Effect of Cultivation, Tillage Practice and Fertilization on Total Organic Carbon, Light Fraction and Microbial Biomass Carbon in Soils from the Loess Plateau of China and the Canadian Prairies

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Abstract

Three soils: Huangmian, Huihe, Heilu soil, from the Loess Plateau and one soil: Orthic Brown Chernozem, from the Canadian Prairies, were used to evaluate the effect of cultivation time, tillage system and fertilization, on total soil organic carbon (SOC), light fraction (LF), and microbial biomass carbon (MB-C). Upon cultivation, Huangmian soil lost 77% of total organic carbon within 5 years (0-20 cm), at a decrease rate of 2.15 tonnes C ha^{-1} yr^{-1}. The Huihe soil lost 70% of total organic carbon at rate of 0.96-1.06 tonnes C ha^{-1} yr^{-1} over 42 years (0-20 cm). Comparably, the Orthic Brown Chernozem lost 11% and 44% of the total soil organic carbon mass (0-20 cm), after 40 and 80 years of cultivation respectively, at a corresponding rate of 0.17 tonnes C ha^{-1} yr^{-1} and 0.45 tonnes C ha^{-1} yr^{-1}. Water erosion for the Huangmian and Huihe soil, and wind erosion for the Brown Chernozem during 1930's, are the main reasons for organic carbon decline. The light fraction of organic carbon (LFOC) decreased more rapidly than total organic carbon: LFOC decreased by 73% and 90% for the Huangmian and Huihe soil for the corresponding period, and decreased by 70% and 74% for Brown Chernozem brought under cultivated 40 and 80 years ago respectively. The change of microbial biomass carbon (MB-C) showed same trend as total organic carbon and LFOC. On the Heilu soil, a 29% decrease of SOC, which was comparable to average 22% decline of SOC during about hundred years of cultivation on the Prairie, was observed after thousands of years of cultivation relative to native sod.

Some management practices had a positive effect on restoring and maintaining soil organic carbon. On the Orthic Brown Chernozem, dry matter of light fraction in 0-5 cm was increased after no-tillage was practised for 7 years. As well, LFOC in 0-5 cm was increased significantly after switching from cereal-fallow to continuous cropping for 10 years. Growing alfalfa for 10 years after 60 years cereal-fallow increased total organic carbon by 80% and 27% in 0-5 cm and 5-10 cm depths respectively, while dry matter of LF and LFOC were increased by 54% and 194%, and 245% and 286% in 0-5 cm and 5-10 cm respectively. Application of manure alone and manure plus chemical fertilizer was found to restore total organic carbon, LFOC, and MB-C in the Heilu soil.

Introduction

Soil organic matter (SOM) contributes to nutrient supply, improvement of soil physical properties, and protection from erosion (Gregorich et al., 1995a; Stenvensen, 1982). The SOM, however, is easily lost upon cultivation by accelerated decomposition to CO_2 as well as erosion. The content of SOM is determined by different environmental factors. Among them, climate and topography are dominant on a large scale (Potter et al., 1998; Stenvensen, 1982). Tillage and rotation can also cause changes in SOM content (Campbell et al., 1996; 1998). For example, the content of SOM may decrease sharply after undisturbed land is cultivated (Carter et al., 1998), and the longer the cultivation period, generally the lower the content of SOM (Dalal and Mayer, 1986; 1987). Fertilization can constrain the decrease of SOM to some extent (Odell et al., 1984) as can the reduction or elimination of erosion (Gregorich et al., 1998).

The decline of SOM is responsible for an overall degradation of soil quality (Gregorich et al., 1995a; Jamalam et al., 1990), in which nutrient supply decreases, soil structure deteriorates and water storage and infiltration are reduced. These changes are usually associated with a decline in the productivity of the agroecosystem.

The Loess Plateau of China, where initial agriculture developed in the paleolithic period along the valley of the Yellow River and its tributaries, has a land area of 275,600km^2. The soils of the Loess Plateau developed from parent material of calcareous loess with a feature of low SOM content, on average around 1% (Soil Survey Office in Gansu, 1996). Comparatively, SOM content in soils of the Canadian Prairies is around 1-10% (Gregorich et al., 1995a). Undoubtedly, the differences in climate and vegetation in the two regions are mainly responsible for the difference in SOM, however, a longer period of cultivation and more severe erosion on the Loess Plateau are other potential causes of lower SOM.

The first objective of this study was to assess and compare the changes in soil organic matter components associated with cultivation of soils of the Loess Plateau and the Canadian Prairies. A second objective was to determine how management practices including rotation, tillage, and fertilization could alter the amounts and distribution of the soil carbon fractions.

