Saskatchewan Soil Conservation Association

Prairie Soil Carbon Balance Project:

Monitoring SOC Change Across
Saskatchewan Farms from 1996 to 2018

Change in SOC at Field Level Component

Report, Feb. 23, 2020

Brian McConkey[1], Mervin St. Luce[2], Brian Grant[3], Ward Smith[3], Alvin Anderson[1], Glenn Padbury[1], Kelsey Brandt[2], Darrel Cerkowniak[4]

[1]AAFC (Retired)

[2]AAFC (Swift Current)

[3]AAFC (Ottawa)

[4]AAFC (Saskatoon)

Executive Summary

There is great interest in the status of soil organic carbon (SOC) as an indicator of soil health and as a measure of removal of the greenhouse gas, carbon dioxide, from the atmosphere. Each ton of SOC in the soil represents a past removal of 3.67 tons of carbon dioxide from the atmosphere so there is much interest from the private and public sector in increasing investment into practices the increase SOC for greenhouse gas mitigation.

The Prairie Soil Carbon Balance Project (PSCB) was initiated by the Saskatchewan Soil Conservation Association to establish a system to monitor SOC on commercial farm fields across Saskatchewan that were converted from conventional management to direct seeding and continuous cropping in 1997. Under this project a network of 136 commercial farm fields in Saskatchewan was established with initial measurement of SOC in fall 1996 with the plan to track SOC change with repeated samplings. A small benchmark, 16 x 7 ft, is in each field, locatable with a buried marker. Within each benchmark at each sampling, a composite sample of six soil cores was taken to 16 inches below the surface in 4-inch increments. For each sampling, a new set of six cores were taken offset from other samplings by 20 to 40 inches from the previous coring locations. The mass of SOC is estimated from analysed SOC concentration and the soil density. The network was resampled in 1999 (136 fields), 2005 (121 fields), 2011 (80 fields), and 2018 (90 fields). The number of fields differed between samplings due to changes with involvement of co-operators over the project duration.

An unexpected finding was there was massive spatial variability of SOC within the benchmark. Therefore, when the new six cores were taken at each sampling, by chance, the six cores could sample soils with high relative SOC or soils with low relative SOC. This creates a random difference between samplings due to spatial variability. With another sampling, the physical offset for the new six cores creates introduces another difference between measurements. To avoid systematic variability due to analysis, comparison was made between SOC for the current sampling and archived 1996 soil that were both analysed at the same time in the same laboratory.

The first major finding of the PSCB was that it is not possible to use one benchmark to reliably estimate SOC change due to the spatial variability of SOC. Nevertheless, the average differences for many fields in the PSCB network are reliable measures that can be detected from differences due to chance alone. To about a 1-ft depth, the change in SOC from 1996 was 0.69 ton/acre in 1999, 0.16 ton/acre in 2005, 1.36 ton/acre in 2011, and 0.99 ton/acre in 2018. The change to 2018 amounts to about 5% of initial SOC in 1996. Although these changes are modest, they conclusively show that SOC in increasing on direct seeded commercial farm fields in Saskatchewan. The smaller change from 1996 for 2005 sampling was related to the depressing effect on SOC of widespread droughts over the 2001-2003 period.

The second major finding of the PSCB was that SOC increase lessened as initial SOC in 1996 increased. This occurred for all depths and across soil zones.

A third major finding was that SOC was increasing at deeper depths than expected based on past research on small plots. In soils with low SOC at depth, there were important gains in SOC at depth regardless of the depth of soil profile development.

The measured changes from the PSCB generally agree with the estimates of SOC change that are contained in Canada's national inventory of greenhouse gas emissions and removals. More site-specific modelling agreed better with national than with observations.

We are indebted to the many farm cooperators who have made the PSCB project possible. We need the co-operators' further assistance to collect data on the management history of the fields so that we can investigate the effect of management on SOC behaviour.

The PSCB project has provided some new and unique information about the behaviour of SOC on commercial farm fields throughout Saskatchewan. We now have confirmation that the fields are increasing in soil carbon and that has market value.

Introduction

Soil organic carbon (SOC) is strongly related to many important aspects of soil quality including nutrient cycling, soil aggregation and structure, movement of air and water into and through the soil, adsorption and breakdown of pesticides, cation exchange capacity, and microbial quantity and diversity. Land management practices that decrease SOC are thus soil degrading, while practices that increase SOC are equated with soil-improving practices. Thus, the change in SOC is a useful indicator of the change in general soil health (Gregorich et al. 1994).

Importantly, changes in SOC also represent removals and emissions of the greenhouse gas (GHG), carbon dioxide (CO_2). Increase in SOC is the storage, or sequestration, of carbon from CO_2 removed from the atmosphere by plants that became SOC.

Soil organic carbon is affected by changes in agricultural land use or land management on agricultural lands. In the prairie region of western Canada, there have been several shifts in land management over the last 30 years, most notably – adoption of direct seeding (seeding without tillage for seedbed preparation), reduction in frequency of summer fallow (leaving cropland out of production during a regular growing season) and use of less intensive soil cultivation equipment over time (shifts from plows to discs to light cultivators). These changes and their effect on SOC have been well documented (McConkey *et al.*, 2003; VandenBygaart *et al.*, 2003; VandenBygaart *et al.*, 2008).

Canada has focused significant efforts on developing a system for measuring, monitoring and verifying SOC changes in Canadian agricultural soils for the purposes of reporting to the United Nations Framework Convention on Climate Change (VandenBygaart et al., 2008) utilizing the guidelines of the Intergovernmental Panel on Climate Change guidelines for national inventories (IPCC, 2006). Canada annually reports changes in SOC in agricultural lands in the National Greenhouse Gas Inventory Report (NIR)(Environment and Climate Change Canada, 2017). The methods are based on applying a modelled approach (Century model) to estimate change in SOC relative from change in management relative to a baseline without that change in management. The SOC changes in the NIR are relative changes compared to a baseline. Vandenbygaart et al. (2008) reported that for the land management changes, the modelled emission change factors were in the range of measured values from small-plot experiments in the scientific literature.

Under their Nationally Determined Contribution for the 2015 Paris Agreement, Canada has pledged to reduce its total emission to 30% below 2005 levels by 2030. Soil sinks are part of the plan, although are not expected to be an important part of the contribution since 2005 had a large soil sink and so it is difficult to add new net soil sink.

There are also questions about whether SOC change is different on commercial farm fields than small-plot experiments.

A new requirement for substantiation of absolute SOC change in Canadian soils is emerging, driven by sustainability requirements of agri-food and/or renewable fuel supply chain. For Canadian agricultural commodities, the demonstration of absolute SOC changes will give a competitive advantage to Western Canadian growers to penetrate these markets.

This report summarizes findings of the "The Prairie Soil Carbon Balance" (PSCB) research project with emphasis on the series of results from the 1999 to the 2018 sampling.

Methods

Project Overview

The Prairie Soil Carbon Balance Project (PSCB) was initiated by the Saskatchewan Soil Conservation Association (SSCA) to establish a system to monitor SOC on commercial farm fields across Saskatchewan that were converted from conventional management to direct seeding and continuous cropping in 1997. Under this project a network of 136 commercial farm fields in Saskatchewan was established with initial measurement of SOC in fall 1996 with the plan to track SOC change with repeated samplings.

The Prairie Soil Carbon Balance Project was designed to measure change in SOC since 1996 in Saskatchewan from the adoption of direct seeding on commercial farm fields. One purpose for the measurements was to support measurement of SOC change for greenhouse gas offsets. The PSCB consists of a network of 136 commercial farm fields (Figure 1).

Each field has a small benchmark (Figure 2). The benchmark is designed to offset samplings a short distance to improve ability to detect small changes in SOC (Ellert et al., 2002). The benchmark was relocated by GPS location and the exact NE corner was then located by sensing a buried passive 3M utility marker. The benchmark location was not visually obvious to the co-operator.

The SSCA and Agriculture and Agri-Food Canada (AAFC) has continuously led the project and provided the in-kind resources that made the project possible. Incremental funding for 1996 and 1999 sampling was provided by GEMCO (Greenhouse Emissions Management Consortium) and AAFC. Incremental funding for 2005 sampling was provided by AAFC. Incremental funding for 2011 sampling was provided by AAFC and Saskatchewan Pulse Growers. Incremental funding for the 2018 sampling was provided by Saskatchewan Pulse Crop Development Board, Saskatchewan Canola Development Commission, Saskatchewan Wheat Development Commission, SaskBarley Development Commission, Saskatchewan Flax Development Commission, Saskatchewan Oat Development Commission, and Saskatchewan Agricultural Development Fund. For the 2018 sampling, the University of Saskatchewan (Dr. Jeff Schoenau) also provided important in-kind resources.

