atmospheric CO<sub>2</sub> remains uncertain. In 1995 and 1996, we measured fluxes of CO<sub>2</sub> in a tillage experiment that had been initiated in 1982 on a silt loam (Typic Haploboroll) in southwestern Saskatchewan. The experiment comprised two spring wheat (*Triticum aestivum* L.) rotations (continuous wheat [Cont. W] and fallow–wheat [F–W]), each with conventional tillage (CT) and no-till (NT) treatments. In Cont. W, CO<sub>2</sub> fluxes tended to be lower under NT than under CT (mean annual flux was ≈20 to 25% less for NT than CT). In F–W, tillage effects on mean annual CO<sub>2</sub> flux were significant ( $P < 0.05$ ) in the wheat phase only (NT ≈ 10% less than CT). Tillage had negligible effect on C inputs in crop residues. Lower CO<sub>2</sub> fluxes under NT than under CT were attributed to slower decomposition of crop residues placed on the surface of NT soil than when they were incorporated. With good growing conditions (and thus large inputs of residues) between 1989 and 1996, there was an accumulation of partially decomposed residues on the surface of NT soil. Carbon in surface residues represented about one-half of the C gained by NT soil. In Cont. W, surface residue C (in 1996) amounted to 3.6 t ha<sup>-1</sup> under NT vs 1.4 t ha<sup>-1</sup> under CT. Residue C amounts were smaller in the F–W system: 1.7 t ha<sup>-1</sup> (NT) and 0.7 t ha<sup>-1</sup> (CT). Based on our results, producers on medium-textured soils in the semiarid Canadian prairies who switch from the traditional wheat production system (conventionally tilled fallow–wheat) to continuous no-till cropping could, potentially, sequester 5 to 6 t C ha<sup>-1</sup> in soil organic matter and surface residues in 13 to 14 yr.

INCREASING CONCENTRATIONS of CO<sub>2</sub> and other radiatively active gases in the atmosphere are a concern because of potential climate changes that could result in an increase in temperature and drought (Houghton et al., 1990). Soils play an important role in regulating the atmospheric concentration of CO<sub>2</sub>. Land management practices that increase the amount of organic C in soil are being promoted for their contribution in offsetting CO<sub>2</sub> emissions from fossil fuel combustion, the main anthropogenic CO<sub>2</sub> source (Kern and Johnson, 1993).

Reduced tillage is regarded as one of the most effective agricultural strategies for sequestering atmospheric C (Kern and Johnson, 1993; Lal and Kimble, 1997). Tillage accelerates organic C oxidation to CO<sub>2</sub> by improving soil aeration, by increasing contact between soil

and crop residues, and by exposing aggregate-protected organic matter to microbial attack (Beare et al., 1994). Reducing tillage intensity may lead to increases in soil C, though the magnitude of the increase can vary widely. The C storage potential of reduced tillage systems is often most apparent when no-till is compared with intensive cultivation (i.e., moldboard plowing) in humid regions (Mahboubi et al., 1993). Eleven years of no-till increased organic C content of a silt loam (0–5 cm depth) in Oklahoma by 65% compared with a moldboard plow treatment (Dao, 1998). In contrast, under dryland conditions where shallow cultivation (10–15 cm depth) is the conventional tillage method, changes in C storage following adoption of reduced tillage practices can be small and difficult to quantify against background variability (Unger, 1991; Campbell et al., 1995, 1996). In such situations, Grant (1997) recommended measurement of CO<sub>2</sub> fluxes as providing a more sensitive indication of C sequestration than low resolution data such as total organic C values. Consistent with that suggestion, Fortin et al. (1996) concluded that CO<sub>2</sub> flux measurements gave early signals of tillage-induced changes in soil C in Ontario.

Almost 80% of Canada's arable land is in the prairie provinces (Alberta, Manitoba, and Saskatchewan), which produce >90% of the 25 million tonnes of wheat grown in the country in a typical year. In semiarid regions of the prairies, the traditional cropping system involves frequent summer fallowing (land fallowed during an entire growing season) with several tillage operations to control weeds during the fallow year. This system is regarded as a worst-case scenario for soil C storage because inputs of C in crop residues are relatively low and frequent tillage promotes organic matter decomposition. However, soil C is expected to increase as a result of recent changes in land use practices (Dumanski et al., 1998). The area of land in summer fallow has steadily declined during the past two decades (Janzen et al., 1998b) and reduced tillage is a rapidly expanding technology for crop production on the prairies (Larney et al., 1994).