Material and Methods

Soil location and sample method

The Loess Plateau soils used in the study are Huangmian soil (Calcaric Cambisols, FAO), Huihe soil (Haplic Greyxems, FAO), and Heilu soil (Calcic Kastanozems, FAO). The Canadian Prairie soil is classified as Orthic Brown Chernozem, Haverhill association (Canadian System of Soil Classification, 1999). The Huangmian, Huihe, and Heilu soil occupy areas of 160,080, 28,300, 21,451 km^2 respectively on the Loess Plateau. Orthic Brown Chernozems are common soil types in the agricultural region of the southern Prairies.

Huangmian soil

A chronosequence of Huangmian soil, which had been cultivated for 0, 5, 40, and 100 years up to the time of sampling, was sampled on sloping fields (<10^o slope) on May 14, 2000. For each field, 20 soil cores of 0-20 cm depth were taken in each of three 70 m^2 areas using a grid sampling method (Crépin and Johnson, 1995). Three composite samples were prepared by combining the cores from the three squares. The chronosequence is located near Tangjiabu in Dingxi County, Gansu province, China. The average annual precipitation of Tangjiabu is 410mm, and average temperature is 6.4^oC. As a result, only sparse vegetation covers hills and ravines. Generally, 25-40 kg N ha^{-1}, 15-25 kg P_2O_5 ha^{-1} and 0.75-1.50 tonnes ha^{-1} of animal manure are applied annually in these sloping fields and 0.75-1.00 tonnes ha^{-1} of cereal grain or peas are harvested each year.

Huihe soil

The Huihe soil, cultivated for 0, 4, 10, 20, and 42 years, was sampled from gently sloping fields ($5\text{-}8^o$) in Beishui, Heshui County of Gansu province on May 25, 2000. The same sampling method was employed as described for the Huangmian soil. The annual rainfall at this site is 590mm, and the average temperature is 7.4^oC. About 60% of rainfall comes in July, August and September. The Huihe soil was developed under forest. However, the original forest was destroyed in Beishui historically and the land was reforested centuries ago. In the last 100 years, farmers cleared the bush and grow 0.75-1.0 tonnes ha^{-1} panic millet or beans, and annually apply 35-70 kg N $ha^{-1}$and 22.5-37.5 kg P_2O_5 ha^{-1}.

Heilu soil

The Heilu soil sampled is part of a 20 year long-term experiment. The soil is near Gaoping in Lingtai County of Gansu province and was sampled on August 15, 2000. The same sampling method was used as for the Huangmian soil. The treatments sampled were follows: (1) Check, no fertilizer. (2) N, nitrogen fertilizer at the rate of 90 kg N ha^{-1}. (3) M, manure at the rate of 7.5 tonnes ha^{-1}. (4) N+P, nitrogen fertilizer at the rate of 90 kg N ha^{-1} and phosphorus fertilizer at the rate of 75 kg P_2O_5 ha^{-1}. (5) N+P+M, manure at the rate of 7.5 tonnes ha^{-1} and nitrogen fertilizer at the rate of 90 kg N ha^{-1} plus phosphorus fertilizer at the rate of 75 kg P_2O_5 ha^{-1}. (6) Straw+N+P, returning wheat straw at the rate of 3.8 tonnes ha^{-1} and nitrogen fertilizer at the rate of 90 kg N ha^{-1} plus phosphorus fertilizer at the rate of 75 kg P_2O_5 ha^{-1}. In treatment (5) and (6), 75 kg P_2O_5 ha^{-1} was applied every two years while in the other treatments, applications were made every year. Strain was returned to treatment (6) but removed along with grain from other treatments. The treatments and yields were described in detail by Zhou and Ding (1996). An area of native sod in the same region was located and the soil was sampled. The nutrient content of applied manure was as follows: organic matter 20-25 g C kg^{-1}, total N 1.5-2.0 g N kg^{-1}, total P 0.8-2.5 g P kg^{-1}, available nitrogen 180-250 mg N kg^{-1}, soluble P 30-40 mg P_2O_5 kg^{-1}, soluble potassium 280-350 mg K_2O kg^{-1}. A winter wheat-soybean-maize rotation system is practised.

The Heilu soil is located on tableland of the Loess Plateau, and the nature of the level land makes cultivation easy. Therefore, the site has an agriculture history longer than 2000 years. The average annual precipitation is 560mm, and average temperature is 10.2^oC in Lingtai County.