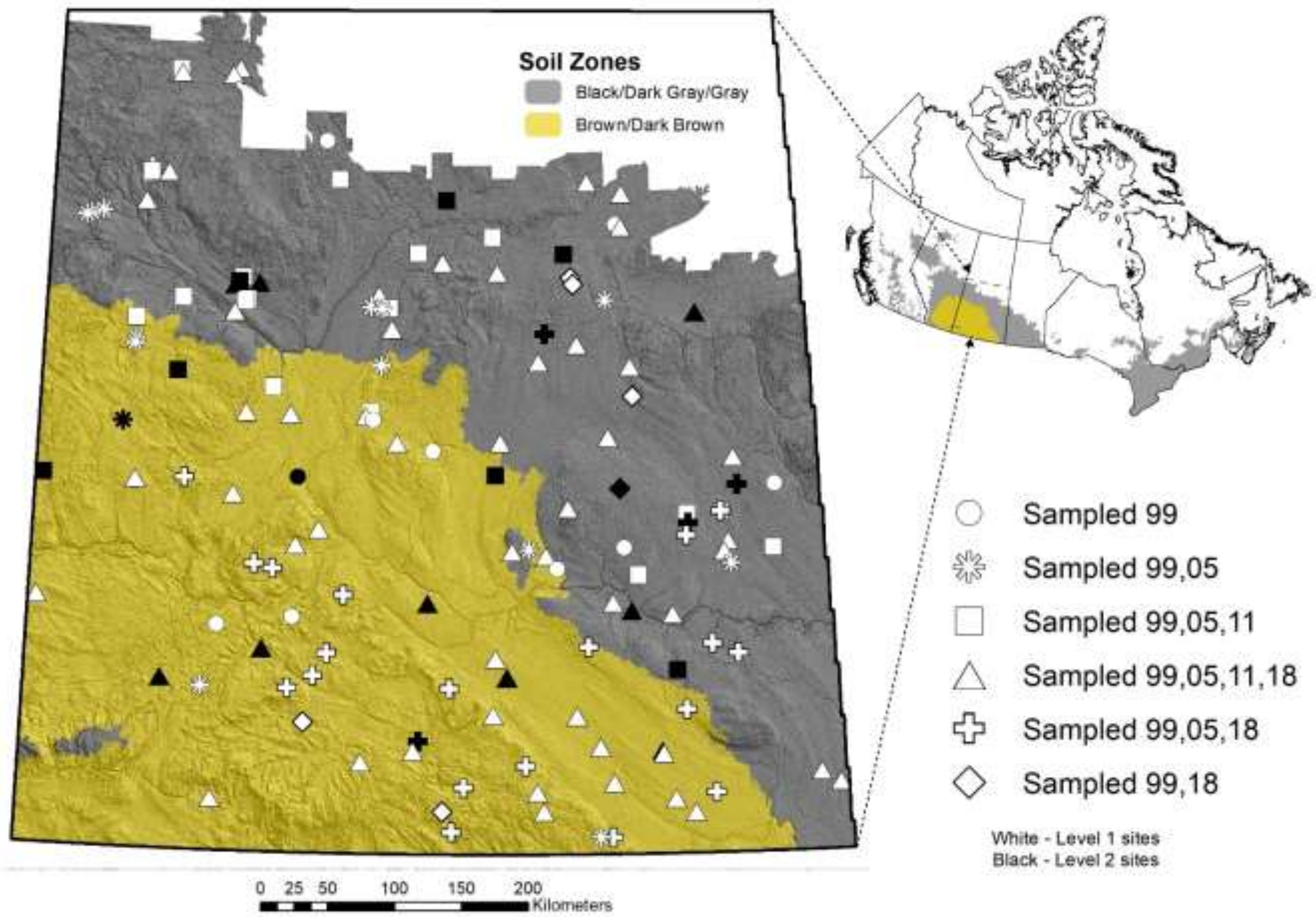


Figure 1. The Prairie Soil Carbon Balance Project field sites.

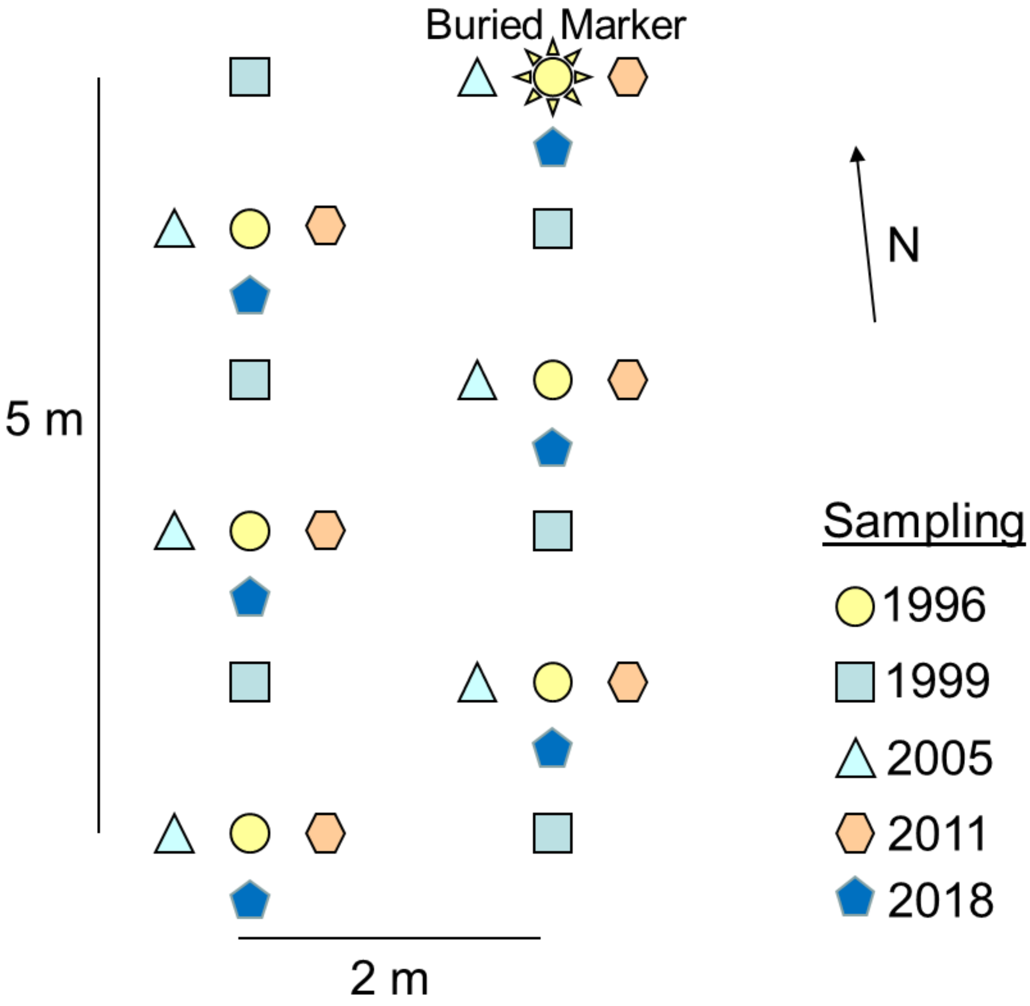


Figure 2. Benchmark layout. The 1999 sampling is offset 1 m from the 1996 sampling, the 2005, 2011 and 2018 samplings are offset 50 cm from the 1996 sampling. (The benchmark is oriented to magnetic north so deviation from true north varies with site location.)

Benchmark Site Selection

The Saskatchewan Soil Conservation Association (SSCA) field staff compiled a list of co-operators in 1996 that had changed land from conventional tillage to direct seeding management in 1996 or were planning to make that change in 1997. The sites were selected from this list so there was representation from a full range of cropped soil conditions present in Saskatchewan. Each site was a field of about 30-65 ha. Irrigated fields, fields having recent application of organic amendments, or recent perennial forages were excluded so that the main factor expected to affect SOC was change in tillage and cropping intensity under rainfed conditions.

Although the criteria were change in tillage system, it needs to be emphasized that in many cases a change to direct seeding was often accompanied by more intensive cropping, i.e. extended rotations and less fallow. Many of the fields were being incorporated into the operation of an experienced no-till farmer. Therefore, there were also usually changes to crop mix and fertilizing practices.

Benchmark locations within field sites were chosen to avoid landscape complications. For instance, benchmarks were placed on relatively level landscape segments to reduce soil erosion and deposition effects. The benchmarks were typically 100 m from either field edges or uncultivated patches and where there were several benchmarks in one field, they were separated by a distance of at least 200 m. Field unconformities (gullies, gravel outcrops, saline seeps, etc.) were avoided. Experienced pedologists relocated benchmarks if coring revealed atypical soil non-uniformity such as evidence of past physical disturbances. An important initial objective of the project was to evaluate the suitability of benchmarks for detecting SOC change over time. To meet that objective, it was not essential that the benchmark be a representative or model soil type for the field as a whole. Therefore, the soil type was not a criterion for site selection.

A level 1 site was one benchmark in a single field. A total of 114 level 1 sites were established (Figure 1). The level 2 sites, in addition to assessing the change in soil organic carbon due to the adoption of direct seeding technology, were designed to provide a measure of the effect of tillage alone on soil carbon sequestration during 1997-99. To affect the comparison between direct seeding and conventional tillage, farmer cooperators were asked to carry out tillage operations representative of a conventional tillage system on a small (5 ha) area within a direct seeded field during 1997-99. Three soil sampling sites were established in the tilled area, and another three in the adjacent direct seeded area. Twenty-three level 2 sites were established (Figure 1). After 1999, there was no more tilled strip and the whole field was managed the same and only one of the original direct-seeded benchmarks was sampled in 2011 and 2018.

