A Simple Model for Quantifying Change in Soil Organic C as Influenced by Tillage and Crop Rotations on the Canadian Prairies

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Abstract

Simulation models are required for quantifying the impact of crop rotations and tillage on soil organic C dynamics, and for aggregating C sequestration over a relatively large area. However, most current models of soil organic C have been built based on kinetically defined discrete pools with different turnover times. Those pools of soil organic C only exist conceptually. They have not been determined experimentally, thus validation of kinetic models describing soil organic C turnover is usually difficult or not independent from actual measurements. Thus, there is a need to develop a simulation model that can be easily validated and used for estimating future projection of C sequestration under specified management practices. A simple model has been developed to quantify the impact of crop rotations and tillage on soil organic C and validated using long-term field experiments conducted on the Canadian prairies. This simple model required a few input parameters and accurately predicted the change of soil organic C with a relative error of 5% or better. Crop rotation in cereal-dominant cropping systems, affected the amount of soil organic C due to differences in the amount of crop residue inputs. Clay content of soil played a vital role in determining the soil organic C sequestered under conservation tillage compared to tilled systems. This study also showed that the rate constant of soil organic C turnover was about the same for all systems in the drier region of the Canadian prairies, regardless of soil texture and the cropping system.

Introduction

Agricultural soil as a potential sink for C sequestration has received considerable attention in recent years because of its potential magnitude of CO_2 mitigation and environmental sustainability. Numerous field experiments have been conducted on the Canadian prairies for the last 40 years to evaluate the impact of crop rotations and tillage practices on soil organic C (SOC) (Campbell et al., 1995; Campbell et al., 1996a,b; Liang et al., 1999a; Janzan et al., 1998). However, quantitative data are still lacking because changes of SOC are usually slow compared to its large storage within a short term, and high spatial variability. To resolve these problems, simulation models of SOC dynamics have been developed to facilitate extrapolation of experimental data from a site-specific to a regional basis. These models vary in complexity, but generally have similar structures. Soil organic C has been conceptually defined as a series of pools that consist of a continuum of decomposition rates (Schimel et al, 1985; Christensen 1996). These pools have been represented in simulation models as kinetically defined fractions with different rate constants (Jenkinson and Raynor, 1977; Parton et al., 1987). A major restriction of current simulation models describing SOC turnover is that the conceptualized pools do not correspond to verifiable fractions and can not be determined experimentally (Cambardella, 1998; McGill and Bailey, 1999). Because of this, validation of kinetic models describing SOC turnover is usually difficult or not independent from actual measurements. Therefore, a need exists to develop a simulation model that can be used to quantify the dynamics of SOC based on verifiable fractions that can be measured experimentally. The objectives of this study were (1) to develop a simple model for quantifying changes in SOC under different tillage and crop rotations, and (2) to validate the model using data collected from some mid- to long-term tillage and crop rotation studies conducted on the Canadian prairies.

Model Development

The amount of SOC depends on the rate of SOC that decomposes and the amount of crop residues that is returned to the soil. At any particular time the amount of SOC can be divided into two components, one derived from native SOC and the other from more recent crop residue inputs since the initiation of experiment or any other reference time. This can be expressed as follows:

Total SOC = Native SOC + SOC derived from crop residue

Under certain climate and management practices, there is a balance between the loss of SOC through decomposition and the gain of SOC through crop residue return that is called the equilibrium level of SOC. The decomposition of SOC can be simply described by a first-order exponential equation

$$SOC_t = SOC_0 \, e^{-kt} \qquad \text{(Eqn. 1)}$$

where SOC_0 and SOC_t are the amount of SOC at t = 0 and t = t (years), respectively and k is the rate constant. Although changes in native SOC over time cannot be accurately determined experimentally, the amount of SOC derived from more recent crop residues can be estimated using stable or radioactive C isotope. When the SOC reaches an equilibrium level under certain conditions the rate constant can be easily calculated.

In order to estimate the accumulation of SOC over time after residue input, Voroney et al. (1989) determined the coefficients and decomposition rate constants in a microplot field study conducted on Sceptre clay in semiarid southwestern Saskatchewan. These coefficients and rate constants were based on a study in which ^{14}C-labeled wheat straw for a fallow-wheat-wheat-wheat rotation was incorporated into the soil and the C monitored annually for 10 years:

$$Y = 0.72\, e^{-1.4t} + 0.28\, e^{-0.081t} \qquad \text{(Eqn. 2)}$$

where, y is the proportion of residue C remaining in the soil and t is years since residue application. Although this study was carried out on two soils at the two different locations in Saskatchewan, the decomposition and rate constants of wheat straw were generally similar. Jenkinson (1977) also obtained a similar equation at Rothamsted in an experiment using ^{14}C-labeled ryegrass over a ten year period. Liang et al. (1998) conducted field studies with continuous corn varying from 3 to 12 years in Ontario and Quebec, and reported that there were large differences in crop residue-C retention in soil as determined by ^{13}C natural abundance method. Fine-textured soils retained a greater proportion of crop residues than coarse-textured soils (Fig. 1). In this paper we estimated SOC derived from crop residues using the results of Liang et al. (1998). Therefore, to quantify the amount of SOC with a certain cropping system under conventional tillage, we propose the following equation