Orthic Brown Chernozem

A chronosequence of Orthic Brown Chernozem soil, cultivated for 0, 10, 20, 40, 80 years as treatment, was sampled on April 4 2001. The soil is located near Central Butte, in southern-central Saskatchewan. In each field, a 100 m^2 area was selected of level topography. In three zones in each area, 20 cores (0-20cm) were taken randomly and mixed together to provide three separate composite samples from the 100 m^2 area. Average annual precipitation is 318 mm and annual average temperature is 2.6^{o}C.

Within the study area, matches of the Orthic Brown Chernozems under different tillage and rotation systems were located within 1x1 km^2. The treatments were: (1) Tillage, cereal-tilled fallow. (2) No-tillage, cereal-no-tilled fallow for 7 years. (3) Continuous cropping, conventional tillage. (4) Crop+alfalfa, cereal-fallow followed by 10 years alfalfa. Treatments (1) and (2) were described in detail by Jowkin and Schoenau (1998). Treatment (3) was shifted into continuous cropping (cereal-oilseed-peas) in 1990 after practising 70 years of cereal-fallow tillage. Treatment (4) was in cereal-fallow for 60 years and then 10 years of alfalfa, with only one crop of spring wheat planted after alfalfa before the soil samples were taken. Chemical nitrogen was not used in treatment (1), (2), and (4), but was used in (3). In each treatment, 5 soil cores of 0-10 cm depth were taken randomly on April 24 2001within a 100 m^2 in which pits were dug to ensure similar topography and parent material. Afterwards the cores were separated into 0-5 cm and 5-10 cm in lab and air dried.

Analytical methods

Total soil organic carbon (SOC)

A 0.15-0.20 g soil sample, which was ground with a ball-mill to pass a 100 mesh sieve, was combusted using Leco CR-12 Analyzer set at 840^{o}C, and the content of soil organic carbon was assessed directly by measurement of the CO_2 using an infrared detection (Wang and Anderson 1998).

Light fraction of organic carbon (LFOC)

A sub-sample of 25 g soil, ground to pass 2 mm sieve, was weighed into a 250-ml centrifuge tube, then 50 ml of NaI with density of 1.70 g ml^{-1} was poured into the tube. The tube was stoppered and shaken at 200 revolutions min^{-1} for 1 hour. The wall of centrifuge tube and the stopper was then washed with 3-5ml NaI and then was centrifuged for 20 minutes at a relative centrifugal force of 1000 g. The light fraction (LF), in suspension after centrifugation, was decanted into vacuum filter unit with 0.45um nylon filter paper. NaI was collected for reuse and the LF on the paper was washed with 75ml of 0.01M $CaCl_2$, followed by at least 75 ml of distilled water. The LF was transferred with water into a vial and the excess water was evaporated. The LF in vial was dried at 50^{o}C for 72 hours and the weight of LF was obtained. The residual material in the centrifuge tube was extracted with NaI one more time and two aliquots of the LF were combined together for a sample (Gregorich and Ellert, 1995b). The combined LF was ground to pass a 60 mesh sieve and combusted on the Leco CR-12 to determine the concentration of organic carbon in LF.

Microbial biomass carbon (MB-C)

Two aliquots of 20 g of fresh soil were weighed into two 200-ml flasks and 40 ml of 0.5 M K_2SO_4 was poured into each flask. 1 ml of chloroform, which was purified two times, was added into one of the two mixtures. The flasks were stoppered and shaken for 1 hour at 200 revolution per minute. The filtrate was collected and bubbled with CO_2 free air for 30 seconds after filtration. For the Chinese soil samples, 8 ml of the filtrate was transferred to a 150-ml flask, 0.075 g of HgO, 10 ml of concentrated H_2SO_4 and 5 ml of concentrated H_3PO_4 was also added into the flask. The mixture was digested at 250^{o} C for 30 minutes, and then was transferred into a 500 ml flask, titrated with 0.017 M $FeSO_4$ using ferroin as an indicator. The test was replicated 3 times for each soil sample. For the Canadian samples, the filtrate was diluted 10 times and then 4 ml solution was used to analyse total organic carbon using a Shimadzu 5050A Total Organic Carbon Analyzer. Microbial biomass carbon was calculated by the difference of carbon content in fumigated and unfumigated soil: MB-C (mg kg^{-1})= $(OC_F-OC_{UF})/0.18$ (Voroney and Winter, 1995).

Statistic methods

Statistical analysis was completed with SAS: ANOVA, REG, and NOLINE were used to conduct the analysis of variance, linear and nonlinear relationship. Mean values are reported in tables and figures.