Samplings

Contact with the cooperators was consistently done by SSCA. There was regular contact between the cooperators during 1997-2004. Already in 1999, there were some sites that had changed land operator. Frequently, new operators agreed to continue with the project. For the 2005 sampling, several cooperators could not be located from existing contact information and some new field managers did not want to continue with the project. Hence, there were only 121 fields sampled that year. By 2011, many of the fields had changed operators and only 80 fields were available for sampling. For 2018, more effort was made to contact cooperators, and 90 fields were sampled. For 1996, 1999, 2005, and 2011, all sampling was done in the fall after harvest. In 2018, the sampling was in the spring, mostly before seeding with some sites sampled after seeding but before crop emergence.

The soil was sampled to 40 cm in 10 cm increments. The 6 cores at each site were composited in the field.

Field Management

Field management information was collected from cooperators by SSCA. Because of change in operators, many cooperators could not provide complete management history. Change of operators was already observed for the 1999 sampling and by 2018 the majority of the sites had changed operator since 1996 and many fields had had three different operators. Frequently, the new operator became a cooperator.

During 1997-99, the cooperators received some consideration for cooperation (level 1 sites received free SSCA membership) and most fields had management data collected, consisting of crop type, yield, level of seeding disturbance (<20% seedbed utilization,), tillage practices, and residue management (baling, burning). After 1999, the cooperators received no consideration and many did not provide management data. Also, new operators could not easily provide management data before they managed the land. For these reasons, the management data is spotty. Currently, there is only one site with management data for every year in the project.

Sites were not dropped based on management not conforming to expected conservation agriculture.

Soils

The soils belonged to the Brown, Dark Brown, Black, and Dark Grey Great Groups of the Chernozemic order and the Grey Great Group of the Luvisolic Order. To have a good number of sites for purposes of the analysis, we divided the sites into the semiarid prairie consisting of the Brown and Dark Brown Chernozemic soils and the subhumid prairie consisting of the Black and Dark Grey Chernozems and the Grey Luvisols.

The horizons were also identified in 1996 sampling for each core. The Ap horizon is the "plow layer" which equals the deepest depth of tillage in previous decade such that it was thoroughly mixed. The A horizon is the topsoil depth. The solum depth is the extent of pronounced soil formation and extends to the bottom of the B horizon. Below the solum depth lies the C horizon that is visibly unaltered parent material except for possible carbonate accumulation derived from the solum. As expected, depth of soil formation was deeper in the subhumid prairie than the semiarid prairie (Table 2). Basically, the 0-10 cm corresponds to the plow layer. For the semiarid prairie, the 0-30 cm depth contains the solum for about one-half of soils, while, for the subhumid prairie, the 0-40 cm depth contains the solum for about one-half of the soils.

Table 2. Soil genetic development by depths of Ap, A, and the depth to C horizon in 1996.

		Average		Depth to C horizon				
Prairie	**Sites**	**Ap**	**A**	**≤20 cm**	**>20&≤30 cm**	**>30&≤40 cm**	**>40&≤50 cm**	**>50 cm**
	n	Cm	cm	n	n	n	n	n
Semiarid	61	9.8	10.9	18	16	12	9	7
Subhumid	75	12.1	15.1	10	18	11	15	21

The texture of the surface was evaluated in 1996 by experienced pedologists. The soil was then assigned into three textural groups: coarse (sand to sandy loam), medium (very fine sandy loam to clay loam) and fine (sandy clay to heavy clay). The majority of soils were overwhelmingly medium textured (Table 3) reflecting the predominance of loamy parent materials of unsorted glacial till and silty glaciolacustrine and aeolian deposits.

Table 3 Number of sites falling into the coarse, medium, and fine soil textural groups

Prairie	Coarse	Medium	Fine
semiarid	3	46	12
subhumid	8	64	3

Soil Analysis

The SOC was analysed using three methods. In 1999 and 2018, the total carbon was determined from dry combustion after soil inorganic carbon (SIC) was removed with acid treatment, thus the measurements reflect soil organic carbon. However, these were done in two different labs. In 2005, the total carbon was also measured using dry combustion. However, organic carbon was assumed to be that evolved from the sample at a temperature of 850ºC, a temperature deemed too low to decompose SIC quickly. Lastly, in 2011, the total carbon was determined by dry combustion from which organic carbon was estimated by subtracting SIC that was measured separately as CO_2 evolved with acid treatment. For each analysis archived soil from 1996 was also analysed using the same method. Due to the variety of analytical methods used, SOC differences will only be considered for the same analytical method, specifically the difference from 1996 (initial) values.

Equivalent Soil Mass

The SOC was expressed on the basis of the average soil mass for 10 cm, 20 cm, and 30 cm for each benchmark across samplings. Using this average allows fair comparison between samplings. If the sampling has more mass than the average, then soil mass with its associated SOC was subtracted from the last increment until the total mass equals the average mass. If the sampling had less mass than the average, then mass and its associated SOC was added from the next deepest soil increment. For the 40 cm, the minimum soil mass was used as the mass for reporting. For samplings with more mass, then mass was subtracted. Using the minimum mass for the last increment preventing having to estimate unmeasured SOC concentration and bulk density below 40 cm. The average effective depth across samplings to achieve the minimum soil mass to 40 cm was 38.6 cm. Hence, we refer to the whole measured profile as 0-39 cm.

The SOC masses results are expressed from the surface. Therefore, the SOC is cumulative from the surface, for example, the SOC change from 0-20 cm includes the SOC change from 0-10 cm as well as from 10-20 cm. The estimate for specific increments can be calculated by subtracting the SOC mass for upper soils. For example, the estimate of the 10-20 cm depth is the 0-20 SOC minus the 0-10 cm SOC. Note that this is for an average 10 cm depth across sampling based on soil mass and not 10 cm depth as measured in a particular sampling.

Modeling with Process Model

The process model DNDC (Li, 1996) was chosen to simulate the SOC for 58 sites that were sampled at each sampling. DNDC is one of the most widely used models globally to estimate SOC change (and soil N_2O emissions) with many application for Canada (Smith *et al.*, 2002; Grant *et al.*, 2004; Smith *et al.*, 2004; Qin *et al.*, 2013; Grant *et al.*, 2015; Guest *et al.*, 2017). Importantly, among widely used models, it is the only one that can simulate SOC by depth increment and to depths below 20 cm. However, this capability to handle deeper depths is a new version of the model and so the results are still preliminary.

The model was run using observed weather from the nearest weather station with available archived data. The soils data was from the observations. A generalized sequence of management was produced to represent the frequency and sequencing of crops and tillage based on available management data.

Work is underway on model calibration and initialization to improve application of this model for this project over the depth increments.

Results

Field Management

There were 56 sites with at least 9 years of management information available (819 site-years of management data). These sites were used to quantify the management practices.

Wheat and canola were the most frequent crops (Table 3). Among the 56 sites, 42 had 5 or more crop species, 11 had 4 species, 3 and 3 species and one had only two species (wheat and canola). Most sites had all of cereal, oilseed, and legume crops although 8 had no legumes and one had no oilseeds. Fallow was reported on 23 of the sites. Excessively wet conditions prevented seeding on much land in in 2010 and 2011 and 12 of the 28 site-years of fallow (43%) occurred in those two years.

There were few examples of fixed rotations even if one- or two-year gaps in data were assumed to follow a preceding or following crop pattern. Only one site followed a fixed rotation (wheat-canola-barley-pea) throughout its management history and another site followed that same rotation for 3 cycles but not the entire period of its management history. One site followed two cycles of a durum-lentil-durum-flax but had different sequences before and after that period. One site had 8 successive wheat crops. There was no evidence of any 3-year or 5-year rotations. A few sites had repeated 2 or 3 cycles of 2-year sequences but all those sites had many other 2-year sequences in addition. There were 84 different sequences in the management data and these generally varied continuously over time. Nevertheless, there was a general pattern as sequences of alternating broadleaf and cereal crops dominated, representing 81% of the 2-year sequences. Two-year sequences of cereal-cereal were 7%, those with fallow were 7%, and those of broadleaf-broadleaf crop were 5% of total sequences. The 2-yr sequence of the same crop accounted for 4% of sequences of which ¾ were wheat-wheat.

The majority (30 sites) of the 56 sites had some tillage. Harrowing (defined as spring tooth or spike tooth harrows) was practiced at 20 of 56 sites. At 18 sites, cultivation (defined as cultivator or tandem disc) was practised. Both types of tillage were practised at 8 sites. Over the 819 site-years of data, harrowing was practiced 73 times (10.5%) and cultivation 54 times (6.8%). It was not uncommon to have more than one of these tillage operations per year: 8 site-years had 2 cultivations, 6 had both a cultivation and harrowing, and 5 had 2 harrowing operations. Therefore, 44 site-years (5.3%) had cultivation and 68 (8.3%) had harrowing.

