Effect of Tillage and Crop Rotations on the Light Fraction Organic Carbon and Carbon Mineralization in Chernozemic Soils of Saskatchewan

Liang[1], B.C., B.G. McConkey[1], C.A. Campbell[2], D. Curtin[3], J. Schoenau[4], G.P. Lafond[5], S.A. Brandt[6], and A. Moulin[7]

[1]Semiarid Prairie Agricultural Research Centre, Agriculture and Agri-Food Canada, P.O. Box 1030, Swift Current, SK, S9H 3X2, [2]Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, Central Experimental Farm, Ottawa, ON, K1A 0C6, [3]Crop & Food Research, Christchurch, New Zealand, [4]Department of Soil Science, University of Saskatchewan, Saskatoon, SK, S7N 0W0, [5]Indian Head Experimental Farm, Box 760, Indian Head, SK, S0G 2K0, [6]Experimental Farm, Research Branch, Scott, SK, S0K 4A0, and [7]Brandon Research Centre, Agriculture and Agri-Food Canada, Brandon, MB, R7A 5Y3

Abstract

Light fraction of soil organic matter represents a major portion of labile soil organic matter, and is a key attribute of soil quality. Six field experiments varying from 8 to 25 years across various soil zones in Saskatchewan were conducted to evaluate the impact of tillage and crop rotations on the light fraction organic C (LFOC), the proportion of LFOC in the soil organic C (SOC) and soil respiration. Any fallow cropping system whether occurring once in two, three or four years resulted in significant reduction in LFOC in comparison with continuous cropping systems in all three soil zones. Continuous cropping also resulted in an increase of the proportion of LFOC/SOC, and soil biological activity as measured by soil respiration. On the other hand, tillage showed little impact on the LFOC in the Brown and Dark Brown soil zones, but had an impact in the Black soil zone. Because no-till had shown a consistent increase in SOC in all these soils, it is concluded that LFOC is not a sensitive indicator of soil quality for these Chernozemic soils in Saskatchewan. It is also found in this study that the proportion of LFOC/SOC is a linear function of sand content. This relationship may be important for partitioning SOC pools with different turnover times while modeling SOC dynamics.

Introduction

The light fraction of soil organic matter consists of a heterogeneity mixture of recent plant residues, small animals and microorganisms, which may be present in various stages of decomposition. This pool of soil organic matter is usually about several times greater than that of soil microbial biomass in agricultural soils (Liang et al., 1998), and of importance for the turnover of organic matter in agricultural soils because it serves as a readily mineralizable substrate for soil microorganisms (Gregorich et al., 1994).

In a long-term study, Bremer et al. (1995) reported that light fraction C concentrations were 38% lower in the fallow-wheat and fallow-wheat-wheat treatments than in the continuous wheat. Reduced light fraction C accounted for about one-third of the decrease in SOC as a result of inclusion of fallow in the crop rotation. They concluded that light fraction organic matter is the most robust indicator of management-induced effects on SOC. Similarly, Biederbeck et al. (1994) reported that frequency of fallow in the crop rotation was the dominant factor influencing labile organic matter such as LFOC. In eastern Canada, Gregorich et al. (1997) also reported that fertilized corn soils for 32 yr had more than twice as much LFOC as their non-fertilized counterparts.

While conservation tillage compared with conventional tillage sequestered soil C in Canadian prairie soils (Liang et al., 1999), it is not clear that how tillage would affect LFOC and soil respiration or C_{min}. Larney et al. (1997) reported that after 16 years of a spring wheat-fallow rotation NT compared with CT significantly increased SOC by 8%, and increased LFOC by 15%. But, the increase in LFOC under NT was not statistically significant, indicating a greater variability of LFOC. It is expected that soil texture plays a key role in controlling both quantity and quality of SOC, but quantitative relationships have been rarely established, excepting that Liang et al. (1998) reported that ratios of LFOC/SOC were greater in light-textured soils than those in fine-textured soils.

The objectives of this study were 1) to evaluate crop rotations and tillage impact on the LFOC and soil respiration, and 2) to evaluate if soil texture influences the ratio of LFOC/SOC in six Saskatchewan soils.

Materials and Methods

Experimental design, cropping systems and tillage practices were similar for the Swinton silt loam, Sceptre clay and Hatton fine sandy loam. Treatments that are relevant to this study are briefly described. Tillage systems for these studies consisted of minimum tillage (MT) and no-tillage (NT). Cropping systems included a continuous spring wheat (Cont W), and fallow-wheat rotations (F-W). Under F-W rotations, wheat or fallow was present each year. Pre-seeding tillage with one operation of heavy-duty sweep cultivator with attached rodweeder, or mounted harrow, was used for MT. Planting was performed with an offset disc press drill (Dyck and Tessier, 1986) for NT and a conventional hoe drill for MT. Plots received approximately 10 kg P ha^{-1} as monoammonium phosphate, seed-placed. Nitrogen fertilizer as ammonium nitrate was broadcasted before seed-bed preparation at a rate based on soil tests (Saskatchewan Agriculture, 1988). Until 1990, N fertilizer as ammonium nitrate was broadcasted before seed-bed preparation at a rate based on soil tests (Saskatchewan Agriculture, 1988). After 1990, N up to 45 kg N ha^{-1} was applied with the seed and the remaining, if any, was broadcast. Fall applications of 2,4-D ester were used to control winter annual broadleaf weeds in all treatments. Other management practices were reported elsewhere (Campbell et al. 1995, Campbell et al. 1996 a, b).

On the Melfort silty clay loam, three tillage systems (CT, MT and NT) under a F-W rotation were used. The heavy-duty cultivator was used for tillage operations on summer-fallow; in some years a rodweeder replaced one or more of the cultivation operations for CT. The first summer-fallow tillage operation was performed usually in early June with subsequent operations performed on an as needed basis, usually at 2 to 3 week intervals. Treatments of NT for weed control generally received a first spraying in late May or early June with repeat applications as required usually in July and August. Tillage operation for MT was similar to that of CT, but the number of tillage operation was reduced to twice a year. Other management practices were reported (Zentner et al., 1990).