Results and Discussion

Soil organic carbon in the chronosequence of three soils

Changes in total soil organic carbon content of soils with cultivation

Total soil organic carbon is reported to decrease upon cultivation, with a sharp decline at the beginning, followed by a slower decrease and eventually levelling off at a new lower equilibrium level (Janzen et al., 1997; Dalal and Mayer, 1986; Campbell, 1978). The relationship can be described satisfactory by the following formula (Dalal and Mayer, 1986):

$$Ct=Ce+(Co-Ce)e^{-kt}$$

Where Ct is the content of soil organic carbon at time t, t is the cultivation time, Co is the content of SOC under native vegetation, Ce is content of SOC at equilibrium, and k is the kinetic parameter which reflects how fast organic matter is lost. The formula can be applied to all component of SOC when soil management was constant and soil erosion was not a factor (Dalal and Mayer, 1986). As shown in figure 1, only the pattern in decline in the Huihe soil fit this model well. As a result, the k value for different regression can not be directly compared among soils. However, large differences in the magnitude and pattern of SOM decline can be observed among the soils.

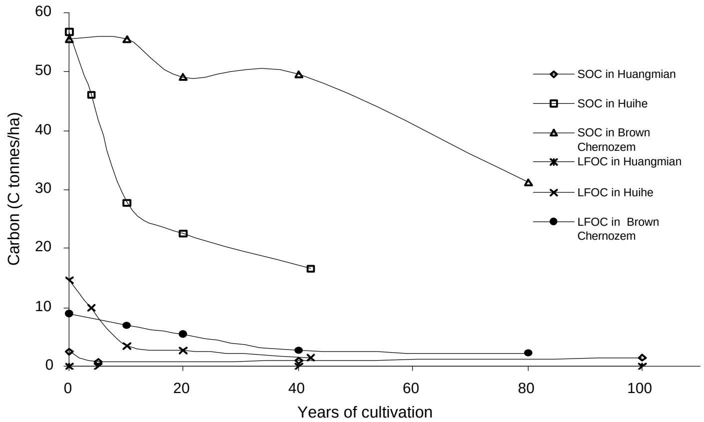

Figure 1. SOC and LFOC in soils with different cultivation years.

Table 1. Total Organic Carbon, Light Fraction, and Microbial Biomass Carbon in Soils (0-20 cm) of Chronosequences.

Soils and cultivation years	Total soil organic carbon (tonnes C ha^{-1})	Light fraction			MB-C (mg C kg^{-1})
		Dry matter (g kg^{-1} soil)	C content (g C kg^{-1} LF)	LFOC (tonnes C ha^{-1})	
Huangmian Soil					
0 yr.	13.94	11.77	112.03	2.59 (18.58[a])	653.81 (9.21[b])
5 yr.	3.18	7.63	38.88	0.71 (22.32)	241.11 (18.26)
40 yr.	5.30	5.76	77.09	0.97 (18.30)	328.75 (13.81)
100 yr.	5.03	6.63	87.16	1.37 (27.23)	242.65 (10.45)
$LSD_{0.05}$	2.34	2.27	19.28	0.31	149.24
Pr.>F	0.001	0.001	0.0002	0.0001	0.011
Huihe Soil					
0 yr.	56.78	37.57	175.03	14.74 (25.96)	775.93 (2.95)
4 yr.	46.89	30.53	141.10	9.88 (21.07)	710.95 (3.49)
10 yr.	27.83	13.20	124.00	3.45 (12.40)	637.91 (4.88)
20 yr.	22.56	8.83	133.57	2.67 (11.84)	342.21 (3.46)
42 yr.	16.66	6.83	95.83	1.41 (8.46)	228.71 (2.90)
$LSD_{0.05}$	14.05	12.35	57.65	7.67	177.99
Pr.>F	0.004	0.0007	0.1134	0.014	0.021
Orthic Brown Chernozem					
0 yr.	55.48	38.03	99.20	8.96 (16.15)	726.66 (3.17)
10 yr.	55.59	30.57	89.27	7.01 (12.61)	529.62 (2.64)
20 yr.	49.04	23.70	82.94	5.34 (10.89)	582.21 (3.30)
40 yr.	49.50	19.47	51.28	2.65 (5.35)	707.56 (4.07)
80 yr.	31.32	18.17	38.25	2.31 (7.38)	406.28 (4.12)
$LSD_{0.05}$	5.13	9.91	21.28	0.76	125.42
Pr.>F	0.0001	0.006	0.0003	0.0001	0.003

[a] The percentage of LFOC in SOC.
[b] The percentage of MB-C in SOC.

