Soil microbial biomass and carbon dioxide flux under wheat as influenced by tillage and crop rotation

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Lupwayi, N. Z., Rice, W. A. and Clayton, G. W. 1999. **Soil microbial biomass and carbon dioxide flux under wheat as influenced by tillage and crop rotation.** Can. J. Soil Sci. **79**: 273–280. Soil organic matter is important both from an agronomic and an environmental perspective because it affects the capacity of the soil to sustain crop growth, and it is a source and sink of atmospheric CO_2-C. Soil microbial biomass comprises a small proportion of total soil organic matter, but it is more dynamic than total soil organic matter. Therefore, measurements of soil microbial biomass may show the effects of soil management on potential changes in soil organic matter before such effects can be detected by measuring total soil organic matter. The effects of tillage and crop rotation on soil microbial biomass and activity were studied in 1995–1997 in the wheat phase of different cropping rotations that had been established in 1992 under zero tillage or conventional tillage in northern Alberta. Soil microbial biomass was often significantly ($P < 0.05$) higher, but never significantly lower, under zero tillage than under conventional tillage. However, CO_2 evolution (basal respiration) was usually higher under conventional tillage than under zero tillage, resulting in higher specific respiration (qCO_2) under conventional tillage than under zero tillage. The higher additions but lower losses of labile C under zero tillage mean that more C is sequestered in the soil in the zero-tillage system. Thus, this system contributes less to atmospheric CO_2 than conventional tillage, and that soil organic matter accumulates more under zero tillage. Plots preceded by summerfallow, especially under conventional tillage, usually had the lowest microbial biomass and CO_2 evolution, and plots preceded by legume crops had higher microbial biomass and lower qCO_2 than other treatments. Tillage and rotation had little effect on total soil organic matter 5 yr after the treatments had been imposed, probably because of the cold climate of northern Alberta, but the results confirm that the labile forms of soil C are more sensitive indicators of soil organic C trends than total soil organic C. These effects of tillage and rotation on soil microbial biomass were similar to those on microbial diversity reported previously. These results confirm that zero tillage and legume-based crop rotations are more sustainable crop management systems than conventional tillage and fallowing in the Gray Luvisolic soils of northern Alberta.

Key words: Carbon sequestration, carbon mineralization, microbial activity, soil organic matter

Lupwayi, N. Z., Rice, W. A. et Clayton, G. W. 1999. **Biomasse microbienne du sol et flux du bioxyde de carbone sous une culture de blé en fonction du régime de travail du sol et de la rotation des cultures**. Can. J. Soil Sci. **79**: 273–280. La matière organique du sol occupe une place importante du point de vue tant agronomique qu'écologique, du fait qu'elle conditionne la capacité du sol à soutenir la croissance des cultures et qu'elle agit comme source et puits du CO_2 atmosphérique. La biomasse microbienne du sol ne constitue qu'une faible proportion de la matière organique totale du sol mais elle est plus active. Les mesures de cette biomasse microbienne peuvent donc servir d'indicateur des effets des techniques de conduite du sol sur les changements éventuels affectant la matière organique du sol avant que ces effets ne puissent être détectés dans la matière organique totale. Nous avons étudié de 1995 à 1997, dans le nord de l'Alberta, les effets du régime de travail du sol et de la rotation des cultures sur la biomasse microbienne du sol et sur son activité dans la sole du blé de diverses rotations qui avaient été mises en place en 1992, en régime de semis direct et de travail classique du sol. La biomasse microbienne du sol (bms) était souvent significativement ($P < 0,05$) plus importante en régime de culture sans labour qu'en régime de travail classique. Elle n'était toutefois jamais significativement moins importante. En revanche l'évolution du CO_2 (la respiration basale) était habituellement plus forte sous travail classique de sorte que le quotient métabolique (qCO_2) était également plus élevé. Les apports plus abondants de C labile combinés à de moindre déperditions observées en régime de semis direct se traduisent par le fait que davantage de C était séquestré dans le sol. Ce régime produit donc moins d'émissions de CO_2 dans l'atmosphère que le régime de travail classique en même temps qu'il favorise davantage l'accumulation de la matière organique dans le sol. C'est lorsque le blé était précédé d'une sole de jachère, en particulier sous régime de travail classique, que la biomasse microbienne et, par conséquent, l'émission de CO_2 étaient les plus basses, alors qu'après une sole de légumineuse, on observait une biomasse microbienne plus importante et un qCO_2 plus bas qu'après les autres précédents culturaux. Le régime de travail et la rotation n'avaient plus guère d'effet sur la matière organique totale du sol 5 ans après les traitements, probablement en raison du climat froid de cette région, mais les résultats obtenus viennent confirmer que les formes labiles du C du sol sont de plus sensibles indicateurs de l'évolution du C organique dans le sol que ne l'est le C organique total du sol. Nos observations sur les effets du régime de travail du sol et de la rotation sur la bms du sol sont semblables à celles que nous avons faites précédemment sur la diversité microbienne. Ces observations confirment que le régime de semis direct et l'inclusion d'une légumineuse dans la rotation favorisent davantage la pérennité des cultures que ne le font le travail classique du sol et l'usage de la jachère dans cette zone de luvisols gris du nord de l'Alberta.