On the Indian Head clay, crop systems consisted of three, 4-yr rotations. One crop rotation included 1 yr of fallow in four (fallow-spring wheat-spring wheat-winter wheat (F-W-W-wW) while the other crop rotations were continuous cropping systems \pea-spring wheat-flax-winter wheat (P-S-X-wW) and spring wheat-spring wheat-flax-winter wheat (W-W-X-wW)](Lafond et al., 1992). Three tillage systems (CT, MT and NT) were used. The soil disturbance in NT occurred during the seeding operation. Minimum tillage included only one tillage operation in the spring using a chisel plow equipped with 41-cm sweeps. Conventional tillage included fall and spring tillage. In the NT system, weeds on fallow were controlled with herbicide applications. In the CT system, weed control was by mechanical means, with 2 to 4 cultivations and 0 to 3 rodweeder operations per year.

On the Elstow clay loam, two rotations including a continuously cropped rotation of wheat-wheat-canola-wheat-wheat-flax \W-W-(C)-W-W-X] and a rotation containing one fallow in three years, fallow-flax-wheat-fallow-canola-wheat (F-X-W-F-C-W), were used. The fallow-containing rotations included two phases \F-X-W-F-(C)-W] and \F-X-(W)-F-C-W]. Tillage systems included CT and NT. Herbicides were used exclusively for weed control in the NT system. This normally involved the use of phenoxy herbicides (2,4-D or MCPA) in late fall or early spring for control of broadleaf winter annual weeds. In the CT system, tillage with a cultivator equipped with spikes or sweeps was performed on stubble in late fall. Early spring tillage was carried out with a cultivator equipped with mounted harrows followed by cultivating or rod weeding just prior to seeding for all CT systems. The tillage fallow normally required three operations with a cultivator and mounted harrows, plus one or two operations with a cultivator or rod-weeder. Seeders were used including a double-disc press drill, an offset double disc press drill and a narrow hoe press drill. Management practices such as N and P fertilizers were reported (Brandt, 1992). Other information regarding soil types, duration of experiments, soil texture and crop rotations are reported (Table 1).

Soil samples were taken from the 0- to 7.5-cm depth for the Hatton fine sandy loam, Swinton silty loam, and Sceptre clay in the spring of 1994, for the Indian Head clay and Melfort silty clay loam in the fall of 1994, and for the Elstow clay loam in the fall of 1995. Four soil cores per plot were extracted and composited by depth. The resulting samples were air-dried and sieved through a 2-mm sieve. Crop residues remaining on the sieve were discarded. Representative sub-samples were ground with a rollermill (<153 µm) and analyzed for soil organic C using an automated combustion technique (Carlo Erba™, Milan, Italy). Analysis of soil organic C involved pretreating the soil with phosphorus acid in a tin capsule after weighing, then drying the sample for 16 h at 75°C prior to analysis for C.

The amount of mineralizable C (C_{min}) and light fraction organic C (LFOC) were determined on soil samples sieved through a 2-mm sieve. For C_{min} field-moist samples (50 g over-dry weight per sample) were wetted to field capacity, conditioned for 3 days at 21°C, and then incubated in biometer flasks at 21°C for 14 days. The evolved CO_2 was trapped in an alkali solution and measured by acid titration. For LFOC, 10 g of air-dry soil was suspended in 40 ml of NaI solution (specific gravity 1.7 g cm^{-3}) and dispersed for 30 seconds using a Virtis homogenizer (Virtis Co., Gardiner, New York). After a setting period of 48 h, the suspended material was transferred by suction to a filtration unit. The soil was re-suspended in NaI solution and the procedure was repeated to ensure complete recovery of light fraction materials. The composited light fraction materials were washed in $CaCl_2$ solution followed by distilled water, dried at 70°C and weighed. The light fraction materials were analyzed for C using the automated combustion technique.

For the Hatton fine sandy loam, Swinton silt loam and Sceptre clay, contrasts were used to separate treatment differences. For these sites two contrasts were selected to compare crop rotation effect including Cont W versus F-W, and F-(W) versus (F)-W. Only one contrast was selected to compare tillage effect, MT versus NT. For the Melfort silty clay loam and Elstow clay loam experimental data were statistically analyzed as one or two-factor factorial, randomized complete block design, while for the Indian Head clay a split-plot design with tillage in main plots and crop rotations in sub-plots was used. For mean separations, the least significant differences were used at *P=0.05* level.

Results and Discussion

Crop rotations played a key role in controlling the amount of LFOC in soils. In the Brown soil zone, Cont W had a higher amount of LFOC in the Hatton fine sandy loam, Swinton silt loam, and Sceptre clay soils, compared with either phase of F-W rotations (Table 2). This increased amount of LFOC with continuous cropping also resulted in a greater proportion of LFOC/SOC, and a greater amount of C_{min}. The phases of F-W rotations had no impact on the amount of LFOC, the proportion of LFOC/SOC, or C_{min} in these soils.

In the Dark Brown soil zone, W-W-(C)-W-W-X had a greater amount of LFOC in the Elstow clay loam, compared with either F-X-W-F-(C)-W or F-X-S-(W)-F-C-W (Table 3). This increased LFOC resulted in a greater proportion of LFOC/SOC and C_{min}. In the Black soil zone, W-W-X-wW also had a higher amount of LFOC in the Indian Head clay, compared with F-W-W-wW. However, crop rotations did not affect the proportion of LFOC/SOC or C_{min}. Any fallow-containing cropping systems whether occurring once in two, three or four years resulted in significant reduction in LFOC in comparison with continuous cropping systems in all three soil zones. On the other hand, the phases of F-W rotations had a relatively small impact on the quantity of LFOC, implying that the contribution of growing a crop in the sampling year to the amount of LFOC in the soil was minor.

Disproportional increases in the proportion of LFOC/SOC were a result of pronounced increase in LFOC relative to SOC with continuous cropping compared with fallow-containing rotations. Greater proportions of LFOC/SOC associated with continuous cropping over fallow-containing crop rotations for all three soil zones indicated that LFOC is a sensitive indicator of change in SOC. These results are consistent with the findings of Bremer et al. (1995) and Biederbeck (1994), who suggest that LFOC is an early indicator of change in SOC under different crop rotations.