The amount of C sequestered when tillage intensity is reduced appears to depend partly on site-specific factors such as soil texture, fertility levels, and crop rotation (Lal et al., 1995; Campbell et al., 1996; Lal and Kimble, 1997). Thus, it is very difficult to predict how much C will be sequestered in prairie soils as a result of the shift to reduced tillage. Further, the time needed to reach a steady state C level under a reduced tillage regime has not been well defined. According to Monreal and Janzen (1993), changes in soil C in response to management perturbations can be relatively rapid with much of the

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**Abbreviations:** Cont. W, continuous wheat; CT, conventional tillage; F–W, fallow–wheat; (F)–W, fallow phase of F–W; F–(W), cropped phase of F–W; NT, no-till.

change occurring in the first 10 yr or so. In this paper we report on a study of the effects of tillage (conventional vs. no-till) on C fluxes in wheat-producing systems differing in summer fallow frequency. Our measurements were made 13 to 14 yr after initiation of no-till cropping and were expected to provide insights on the time frame in which tillage-induced disturbances of the C cycle might persist in dryland wheat farming.

## MATERIALS AND METHODS

### Experimental Treatments

The field experiment was initiated in 1982 on a gently sloping Swinton silt loam (Typic Haploboroll) at the Semiarid Prairie Agricultural Research Centre, Swift Current, Saskatchewan, Canada. The mean annual precipitation and temperature are 350 mm and 3.3°C, respectively, and the number of frost-free days averages 117 per year (Campbell et al., 1990). In the previous 70 to 80 yr, this land had been managed in a fallow-wheat rotation using conventional tillage methods. When the experiment was initiated, the organic C content in the top 15 cm was 27 t ha<sup>-1</sup> (Campbell et al., 1995). Two spring wheat rotations were established as main treatments: F-W and Cont. W. Both phases of the F-W rotation were present each year. Each rotation had a CT and a NT sub-treatment. Treatments were arranged in a complete block design with four replicates. Plots were 15 m wide by 76 m long. Full-sized farm equipment was used to perform most field operations.

Details of tillage and other management practices have been reported by McConkey et al. (1996). Herbicides were used exclusively for weed control under NT. The NT fallow plots were treated (one to three applications) with broad-spectrum herbicides (tank-mixes that included herbicides such as glyphosate [*N*-(phosphonomethyl)glycine] with or without dicamba [3,6-dichloro-2-methoxybenzoic acid], as required) with the first application being made in mid to late June. All treatments (CT as well as NT) received applications of 2,4-D ester [(2,4-dichlorophenoxy)acetic acid] each fall to control winter annual broadleaf weeds.

The CT methods used in this study were typical of those practiced in southwestern Saskatchewan. The Cont. W system was tilled once each year, prior to seeding, using a heavy-duty sweep cultivator with an attached rodweeder or mounted harrow (Tessier et al., 1990). On CT fallow plots, weeds were controlled by one to four operations with a heavy-duty cultivator. Tillage depth was 5 to 10 cm.

Hard red spring wheat (cv. Lancer) was sown at a rate of 67 kg ha<sup>-1</sup>. An offset disc drill (Dyck and Tessier, 1986) was used to plant the NT treatment, and a conventional hoe press drill was used in the CT treatment. In the years in which C fluxes were measured (1995 and 1996), wheat was seeded on 8 and 9 May. All treatments received 10 kg P ha<sup>-1</sup> as monoammonium phosphate, which was placed with the seed. Inputs of fertilizer N (NH<sub>4</sub>NO<sub>3</sub>) were based on soil NO<sub>3</sub><sup>-</sup> levels, measured in the upper 60 cm of the profile in the fall, and regional fertilizer recommendation guidelines provided by the Saskatchewan Advisory Council on Soils (Saskatchewan Agriculture, 1988). The N fertilizer was broadcast prior to seedbed preparation or seeding until 1990. Thereafter, up to 45 kg N ha<sup>-1</sup> was applied with the seed and any additional fertilizer required was broadcast on the surface. Wheat was harvested at full maturity (5 Sept. 1995 and 3 Sept. 1996) using a conventional, direct-cut header combine. All crop residues were spread behind the combine with straw and chaff spreaders.

### Measurement of Carbon Dioxide Fluxes

In 1995 and 1996, CO<sub>2</sub> emissions were measured with a portable infrared analyzer (LI-COR model LI-6200, Licor, Lincoln, NE) to determine accumulation of CO<sub>2</sub> in a vented chamber that enclosed an area of 177 cm<sup>2</sup>. The chamber was attached to a collar, which was inserted into the soil to a depth of 4 cm. Head space volume was 2 L. Fluxes of CO<sub>2</sub>, expressed as μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> (1 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> ~ 10 kg C ha<sup>-1</sup> d<sup>-1</sup>), were estimated from the rate of increase in CO<sub>2</sub> in the chamber during a 60-s deployment period. Flux measurements were usually made once each week from spring until the soil froze in late fall (all measurement were made during day time, i.e., 1000–1700 h). Generally, three measurements were made in each plot at locations 3 to 4 m apart (the distance between sampling locations was determined from a preliminary study of spatial pattern of CO<sub>2</sub> emissions). Designated sampling locations were marked using flags and measurements were always made within 1 m of the flags. In-crop measurements were made by placing the chamber between plant rows (row spacing for wheat was 17.5 cm). Analysis of variance was performed to assess the effects of tillage and crop rotation on CO<sub>2</sub> fluxes on each measurement date. In this analysis, the two phases of the F-W system were treated as separate rotations. Because flux measurements tend to be variable (coefficients of variability [*n* = 4] were usually in the 15–40% range), hypotheses were tested at the *P* = 0.10 level of significance.