$$SOC_t = SOC_0\, e^{-kt} + F \sum_{1}^{t} CRC \qquad \text{(Eqn. 3)}$$

where F (%) is the fraction of crop residue-C retained in the soil, which is a simple function of silt plus clay content of soil ($F = 15.6 - 0.205X + 0.00457X^2$, X = silt plus clay (%)), and CRC is the total amount of crop residue-C returned to the soil from t = 1 to t = t years (Mg C ha^{-1}).

In order to derive the rate constant of SOC we used a crop rotation study that was conducted on the Swinton loam in the semiarid region of southwest Saskatchewan from 1967 to 1996. The soil was broken from native prairie for annual crop production in 1911, and had been under a traditional fallow-wheat rotation prior to 1966. Detailed treatments and managements practices have been reported elsewhere (Campbell et al., 1999). During the 30-yr period amounts of SOC in the top 15-cm soil were measured seven times, and values of SOC for the FW(N+P) were plotted on Fig. 2. It is clear that SOC remained relatively unchanged at approximately 30.5 Mg C ha^{-1} from 1967 to 1990, but gradually increased to 34 Mg C ha^{-1} in 1996. This increase in SOC has been attributed to higher crop yields resulting from above average precipitation in early 1990's (Campbell et al., 1999). It is assumed that the equilibrium level of SOC for the FW rotation was 30.5 Mg C ha^{-1}, and higher amounts of SOC in 1990's resulted from additional crop residue inputs because of higher crop yields. Total amounts of crop straw plus estimated roots returned to the soil by the FW rotation during the 30-yr period were 86 Mg ha^{-1}, and approximately 39 Mg C ha^{-1}. Based on the retention of crop residues of 22.4% for the Swinton loam, it is estimated that 8.7 Mg C ha^{-1} in the soil derived from crop residues during the 30-yr period. The amount of difference in SOC between the equilibrium level (30.5 Mg C ha^{-1}) and the amount of SOC measured in 1996 (34.0 Mg C ha^{-1}) should be subtracted from the amount of SOC derived from crop residues (8.7 Mg C ha^{-1}). This net amount of crop residue derived C (5.2 Mg C ha^{-1}) is the amount of native SOC that was lost by decomposition during the 30-yr period (assuming no erosion occurred). Thus, the rate constant can be calculated based on Equation (1)

$$k = {}^{ln((30.5-5.2)/30.5)}\!\big/_{(-30)} = 0.0062 yr^{-1}$$

In the Dark Brown soil zone at Lethbridge, Alberta, the amount of SOC for the continuous wheat and fallow-wheat rotations has been measured five times during the 37-yr experiment (Fig. 3). It can be seen that the amount of SOC under the FW reached the equilibrium level at 29.0 Mg C ha^{-1} in 1974. The total amount of crop residue C returned to the soil was 16.9 Mg C ha^{-1} from 1974 to 1991 (Campbell et al., 1999). Assuming the retention of crop residues was 17.8%, then the amount of SOC derived from crop residues during this period was 3.0 Mg C ha^{-1}. Therefore, the rate constant for the Lethbridge FW soil was 0.0064 yr^{-1}.

Because measurements of SOC were only made twice during the last 10 years of the 30-yr experiment in the sub-humid region of the prairie at Indian Head, Saskatchewan, the equilibrium level of SOC could not be determined with certainty. However, we assumed the equilibrium SOC level at 29.0 Mg C ha^{-1} in the 0-15-cm soil, which was the value observed for the FW rotation with fertilization (Table 4). Based on other parameters provided in Table 4, we can calculate the rate constant for the Indian Head clay soil to be 0.0173 yr^{-1}.

The impact of tillage on SOC was quantified empirically based on soil texture. The relative annual increase in SOC under different tillage systems was calculated as follows

$$RAISOC = \frac{SOC_{NT} - SOC_{CT}}{SOC_{CT} \bullet Year} \bullet 100 \qquad \text{(Eqn. 4)}$$

where RAISOC (% yr^{-1}) was the relative annual increase in SOC per year under NT; SOC_{NT} was the amount of SOC under NT (Mg C ha^{-1} in the 0-15-cm soil); SOC_{CT} was the amount of SOC under CT or MT (Mg C ha^{-1} in the 0-15-cm soil), and Year was number of years since the establishment of tillage treatments. Liang et al. (1999a,b) analyzed results from a number of short to long-term field experiments conducted in

Saskatchewan, and concluded that RAISOC for NT compared with tilled systems was directly related to clay content (Fig. 4). Thus, the amount of SOC gains under NT, or tillage factor (TF, Mg C ha^{-1}) can be expressed as

$$TF = SOC \bullet RAISOC \bullet t/10 \qquad \text{(Eqn. 5)}$$

where t is number of years under NT. The relative annual increase in SOC under NT is a function of clay content as defined by RAISOC = -0.30 + 0.024 Clay.