Baling or burning occurred on 16 of the sites with 8 sites-years with burning (for 2 of these the comment noted burning was unintentional), and 17 site-years with baling. Manure application was reported for 2 site-years.

Table 3. The frequency of crops and two-year sequences showing all sequences representing 2% or more of all sequences

Crop	Site-Years	%	Sequence	Site-year pairs	%
Wheat	203	25	wheat-canola	73	10
Canola	179	22	canola-wheat	66	9
Peas	95	12	pea-wheat	45	6
Durum	83	10	canola-barley	41	6
Barley	80	10	wheat-pea	34	5
Lentils	52	6	barley-canola	30	4
Flax	41	5	durum-lentil	23	3
Fallow	28	3	barley-pea	21	3
Oats	22	3	wheat-wheat	21	3
chickpeas	11	1	lentil-durum	20	3
canaryseed	10	1	flax-wheat	18	2
mustard	7	1	pea-durum	17	2
Alfalfa	2	<1	durum-canola	15	2
soybean	2	<1	wheat-flax	14	2
dry bean	1	<1	wheat-lentil	13	2
safflower	1	<1	canola-durum	12	2
sunflower	1	<1	wheat-fallow	12	2
triticale	1	<1	oat-canola	11	2
Total	819		fallow-canola	11	2
			other cereal-broadleaf and broadleaf-cereal crops	125	17
			broadleaf-broadleaf crops	39	5
			other cereal-cereal crops	30	4
			other sequences with fallow	26	4
			Total	729	

Variability of SOC

There was variability in the SOC for 1996 for different analyses. Figure 3. shows the differences for the 58 sites that had all samplings. Compared to 1999 analysis, the linear fit indicated that the other analyses tended to produce lower estimates as SOC concentration increased. However, the overall average SOC concentration was not significantly different between analysis year (Table 4). Some of the variability would be due to variation between subsamples used for analysis. Other variability from different laboratory analysis methods. The latter was controlled by always comparing the subsequent year SOC with the SOC for 1996 that had been determined using the same laboratory techniques.

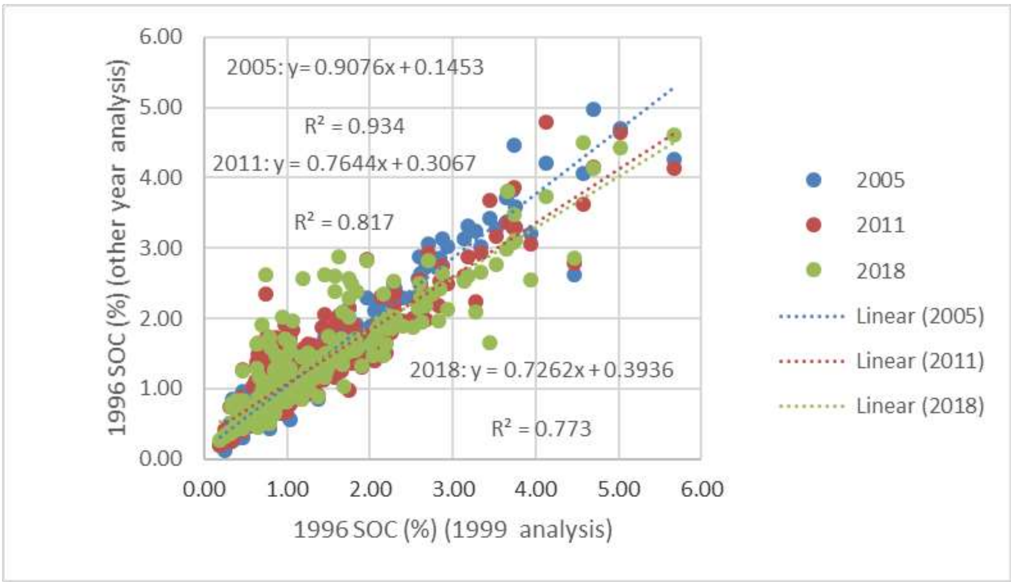


Figure 3. Variability of SOC to 39 cm for soil sampled in 1996 for analysis years of 1999, 2005, 2011, and 2018.

Table 4. Mean soil organic carbon concentration for the four analysis years.

Analysis Year	Organic carbon concentration (%)
1999	1.44
2005	1.45
2011	1.41
2018	1.43
LSD (P=0.05)	0.14

In 1996, a 1x1 m grid of cores was taken at eight of the sites. These revealed that there was much more spatial variability than expected over the benchmark area. Figure 4 is an example of the variation.

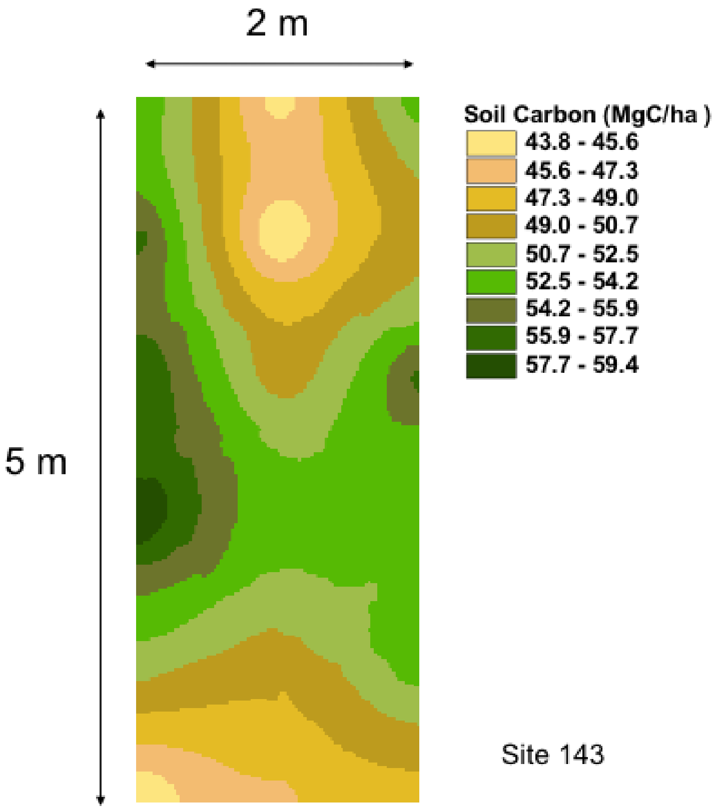


Figure 4. Example of SOC variability within one benchmark.

The result is that the spatially offset sampling will, by chance, sometimes be of soil with much more or much less than the initial sampling. This introduces a huge amount of variability. In fact, using a method called bootstrapping, we estimated that the variability for different composite samples of six cores would only allow us to estimate the SOC content of the benchmark area to ±3.6 Mg C/ha in 1996. Unfortunately, as a result, the benchmark method is not useful for estimating SOC change on one field.

The variability from both spatial variability and subsampling was obvious comparing different samplings for the 58 sites that were sampled at all sampling (Figure 5). Since the SOC change from 1996 to 2018 would be affected by the change from 1996 to 1999, 2005, and 2011, we would expect that there would be a positive relationship between those changes. In fact, we see that the sampling to sampling variability is large. Further, there is no evidence of a positive relationship, correlation coefficients of -0.069, -0.16, and 0.01 for 1999, 2005, and 2011, respectively, none significant at P=0.05). Those sites where SOC change was negative from 1996 to 2018 were just about as likely to have positive as negative change in other samplings (Figure 5). Again, due to the variability there is no way to meaningfully interpret the results over time for an individual field.

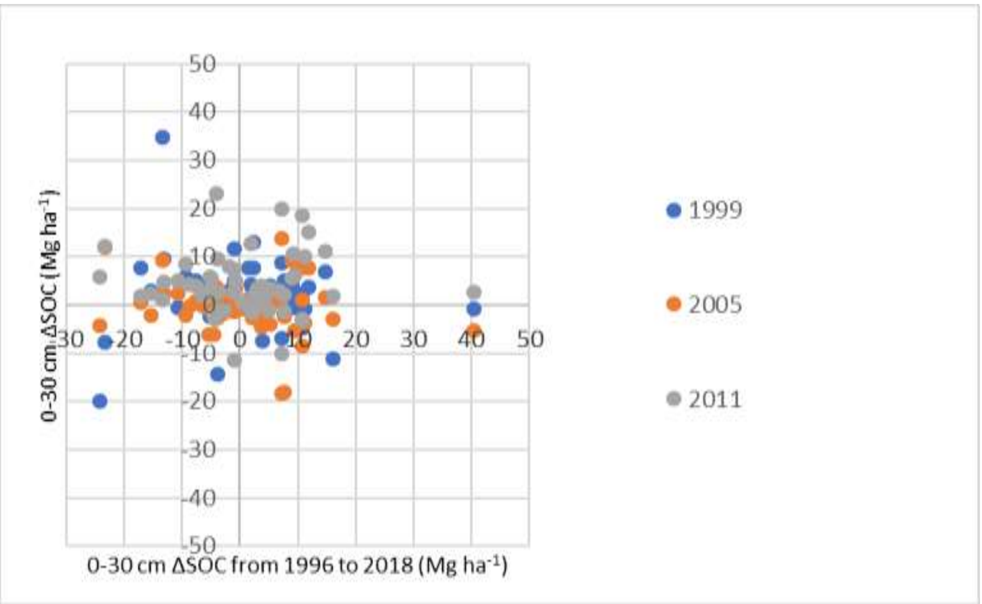


Figure 5. 0-30 cm SOC change (Mg ha^{-1}) for 1999, 2005, and 2011samplings compared to SOC measured change for 2018.