The impact of tillage systems on the amount of LFOC was relatively less consistent than that of crop rotations. In the Brown soil zone, NT had no impact on the amount of LFOC or the ratio of LFOC/SOC in the Hatton fine sandy loam, Swinton silt loam and Sceptre clay, but had a higher amount of C_{min} at $P=0.10$ probability level for these soils compared with MT (Table 4). In the Dark Brown soil zone, NT did not affect the LFOC, the ratio of LFOC/SOC, or C_{min} in the Elstow clay loam (Table 5). In the Black soil zone, on the other hand, NT had a higher amount of LFOC and C_{min}, and a greater ratio of LFOC/SOC in the Melfort silty clay loam, and had a higher amount of LFOC in the Indian Head clay. Minimum tillage showed no impact on the LFOC, the ratio of LFOC/OC or C_{min} over CT in the Melfort silty clay loam, but was more effective in increasing LFOC in the Indian Head clay. It should be noted that tillage operations for MT on the Indian Head clay were less frequent than that on the Melfort silty clay loam because of the fallow every two years for the latter experiment.

It is clear that tillage generally had no impact on the amount of LFOC or the ratio of LFOC/SOC in the Brown and Dark Brown soil zones. Although NT had a higher amount of LFOC in the Melfort silty clay loam and Indian Head clay in the Black soil zone compared with CT, NT only had a higher ratio of LFOC/SOC in the Melfort silty clay loam. Therefore, it is generally concluded that neither LFOC nor C_{min} is a sensitive indicator of change in SOC in all three soil zones.

The amount of C_{min} was positively correlated with LFOC for all six soils, and r^2 varied from 0.26 to 0.88 ($P<0.01$)(Fig. 1). Correlations between C_{min} and LFOC were better for light- and heavy-textured soils than medium-textured soils. Linear correlations between C_{min} and LFOC have been also reported on medium- and fine-textured soils (Bremer et al., 1994; Janzen et al., 1992). All these suggest that LFOC directly associated with that portion of SOC affected in short term by soil microbial and enzyme activity.

Soil texture has been known to affect both quantity and quality of SOC. The relationship between the proportion of LFOC/SOC and the sand content of soil was examined. Although there was a very strong linear correlation between the proportion of LFOC/SOC and the sand content (Fig. 2, $r^2 = 0.90$, $P<0.01$), because of uneven distribution of sand contents, the influential test was carried out using SAS (Proc Reg, Option Influence) (SAS Institute, 1990). The test indicated that the observation of the proportion of LFOC/SOC associated with the Hatton fine sandy loam soil had an influential impact on the overall relationship. In other words, this relationship may not be true in nature. Additional data that were obtained under continuous corn in Ontario and Quebec, and published by Liang et al. (1998) were used for the regression analysis. Regression analysis using combined data confirmed that the proportion of LFOC/SOC is a simple linear function of sand content. No single observation had an influential impact on the overall relationship. The linear relationship between the proportion of LFOC/SOC and the sand content of soil has an implication on partitioning SOC into various pools with different turnover times for modeling SOC dynamics. At the present time, SOC pools with different turnover times such as active, slow and passive used in the Century model (Parton et al., 1987), only exist conceptually, and can not be determined experimentally. As a result, the sizes of these C pools are assigned arbitrarily, and more often subjectively. The size of LFOC is usually a few to more than 10 times greater than that of microbial biomass C (Liang et al., 1998). Thus, we propose to use the proportion of LFOC as the size of active SOC in which the actual size of this pool is a linear function of soil sand content.

Conclusions

Crop rotations and tillage affects both total and labile SOC. Based on the fact that crop rotations, continuous cropping compared with fallow-containing crop rotations consistently increased the proportion of LFOC/SOC, but tillage did not, it is concluded that LFOC is a more sensitive indicator of soil organic matter quantity associated with crop rotations but not tillage systems. Correlations between LFOC and C_{min} for all six soils suggest that LFOC is directly associated with that fraction of SOC acted on in short term by soil microbial or enzyme activity. Quantitative relationship between the proportion of LFOC/SOC and the sand content of soil has a significant implication for assessing soil organic matter quality, and for modeling soil organic matter dynamics.

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Table 1. Soil types, locations, duration of tillage experiments, soil texture, crop rotations, tillage and soil organic C in six mid- to long-term tillage experiments in Saskatchewan

Soil	Taxonomy	Location	Years after initiation	Soil texture		Crop rotation[1]	Tillage system[2]
				Sand	Clay		
			--- yr ---	------ % ------			
Hatton fine sandy loam	Orthic Brown Chernozem	50°24'N 108°00'W	11	70.8	15.3	Cont W, F-(W), (F)-W	MT, NT
Swinton silt loam	Orthic Brown Chernozem	50°16'N 107°44'W	12	32.6	27.6	Cont W, F-(W), (F)-W	MT, NT
Sceptre clay	Rego Brown Chernozem	50°36'N 107°48'W	11	25.7	42.7	Cont W, F-(W), (F)-W	MT, NT
Indian Head clay	Rego Black Chernozem	50°32'N 103°40'W	8	16.3	63.1	W-W-X-wW, P-S-X-wW, F-W-W-wW	CT, MT, NT
Melfort silty clay loam	Orthic Black Chernozem	52°51'N 104°37'W	25	16.0	44.0	F-(W)	CT, MT, NT
Elstow clay loam	Orthic Dark Brown Chernozem	52°22'N 108°50'W	16	29.0	31.0	W-W-(C)-W-W-X, F-X-W-F-(C)-W, F-X-(W)-F-C-W	CT, NT

[1] Letters in the parenthesis indicate the rotation phase sampled, W=spring wheat, F=fallow, X=flax, wW=winter wheat, P=pea, C=canola.
[2] CT=conventional tillage (full tillage after crop, preseeding tillage, tillage as required for weed control during fallow)
MT=minimum tillage preseeding tillage, herbicides and tillage used for weed control during fallow)
NT=no tillage (low disturbance direct seeding, all weed control with herbicides)

Table 2. Impact of crop rotations on the light fraction organic C (LFOC), proportion of LFOC/SOC, and soil respiration (C_{min}) in the Hatton fine sandy loam, Swinton silt loam and Sceptre clay.