It is also assumed in this paper that the effects of crop rotations and tillage on SOC are independent of each other (Liang et al., 1999a). Thus, to quantify the impact of both tillage and crop rotations on SOC it becomes a simple addition of (Eqn. 3) and (Eqn. 5).

Materials and Methods

A number of crop rotations and tillage studies were conducted in various ecozones on the Canadian prairies. These studies varied in length from mid-term (11 yrs) to long -term (more than 30 yrs). A brief description of studies used in this paper either for model development or validation is provided.

Four field experiments have been conducted in the Brown soil zone at or near Swift Current, Saskatchewan. A long-term crop rotation study was initiated in 1967 on a Swinton loam with conventional tillage (Campbell et al., 1999). Crop rotations consisted of continuous wheat with P (CW(P)), fall rye-wheat-wheat with N and P (RWW(N+P)), wheat-lentil with N and P (WL(N+P)), fallow-wheat with N and P (FW(N+P)), fallow-wheat-wheat with N (FWW(N)), fallow-wheat-wheat with P (FWW(P)), and fallow-wheat-wheat with N and P (FWW(N+P)). Three tillage crop rotation studies were also initiated in 1982 on a Swinton loam, and in 1983 on a Hatton fine sandy loam and on a Sceptre clay (Campbell et al., 1995; Campbell et al., 1996a,b). Experimental designs for these three studies were similar, and contained FW and CW rotations, and CT and NT. In general, CT in the Brown soil zone consisted of fall tillage after crop, preseeding tillage, and tillage as required for weed control during fallow. No tillage consisted of low disturbance direct seeding and weed control with herbicides. More detailed description of tillage and management practices have been provided elsewhere (Campbell et al., 1995; Campbell et al., 1996a, b; Liang et al., 1999a,b).

The 37-yr experiment in the Dark Brown soil zone at Lethbridge, Alberta was established in 1951 on land that had been broken from tall and short grass prairie in 1910. Crop rotations contained mixed crop rotations that included legumes (Bremer at al., 1994). However, only two rotations, CW and FW, are discussed in this paper.

The 40-yr experiment in the Black soil zone at Indian Head, Saskatchewan was initiated in 1957, and contained a number of crop rotations including FW, FWW and CW with N +P and also unfertilized. Crop yields data are available for the entire experimental period, but SOC in the 0-15-cm soil was only measured in 1987 and 1996. Thus, SOC and crop residue-C input data from 1987 to 1996 are used to validate the model. More detailed information on soil properties, crop rotations and tillage systems used for the present study is provided (Table 1). General climatic information at Swift Current and Indian Head, Saskatchewan, and Lethbridge, Alberta, is listed (Table 2).

For most sites, actual straw yields were determined each year. For sites where only grain yields were measured straw yields are calculated based on a fixed harvest index of 40%. We estimated the potential C input from crop residues by assuming the root/straw ratio was 0.59 (Campbell et al., 1977) and the C concentration of tissues was 45% (Millar et al. 1936).

Model Validation

The amount of crop residue C retained in the Hatton fine sandy loam, Swinton loam and Sceptre clay was estimated using the methods of Voroney et al. (1989) and Liang et al. (1998), and shown in Table 3. Both methods estimated about the same amount of SOC derived from crop residues for the medium-textured soils, but the method of Voroney et al. (1989) tended to overestimate the amount of SOC derived from crop residues for the light-textured soils, and likewise underestimate the amount of SOC derived from crop residues for the fine-textured soils. This is because the method of Voroney et al. (1989) did not account for differences in soil texture. We validated the model using independent measurements, either from the same experiments from which the rate constant was derived on, but different crop rotations or from different experiments. The tillage component of the model was also validated using various tillage studies conducted in southwest Saskatchewan.

The rate constant of 0.0062 yr^{-1} was derived from the 30-yr crop rotation experiment conducted on the Swinton loam under conventional tillage with the traditional FW rotation. We applied the same rate constant to the CW for the same study. The total straw yields during the 30 years for the CW were 78.2 Mg ha^{-1}. The amount of crop residue C retained in the 30-yr period was 12.5 Mg C ha^{-1}. The amount of native SOC decomposed from 30.5 Mg C ha^{-1} with a rate constant of 0.0062 yr^{-1} for 30 years was 25.3 Mg C ha^{-1}. The amount of observed SOC in 1996 was 39.5 Mg C ha^{-1}. Thus, the model underestimated about 4% of the actual observed SOC.