Mots clés: Séquestration du carbone, minéralisation du carbone, activité microbienne, matière organique du sol

Maintaining or increasing soil organic matter is justified both from an agronomic and an environmental perspective because it affects the capacity of the soil to sustain crop growth (Campbell 1978) and it is also a source and possible sink of atmospheric CO_2-C (Paustian et al., 1997). Although soil microbial biomass comprises a small proportion of total soil organic matter, it is very dynamic and fluctuates more over time than total soil organic matter. Therefore, measurements of soil microbial biomass (and other labile forms of organic matter) may show the effects of soil management on potential changes in soil organic matter long before such effects can be detected by measuring total soil organic matter (Powlson and Jenkinson 1987). In addition, since microbial biomass is readily decomposable, it is an important source of plant nutrients.

The basal respiration (CO_2 evolution) of a soil reflects the overall activity or energy spent by the indigenous soil microbial pool (Anderson and Domsch 1990). If respiration is related to the corresponding size of the microbial biomass, we obtain a microbial metabolic quotient for CO_2 (qCO_2), or specific respiration rate of the biomass, which represents the CO_2-C produced per unit of biomass over time. This quotient, like microbial biomass, also responds readily to changes in soil management and can provide an effective early warning of deterioration of soil quality. Disturbances (or any other stress) apparently cause an elevation of qCO_2 as the microorganisms become less efficient at conserving C (Anderson and Domsch 1993).

Concerns about the environmental impact of intensive agriculture, particularly loss of soil organic matter and contamination of ground water by agro-chemicals, are shifting focus away from conventional (high-input) agricultural systems to more ecologically sustainable systems. The management of these systems includes the use of reduced tillage, inputs of organic materials and nutrient cycling strategies based on crop rotations (Pankhurst et al. 1996). The effects of these management practices on soil microbial dynamics have been reviewed (Doran and Linn 1994; Elliott and Stott 1997). In northern Alberta, Lupwayi et al. (1998) found that zero tillage and legume-based crop rotations enhanced soil microbial diversity. In this work, we report on how microbial biomass, CO_2 evolution, qCO_2 and total soil organic matter were affected by tillage and crop rotation in the plots used in the previous study.

MATERIALS AND METHODS

The study was conducted at Fort Vermilion (58°23′N, 116°02′W) on a Gray Luvisol in an existing crop management field trial, which was an agronomic evaluation of tillage systems and legume-based crop rotations. The trial was established in 1992 as a split plot factorial experiment in a randomized complete block design with three replicates. The main plots were tillage (conventional tillage and zero tillage) and the sub-plots were crop rotation. Soil samples were collected from wheat (*Triticum aestivum* L.) plots that had been preceded by **field peas** (**FP**) (*Pisum sativum* L.), **red clover** (**RC**) (*Trifolium pratense* L.) green manure, **summerfallow** (**SF**) or **continuous wheat** (**CW**). Conventional tillage included both fall and spring operations. Fall (September) tillage involved heavy-duty cultivator or disk operation to a depth of 10 to 15 cm and spring (May) tillage consisted of two operations with a field cultivator followed by harrowing/packing to incorporate crop residues. In zero-tillage fallow, weeds were controlled using herbicides and in the conventional tillage fallow, weed control was entirely mechanical, requiring three to four tillage operations with a field cultivator throughout the growing season. Further details of the site, treatments and field operations are described elsewhere (Lupwayi et al. 1998).