Among the two soils from the Loess Plateau, Huangmian soil has the lowest total organic matter under natural vegetation and SOC mass was decreased by 77% in this soil after 5 years of cultivation, with a decline rate of 2.15 tonnes C ha^{-1} yr^{-1} (Figure 1 and Table 1). Severe water erosion on this steeply sloping land and the decomposition of soil organic matter are primary causes for the sharp decline after only 5 years. Tillage erosion may also be a factor as farmers in this area practice contour ploughing on slopes. As a result, a 2-3 m high steep cliff at upper side and a 2-3 m wide terrace down the cliff is formed, and soil is always moved from the upper point to the lower by the plough even though contour tillage is practised. This area is also one of the districts that has the most severe soil erosion by water, with an estimated 6,050 tonnes ha^{-1} yr^{-1} of surface soil lost by water and wind erosion (Scientific Survey Office of the Loess Plateau in CAS, 1991).

The Huihe soil was formed under forest, with the highest content of SOC (56.78 tonnes C ha^{-1}) under native vegetation on the Loess Plateau. Its decline of SOC can be fit into $Ct=16.328-(57.683-16.328)e^{-0.1058t}$ and the value of Ce, Co and k are similar to that reported for Australian soils (Dalal and Mayer, 1986). There was a 70% reduction in SOC mass (0-20 cm) after 42 years of cultivation with a decline rate of 1.06 tonnes C ha^{-1} yr^{-1} for the first 4 years and 0.96 tonnes C $ha^{-1}yr^{-1}$ for 0-42 years (Table 1), which is comparable to the Riverview soil of Australia (Dalal and Mayer, 1986). It can be estimated according to the formula that only 1/3-1/4 of soil organic carbon would be remaining in soil if an equilibrium was reached under the conditions that only chemical fertilizer is used and the slope of the field usually is less than 5-8^{o}. Within the area, although erosion by water is estimated to be 182 to 955 tonnes soil ha^{-1} yr^{-1} under native vegetation, it could be as high as 7,330 tonnes soil ha^{-1} yr^{-1} upon cultivation (Scientific Survey Office of the Loess Plateau in CAS, 1991). Therefore, water erosion is likely the main reason and decomposition of SOM a secondary reason for the decline of SOC in the Huihe soil.

The decline of SOC in the Orthic Brown Chernozem can be divided into two phases: the soils cultivated for less than 40 years had a slower decrease rate (0.173 tonnes C $ha^{-1}yr^{-1}$) and ones cultivated longer than 40 years had higher decrease rate (0.454 tonnes C $ha^{-1}yr^{-1}$). The SOC (0-20 cm) decrease for the former was 11%, and for the latter was 44%, that is comparable to the reported average SOM loss of 22%-30% for Prairie soils (Gregorich et al. 1995a; Harse and Evans, 1957; McGill, 1988). The main reason for the larger decline in soil cultivated longer than 40 years is that there was very severe wind erosion during the period of 1930-1939 on the Canadian Prairies because soil was ploughed, disced and thus was vulnerable to wind erosion during this period of drought years (Lindwall, 1988; Anderson, 1975). The first use of the wide blade cultivator in 1936 began the history of retaining trash cover, and as a result, wind erosion was reduced (Lindwall, 1988; Campbell et al., 1988). Soil conservation was enhanced by the use of the combine harvester and thus stubble mulch became prevalent after World War II. After the1960s, wind erosion was controlled through improved cultural practices and the loss rate of SOC became slower. Therefore, the low rate of SOC loss from 1960 to present reflects mainly the decomposition of SOM under conservation tillage practices.

Another clear tendency is that the decline of SOC for the Chernozem in our study does not follow the equation described by Dalal and Mayer (1986). The reason is likely that the loss of SOC in early stages, for example, in 1930-1939, was largely due to severe wind erosion, and is compared to a soil cultivated for 40 years encompassing a period when erosion was reduced owing to modern farming techniques. A sharp decline of SOM in first decades after cultivation and then abatement in latter decades was observed on the Prairie (Monreal and Janzen, 1993;

Janzen, 1995), which was made in long-term experiments in small scale replicated field plots where erosion was not a major factor. Our investigation was made on soils in farm fields that were brought under cultivation at different dates and strongly reflected changes in tillage systems and environmental conditions over time.