We also applied the rate constant of 0.0064 yr^{-1} which was derived from a 37-yr study under FW at Lethbridge, Alberta to the CW rotation in the same study. The amount of crop residue C for CW from 1974 to 1991 were 20.4 Mg ha^{-1}. The amount of SOC derived from crop residues during this period was 3.6 Mg

C ha^{-1}. The amount of native SOC decomposed from 31.6 Mg C ha^{-1} with a rate constant of 0.0064 yr^{-1} for 17 years was 28.3 Mg C ha^{-1}. The measured SOC for CW in 1991 was 31.7 Mg C ha^{-1}. Thus, the simulated SOC value was about the same as that of the actual observed value. It is clear that although the rate constant was derived from the FW rotation for the Swift Current and Lethbridge studies, this same rate constant can be used for the other rotations at the same site such as CW, suggesting that the native SOC decomposed in a similar rate regardless of the difference in crop rotations. This is consistent with the finding of Gregorich et al. (1996), who reported that after a 35-yr of continuous corn SOC increased with N fertilization compared with non-N fertilization. This increased SOC with N fertilized treatments derived from C_4 source, and the native SOC from C_3 source for both fertilized and non-fertilized treatments remained the same.

The rate constant of the native SOC for the Swinton loam and the Lethbridge clay loam was almost identical even though the climatic factors such as annual mean temperature, annual precipitation and moisture deficit for the two locations were quite different. It seems that the higher annual mean temperature, higher annual precipitation and less moisture deficit would favor the decomposition of the native SOC in the Lethbridge clay loam, thus a greater rate constant would be expected. However, this is not supported by our observations. Perhaps, the climatic differences between the two sites are not large enough to cause any significant change in the rate constant. On the other hand, the rate constant derived from the drier region of the prairies cannot be used for the sub-humid region of the prairies. In fact, the rate constant derived from the Indian Head clay is nearly triple that of the Swinton loam. We would expect that the sub-humid environment may favor the decomposition, but moisture deficit alone may not provide satisfactory explanation. Perhaps, a combination of moisture deficit and temperature affects the rate constant for the sub-humid region of the prairies.

In the Brown soil zone, the model correctly predicted the effect of crop rotations on SOC for the Hatton fine sandy loam, Swinton loam and Sceptre clay, and the tillage factor for the Swinton loam and Sceptre clay (Table 3). The model tended to underestimated the tillage factor for the sandy soil. This is because the model does not account for any additional benefit of C sequestration as a result of reduced wind erosion on the light-textured soil under NT (Liang et al., 1999a). Except for the sandy soil, the model predicted the actual amount of SOC with a relative error of 5% or better. In the Black soil zone, the model accurately predicted the changes in SOC, and the differences between simulated and observed values varied from -0.3 to 0.8 Mg C ha^{-1} for the majority of the treatments except for the CW(F), where the model overestimated the amount of SOC by 3.6 Mg C ha^{-1} (Table 4). However, it is not clear why the high productivity level associated with the CW(F) could not sustain the SOC level during the last 10 years of the experiment.

It should be recognized that this model is most suitable for short- to mid-term use, typically from 5 to 30 years because most coefficients for the model were derived from mid-term studies. In addition, this model may be extended for use in crop rotations containing legumes in a similar climatic condition, if proper coefficients such as shoot/root ratios can be assigned. However, this assumption can not be validated due to lack of available data.

Conclusions

This model correctly predicted the absolute changes in SOC over time within a short or mid-term under a cereal-dominant crop rotation as well as the relative change in SOC among cropping systems on the Canadian prairies, especially for the drier region of the prairies. This model also reveals the importance of soil texture and the quantity of crop residues that are returned to the soil in controlling the level of SOC, probably the two most influential factors besides erosion. The relationship between the proportion of crop residue-C retained in the soil and soil texture may be independent of climatic factors because the decomposition rate constant or retention of cereal residues in a similar soil texture was almost the same regardless of where the studies were carried out whether in Rothamsted, England (Jenkinson, 1977), Saskatchewan (Voroney et al., 1989), or Ontario and Quebec (Liang et al., 1998). Note that the rate constant for the drier region of the prairies in the Brown and Dark Brown soil zone is about the same regardless of soil texture even though the amount of SOC in different-textured soils varied greatly. This is probably because the readily biodegradable SOC, in proportion to the total amount of SOC, in a similar climatic region, is about the same. This would greatly enhance the model applicability. The tillage factor in this model although derived empirically, should be widely applicable on the Canadian prairies because the initial studies covered a wide range of climatic zones, soil texture and duration of experiments. This simple model will provide a useful tool not only for soil scientists in the areas of assessing soil sustainability and C sequestration, but also for policymakers wishing to project greenhouse gas emission reduction through improved management practices of agricultural soils.