Crop rotation	Hatton fine sandy loam			Swinton silt loam			Sceptre clay		
	LFOC	LFOC/SOC	C_{min}	LFOC	LFOC/SOC	C_{min}	LFOC	LFOC/SOC	C_{min}
	mg C g^{-1}	%	mg C kg^{-1}	mg C g^{-1}	%	mg C kg^{-1}	mg C g^{-1}	%	mg C kg^{-1}
F-(W)	0.81	9.0	55.7	0.85	5.6	109.6	0.79	5.3	132
(F)-W	0.84	9.1	49.7	0.74	5.0	91.5	0.76	5.2	121
Cont W	1.52	14.5	90.3	1.30	7.8	135.2	1.32	7.6	215
Contrast "F-(W) vs (F)-W"	NS	NS	NS	NS	NS	NS	NS	NS	>0.10
Contrast "Cont W vs F-W"	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.001

Table 3. Impact of crop rotations on the light fraction organic C (LFOC), proportion of LFOC/SOC, and soil respiration (C_{min}) in the Elstow clay loam and Indian Head clay.

Soil	Crop rotation	LFOC	LFOC/SOC	C_{min}
		mg C g^{-1}	%	mg C kg^{-1}
Elstow clay loam	W-W-(C)-W-W-X	3.6a	10.7a	269a
	F-X-W-F-(C)-W	2.2b	6.5b	199b
	F-X-(W)-F-C-W	1.9b	7.5b	138c
Indian Head clay	P-S-X-wW	1.9ab	8.2a	356a
	W-W-X-wW	2.1a	8.7a	364a
	F-W-W-wW	1.5b	6.9b	296a

Means followed by the same letters within the same column of the same soil are not significantly different at *P=0.05* probability level.

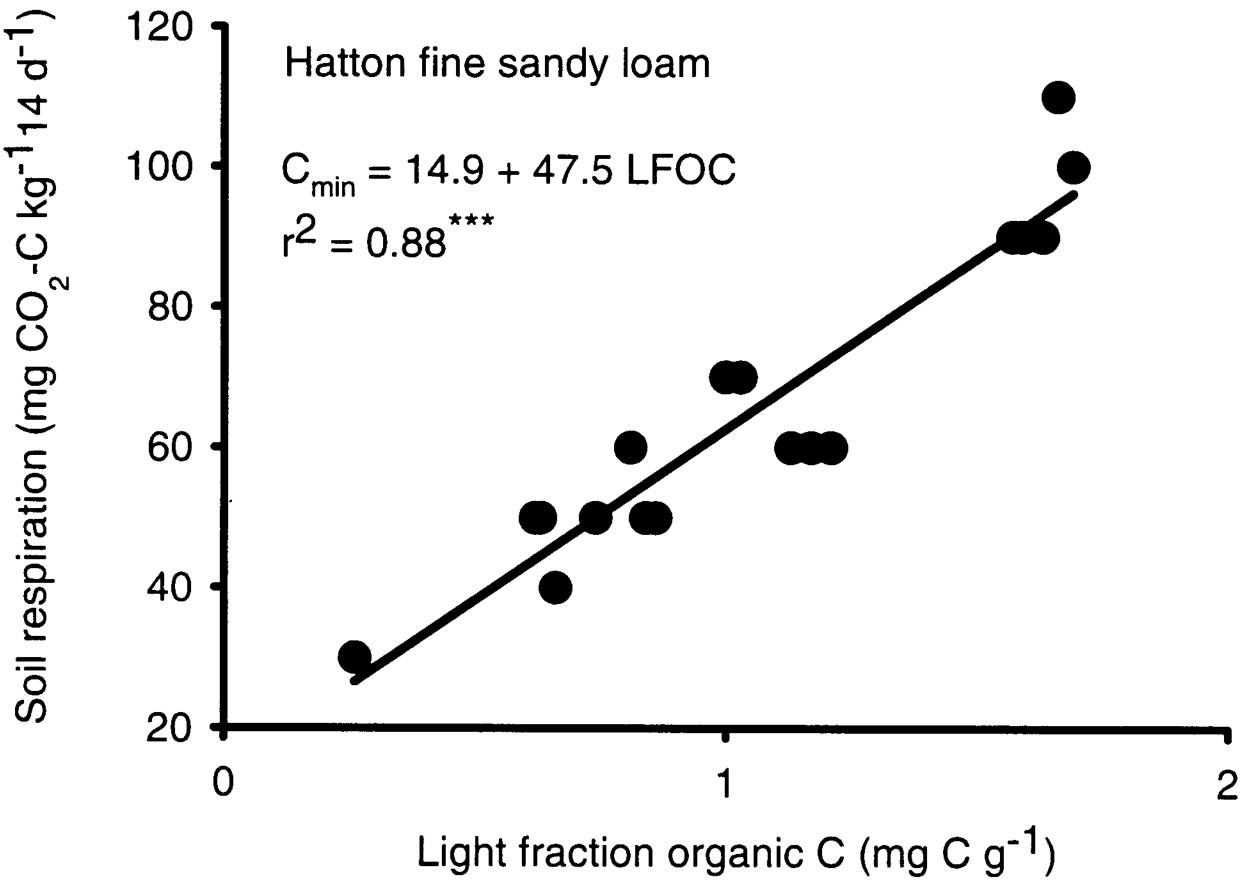
Table 4. Impact of tillage on the light fraction organic C (LFOC), proportion of LFOC/SOC, and soil respiration (C_{min}) in the Hatton fine sandy loam, Swinton silt loam and Sceptre clay.