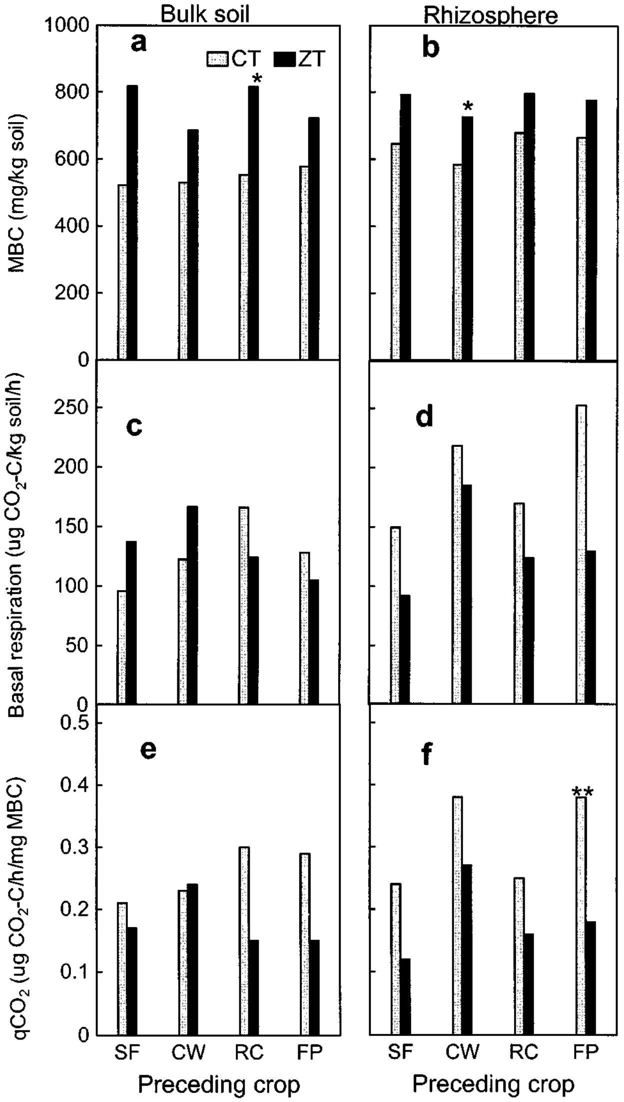

Fig. 1. Effects of tillage and preceding crops in rotation on microbial biomass C (MBC) (a and b), CO_2 evolution (c and d), and metabolic quotient (qCO_2) (e and f) in the bulk soil (a, c and e) and rhizosphere (b, d and f) at flag-leaf stage of wheat growth in 1995. Each bar is a mean of three replicates. CT = conventional tillage, ZT = zero tillage, SF = summer fallow, CW = continuous wheat, RC = red clover, FP = field peas, * = significant tillage effect, within each rotation, at 5% level of significance, ** = significant at 1% level of significance. See Table 1 for other statistics.

Table 1. Summary of effects of tillage and crop rotation on MBC, CO_2 evolution, metabolic quotient (qCO_2), total SOC and MBC/SOC percentage in 1995, 1996 and 1997

			F value					
			Bulk soil			Rhizosphere		
Year	Wheat growth stage or time of year	Measured parameter	Tillage	Rotation	Interaction	Tillage	Rotation	Interaction
1995	Flag-leaf stage	MBC	22.55^{*z}	0.59NS	0.77NS	4.83NS	0.79NS	0.05NS
		CO_2 evolution	0.07NS	0.88NS	1.61NS	67.07*	1.47NS	0.41NS
		qCO_2	3.07NS	0.14NS	0.60NS	1025.59**	1.48NS	0.23NS
1996	Flag-leaf stage	MBC	1.06NS	2.73NS	0.44NS	1.12NS	1.37NS	2.25NS
		CO_2 evolution	25.54*	1.59NS	2.74NS	1.47NS	0.98NS	1.00NS
		qCO_2	2.70NS	2.21NS	3.84*	38.71*	0.87NS	1.63NS
1997	May	MBC	7.89NS	12.03**	2.60NS			
		CO_2 evolution	11.64NS	1.26NS	1.79NS			
		qCO_2	14.94NS	0.70NS	3.20NS			
		SOC	0.42NS	0.63NS	0.20NS			
		MBC/SOC	9.58NS	5.87*	2.29NS			
	June	MBC	19.15*	9.08**	1.25NS			
		CO_2 evolution	0.84NS	4.03*	3.77*			
		qCO_2	7.35NS	10.65**	2.82NS			
	July	MBC	47.08*	4.08*	1.90NS			
		CO_2 evolution	12.88NS	0.88NS	2.16NS			
		qCO_2	207.39**	1.09NS	1.84NS			
		SOC	0.25NS	2.04NS	2.33NS			
		MBC/SOC	320.79**	3.53*	2.30NS			
	August	MBC	0.02NS	7.41**	3.31NS			
		CO_2 evolution	21.35*	0.66NS	0.97NS			
		qCO_2	0.79NS	2.21NS	1.18NS			
	September	MBC	0.09NS	4.45*	1.31NS			
		CO_2 evolution	11.01NS	2.23NS	0.58NS			
		qCO_2	18.88*	1.36NS	0.63NS			
		SOC	0.24NS	0.88NS	1.97NS			
		MBC/SOC	0.62NS	8.30**	4.16*			

*,**Significant at 5% level and 1% level of significance, respectively; NS not significant at the 5% level.