Light fraction of soil organic matter

The light fraction is mainly recent debris of plant, animals and microorganisms. They are in various stages of decomposition and serve as a readily decomposable substrate for soil microorganisms and as a short-term reservoir of plant nutrients. As a result, light fraction is sensitive to the recent inputs of plant residue and thus can be a better indication of effects of soil management and cropping systems than total organic matter in soils (Gregorich et al. 1994; Janzen et al. 1992; Mensah, 2000).

The light fraction of carbon (LFOC) in the Huangmian soil accounted for 18.3-27.2% of total organic carbon in soil (Table1). The dynamics of LFOC was very similar to that of total organic carbon in this soil: a sharp decline in first 5 years followed by a small but significant increase in successive intervals (Table 1).

The Huihe soil had more dry matter of light fraction than the Huangmian soil under native vegetation. The reason is likely related to different climate: the Huihe soil developed in a sub-humid area, but the Huangmain soil was formed under sparse grass in a semi-arid region.

Because LF is composed of mineral particles and partly decomposed plant debris (Turchenek and Oades, 1979), we can thus speculate that organo-mineral complexes may more easily form in Huihe soil than in Huangmian soil. The reason is that the proportion of mineral material in the LF of Huihe was higher than that in LF of Huangmian because C content of LF in the former was lower than in the latter. In Huihe soil, LFOC was 8.5%-26.0% of total soil organic carbon, and the proportion decreased sharply when the years of cultivation increased, possible reflecting less recent C input and greater decomposition under cultivation (Voroney et al., 1981).

The Orthic Brown Chernozem has highest dry matter of LF, lowest C concentration in the LF and intermediate LFOC amounts among the three soils. The highest dry matter of LF and the lowest C concentration in LF implies ready combination of recent plant debris and mineral particles to form organo-mineral complexes.

Microbial biomass carbon

Microbial biomass carbon is an important attribute of soil organic matter quality as it provide an indication of a soil's ability or capacity to store and recycle nutrients and energy. As a measure of organic matter quality, it also serves as a sensitive indicator of change and future trends in organic matter level (Gregorich et al. 1994). MB-C is determined by the quantity and quality of C input into a soil. Thus, it is influenced by agriculture practices such as tillage, cropping sequences and manuring, as well as by climatic conditions (Insam et al., 1989).

Overall, MB-C of the three soils decreased with increase in cultivation time (Table 1). The proportion of total soil organic carbon comprised of MB-C for the Huangmian soil ranged from 9.2% to 18.3%, which was much higher than that reported by others (Insam et al. 1989; Anderson and Domch, 1989). It may reflect that Huangmian soil is in a semi-arid environment and the soil samples were taken two days after a shower, which would stimulate microbial activity. The MB-C proportion for the Huihe and Chernozem was 2.90%-4.88% and 2.64%-4.12%. MB-C was strongly related to total organic carbon and LFOC (Figure 2, 3)

Influence of tillage, rotation and fertilization on soil organic matter fractions

Management factors that affect the input and output of carbon in a system have an influence on the content of SOC. These management factors include tillage system, crop rotation, and fertilization practice.

The effect of tillage system

Several tillage systems were selected to reveal their effects on SOM in the Orthic Brown Chernozem (Table 2). Elimination of tillage can increase SOM and restore soil fertility, which was shown by several researchers (Campbell et al. 1996; Peterson et al. 1995; Larney et al. 1997). However, SOC was not increased in 0-5 cm and 5-10 cm layer by practising no-till during the fallow phase of the rotation for 7

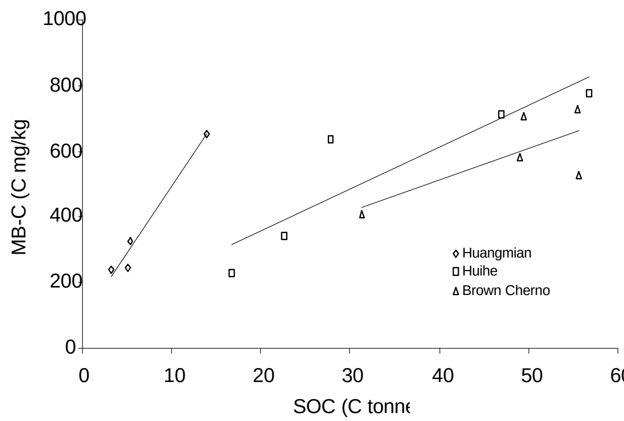

Figure 2. Correlation between SOC and MB-C.