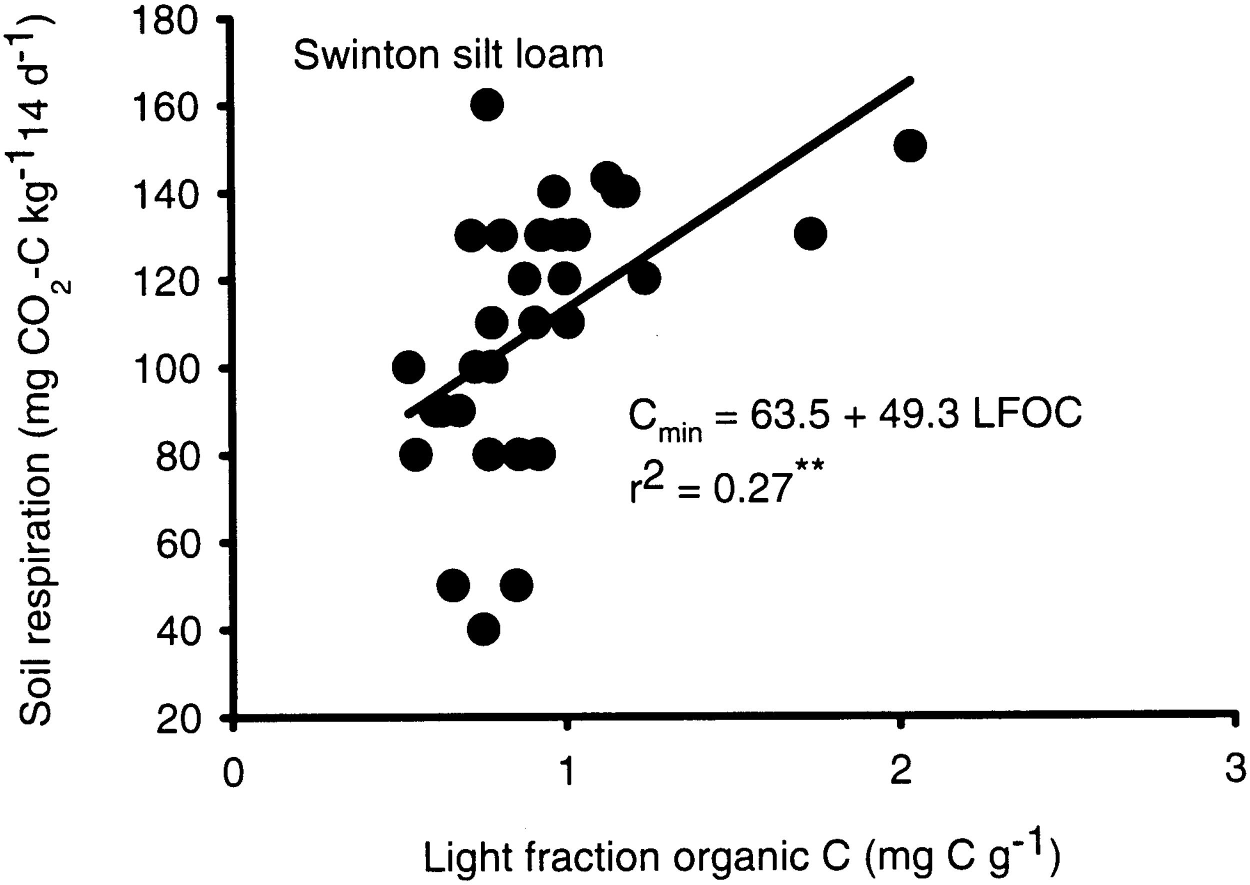
Tillage	Hatton fine sandy loam			Swinton silt loam			Sceptre clay		
	LFOC	LFOC/SOC	C_{min}	LFOC	LFOC/SOC	C_{min}	LFOC	LFOC/SOC	C_{min}
	mg C g^{-1}	%	mg C kg^{-1}	mg C g^{-1}	%	mg C kg^{-1}	mg C g^{-1}	%	mg C kg^{-1}
MT	1.4	14.6	83.1	0.9	6.0	122	0.9	6.0	146
NT	1.6	14.4	97.5	1.0	6.0	104	1.1	6.3	176
Contrast "MT vs NT"	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 5. Impact of tillage on the light fraction organic C (LFOC), proportion of LFOC/SOC, and soil respiration (C_{min}) in the Melfort silty clay loam, Elstow clay loam and Indian Head clay.

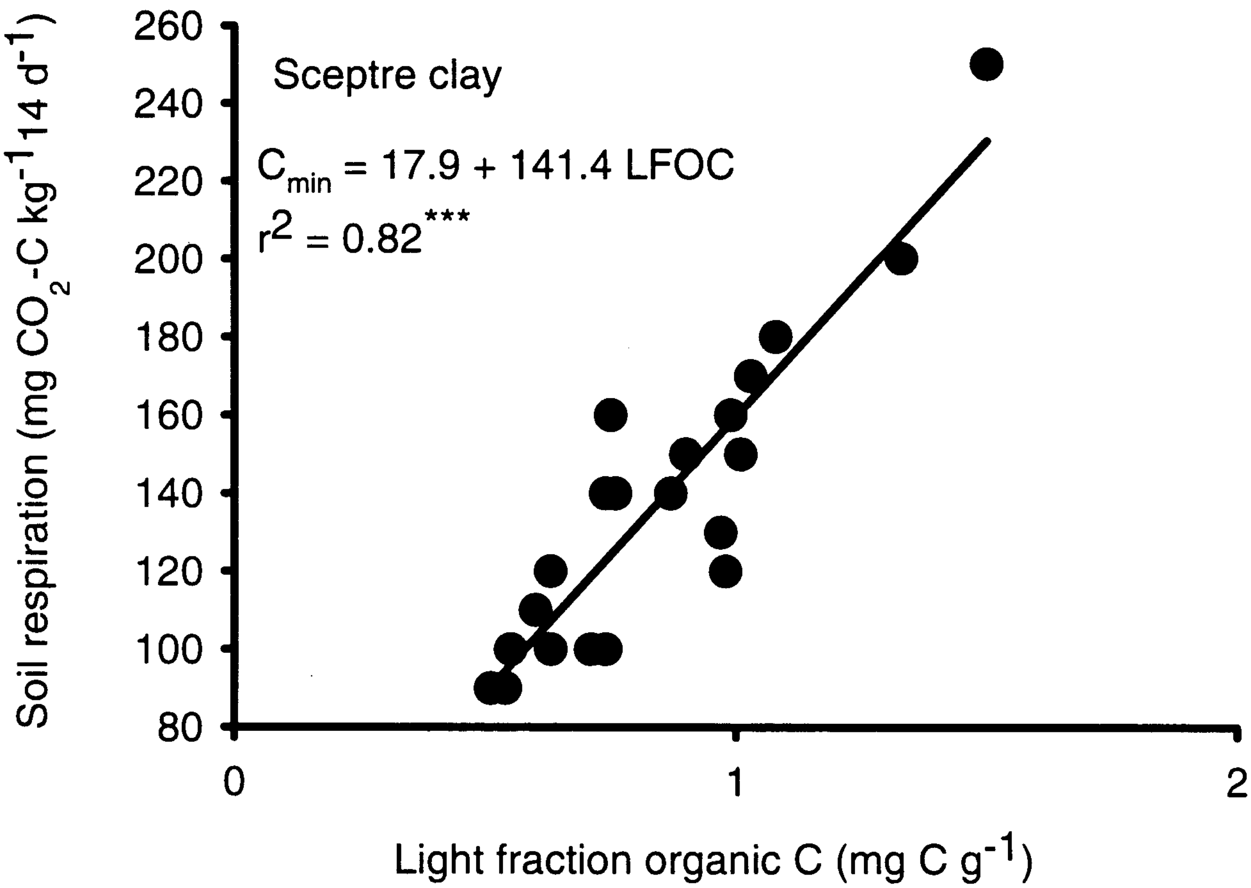
Soil	Tillage	LFOC	LFOC/SOC	C_{min}
		mg C g^{-1}	%	mg C kg^{-1}
Elstow clay loam	CT	2.4a	8.2a	206a
	NT	2.7a	8.3a	198a
Melfort silty clay loam	CT	1.5b	4.5b	113b
	MT	1.5b	4.6b	105b
	NT	2.6a	7.0a	187a
Indian Head clay	CT	1.5b	7.4a	293a
	MT	1.9ab	7.7a	360a
	NT	2.1a	8.8a	363a