However, when the results for many fields are combined, then statistical inferences can be made as to the behaviour of SOC. The overall frequency distribution of changes (Figure 6) could not be rejected from a normal distribution. Some of the measured differences between samplings are so largely negative or positive that they are unlikely due to the effect of land management and weather conditions alone. However, since these values are consistent with what would be expected with a normal distribution, there is no reason to discard any as outliers.

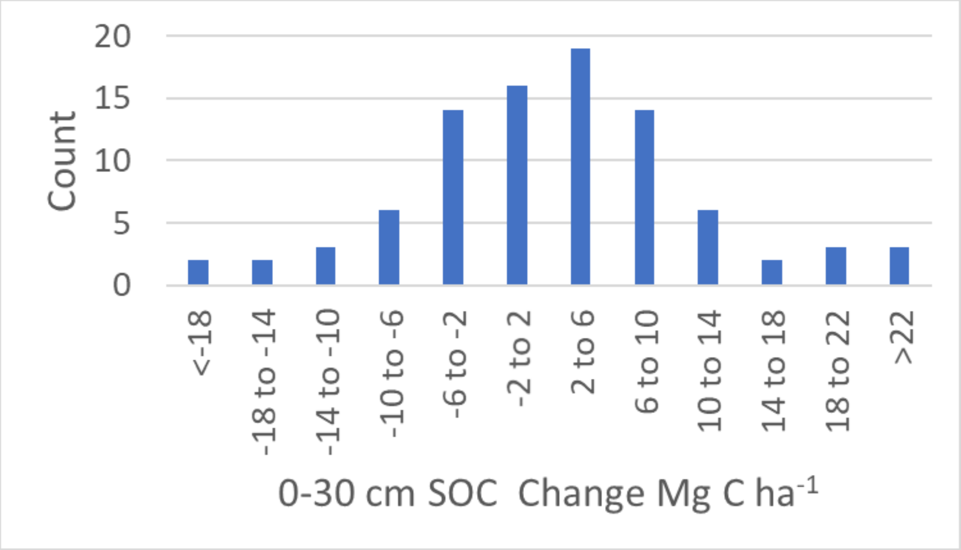


Figure 6. Histogram of the frequency of sites by class of SOC change from 1996 to 2018.

SOC

As is already well known, the subhumid prairie soils contained more SOC than the semiarid prairie soils (Table 5). The subhumid prairie SOC was 37% more over the measured profile than the semiarid prairie but was about 60% more in the surface 10 or 20 cm.

Table 5. Average cumulative 1996 SOC (Mg/ha) for the sites by depth from the soil surface.

Depth (cm)	**Subhumid prairie**	**Semiarid prairie**	**All sites**
0-10	39.15	23.43	32.04
0-20	63.58	40.50	53.14
0-30	73.62	50.67	63.23
0-39	81.87	59.56	71.88

Change in SOC

1996-1999 Level 2 sites

For the level 2 sites, SOC increased with depth from 1996 to 1999 (Figure 7). In the 0-30 cm depth, the mean SOC for direct seeded sites was 2.32 Mg ha^{-1} or an average SOC change rate of 0.77 Mg ha^{-1} yr^{-1}. For the conventionally tilled strips in the level 2 sites, a mean SOC was 0.74 Mg ha^{-1} or an average SOC change rate of 0.25 Mg ha^{-1} yr^{-1}. Despite the large difference observed between the two types of crop management, there was no significant difference in SOC change between tilled strips and direct seeded level 2 sites. Given the large variability in SOC, against a relatively large backdrop of soil organic carbon stores, no solid conclusions of differences in tillage intensity could be made.

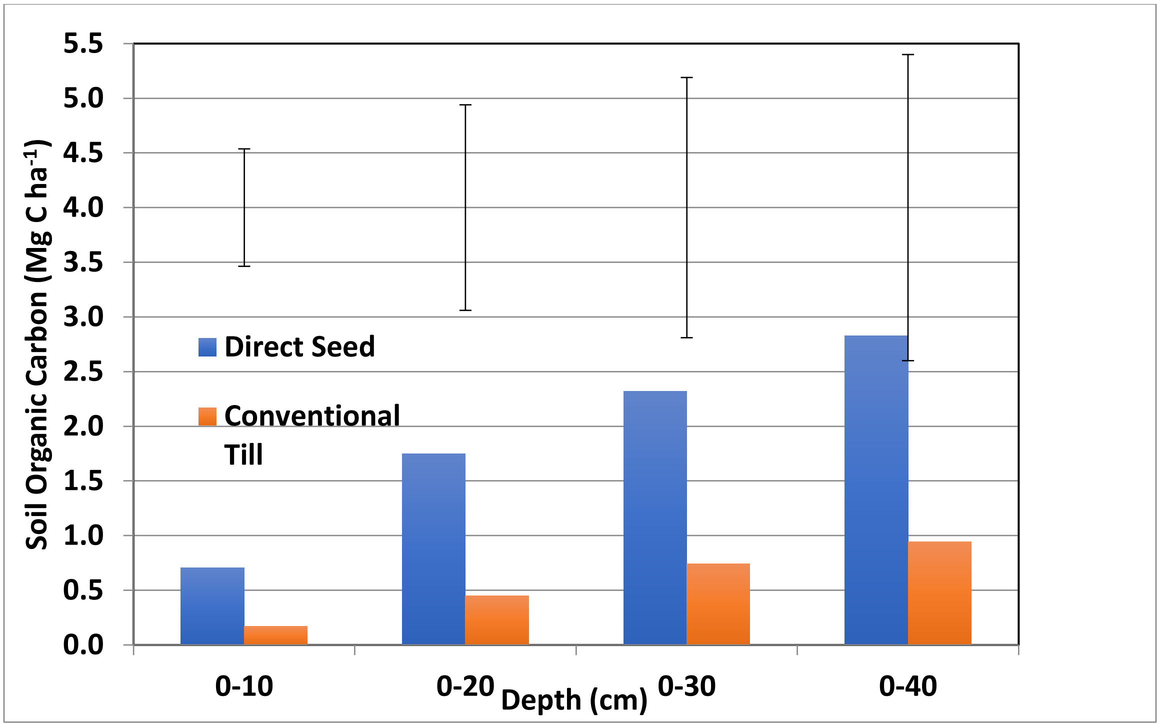


Figure 7. Soil Organic Carbon under direct seeding versus conventional tillage from 1996 to 1999 at 4 depth increments with 5% confidence limits of difference.

1996-2018 SOC Changes

For the whole network (only single direct-seeded level 2 site benchmark included), the changes in SOC concentration and bulk density were small (Table 6). Differences in SOC, therefore, were a result of the combination of the bulk density and SOC. Note that there were never any significant differences in SOC concentration. In contrast, the bulk density increased from 1996 values with significantly higher bulk density in 2011 and 2018. The increased bulk density is largest in the surface and the 30-40 cm depth. Clearly, reporting on equivalent soil mass is essential to minimize the bias introduced by changing bulk density. On a volumetric (depth of sampling) basis, there would be more soil mass and hence more associated SOC in 2011 and 2014 due to higher bulk densities than reported herein on a mass equivalency basis. It is not a fair comparison to report on SOC on a volumetric basis when bulk densities change over time.

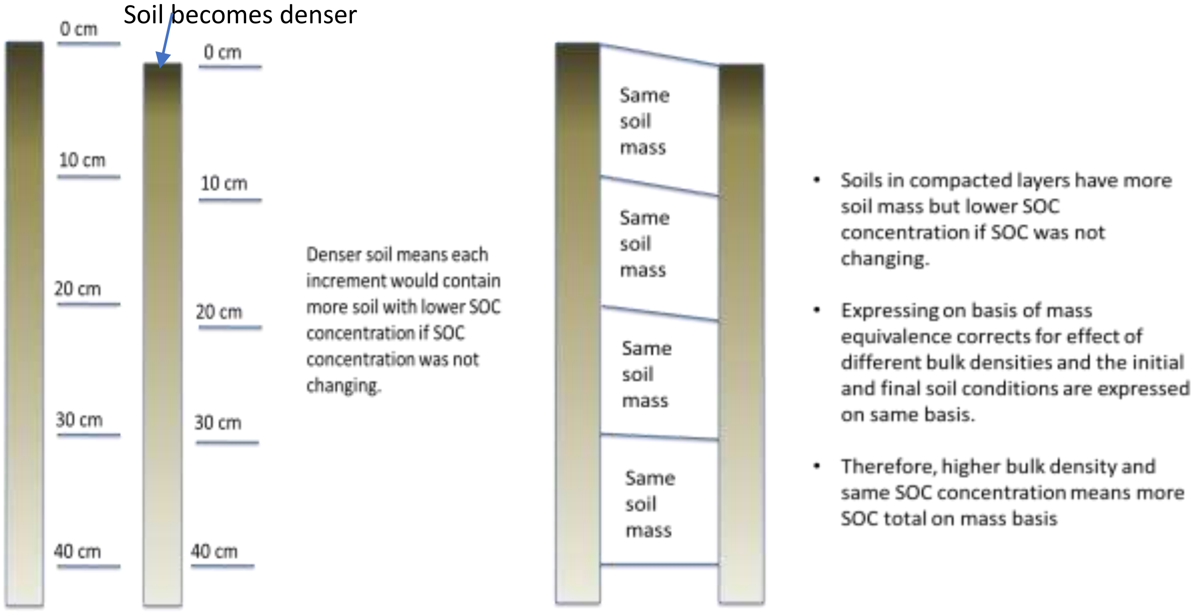
Table 6. Bulk density (BD), soil organic carbon concentration, and probability (0-1) that difference is due to chance (P value) for the comparisons between 1996 and 1999, 2005, 2011, and 2018. (**bolded values** are significantly different with P<0.05)