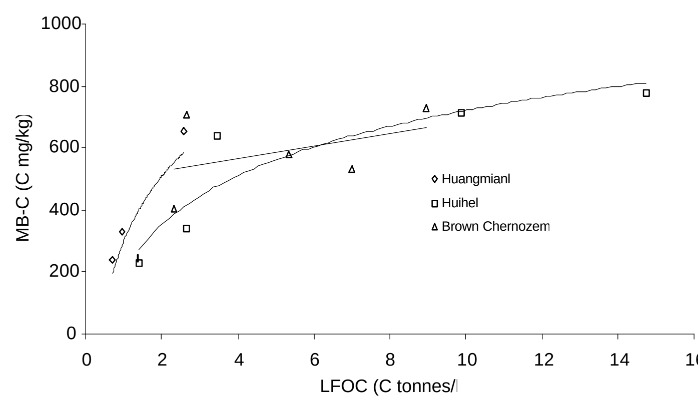

Figure 3. Correlation between LFOC and MB-C.

years after 70 years tillage. Nevertheless, the dry matter of LF was increased significantly in 0-5 cm of notillage, showing a tendency for combination of debris and mineral particles to form organo-mineral complexes. Elimination of tillage alone cannot be expected to increase SOM in a short period, especially when erosion losses by wind were not significant over the time.

Table2. The Effect of Tillage and Rotation on Total Soil Organic Carbon, Light Fraction Organic Carbon, and Microbial Biomass Carbon in the Orthic Brown Chernozem.

Tillage and rotation	Total soil organic carbon (tonnes C ha^{-1})	Light fraction			MB-C (mg C kg^{-1})
		Dry matter (g kg^{-1} soil)	C content (g C kg^{-1} LF)	LFOC (tonnes C ha^{-1})	
0-5cm					
Tillage	8.63	29.14	66.47	1.20 (13.91[a])	595.91 (4.41[b])
Notillage	6.65	43.20	36.39	1.09 (16.45)	559.63 (5.88)
Cont. Crop	9.27	49.46	46.30	1.49 (16.07)	570.69 (3.97)
Crop+Alfalfa	15.45	44.94	107.77	4.15 (26.87)	830.43 (3.45)
$LSD_{0.05}$	1.72	10.42	21.85	0.94	152.84
Pr>F	0.001	0.005	0.0001	0.0001	0.01
5-10cm					
Tillage	7.59	7.06	83.68	0.38 (4.94)	316.33 (2.93)
Notillage	6.28	6.58	50.30	0.22 (3.4)	279.49 (3.27)
Cont. Crop	7.96	11.70	61.67	0.48 (6.07)	486.70 (4.02)
Crop+Alfalfa	9.66	20.94	83.62	1.43 (14.83)	505.19 (3.76)
$LSD_{0.05}$	2.81	5.20	42.39	0.56	88.30
Pr>F	0.199	0.0001	0.284	0.001	0.001

[a] The percentage of LFOC in SOC.
[b] The percentage of MB-C in SOC.

Continuous cropping increased SOC by 7.5% and 4.8% in 0-5 cm and 5-10 cm respectively, compared with cereal-fallow. Dry matter of LF was significantly increased by 70% and 65% while LFOC increased by 24% and 29% in the 2 layers. It has been reported that continuous cropping can increase input of plant residue compared with a rotation system in which fallow was involved (Janzen et al., 1992). Besides continuous cropping, other measures that reduce summerfallow frequency from one fallow period every 2 years, to once in every 3 or 4 years, can also function to restore soil organic carbon (Peterson et al. 1998; Janzen et al. 1998; Biederbeck et al. 1994; Larney et al. 1997). Therefore, in the absence of erosion, extending the rotation could be more important in increasing SOC than elimination of tillage.

SOC can be increased when a long-term forage legume crop is introduced into rotation. Growing alfalfa for 10 years after 60 years of cereal-fallow resulted in which SOC was 80% and 27% higher in 0-5 cm and 5-10 cm respectively, compared with cereal-fallow. At the same time, dry matter of LF, LFOC were increased by 54% and 194%, 245% and 286% in the 2 layers respectively. The proportion of SOC comprised of LFOC was increased by 1 to 3 times (Table 2). Obviously, light fraction was rapidly restored by planting alfalfa. Janzen et al. (1997) and Campbell et al. (1997) also found that SOC was increased when a legume was introduced into the rotation.

The effect of fertilization

It has been shown that application of chemical fertilizer and manure can increase SOM (Biederdeck et al., 1994; Campbell et al., 1991). Chemical fertilizer can increase shoot and root production of a crop, eventually increasing residue input into soil. Comparably, manure contains material that is a precursor to SOM and also provides available nutrients. This effect has been realized and used for nearly 4000 years in China, Japan, and Korea (Dormaar et al. 1988) to restore soil fertility and get a satisfactory yield.