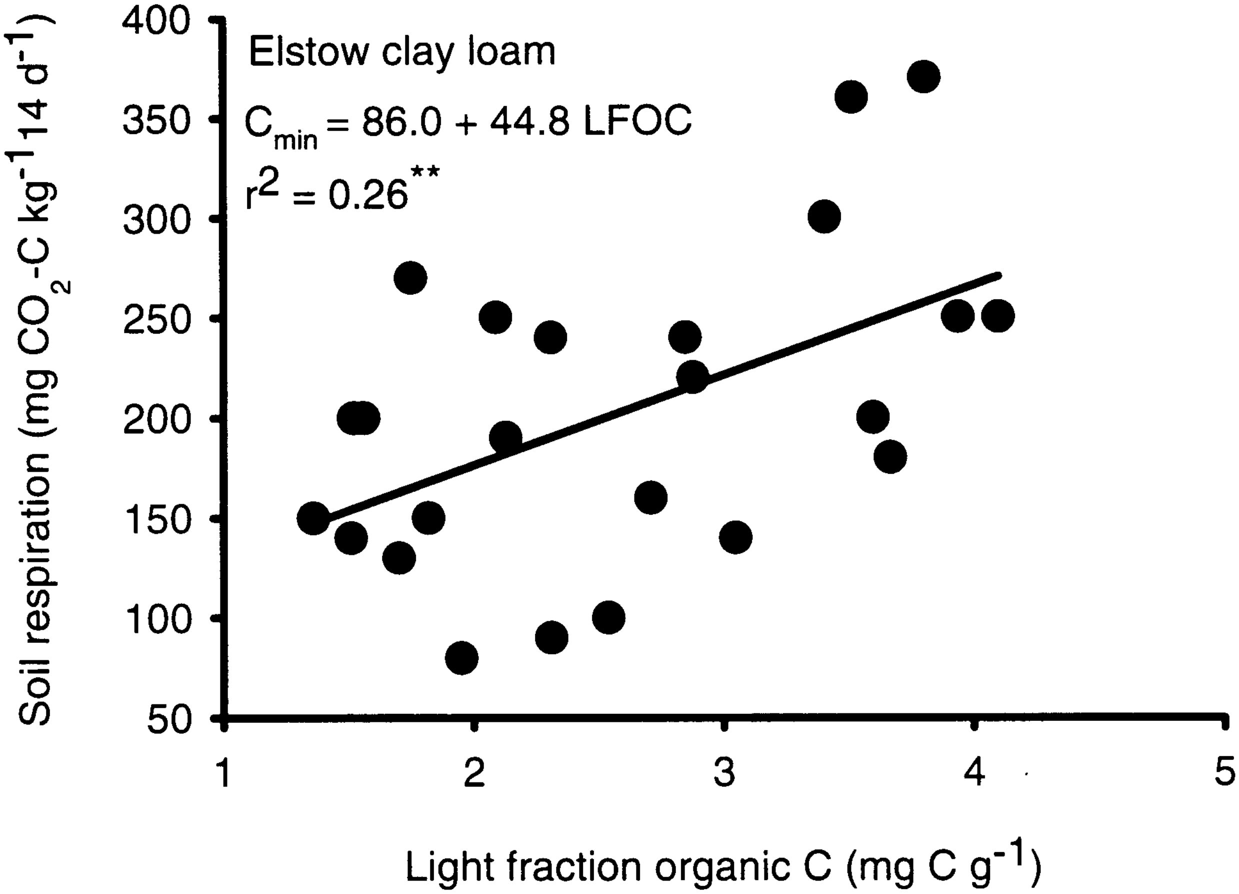
Means followed by the same letters within the same column of the same soil are not significantly different at *P=0.05* probability level.