In 1995 and 1996, surface (0–7.5 cm) soil samples were collected at the flag-leaf stage of wheat growth. Plants were excavated from ten random 0.5-m lengths of row from each plot. Loose soil was shaken off the roots, and the soil that adhered strongly to the roots was carefully brushed and kept as rhizosphere soil. Non-rhizosphere (bulk) soil was sampled from the middle of two adjacent wheat rows at each of the 10 locations per plot. The 10 bulk or rhizosphere samples from each plot were bulked, sieved through a 2-mm sieve and stored at 4°C until required for analysis.

Microbial biomass C (**MBC**) was determined using the fumigation-incubation method (Horwath and Paul 1994). Two subsamples (40 g dry weight) were collected from each soil sample. The subsamples were placed in separate beakers, wetted to field capacity and conditioned for 3 d at room temperature. One subsample was then fumigated with chloroform in a steel vacuum chamber for 24 h and the other subsample (control) was left unfumigated. The samples were then placed in separate 1-L incubation jars, in which vials containing sodium hydroxide (1.0 M NaOH) were also placed, and the jars were sealed with lids. The samples were incubated at 22°C for 10 d (day 0 to day 10), after which the NaOH in the unfumigated controls was removed, replaced with fresh NaOH, and incubated for 10 more days (day 10 to day 20). After the first 10 d of incubation (day 0 to day 10), the NaOH in fumigated subsamples was removed from the jars and titrated with hydrochloric acid (0.2 M HCl) to estimate the amount of CO_2 respired by the microbial biomass. The NaOH in unfumigated controls was titrated after the additional 10-d incubation. Microbial biomass C was calculated using the following equation (Horwath et al. 1997):

$$MBC = 1.73F_C - 0.56UF_C$$

where MBC = microbial biomass C, F_C = CO_2-C evolved from the fumigated subsample (day 0 to day 10 incubation), and UF_C = CO_2-C evolved from the unfumigated control subsamples (day 10 to day 20 incubation). The rate of CO_2 evolution in the unfumigated control samples in the second 10-day incubation period (day 10 to day 20) was attributed to basal respiration. Microbial metabolic quotient (qCO_2) was calculated by dividing basal respiration by MBC.

The titrimetric procedure for measuring the amount of CO_2 evolved was used for 1995 samples. In 1996, the amount of CO_2 accumulated in the head space of each incubation jar was measured by gas chromatography (Zibilske 1994), but the calculations were the same (Horwath et al. 1997).

In 1997, CO_2 evolution was measured in situ by inserting inverted 1-L incubation jars, with their bases removed, 4 cm