Table 3. The Influence of Fertilization on Total Organic Carbon, Light Fraction, and Microbial Biomass Carbon in the Heilu Soil (0-20 cm)

Treatment	Total soil organic carbon (tonnes C ha^{-1})	Light fraction			MB-C (mg C kg^{-1})
		Dry matter (g kg^{-1} soil)	C content (g C kg^{-1} LF)	LFOC (tonnes C ha^{-1})	
Native sod	25.89	9.83	185.72	5.17 (19.97[a])	608.72 (5.83[b])
Check	19.49	5.50	142.40	2.13 (10.93)	428.27 (5.90)
N	15.85	4.90	150.67	2.00 (12.62)	503.15 (8.63)
M	25.99	8.23	186.50	3.83 (14.73)	724.27 (6.59)
N+P	15.90	6.00	117.22	1.64 (10.31)	663.82 (9.98)
M+N+P	24.01	10.27	159.77	3.89 (16.20)	903.30 (8.98)
Straw+N+P	18.83	6.80	129.50	2.17 (11.52)	671.37 (8.93)
$LSD_{0.05}$	2.85	1.92	28.06	0.75	160.25
Pr>F	0.001	0.0001	0.0006	0.0001	0.01

[a] The percentage of LFOC in SOC.
[b] The percentage of MB-C in SOC.

The results of a long-term experiment on Heilu soil of the Loess Plateau (Table 3) demonstrated the positive effect of manure amendment on SOM. The addition of 7.5 tonnes manure $ha^{-1}yr^{-1}$ for 20 years produced the highest SOC and LFOC in 0-20 cm layer among treatments, with SOC as high as the native sod.

The SOC and LFOC of the fertilized treatments: N and N+P were the lowest, even lower than the treatment of no fertilizer application (Check). Applying straw with nitrogen and phosphorus (Straw+N+P) fertilizer resulted in higher SOC and LFOC than N and N+P alone, but SOC and LF for the treatment was still lower than that of the Check. The chemical fertilizer alone may have had the effect of enhance the decomposition of SOM in this soil. This observation contradicts others observed on the Loess Plateau and the Canadian Prairie (Bremer et al. 1994; Campbell et al. 1991; Odell et al. 1984; Wang, 1996). The possible reason is the chemical fertilizer changed the biochemical condition of soil and thus the equilibrium shifted toward decomposition. The evidence is that MB-C in soils that received chemical fertilizer was 17%-110% higher than the Check. Higher MB-C suggests more intense activity of microorganisms and thus more decomposition of soil organic matter (Anderson and Domsch, 1990). Insam et al. (1989) also found that MB-C was higher in the plots that received chemical fertilizer than the non-fertilized.

This long-term experiment is located in a flat area of the Loess Plateau. On this level land, agriculture has been conducted for more than 2000 years. However, SOC was 29% lower when only chemical fertilizer was used compared to native sod. That there is not water corrade but little wind erosion is responsible to the depletion. Meanwhile, manure application was most effective in maintaining the SOC of cultivated land there.

Applying straw and fertilizer together has a positive effect over fertilizer alone. Returning of straw using a combine harvester has been occurring on the Canadian Prairies for more than 50 years. This may also explain why the rate of SOC decline for the soil cultivated 10-40 years ago was only 1/3 of that cultivated 40-80 years, as more residues was left on soil as compared to the burning of straw piles left by stationary threshing machines. Within tableland area of the Loess Plateau, now about 1/3 winter wheat is harvested with combines, because the cost to hire labour is higher than to rent a machine. As a result, return of residue cover will be more prevalent in the region besides manure application, keeping soil fertility sustainable in the future on the Loess Plateau.

Conclusion

The SOC of newly cultivated land on the Loess Plateau decreased sharply, by about 70%-79% on steeply sloping farmland (Huangmian and Huihe soil) over a short period (5-42 years). However, SOC only decreased by about 29% on a flat area (Heilu soil) of the region after thousands years of cultivation. The comparison illustrates that soil erosion, mainly water erosion in the steeply sloping land, is the main reason for SOC loss on the Loess Plateau. This is also true for the Orthic Brown Chernozem, for which the greatest decline in SOC was associated with the time period encompassing severe wind erosion during the 1930's.

Application of manure, or manure plus chemical fertilizer on the Loess Plateau, has a positive effect on SOC restoration. Extending the crop rotation, involving legume crops in rotation (especially as long-term forage legume) and eliminating tillage appear to be effective strategies to increase SOC on the Canadian Prairies.

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