### Carbon Inputs

Estimates of C inputs in crop residues in 1995 and 1996 were obtained from aboveground biomass, measured by taking three random samples (1 m<sup>2</sup>) in each plot at crop maturity (22 August in both 1995 and 1996). The plant material was dried (60°C), weighed, and separated into grain and straw. Straw was analyzed for C using an automated C/N analyzer (Carlo Erba, Milan, Italy). Carbon inputs in roots were estimated assuming a root/straw ratio of 0.59:1 (Campbell et al., 1977a, 1997b) and a root C content of 45%.

### Surface Residue Amounts

The amount of crop residue on the soil surface was determined annually (1982–1996) by taking five 0.5-m<sup>2</sup> samples per plot each fall. The samples included all residue that was <15° erect. These samples were gently washed in flowing water to remove any adhering soil, dried (60°C) and weighed. Residue C for samples collected up to 1995 was estimated assuming a C content of 40%. The 1996 samples were analyzed for C using the C/N analyzer.

## RESULTS AND DISCUSSION

### Weather Conditions and Crop Growth

The 1995 growing season (1 May–31 July) was relatively wet, with ≈14% more precipitation than the long-term mean of 168 mm (Fig. 1). In 1996, precipitation in April (26 mm), May (65 mm), and June (78 mm) was near, or above, the long-term average for these months (i.e., 22, 44, and 72 mm for April, May, and June, respectively). A dry period in July and August 1996 was followed by an especially wet September when precipitation exceeded 100 mm. The frost-free period in 1995 was 24 May to 20 September and in 1996 it was 12 May to 24 September. Mean daily temperatures in the growing season were 0.6°C (1995) and 1.3°C (1996) below the long-term average (15.0°C).

Grain and straw yields and, by extension, inputs of

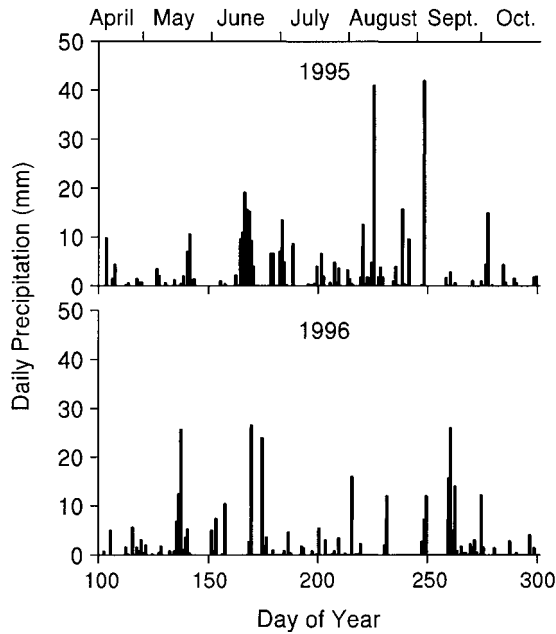


Fig. 1. Daily precipitation in 1995 and 1996, measured at a meteorological station  $\approx 0.5$  km from the field site at the Semiarid Prairie Agricultural Research Centre, Swift Current, Saskatchewan, Canada.

C in crop residues were above average in all treatments in 1995, with grain production (Table 1) being 16 to 47% greater than the mean values reported by McConkey et al. (1996) for the 1982 to 1993 period. In 1996, yield of Cont. W exceeded the 1982 to 1993 average by 20 to 21%, while wheat grown on fallow was within 10% of the average yield.

Yields of Cont. W were not significantly ( $P > 0.05$ ) affected by tillage in 1995 or 1996 (Table 1). In the F-W rotation, tillage had no effect on yield in 1996, but there was a significant ( $P < 0.05$ ) advantage to CT in 1995. Data for the earlier years of the experiment also show that tillage had little effect on biomass production in the Cont. W system (McConkey et al., 1996). In F-W, there was a tendency for higher yields under CT in wetter years, but the average yield for the 1982 to 1993

Table 1. Effects of rotation and tillage on biomass production and inputs of C in crop residues in 1995 and 1996.