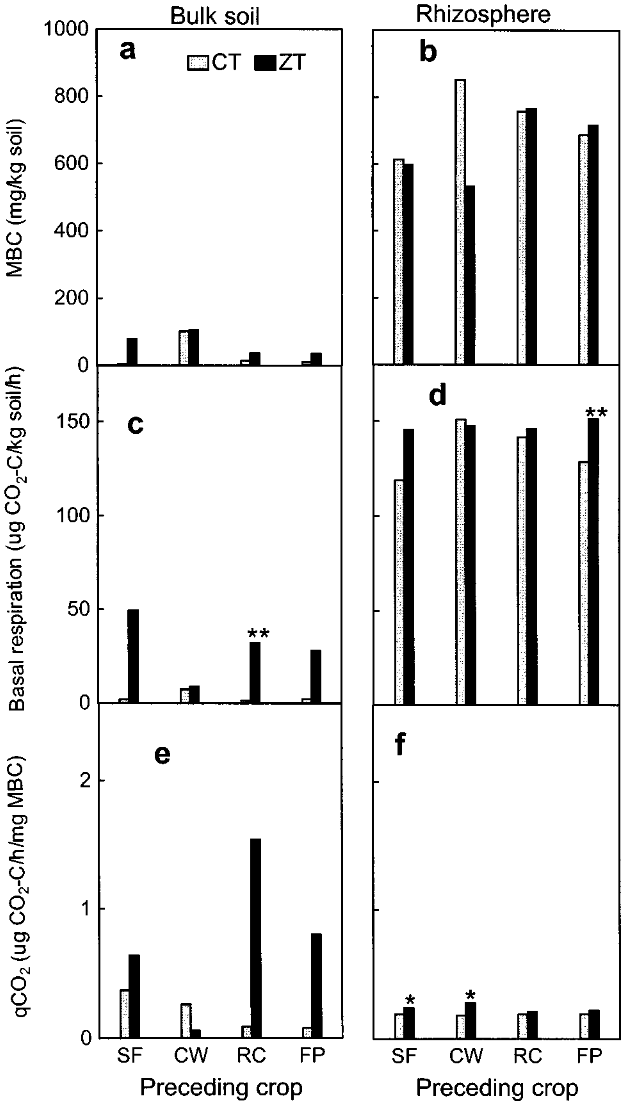

Fig. 2. Effects of tillage and preceding crops in rotation on microbial biomass C (MBC) (a and b), CO_2 evolution (c and d), and metabolic quotient (qCO_2) (e and f) in the bulk soil (a, c and e) and rhizosphere (b, d and f) at flag-leaf stage of wheat growth in 1996. Each bar is a mean of three replicates. CT = conventional tillage, ZT = zero tillage, SF = summer fallow, CW = continuous wheat, RC = red clover, FP = field peas, * = significant tillage effect, within each rotation, at 5% level of significance, ** = significant at 1% level of significance. See Table 1 for other statistics.

into the soil in the middle of two adjacent rows of wheat. After 1 h of gas accumulation (longer periods had been found to be unsuitable), the gas was sampled with a syringe through a rubber septum on the lid of each jar and injected into disposable vacutainers. The vacutainers were transported to the laboratory where CO_2 was analysed by gas chromatography. The soil on the spots where the jars had been positioned was sampled (to 7.5 cm depth) for MBC and **total soil organic C** (**SOC**) determinations. Microbial biomass C was measured using the **substrate-induced respiration** (**SIR**) method (Horwath and Paul 1994), in which 300 mg of glucose was dissolved in 4.5 mL of water and added to 50 g dry soil (to bring it to 50% of its water-holding capacity). The soil was incubated in 1-L jars for 3 h at 22°C, and the amount of CO_2 that accumulated in the head space was measured by gas chromatography. MBC was calculated as (Horwath and Paul 1994):

$$MBC = 40.04y + 0.37$$

where MBC is microbial biomass C and y is the rate of CO_2 evolution. Total soil organic C was measured using the wet oxidation (potassium dichromate) method. CO_2 evolution and MBC were measured monthly from wheat planting (May) to harvest (September), but SOC was measured only in May, July and September. In situ CO_2 evolution was calculated on a land area (m^2) basis. For calculation of qCO_2, CO_2 evolved per unit area was converted to soil mass basis by estimating the mass of soil in 1 m^2 to 4 cm depth, assuming a bulk density of 1.33 g cm^{-3}. The 4 cm was the soil depth to which the sampling jars for measuring CO_2 evolution had been inserted.

Treatment effects were evaluated by analysis of variance according to the split-plot design of the experiment, and means were separated by the least significant difference (LSD) method at 5% level of significance.

RESULTS

In 1995, MBC was significantly ($P < 0.05$) higher under zero tillage than under conventional tillage in the bulk soil, particularly in plots preceded by red clover (Fig. 1a and Table 1), but neither basal respiration (Fig. 1c) nor qCO_2 (Fig. 1e) was affected significantly by tillage. Crop rotation had no significant effect on any of these parameters, and interactions between tillage and rotation were not significant (Figs. 1a, c and e and Table 1). In the rhizosphere, although MBC under zero tillage was significantly higher than that under conventional tillage in the **continuous wheat** (**CW**) treatment (Fig. 1b), the overall tillage effect was not statistically significant (Table 1). However, basal respiration (Fig. 1d) and qCO_2 (Fig. 1f) were both significantly higher under conventional tillage than under zero tillage (Table 1). Differences in MBC, basal respiration, or qCO_2 were not affected by crop rotation, and significant interactions between tillage and crop rotation were not present (Table 1).

In 1996, MBC in the bulk soil was low compared with 1995. In the bulk soil, there were no significant differences between tillage treatments in MBC (Fig. 2a) or qCO_2 (Fig. 2e) even though basal respiration (Fig. 2c) was significantly higher under zero tillage than under conventional tillage (Table 1). Although rotation had no significant effects on any of the measured parameters, there was a significant interaction between tillage and rotation in qCO_2 in bulk soil (Fig. 2e and Table 1), mainly because tillage in the continuous wheat rotation had an opposite effect compared with the other three rotations. In the rhizosphere, tillage, crop rotation, or interactions between them had no significant effects on MBC (Fig. 2b) or basal respiration (Fig. 2d). However, qCO_2 was significantly higher under zero tillage than under conventional tillage, especially in continuous wheat plots or those following summer fallow (Fig. 2f and Table 1).