Depth (cm)	**BD (Mg/m^3)**		**Number & P value**	**OC (%)**		**Number & P value**
	1996^z	1999	n=136	1996^y	1999	n=136
0-10	**1.254**	**1.305**	0.001	2.549	2.562	0.918
10-20	1.422	1.399	0.101	1.523	1.530	0.935
20-30	1.406	1.383	0.128	0.955	0.977	0.67
30-40	1.395	1.39	0.743	0.734	0.756	0.523
	1996	2005	n=121	1996	2005	n=121
0-10	1.253	1.238	0.328	2.496	2.548	0.684
10-20	1.419	1.420	0.908	1.460	1.455	0.943
20-30	1.407	1.412	0.77	0.984	0.957	0.600
30-40	1.394	1.411	0.269	0.759	0.76	0.977
	1996	2011	n=80	1996	2011	n=80
0-10	**1.261**	**1.325**	<0.001	2.232	2.296	0.661
10-20	1.413	1.444	0.157	1.341	1.365	0.822
20-30	1.404	1.437	0.123	1.033	1.069	0.658
30-40	**1.385**	**1.485**	0.006	0.990	1.030	0.595
	1996	2018	n=90	1996	2018	n=90
0-10	**1.260**	**1.415**	<0.001	2.126	2.202	0.556
10-20	**1.421**	**1.469**	0.017	1.376	1.296	0.308
20-30	**1.406**	**1.465**	0.004	1.046	1.043	0.964
30-40	**1.388**	**1.469**	<0.001	0.944	0.965	0.745

^{z} the values of BD for 1996 vary between sampling because the sites involved differ between samplings.

^{y} the values for OC for 1996 vary because of different sites as described for BD and because of differences due to analytical procedures among samplings.

Figure 8 shows how expressing SOC on a mass equivalent depth basis corrects for the effect of bulk density changes.



Denser soil means each increment would contain more soil with lower SOC concentration if SOC concentration was not changing.

- Soils in compacted layers have more soil mass but lower SOC concentration if SOC was not changing.
- Expressing on basis of mass equivalence corrects for effect of different bulk densities and the initial and final soil conditions are expressed on same basis.
- Therefore, higher bulk density and same SOC concentration means more SOC total on mass basis

Figure 8. Correcting to the same soil mass helps correct for the effect of changing soil bulk density on soil organic carbon mass.

Across all sites, the change in SOC from 1996 to 2018 was 5% of initial SOC for the 0-10 cm layer and 4% for the whole 0-30 cm layer. Despite the SOC variability and the relatively small changes in SOC, there were significant detectable increases in all samplings at P value of 0.05 or lower (Table 7).

The depth of 30 cm is considered the *de facto* world standard depth for estimating SOC change. This 0-30 cm SOC change has generally increased to 2011 and may have leveled off currently (Figure 9). The uncertainty of the estimate, as indicated by the confidence limits (Figure 9), were highest in 2018. The confidence limits in 2011 were higher than those in 1999 or 2005. Thus, the uncertainty has increased with time since 1996. This reflects the effect of the differences in the widening range of combinations of growing conditions and management across the PSCB project with time.

Table 7. Change in cumulative SOC change from the soil surface, expressed on an equivalent mass basis for 1996 to 1999, 2005, 2011, 2018 for the semiarid prairie sites, subhumid prairie sites, and all sites. The number of sites and P value of a non-zero value are also shown. (**bolded values** are significantly different from zero with P<0.05)

	Semiarid[z]		**Subhumid[z]**		**All Sites**	
Depth (cm)	**SOC change (Mg/ha)**	**Number & P value**	**SOC change (Mg/ha)**	**Number & P value**	**SOC change (Mg/ha)**	**Number & P value**
1996 to 1999						
	n=61		n=75		n=136	
0-10	0.16	0.441	**1.03**	0.010	**0.64**	0.008
0-20	0.71	0.051	**1.59**	0.050	**1.19**	0.012
0-30	0.82	0.094	**2.13**	0.023	**1.54**	0.006
0-39	1.14	0.050	**2.43**	0.015	**1.85**	0.002
1996 to 2005						
	n=54		n=66		n=120	
0-10	0.35	0.164	**0.84**	0.002	**0.62**	0.001
0-20	-0.15	0.743	**1.19**	0.038	0.58	0.120
0-30	-0.71	0.223	1.21[z]	0.075	0.35	0.450
0-39	-0.89	0.166	1.34[z]	0.069	0.34	0.503
1996 to 2011						
	n=33		n=47		n=80	
0-10	**1.09**	0.020	1.01	0.159	**1.04**	0.023
0-20	**1.50**	0.061	**2.43**	0.006	**2.04**	0.001
0-30	**2.51**	0.032	**3.41**	0.001	**3.04**	0.001
0-39	**3.59**	0.022	**3.91**	0.001	**3.78**	0.001
1996 to 2018						
	n=43		n=47		n=90	
0-10	**1.69**	0.004	1.30	0.162	**1.49**	0.008
0-20	**2.66**	0.010	0.91	0.485	**1.74**	0.036
0-30	**2.62**	0.027	1,83	0.296	**2.21**	0.038
0-39	**2.85**	0.026	2.32	0.209	**2.58**	0.023

[z] Semiarid and subhumid soils were not significantly different (P<0.05) except for 0-30 and 0-39 depths in 2005.

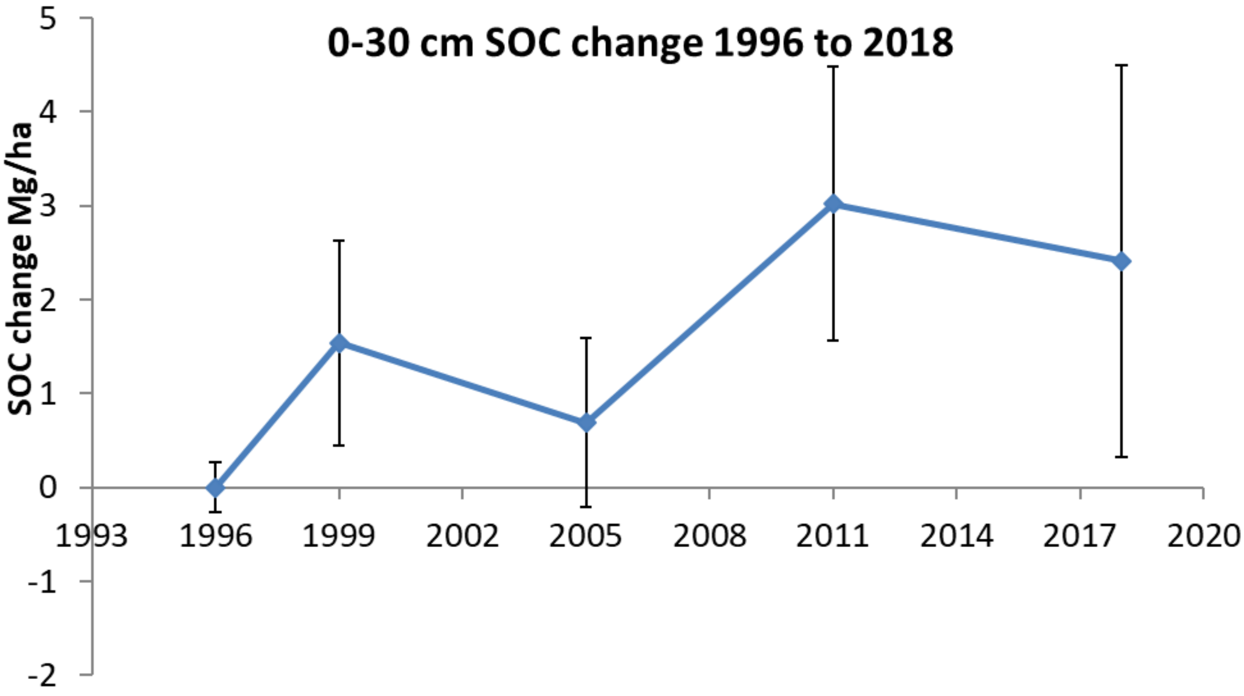


Figure 9. 0-30 cm SOC change over the PSCB project with 95% confidence limits. The confidence limits for 1996 show the expected variation for an immediate repeat sampling within the benchmarks.