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Table 1. List of field experiments, soil properties, crop rotations and tillage studies conducted in Saskatchewan and Alberta, Canada

Soil	Township	Soil texture			Initial SOC	Years of study	Crop rotation	Tillage
		Sand	Silt	Clay				
		---------- % -----------			- Mg C ha^{-1} -	-- yr --		
Swinton loam	Swift Current, SK	32.6	39.8	27.6	28.0	12	CW, FW	CT, NT
Swinton loam	Swift Current, SK	32.6	39.8	27.6	30.5	30	CW, FW	CT
Hatton fine sandy loam	Cantuar, SK	70.8	13.9	15.3	18.3	11	CW, FW	CT, NT
Sceptre clay	Stewart Valley, SK	25.7	31.6	42.7	25.6	11	CW, FW	CT, NT
Lethbridge clay loam	Lethbridge, AB	46.0	28.0	26.0	29.0	37	CW, FW	CT
Indian Head clay	Indian Head, SK	16.3	20.6	63.1	See Table 3	40	CW, FW	CT

Table 2. Mean annual windspeed, temperature, precipitation, calculated potential evaporation (ET_P), and moist deficit at Swift Current and Indian Head, Saskatchewan, and Lethbridge, Alberta

Location	Wind	Temperature	Precipitation	ET_P	Moisture deficit[a]
	-- $km.h^{-1}$ --	---- °C ---	------------ mm ----------		
Brown soil zone					
Swift Current	22.9	3.3	334	729	395
Dark Brown soil zone					
Lethbridge	20.4	5.0	413	681	268
Black soil zone					
Indian Head	15.8	2.0	427	607	180

[a] Potential evaporation minus mean annual precipitation (Campbell et al., 1990)

Table 3. Validation of model using soil organic C data collected from various tillage and crop rotations studies conducted in various locations of Saskatchewan[a].

Soil	CW (CT)	CW(NT)	FW(CT)	FW(NT)
	------------------ Mg ha^{-1}	------------------		
Hatton fine sandy loam (1983 - 1993)				
Straw yields	17.4	17.9	18.0	18.9
SOC derived from crop residues estimated from Voroney et al. (1989)	2.8	3.0	2.9	3.1
Retained SOC estimated from Liang et al. (1998)	1.7	1.8	1.8	1.9
Native SOC	17.1	17.1	17.1	17.1
Tillage factor	0.0	0.2	0.0	0.2
Native SOC + Retained C + Tillage factor	18.8	19.1	18.9	19.2
Observed SOC	18.6	20.4	20.0	20.6
Swinton loam (1982 - 1993)				
Straw yields	34.5	34.4	21.8	20.9
SOC derived from crop residues estimated from Voroney et al. (1989)	5.0	5.0	3.6	3.0
Retained SOC estimated from Liang et al. (1998)	5.5	5.5	3.5	3.3
Native SOC	26.0	26.0	26.0	26.0
Tillage factor	0	1.3	0	1.3
Native SOC + Retained C + Tillage factor	31.5	32.8	29.5	30.6
Observed SOC	30.3	33.2	29.0	29.5

Table 3 (Cont')

Soil	CW (CT)	CW(NT)	FW(CT)	FW(NT)
	------------------ Mg ha^{-1} ------------------			
Sceptre clay (1983 - 1993)				
Straw yields	23.1	23.8	21.3	18.3
SOC derived from crop residues estimated from Voroney et al. (1989)	4.1	4.2	4.0	3.4
Retained SOC estimated from Liang et al. (1998)	4.1	4.3	3.9	3.3
Native SOC	23.9	23.9	23.9	23.9
Tillage factor	0.0	2.2	0.0	2.1
Native SOC + Retained C + Tillage factor	28.0	30.4	27.8	29.3
Observed SOC	27.5	30.5	25.5	30.7

[a] CW=continuous wheat, FW=fallow-wheat, CT=conventional tillage, and NT=no-tillage

Table 4. Effects of crop rotations on soil organic C for the last 10 years of the 40-yr experiment from 1957 to 1996 at Indian Head, Saskatchewan[a]

Crop rotations	CW (F)	CW(UF)	FWW(F)	FWW(UF)	FW(F)	FW(UF)
			------------------ Mg ha^{-1} ------------------			
Straw yields	38.1	13.4	28.6	13.5	21.3	13.0
Retained SOC estimated from Liang et al. (1998)	8.2	2.9	6.1	2.9	4.6	2.8
Measured SOC in 1987	34.5	30.8	29.9	29.8	29.1	28.8
Native SOC, k=0.0173 yr^{-1}	29.0	25.9	25.1	25.0	24.5	24.2
Native SOC + Retained C	37.2	28.8	31.2	27.9	28.7	27.0
Observed SOC in 1996	33.6	28.0	31.1	28.2	28.7	26.2