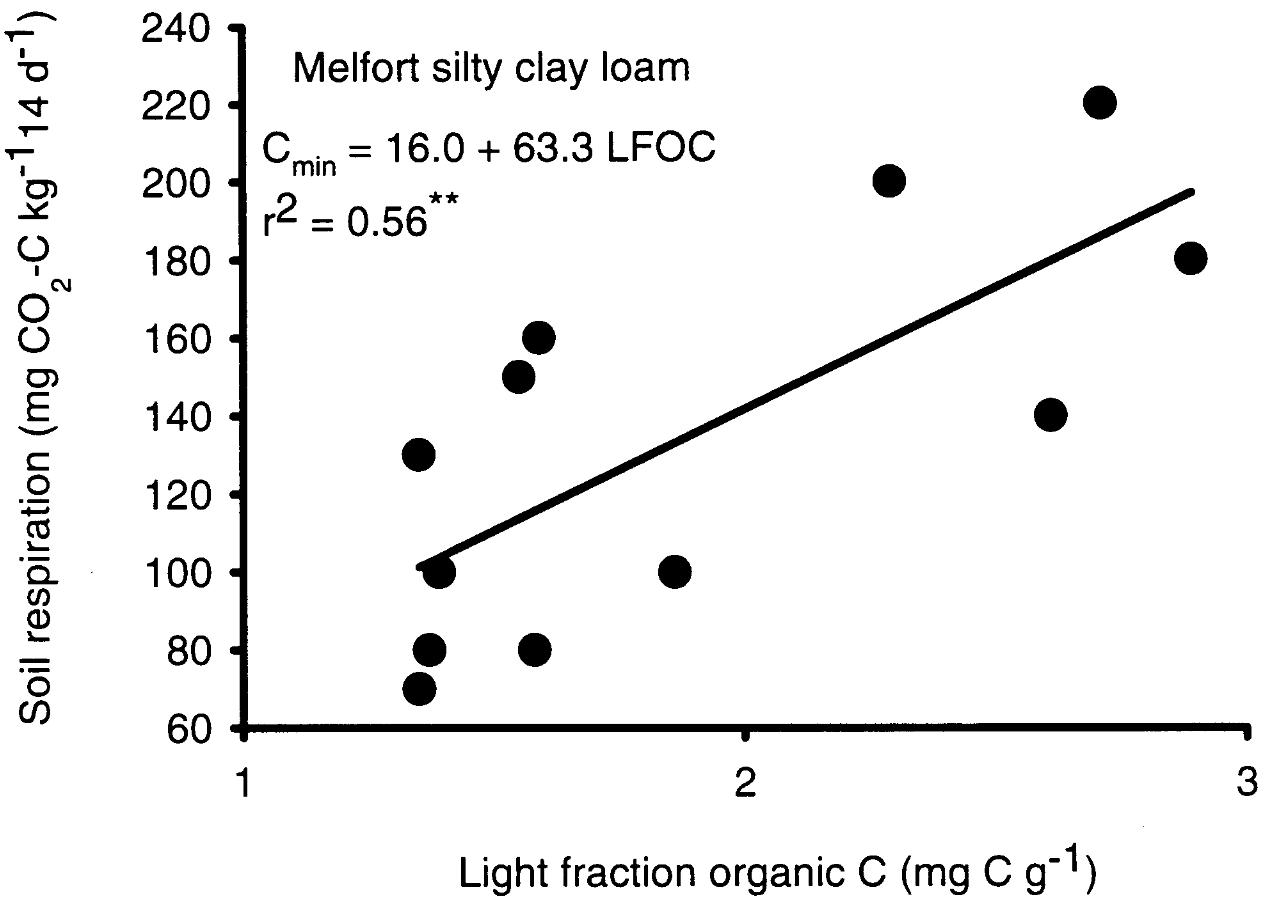

Hatton fine sandy loam
Cmin = 14.9 + 47.5 LFOC
r2 = 0.88***
Soil respiration (mg CO2-C kg-1 14 d-1)
120
100
80
60
40
20
0
1
2
Light fraction organic C (mg C g-1)



Swinton silt loam
C_{min} = 63.5 + 49.3 LFOC
r^2 = 0.27**
Soil respiration (mg CO_2-C kg^{-1} 14 d^{-1})
180
160
140
120
100
80
60
40
20
0
1
2
3
Light fraction organic C (mg C g^{-1})


Sceptre clay
C_min = 17.9 + 141.4 LFOC
r^2 = 0.82***
Soil respiration (mg CO2-C kg-1 14 d-1)
260
240
220
200
180
160
140
120
100
80
0
1
2
Light fraction organic C (mg C g-1)


Elstow clay loam
C_{min} = 86.0 + 44.8 LFOC
r^2 = 0.26**
Soil respiration (mg CO_2-C kg^{-1} 14 d^{-1})
400
350
300
250
200
150
100
50
1
2
3
4
5
Light fraction organic C (mg C g^{-1})


Melfort silty clay loam
C_{min} = 16.0 + 63.3 LFOC
r^2 = 0.56**
Soil respiration (mg CO_2-C kg^{-1} 14 d^{-1})
240
220
200
180
160
140
120
100
80
60
1
2
3
Light fraction organic C (mg C g^{-1})