Model Results

The preliminary model runs did not agree well with observation for the 58 sites regarding the values on an annual basis (Figure 10). In particular the pattern of SOC 1999 and overestimated the SOC compared to observed in 2005 and 2018. The model did simulate an SOC increase over time with magnitude similar to larger set of observations for 2011 and 2018 (Table 7). The model also simulated that most SOC gain was in surface depth but with some in all lower depths as well (data not shown).

Work is underway to refine initialization, calibration, and management input to improve model performance and to provide a stronger basis to compare with model with observations.

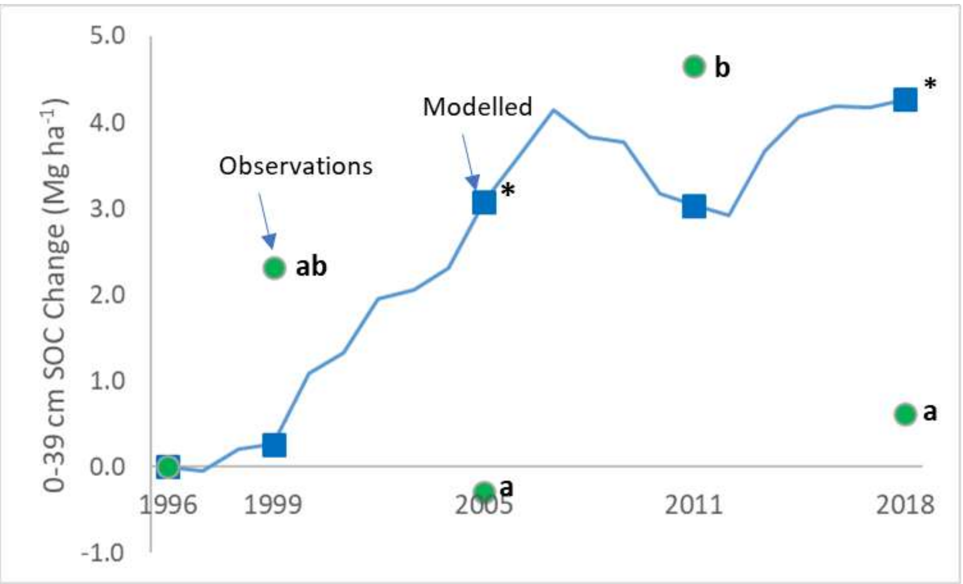


Figure 10. Modeled and observed SOC change from 1996 for 58 sites common to all samplings, letters indicate significant difference ($P<0.05$) between observations, * indicates significant difference ($P<0.05$) between observation and modelled value for individual years based of observation variability only.

Discussion

SOC Change Amount and Duration

The increases in SOC occurred despite no signification increase in SOC concentration (Table 4). However, the way to look at this is that the soil became denser so the same mass of soil in later years would involve a deeper soil layer in 1996. To illustrate, the mass of soil in 2018 to 10 cm would represent about 11 cm depth of soil in 1996. The deeper soil has a lower SOC concentration, so that would lower its SOC concentration. Consequently, a similar SOC concentration for a denser soil actually represents an increase is SOC. The equivalent mass method accounts for this effect and that is why there are significant increases in SOC amount with significant increases in SOC on a volumetric (fixed depth) basis.

The 1996 to 2018 SOC changes, occurring over 21 years, should provide the best indication of patterns in SOC behaviour. The gains from 1996 to 2018 were modest (4% of initial SOC) and higher gains for conservation cropping (reduced tillage and reduced fallow) have been recorded in research plots compared with a non-conservation cropping baseline. The variability in soils and in management make it difficult to discern the effect of conservation cropping, especially when the comparison is only against the 1996 value rather than a baseline.

The apparent drop in SOC between 2011 and 2018 could indicate that C sequestration has stopped. However, the PSCB project is not well suited to determine C sequestration with shorter duration weather-driven SOC changes. The general guide to estimate the effect of a change in management is to compare the changed system with baseline without the change. That baseline could be measured or modelled. The PSCB lacks a baseline as all comparisons are against 1996

SOC level. If an actual baseline of unchanged cropping conditions had dropped between 1996 and 2018, then the SOC gain using 1996 as a baseline would underestimate the relative real SOC gain. Of course, if the baseline increased in SOC to 2018, then the reported SOC gain is overestimated. Based on one sampling and without a dynamic baseline, it is not possible to conclude that actual C sequestration has stopped. If sampling had stopped in 2005, we would have concluded that sequestration had stopped by that year compared to the 1999 sampling. But the 2011 and 2018 samplings show that C sequestration continued. Further samplings would be necessary to determine when C sequestration stops.

One notable advantage of comparing against the 1996 baseline is that it reflects the C emissions and removals to and from the atmosphere since 1996.

Saturated refers to the concept that there is a finite amount of organic carbon that can be stored stably in the soil. The concept is related to the locations where SOC can be protected from further decomposition either in close association with clay or fine silt or within very small aggregates. Invariably, SOC under unirrigated cropland is less than if same soil was in a long-term grassland. Consequently, we know that these soils can maintain higher values of SOC. Therefore, there is no strong reason to assume that the flattening of increase from 2011 to 2018 should not be interpreted as indication that the soil is saturated with respect to SOC.

Influence of Initial SOC Amount

On average the soils with least SOC in 1996 gained the most SOC from 1996 to 2018 while those with the most SOC in 1996 lost SOC to 2018 (Figure 11).

The high variability observed may also be from the interactions between SOC amount within the benchmark and the prevailing conditions. In particular, the soils within the benchmark with most SOC may be losing SOC while those with least are gaining. This interaction, combined with the variability from spatial variability, would add to the variability compared to a situation where all soils within the benchmark had similar SOC change over time.

The apparent effect of initial SOC is consistent with a concept of C saturation. Basically, C saturation is a limited ability of soils to store SOC and once that storage capacity is reached, the soils will not store more SOC even if conditions, otherwise, would be expected to increase SOC (e.g. rising C input to the soil and less soil disturbance). Therefore, gains should be greater the lower the SOC is from the C saturation point. Soils that are above C saturation will tend to lose SOC. Of course, the general observed relationship regarding the effect of initial SOC amount is not conclusive proof of C saturation and there are many observed exceptions of soils with high SOC gaining SOC and soils with low SOC losing SOC.

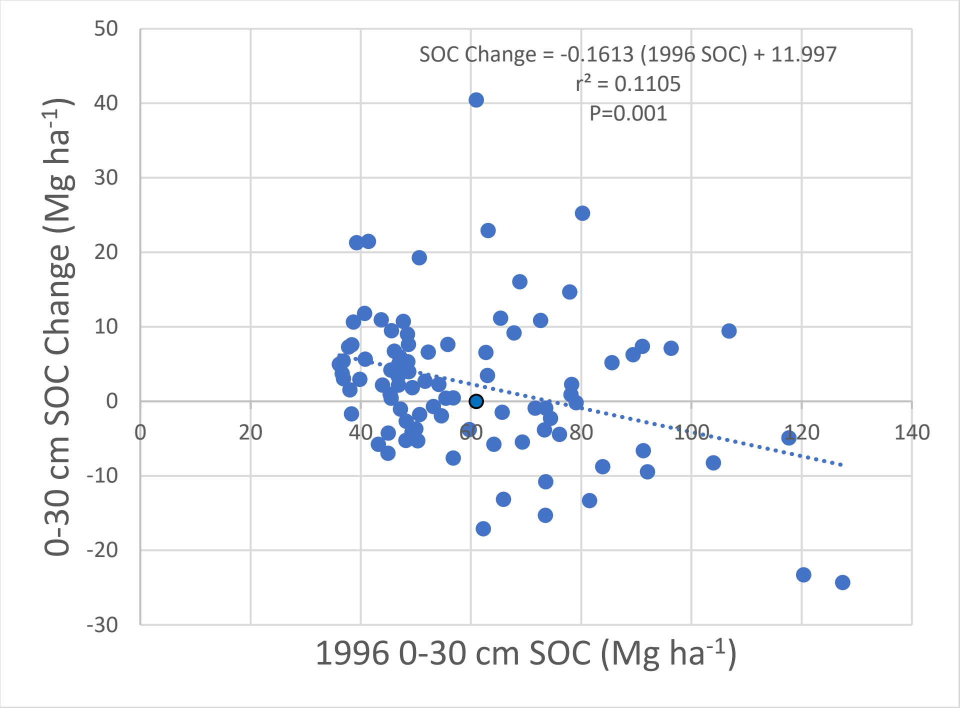


Figure 11. Impact of initial SOC on change in 0-30 cm SOC.

Effect of Soil Zone

With the exception of 2005, the SOC changes were quite similar between the Brown/Dark Brown soil zones and the Black/Dark Grey/Grey soil zones (Table 5). One reason may be that the semiarid prairie has less SOC so, given that SOC gain was inversely proportion to total SOC, they would tend to gain more. Another reason may be those soils were more degraded since in past they probably were under more frequent fallow and may have suffered more erosion than the subhumid sites.