Table 2. Main effects of tillage, rotation and time of year on MBC, in situ CO_2 evolution and SOC in 1997

Treatment	MBC (mg kg^{-1} soil)	CO_2 evolved (g CO_2-C m^{-2} d^{-1})	qCO_2 (µg CO_2-C h^{-1} mg^{-1} MBC)	SOC (g kg^{-1} soil)	MBC/SOC (%)
Tillage					
CT[z]	382.30*a*[y]	1.70*a*	3.92*a*	20.68*a*	2.00*a*
ZT	516.36*a*	1.27*b*	2.13*a*	21.83*a*	2.52*a*
SEM	37.72	0.05	0.35	1.44	0.12
Preceding crop					
SF	322.68*c*	1.21*b*	3.45*a*	19.53*a*	1.84*c*
CW	432.25*b*	1.73*a*	3.40*ab*	22.06*a*	2.20*b*
RC	593.99*a*	1.55*a*	2.47*c*	21.94*a*	2.75*a*
FP	448.40*b*	1.46*ab*	2.80*bc*	21.49*a*	2.25*b*
SEM	31.52	0.11	0.20	1.12	0.10
Month					
May	535.06*a*	0.42*c*	0.66*d*	20.31*b*	2.64*a*
June	487.20*a*	1.53*b*	2.87*c*	ND	ND
July	491.95*a*	3.45*a*	6.41*a*	22.96*a*	2.14*b*
August	322.40*c*	1.63*b*	4.40*b*	ND	ND
September	410.05*b*	0.41*c*	0.79*d*	20.49*b*	2.00*b*
SEM	18.59	0.12	0.28	0.31	0.09

[z] Abbreviations: CT = conventional tillage, ZT = zero tillage, SF = summer fallow, CW = continuous wheat, RC = red clover, FP = field peas, SEM = standard error of the mean, ND = not determined.

a–d Means followed by the same letter within each factor (tillage, preceding crop or month) are not significantly different at 5% level of significance.

In 1997, all measurements were done using the bulk soil only. Analysis of the data for the whole season showed no significant difference in MBC between zero tillage and conventional tillage (Table 2). Monthly analysis of the data showed that MBC was significantly higher under zero tillage than under conventional tillage in June and July (Fig. 3a and Table 1). Preceding crops in rotation had a significant effect on MBC; the plots preceded by red clover had higher MBC than those preceded by field peas or wheat, which in turn had higher MBC than those preceded by summer fallow (Table 2). Figure 3a shows that zero-till plots preceded by red clover green manure had almost invariably the highest, and conventionally-tilled plots preceded by summer fallow had the lowest MBC throughout the season. Figure 3a also shows that while MBC under conventional tillage (open symbols) was almost constant throughout the season, MBC under zero tillage (closed symbols) was constant up to July, then decreased by about 50% in August and September.

Evolution of CO_2 was significantly lower under zero tillage than under conventional tillage (Table 2), and although Table 1 shows that this difference was significant only in August, this was due to high CO_2 evolution in continuous wheat under zero tillage from July to September (Fig. 3b). CO_2 evolution was significantly lower in the rotation that included summer fallow than in other rotations (Table 2), and Table 1 shows that the rotation effect was significant only in June (Fig. 3b). The rate of CO_2 evolution was increasing in the first half of the season (May to July) and decreasing in the second half (July to September).

Averaged over the growing season, qCO_2 was not affected significantly by tillage (Table 2). Within the season, qCO_2 was significantly lower under zero tillage compared with conventional tillage in July and September (Fig. 3c and Table 1). With regard to rotation effects, plots preceded by legumes had significantly lower qCO_2 than those preceded by fallow or wheat (Table 2).

Neither tillage nor crop rotation had significant effects on SOC overall (Table 2) or at any time within the season (Fig. 4a and Table 1). However, the lowest value was observed in the rotation including summer fallow (Table 2). Overall, tillage had no significant effect on the ratio of MBC to SOC (MBC/SOC) (Table 2) even though, within the season, MBC/SOC was significantly higher under zero tillage than under conventional tillage in July (Fig. 4b and Table 1). Plots that followed summer fallow had the lowest MBC/SOC and those that followed red clover had the highest, (Table 2), and Fig. 4b shows that this was true almost throughout the season. The ratio of MBC to SOC under zero tillage tended to decline as the season progressed, probably due to the seasonal decline in MBC under zero tillage as indicated in Fig. 3a.