[a] CW=continuous wheat, FW=fallow-wheat, FWW=fallow-wheat-wheat, F=fertilization, and UF=no fertilization

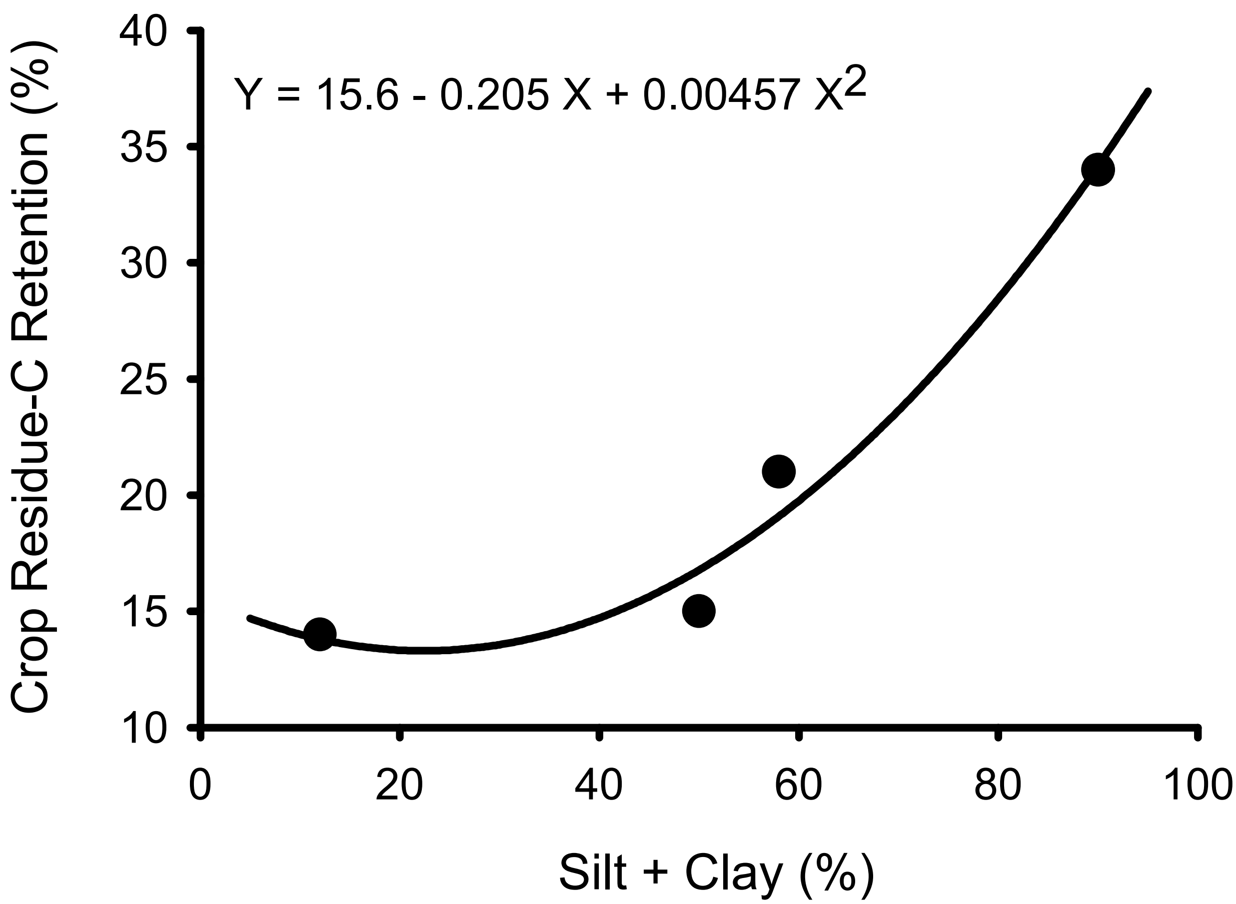

Fig. 1. Retention of corn residue-C vs clay + silt content of soil (redrawn after Liang et al., 1998)