Rotation†	Tillage	Grain yield	Straw yield		Roots‡	C input
			kg ha <sup>-1</sup>			
1995						
Cont. W	CT	2809	5260	(3241)§	3100	3760
Cont. W	NT	2604	4623	(3460)	2720	3310
F-W	CT	3364	6305	(2005)	3720	4510
F-W	NT	2728	4820	(1919)	2840	3450
LSD ( $P < 0.05$ )		426	940			
1996						
Cont. W	CT	2320	4011		2370	2870
Cont. W	NT	2297	3989		2350	2850
F-W	CT	2243	3984		2350	2850
F-W	NT	2382	3984		2350	2850
LSD ( $P < 0.05$ )		351	535			

† Cont. W is continuous wheat; F-W is fallow-wheat rotation.  
 ‡ Root production was estimated assuming a root/straw ratio of 0.59 (Campbell et al., 1977a, 1997b).  
 § Values in parentheses are annualized straw yields (mean for the 1982-1994 period).

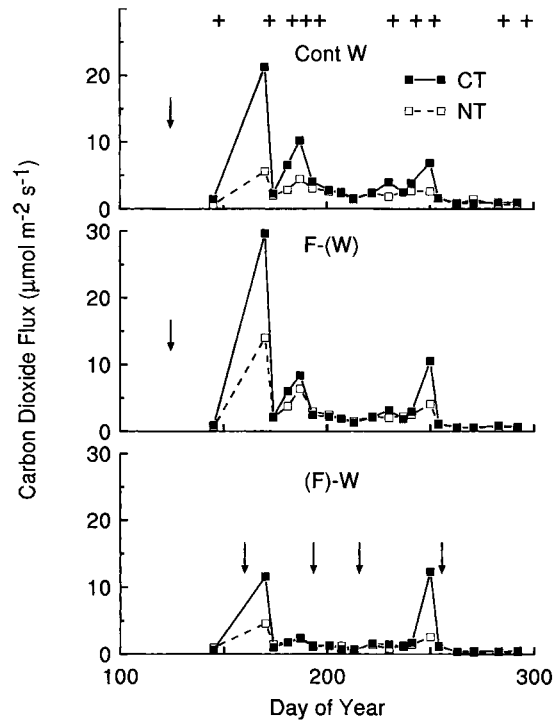


Fig. 2. Effect of tillage on fluxes of CO<sub>2</sub> from continuous wheat (Cont. W), cropped phase of a fallow-wheat rotation [F-(W)], and fallow phase of a fallow-wheat rotation [(F)-W] in 1995. Measurement dates when tillage or tillage  $\times$  rotation effects were significant ( $P < 0.10$ ) are denoted by "+". CT is conventional tillage; NT is no-till. Arrows indicate dates of tillage operations in the CT treatment.

period was very similar for the two tillage treatments (i.e., 2480 kg ha<sup>-1</sup> for CT and 2380 kg ha<sup>-1</sup> for NT). Corresponding values for Cont. W were 1920 and 1910 kg ha<sup>-1</sup> for CT and NT, respectively. Except for F-W in 1995, inputs of C in crop residues were very similar for the two tillage systems (Table 1). However, C inputs were considerably greater for Cont. W than for F-W because the latter rotation produced a crop every second year only. Mean annual residue inputs under F-W, estimated from 1982 to 1994 straw yield data (Table 1), were  $\approx 60\%$  of those under Cont. W.

### Carbon Dioxide Fluxes

Fluxes of CO<sub>2</sub> ranged from  $< 0.5 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  to  $> 10 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ , although values  $> 3 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  were uncommon (Fig. 2 and 3) and were only observed following heavy rainfall. Tillage effects on CO<sub>2</sub> evolution were most apparent following heavy rains in June 1995 (Day of Year 170) and September 1995 (Day of Year 250) when exceptionally high fluxes were measured in CT plots (Fig. 2). Within a few days, emissions returned to normal levels. Previous flux measurements (Curtin et al., 1998) on a Swinton loam (the soil type at our site), into which 2800 kg straw ha<sup>-1</sup> (average wheat straw yield in semiarid areas of Saskatchewan) had been incorporated, suggest that CO<sub>2</sub> production by microbial respiration in fallow soil at optimum moisture ( $\approx$ field capacity) would probably not exceed  $\approx 3 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ . Thus, fluxes from CT plots exceeding  $10 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  (Fig. 2) probably