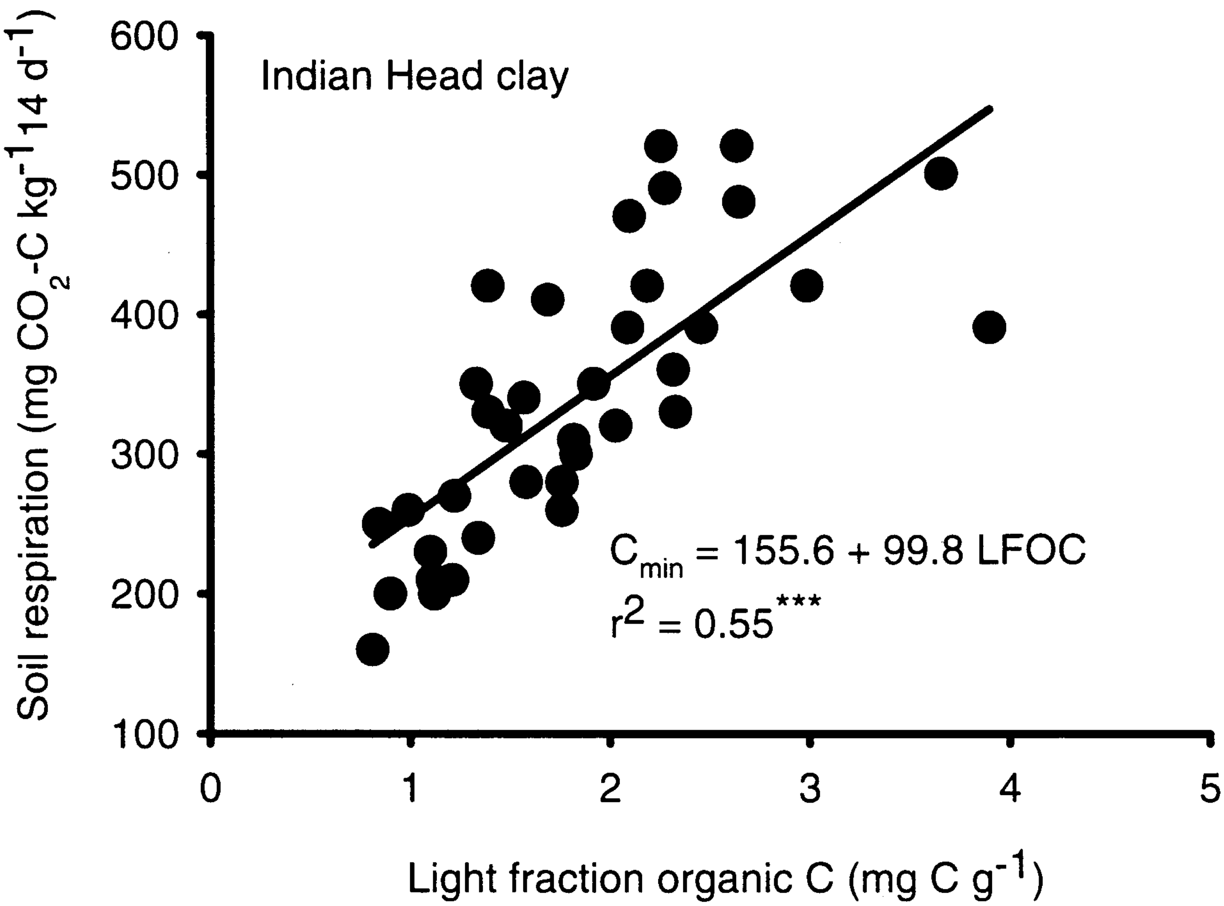


Figure 1. Relationship between C_{min} and light fraction organic C of soil in the Hatton fine sandy loam, Swinton silt loam, Sceptre clay, Elstow clay loam, Melfort silty clay loam and Indian Head clay

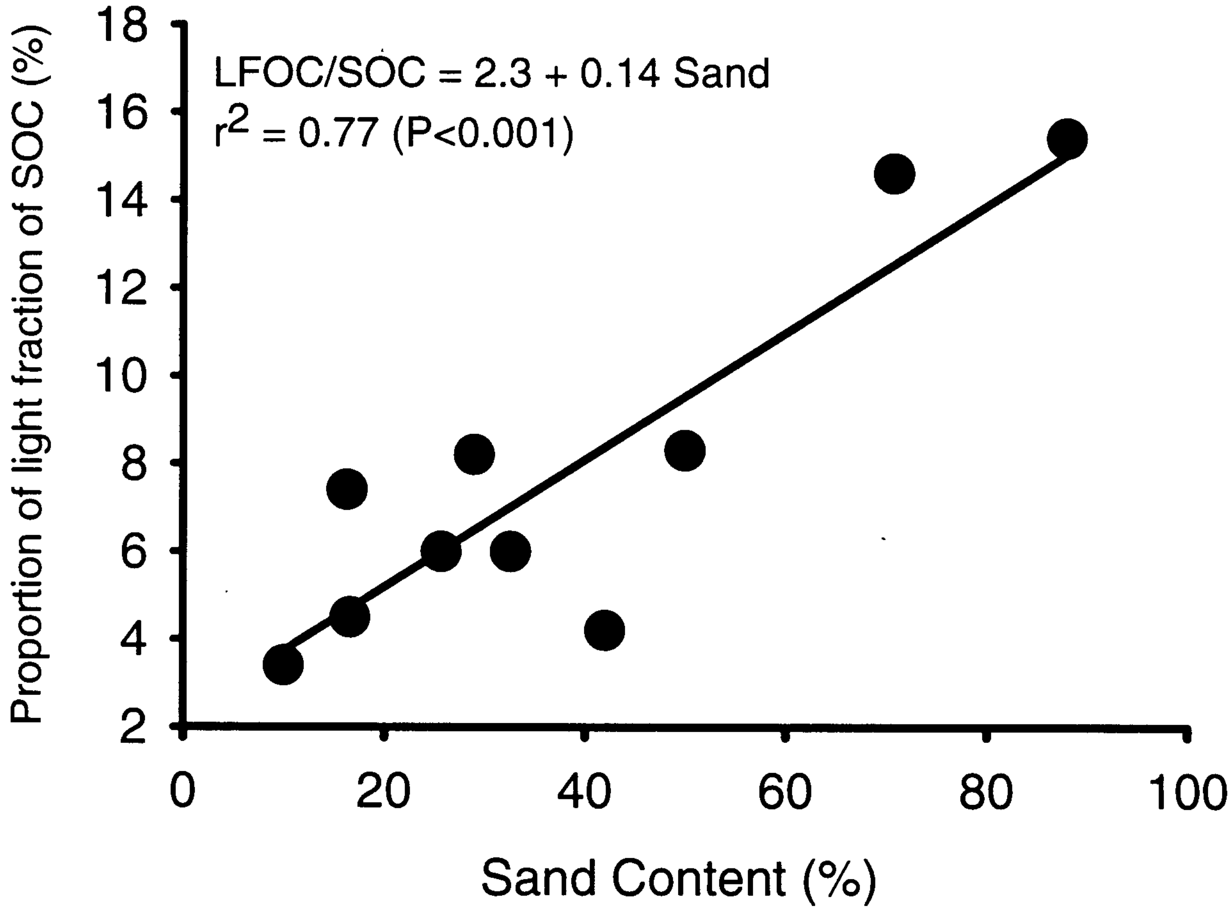


Figure 2. Relationship between the proportion of LFOC/SOC and the sand content of soil.