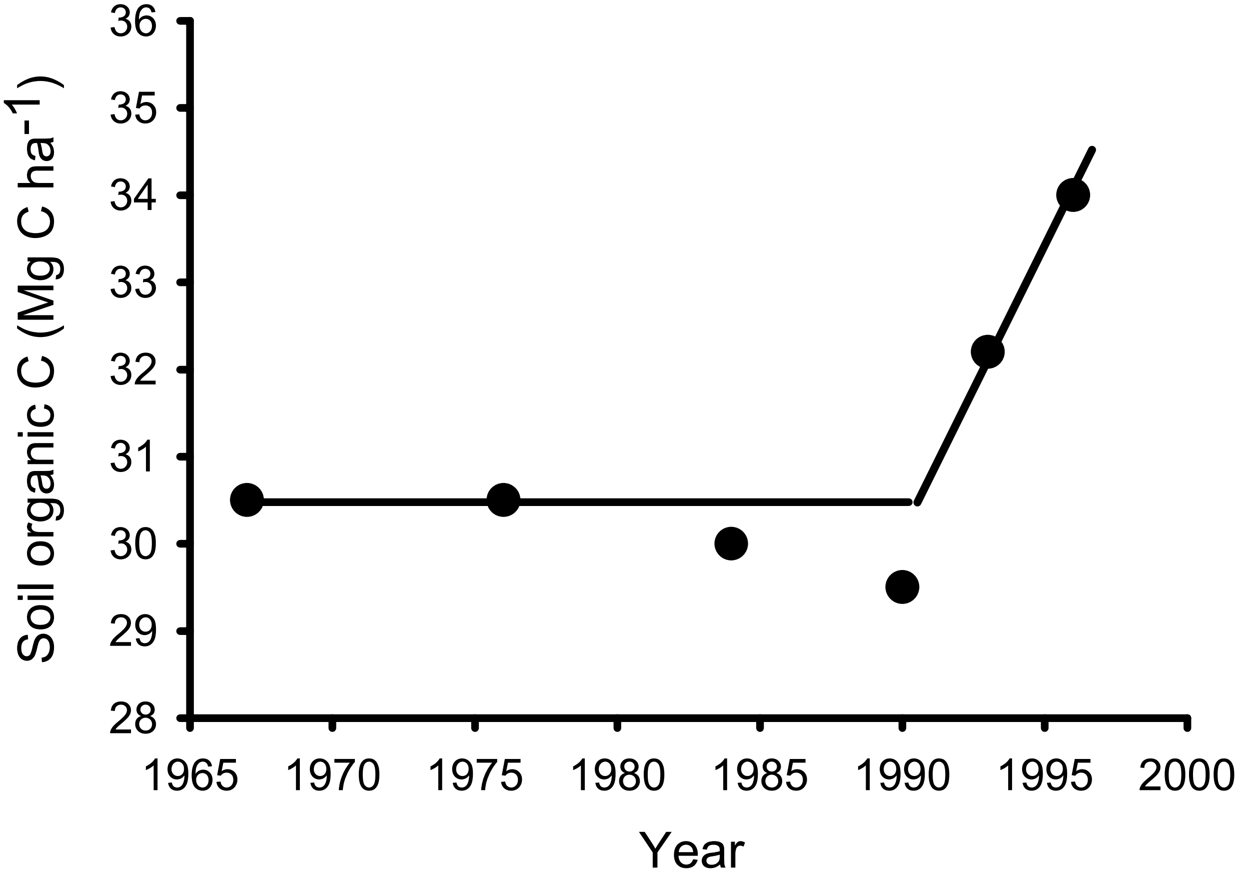

Fig. 2. Dynamics of soil organic C for the fallow-wheat rotation in a 30-yr experiment conducted at Swift Current, Saskatchewan (redrawn after Campbell et al., 1999)