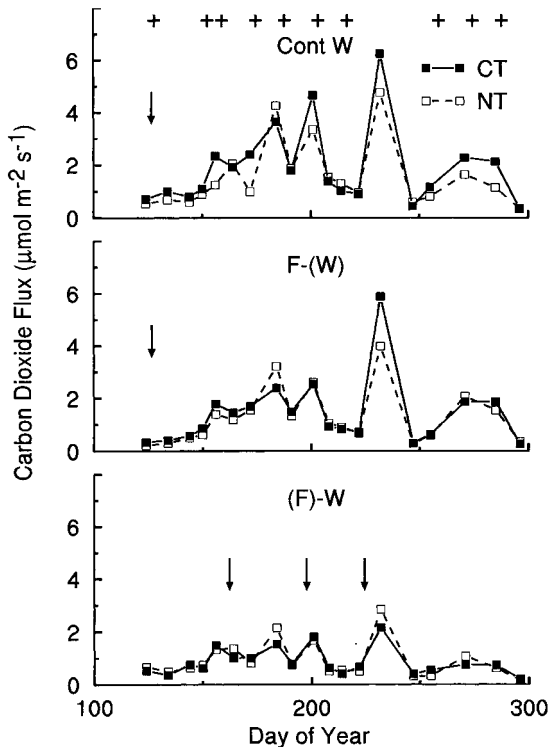


Fig. 3. Effect of tillage on fluxes of  $\text{CO}_2$  from continuous wheat (Cont. W), cropped phase of a fallow-wheat rotation [F-(W)], and fallow phase of a fallow-wheat rotation [(F)-W] in 1996. Measurement dates when tillage or tillage  $\times$  rotation effects were significant ( $P < 0.10$ ) are denoted by "+". CT is conventional tillage; NT is no-till. Arrows indicate dates of tillage operations in the CT treatment.

cannot be explained by normal respiratory output of  $\text{CO}_2$ . We hypothesize that, under raindrop impact, the soil surface may have sealed, temporarily trapping  $\text{CO}_2$ . As the soil surface dried, trapped  $\text{CO}_2$  was released in a brief, intense burst. Elimination of tillage has substantially improved the water-stability of soil aggregates at this site (McConkey et al., 2000). Better soil structure combined with greater surface residue cover (discussed below), may have prevented surface sealing under NT. An alternative explanation is that the high fluxes were associated with the rapid release of dissolved gas when saturated soil began to drain. Better drainage under NT vs. CT may have reduced the accumulation of dissolved  $\text{CO}_2$  in NT soil. When the high fluxes in 1995 were excluded, tillage effects were relatively small in the F-W rotation and there was a reasonably good 1:1 relationship (slope = 0.98; intercept = 0.02;  $R^2 = 0.92$ ,  $P < 0.001$ ; two outlying observations were omitted from this regression) between fluxes in the two tillage treatments (Fig. 4). In Cont. W, CT often had significantly ( $P < 0.10$ ) higher  $\text{CO}_2$  fluxes than NT.

To quantify the effect of tillage on  $\text{CO}_2$  emissions, estimates that integrate the measured fluxes across an entire season were needed. In addition to mean fluxes for 1995 and 1996, we estimated total  $\text{CO}_2$ -C emissions for each year by linear interpolation of the measured fluxes and integration over time. The latter approach provides values that may be used to compare treatments. However, because the measurement frequency was relatively low and no adjustment was made for factors such

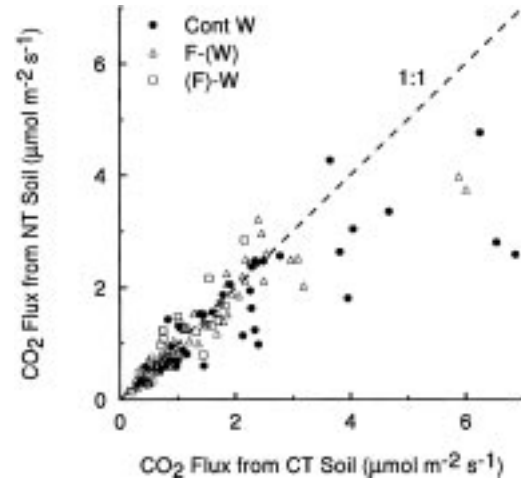


Fig. 4. Fluxes of  $\text{CO}_2$  from no-till (NT) soil vs. those from conventional till (CT) soil under continuous wheat (Cont. W), cropped phase of a fallow-wheat rotation [F-(W)], and fallow phase of a fallow-wheat rotation [(F)-W] (data for 1995 and 1996 are pooled).

as temperature-related, diurnal variation in emissions (Akinremi et al., 1999), the values shown in Table 2 should not be considered true measures of annual C output. In 1996, the mean flux from Cont. W was  $\approx 20\%$  lower under NT compared with CT (Table 2). There was a significant tillage  $\times$  rotation interaction, with the tillage effect being greater for Cont. W than for wheat grown on fallow. Tillage had no significant effect on the mean flux from fallow. When the abnormally high fluxes in June and September 1995 were excluded, the mean flux from Cont. W in 1995 was  $\approx 25\%$  less under NT than under CT. As in 1996, the effect of tillage decreased in the order: Cont. W  $>$  cropped phase of F-W [F-(W)]  $>$  fallow phase of F-W [(F)-W]. Total  $\text{CO}_2$  emissions for 1995 and 1996 showed a similar pattern to the mean fluxes (Table 2). Total emissions were less under NT than under CT by 20 to 23% for Cont. W and by 10% for wheat grown on fallow, with tillage having no effect on total emissions from fallow.