DISCUSSION

Soil microbial biomass was often significantly higher, but never significantly lower, under zero tillage than under conventional tillage. Several workers have also reported higher MBC under zero (or reduced) tillage than under conventional tillage, both in Canada (Franzluebbers and Arshad 1996, 1997; Grant 1997) and elsewhere (Gupta et al. 1994; Meyer et al. 1997; Salinas-Garcia et al. 1997). In the same plots in 1995 and 1996, bacterial diversity was also found to be higher under zero tillage than under conventional tillage (Lupwayi et al. 1998). The high MBC under zero tillage means that more labile C is accumulating in this soil management system than in the conventionally tilled system. With regard to C loss through mineralization, CO_2 evolution (basal respiration) was usually higher under conventional tillage than under zero tillage, resulting in specific respira-

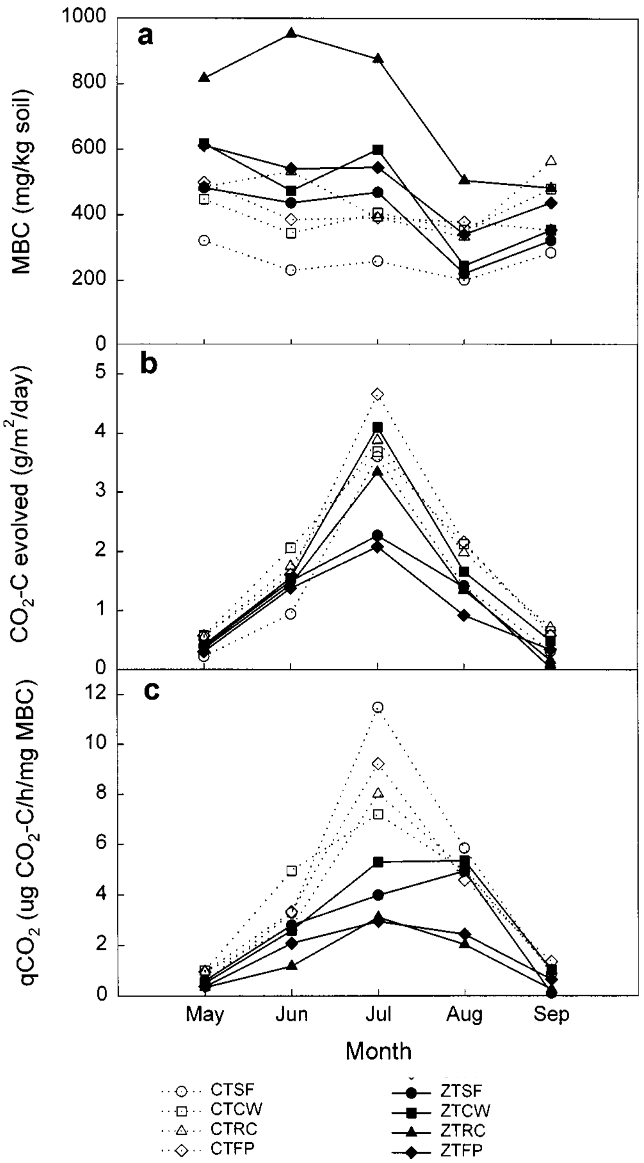

Fig. 3. Effects of tillage and preceding crops in rotation on seasonal variations of microbial biomass C (MBC) (a), in situ CO_2 evolution (b), and metabolic quotient (qCO_2) (c) in the bulk soil in 1997. Each point is a mean of three replicates. CT = conventional tillage, ZT = zero tillage, SF = summer fallow, CW = continuous wheat, RC = red clover, FP = field peas. See Tables 1 and 2 for other statistics.

tion (qCO_2) being higher under conventional tillage than under zero tillage. Low CO_2 fluxes from the soil with reduced tillage were also found by Reicosky and Lindstrom (1993), Lee et al. (1996) and Dao (1998), but opposite results have also been reported (Constantini et al. 1996). As evidenced by differences in qCO_2, soil disturbance by tillage is probably a major factor in the tillage effects. These disturbances may result in reductions in the population and diversity of soil organisms due to desiccation, mechanical destruction, soil compaction, reduced pore volume and disruption of access to food resources (Giller 1996). Tillage also accelerates C mineralization by increasing soil aeration and the contact between soil and residues (Reicosky et al. 1995).

The high additions but low losses of labile C under zero tillage also mean that more C is sequestered in the soil in the zero-tillage system; thus, this system contributes less to atmospheric CO_2 than conventional tillage. It also suggests that soil organic matter accumulates more under zero tillage. Similar trends were observed in other parts of Canada (Campbell et al. 1996; Grant 1997) and elsewhere (Constantini et al. 1996; Salinas-Garcia et al. 1997) although they are not always statistically significant (Alvarez et al. 1995). Besides increasing C mineralization as discussed above, tillage accelerates erosion of soil C by increasing soil exposure to wind and rain (Reicosky et al. 1995).

Plots preceded by summer fallow, especially under conventional tillage, usually had the lowest MBC and/or CO_2 evolution, and plots preceded by legume crops had higher MBC and/or lower qCO_2 than other treatments. Similar results have been reported by Zelles et al. (1992) and Biederbeck et al. (1994). Crop rotation effects on bacterial diversity in the same plots were similar to the effects on MBC (Lupwayi et al. 1998). The low microbial biomass and activity in conventionally tilled plots preceded by summer fallow may be due to a combination of the adverse impact of tillage, because these plots had extra tillage passes in summer to control weeds, and the low plant biomass during the preceding fallow phase of the rotation.