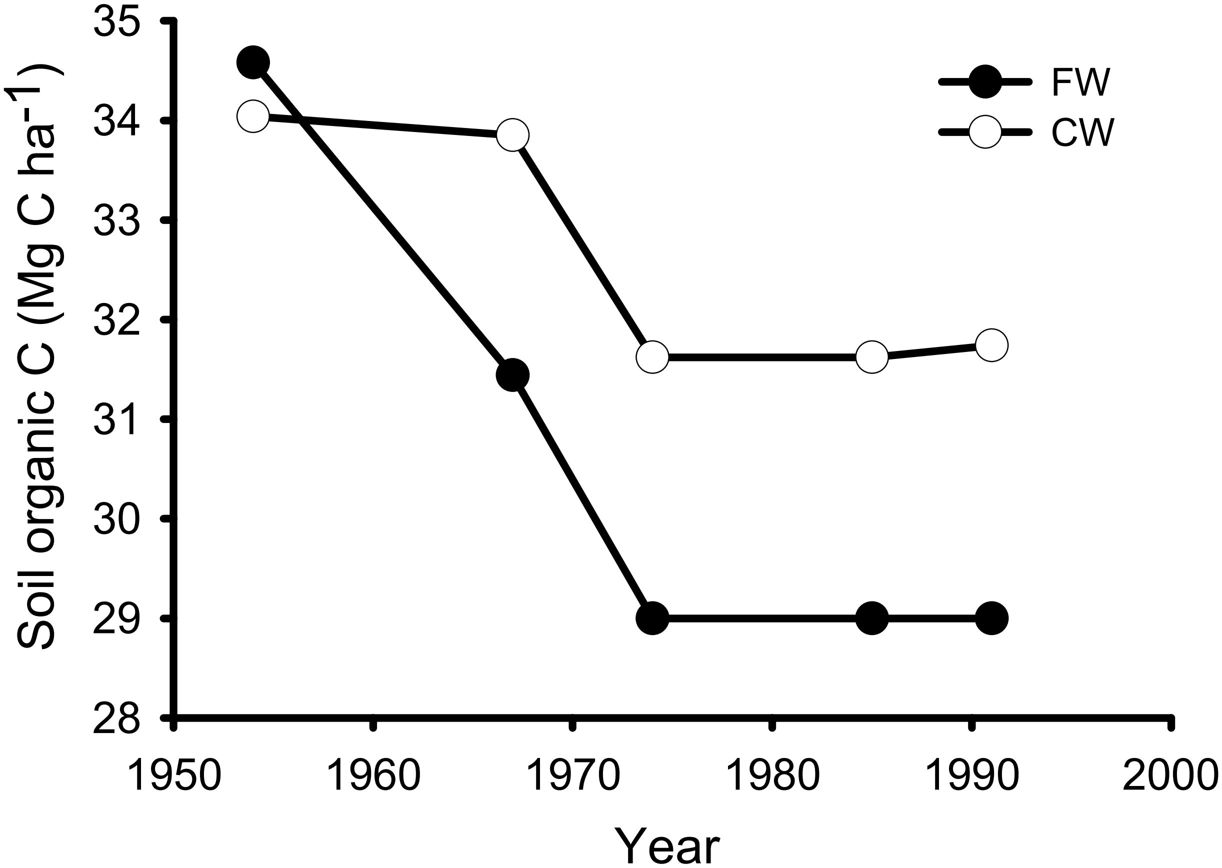

Fig. 3. Dynamics of soil organic C under fallow-wheat and continuous wheat in a 37-yr experiment conducted at Lethbridge, Alberta (adapted from Campbell et al., 1999)

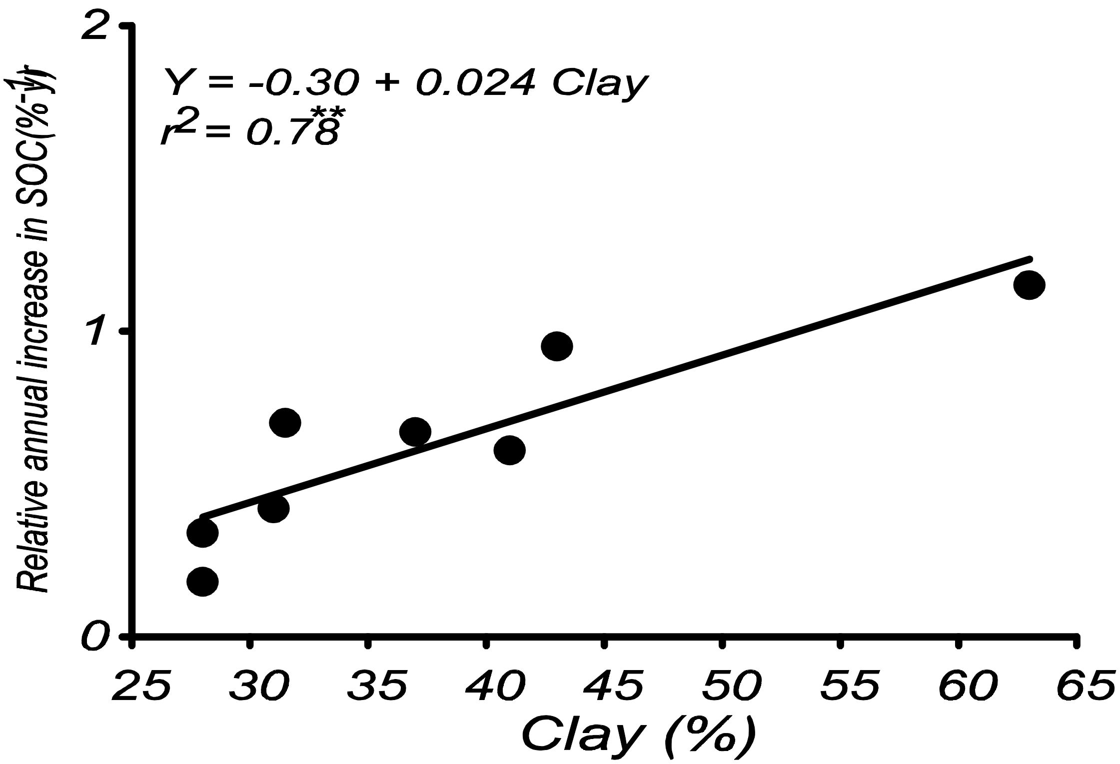

Fig. 4. Relative annual increase in soil organic C under no-tillage as influenced by the clay content of soil from 8 field studies conducted on the Canadian prairie (adapted from Liang et al., 1999)