Inclusion of the very high fluxes recorded following heavy rains in 1995 resulted in mean flux values for 1995 that showed a strong tillage influence (Table 2). As elevated fluxes from CT vs. NT under very wet soil conditions may be due to physical factors that affect the transmission of  $\text{CO}_2$  to the atmosphere, rather than due to differences in  $\text{CO}_2$  production in the soil, a more meaningful assessment of tillage effects on the soil C balance may be obtained when flux measurements are delayed to allow the soil to drain after heavy rains.

Tillage operations may physically release gas from the soil and cause enhanced  $\text{CO}_2$  fluxes for up to  $\approx 24$  h (Ellert and Janzen, 1999). This short-term effect of tillage did not contribute to the differences in emissions between CT and NT, shown in Table 2, because the number of tillage operations was small and measurements were not made within a day of cultivation. Disturbance of the soil during installation of the measuring chamber may enhance  $\text{CO}_2$  fluxes, though the disturbance effect is likely to be small and, presumably, similar in all treatments. Ellert and Janzen (1999) estimated that  $\text{CO}_2$  released as a result of soil disturbance associ-

**Table 2.** Mean CO<sub>2</sub> fluxes for 1995 and 1996 and estimated total emissions of CO<sub>2</sub>-C in each year as influenced by crop rotation and tillage.

Rotation‡	Tillage	Mean CO <sub>2</sub> flux		Total CO <sub>2</sub> -C emitted	
		1995	1996	1995	1996
		μmol m <sup>-2</sup> s <sup>-1</sup>		kg ha <sup>-1</sup>	
Cont. W	CT	2.45§ (4.17)¶	1.96	3640§	3680
Cont. W	NT	1.80 (2.20)	1.57	2810	2940
F-(W)#	CT	1.96 (4.30)	1.44	2920	2790
F-(W)	NT	1.75 (2.83)	1.29	2620	2510
(F)-W#	CT	1.01 (2.20)	0.87	1510	1610
(F)-W	NT	0.99 (1.35)	0.93	1570	1730
<b>Prob. of significant F ratio</b>					
Rotation††		*** (***)	***	***	***
Tillage		** (***)	*	*	†
Rotation × Tillage		† (*)	†	†	†
LSD ( <i>P</i> < 0.05)		0.21 (0.35)	0.14	310	323

\* Significant at the 0.05 probability level.

\*\* Significant at the 0.01 probability level.

\*\*\* Significant at the 0.001 probability level.

† Significant at the 0.10 probability level.

‡ Cont. W, continuous wheat; F-(W), cropped phase of fallow-wheat rotation; (F)-W, fallow phase of fallow-wheat rotation.

§ Values calculated after excluding the very high CO<sub>2</sub> fluxes measured on Days of Year 170, 187, and 250 following heavy rains.

¶ Values recorded on Days of Year 170, 187, and 250 were included in mean calculation.

# Data are for the rotation phase in parentheses.

†† In the analysis of variance, the two phases of F-W were treated as separate rotations.

ated with 10 passes with a cultivator would amount to <5% of total annual CO<sub>2</sub> emissions from soil in Alberta, Canada.

Emissions of CO<sub>2</sub> from Cont. W generally exceeded those from F-(W) (Table 2). This may seem surprising given that soil moisture levels are often more favorable for microbial and root activity under F-(W) than under Cont. W (Grant, 1997), but it is probably a reflection of the importance of fresh crop residues as a C source for soil microbes (Curtin et al., 1998). The Cont. W system received fresh residues every year, but in the case of F-(W), a growing season had elapsed without residue addition. In the F-W rotation, crop residues probably decompose to a large extent during the fallow year, resulting in relatively low residue-derived CO<sub>2</sub> emissions from the wheat phase of this rotation.