Tillage and crop rotation resulted in significant differences in MBC, CO_2 evolution, qCO_2 and MBC/SOC, but these factors had little effect on SOC 5 yr after the treatments had been imposed, even though similar (but less pronounced) trends in SOC were detected. Flanzluebbers and Arshad (1996, 1997) have suggested that the rate of conversion of labile C to SOC may be slower in the cold climate of northern Alberta than in warmer climates. However, the results confirm that these labile forms of soil C are more sensitive indicators of SOC trends than total SOC.

The reasons for MBC being much lower in 1995 than in 1996, and for the big differences in MBC between bulk soil and rhizosphere in 1996 but not in 1995, are unknown. The 1995 growing season was drier than the 1996 season, and soil moisture may have affected movement of microbes through the soil. Tillage effects on the diversity of bacteria in these plots was more pronounced in 1996 than in 1995 (Lupwayi et al. 1998).

These results complement the microbial diversity results on the same soils, which showed greater bacterial diversity under zero tillage than under conventional tillage and, to a lesser degree, greater diversity in legume-based rotations than those without legumes (Lupwayi et al. 1998). The sequestration of soil organic matter clearly indicates that zero tillage and legume-based crop rotations are more sustainable crop management systems for the Gray Luvisolic soils of northern Alberta than conventional tillage and fallowing. The agronomic benefits of increased soil organic matter are likely to make zero tillage and crop rotation appealing to producers. The environmental effect of reduced

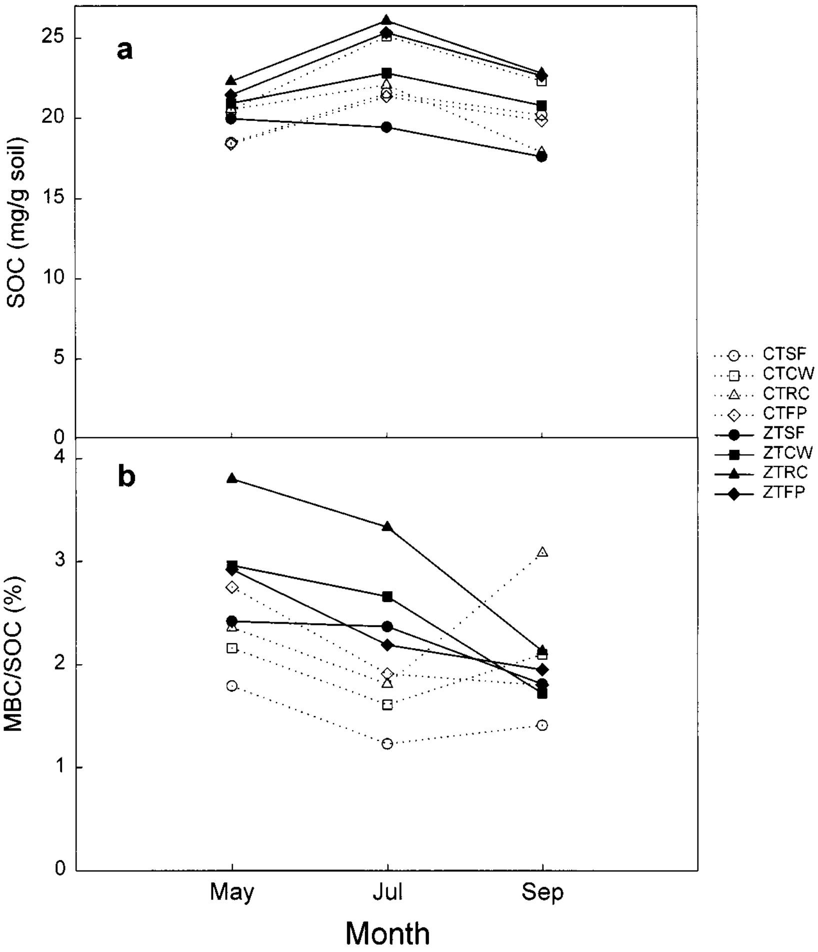

Fig. 4. Effects of tillage and preceding crops in rotation on seasonal variations of total soil organic C (SOC) (a) and the percentage of MBC to SOC (MBC/SOC) (b) in the bulk soil in 1997. Each point is a mean of three replicates. CT = conventional tillage, ZT = zero tillage, SF = summer fallow, CW = continuous wheat, RC = red clover, FP = field peas. See Tables 1 and 2 for other statistics.

CO_2 evolution under zero tillage may be of secondary importance to producers, but it is an important bonus.

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