Fluxes of CO<sub>2</sub> from (F)-W were lower than those from the cropped phase of that rotation or from Cont. W, due to the absence of root respiration in fallow soil (Table 2). Partitioning CO<sub>2</sub> emissions into root (rhizosphere) and microbial contributions is one of the most intractable problems in soil C cycling (Rochette and Flanagan, 1997). One approach is to assume that differences in fluxes between cropped and fallow treatments are due to root respiration. Attributing the difference between cropped and fallow phases of the F-W rotation to root respiration might result in underestimation of root respiration (i) because soil moisture levels in the fallow phase are generally more favorable for microbial activity than in the cropped phase (Grant, 1997) and (ii) because the fallow phase recently received fresh residues, whereas, in the case of the cropped phase, an entire growing season would have passed without residue addition. The confounding effect of residues may be avoided by comparing the fallow phase of F-W with Cont. W, but since fallow is more moist, the difference between Cont. W and (F)-W may again underestimate root respiration. When data for the two tillage treatments and for the 2 yr were pooled, the following

regression equations were obtained between fluxes from fallow (*x*) vs. those from the cropped phase of F-W and Cont. W (*y*):

$$\text{F-(W): } y = -0.22 + 1.94x \\ (R^2 = 0.73, P < 0.0001; n = 72) \quad [1]$$

$$\text{Cont. W: } y = 0.10 + 1.88x \\ (R^2 = 0.66, P < 0.0001; n = 71) \quad [2]$$

The intercept values were not significantly different from zero (*P* > 0.05), and the slopes of the two equations were similar. If we ignore the intercept, the average contribution of root respiration to CO<sub>2</sub> emissions may be approximated as  $(1 - 1/b)100$ , where *b* represents the slope in Eq. [1] and [2]. Such calculations suggest that root respiration contributed almost one-half (47–48%) of the CO<sub>2</sub> emitted from soil cropped to wheat.

### Soil Carbon Balance

Elimination of tillage reduced CO<sub>2</sub>-C emissions, but had little effect on C inputs. Our results indicate that NT soil gained C compared with CT soil, particularly under continuous cropping. The C flux data are generally consistent with soil organic C measured in 1994, 12 yr after initiation of the experiment (Campbell et al., 1995). In Cont. W, ≈2.5 t ha<sup>-1</sup> more C was stored in the soil (0–7.5 cm depth) under NT relative to CT, but in the F-W rotation, the balance in favor of NT was small (0.9 t ha<sup>-1</sup>) (Table 3). Tillage (or rotation) had no effect on C levels in the 7.5- to 15-cm soil depth (Campbell et al., 1995). By the time our flux measurements were made (13–14 yr after initiation of NT), soil C levels were expected to have reached a steady state under NT; data of Campbell et al. (1995) suggested that organic C in the NT soil had stabilized by 1990. However, all growing seasons between 1989 and 1996 had average or above-average precipitation, and the large inputs of crop residues in those years provided impetus for further C gains

**Table 3. Effect of crop rotation and tillage on total soil organic C† and light fraction C‡ in the 0 to 7.5-cm depth and on C in surface residues.§**

Rotation¶	Tillage	Soil organic C			Surface residue C			Light fraction C		
		t ha <sup>-1</sup>								
Cont. W	CT	14.36	(0.44)#	1.37	(0.68)#	1.11	(0.30)#			
Cont. W	NT	16.84	(2.92)	3.55	(2.86)	1.50	(0.70)			
F-W††	CT	13.92	(0)	0.69	(0)	0.80	(0)			
F-W	NT	14.78	(0.86)	1.67	(0.98)	0.78	(-0.02)			

† Soil C values (for 1994) taken from Campbell et al. (1995). In the 7.5 to 15-cm depth, tillage or rotation had no effect ( $P > 0.05$ ) on organic C, which averaged 15.44 Mg ha<sup>-1</sup>.

‡ Unpublished data of B.G. McConkey, 2000. Light fraction organic matter was isolated from soil by flotation on NaI solution (specific gravity 1.7), as described by Janzen et al. (1992).

§ Data for surface residue C were obtained from a sampling carried out in fall 1996.

¶ Cont. W is continuous wheat; F-W is fallow-wheat rotation.

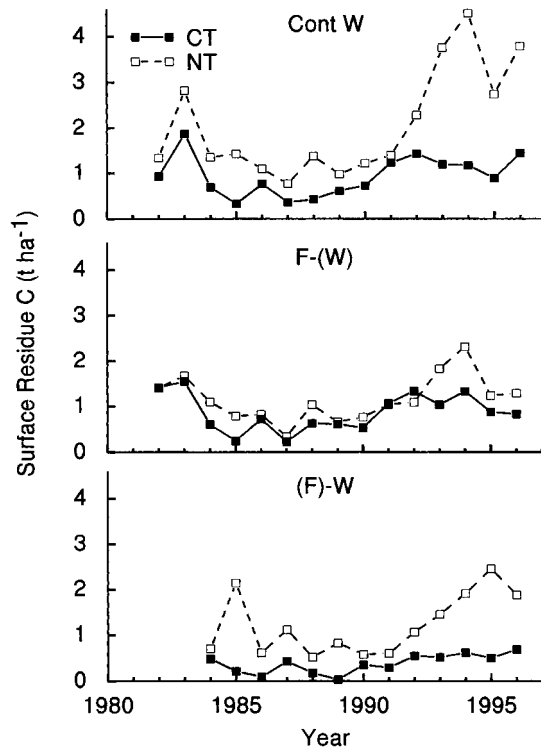
# Values in parentheses represent increases in C relative to conventionally tilled F-W, the system with least C sequestration potential.

†† Values for F-W were averaged for the two-rotation phases.

under NT. Data in Fig. 5 show that under NT there was an accumulation of surface residues since about 1990, especially in Cont. W. It is noteworthy that management effects on surface residue C, measured in 1996, were similar in magnitude to those observed for soil organic C (Table 3). These results show that surface residues can be as important as soil organic matter (operationally defined as organic matter in sieved [ $<2$  mm] soil) as a C repository under NT and should be considered when evaluating tillage effects on C dynamics. Relative to the traditional management system in semiarid regions of the Canadian prairies (F-W with conventional tillage), all systems showed increases in surface residue C: F-W (CT) < Cont. W (CT) < F-W (NT)  $\ll$  Cont. W (NT) (Table 3).

Since tillage had negligible effect on C inputs, lower CO<sub>2</sub> emissions under NT compared with CT can be attributed to slower decomposition of crop residues on the surface of NT soil than when they were incorporated by tillage. The C flux measurements and the soil and surface residue C data all suggest that C sequestration due to adoption of NT is likely to be less in a fallow-wheat system than in continuously cropped soil. This is presumably because the 2-yr period between residue additions in F-W provides an extended opportunity for decomposition, partly offsetting the slow rate of decomposition under NT. There is evidence from a number of other studies in semiarid regions that inclusion of fallow in the crop rotation limits C accumulation under NT (Potter et al., 1997; Peterson et al., 1998).

Soil C gains in response to NT in our experiment were within the range observed at other sites in the northern Great Plains (0–7.5 t C ha<sup>-1</sup>; Janzen et al., 1998a; Peterson et al., 1998). The variability of the response of soil C to NT may be attributed to several factors including crop rotation, fallow frequency, residue removal, fertilizer application, management history, and soil conditions (Janzen et al., 1998a). Apart from the study of Peterson et al. (1998), C in surface residues appears to have been ignored in assessments of the effects of tillage on soil C. The data in Table 3 clearly highlight the importance of including residue C in the C budget of NT soil.



**Fig. 5. Effect of tillage on C in surface residues (measured in fall) in continuous wheat (Cont. W), cropped phase of a fallow-wheat rotation [F-(W)], and fallow phase of a fallow-wheat rotation [(F)-W]. CT is conventional tillage; NT is no-till.**

From a C sequestration perspective, the preferred outcome from adoption of NT would be increased C in nonlabile or passive soil organic matter fractions. Because surface residues are relatively easily decomposed, amounts may fluctuate rapidly in response to environmental conditions and management practices, making them an ephemeral C store. Even a single tillage operation might result in a significant loss of this accumulated surface residue C. Also, a series of dry years may cause surface residue amounts to decline to levels observed during the mid 1980s when dry conditions prevailed. In the continuously cropped system, a portion of the C gained under NT was in the light fraction of soil organic matter (Table 3), which is also labile and susceptible to decomposition in the short term (Gregorich and Janzen, 1996). There is evidence (Beare et al., 1994) that some of the organic C gained under NT may be sequestered within soil aggregates, where it is protected from rapid decomposition. Previous work in Saskatchewan (Campbell et al., 1996) produced evidence that C gains under NT become greater as clay content increases. That observation could be consistent with an aggregate-protection mechanism, but further work is clearly needed to identify factors that determine the size and stability of the C sink created by the introduction of NT management.

## SUMMARY AND CONCLUSIONS

After 13 to 14 yr, fluxes of CO<sub>2</sub> from land that was continuously cropped to wheat were lower under NT

than under CT due to slower decomposition of surface vs. incorporated crop residues. In F–(W), mean CO<sub>2</sub> fluxes for 1995 and 1996 were slightly lower (by 10%) under NT compared with CT, but tillage did not have a significant effect on fluxes from the fallow phase of this rotation. Our results suggest that producers on medium-textured soils in the semiarid Canadian prairies who switch from the traditional system of wheat production (conventionally tilled F–W) to continuous, no-till cereal cropping could, potentially, sequester 5 to 6 t C ha<sup>-1</sup> in soil organic matter and surface residues. The time required to gain this amount of C under NT will be strongly dependent on weather conditions (which exert a controlling influence on C inputs via crop residues), but our data suggest that 12 to 15 yr may be a realistic time frame. Maintaining the sequestered C may require careful management because a sizable proportion of it will be in pools that may decline rapidly if the soil is disturbed mechanically.

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