The proportional change in SOC was about twice as high in the semiarid prairie than in the subhumid prairie. The change in SOC from 1996 to 2018 for the semiarid prairie was 8% of initial SOC for the 0-10 cm depth and 6% for the 0-30 cm depth. The values for the subhumid prairie were 4% for the 0-10 cm depth and 3% for the 0-30 cm depth.

Depth of SOC Change

Small plot experiments had generally shown that the impact of cropping system changes is concentrated in the upper 10 to 20 cm. In 2005, the entire SOC increase was in the surface depth with no additional C at deeper depths across all soils (the 2005 results will also be discussed later in context of weather). But, for the other three samplings, there was significant gain below 20 cm when considering all soils. This was most evident in 1999 and 2011, when the surface depth accounted for less than a third of sequestered C. By 2018, 57% of the sequestered C was that in the upper 10 cm. This is expected since that majority of C input to the soil from plant residues, including roots, are in the upper 10 cm of soil.

One possible explanation for the unexpected SOC increase at depth is that 1) the soil at the sites was more degraded initially than that used for small plot experiments on research farms, and 2) the sites also underwent an important decrease in fallow (the average fallow frequency in the 1990-96 period for the sites was about one year in four). Assuredly, there would be an increase in C inputs at depth with fallow reductions that should lead to some SOC increase at depth. If the soils were more degraded than research farms, then the relative increase would be larger and more detectable.

By depth increment only the surface depth had significant SOC change for 2018 (Table 8). Therefore, the surface depth contributes the greatest proportion of the signal. However, if the lower depth increments were not contributing SOC signal, then the additional variability by considering more soil would increase variability with depth and thereby make it harder to detect SOC change as depth increases. This is what exactly what is seen for the all sites in 2005 (Table 7) and what has frequently been observed in small-plot experiments. Although each increment below 10 cm is itself not contributing a significant amount of stored C, over the profile it is contributing more than it is contributing variability, so it is important to include these depths. This is the reason why it is best to consider the SOC change from the surface down rather than by depth increment.

Table 8. SOC change from 1996 to 2018 by depth increment and region.

	Semiarid (N=43)		Subhumid (N=47)		All (N=90)	
Depth	ΔC (Mg ha^{-1})	P	ΔC (Mg ha^{-1})	P	ΔC (Mg ha^{-1})	P
0-10	1.69	0.004	1.30	0.162	1.485	0.008
10-20	0.97	0.110	-0.39	0.596	0.259	0.591
20-30	-0.04	0.914	0.92	0.203	0.464	0.261
30-39	0.23	0.554	0.52	0.371	0.368	0.280
0-39	2.85	0.026	2.32	0.204	2.577	0.023

For the subhumid zone, there was weak evidence that reduction in tillage was causing a loss of SOC immediately below the plow layer, the 10-20 cm depth increment. However, tillage reduction was increasing SOC at deeper depths.

Although it was expected that soils with relative C horizon would have less SOC at depth, the data showed, that the trend was actually the opposite, the shallower soils actually had more SOC in the 20-39 cm than the deeper soils (Table 9).

Table 9. Soil Organic Carbon (Mg ha^{-1}) in 1996 for sites sampled in 2018 by depth increment for shallow soils (C horizon < 29.5 cm from surface mean =18 cm for semiarid and 18.8 cm for subhumid) and deeper soils (C horizon > 29.5 cm from surface) by region.

Depth (cm)	Semiarid Prairie		Subhumid Prairie	
	Shallow (n=26)	Deep (n=17)	Shallow (n=19)	Deep (n=28)
0-10	18.6	20.4	33.5	34.2
10-20	15.0	14.8	23.2	27.6
20-30	13.4	12.0	20.3	13.2
30-39	10.1	9.1	15.3	8.3

There was no apparent effect of profile depth class on SOC other than from differences in initial SOC (not shown). Across depth increments, regions, and profiles, the primary factor affecting SOC change was initial SOC (Figure 12). The slopes of the relationship between SOC in 2018 and 1996 are consistently less than one showing that the relative SOC amount in 2018 decreases as the SOC in 1996 increases.

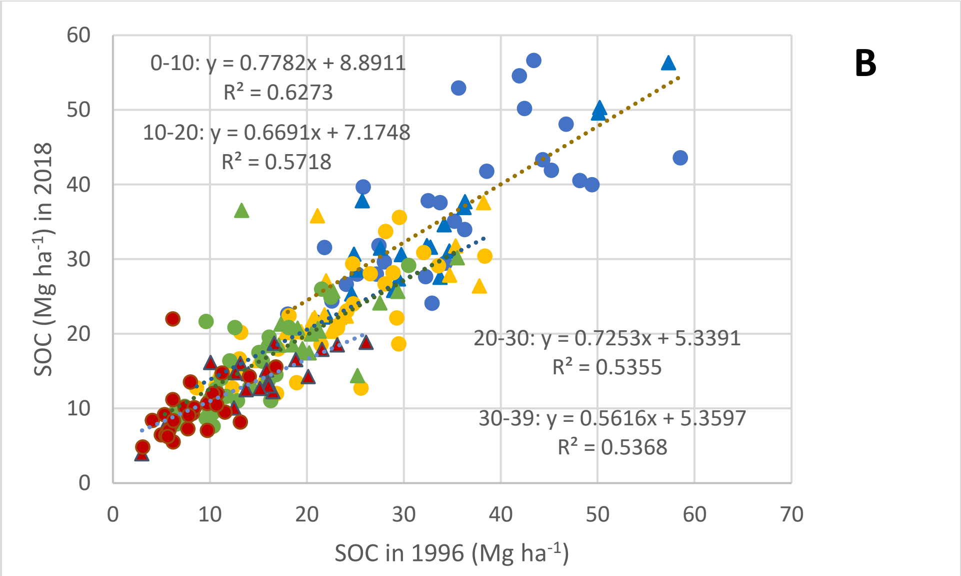


Figure 12. Soil organic carbon (SOC) in 2018 compared to 1996 by depth increment (blue is 0-10, yellow is 10-20, green is 20-30, and red is 30-39 cm, profile depth (triangles are profiles with C horizon < 29.5 cm from surface and circles are profiles with C horizon > 29.5 cm from the surface), and region (A is semiarid prairie, B is subhumid prairie),

Influence of Crop Yields on SOC.

The decrease in SOC for 2005 may be explained by the consequences of low yields due to drought that occurred in the 2001-2003 period (Figure 13). Across the entire PSCB network, there was no significant change in SOC from 1996 below 10 cm (Table 5). The SOC decline was more pronounced in the semiarid sites. The relative effect of drought on C input must have been larger on those sites. However, across the whole PSC|B network, the surface depth did have significant SOC increase since 1996 in 2005. This may reflect the fact that surface SOC was less affected by the drought and/or was quickest to rebound during 2004 and 2005 years following the 2001-2003 drought years.

Generally increasing yields from mid 2000s onward would be expected to increase SOC. However, there was no evidence of this response within the PSCB comparing 2011 to 2018.

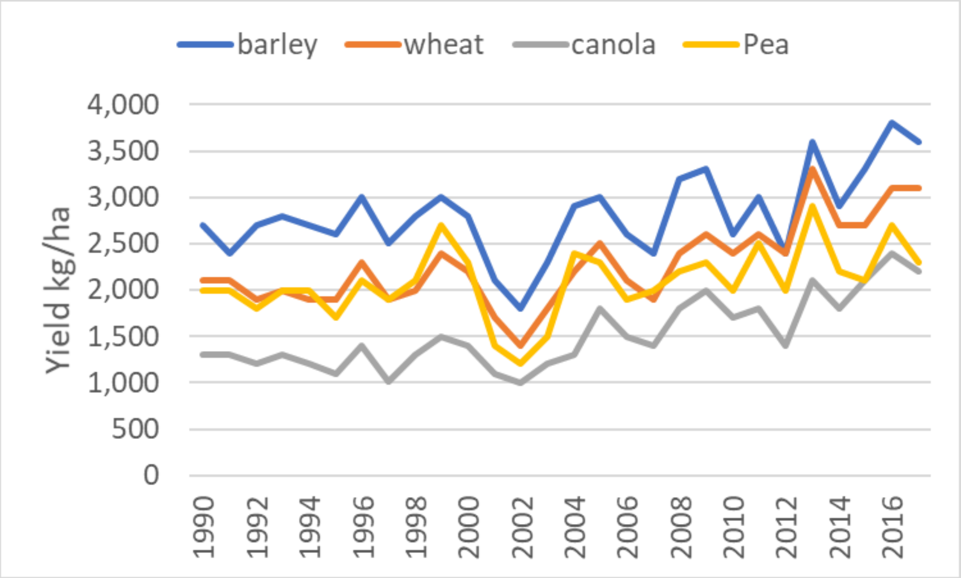


Figure 13. Saskatchewan average grain yields showing the impact of drought in 2001-2003.

Effect of Management

Currently, we have insufficient data on the field management to reliably subdivide into different categories to see if there was an effect. Possible effects could be if occasional residue removal by baling or burning has an effect or the frequency of tillage. From the data we have we know many fields had several tillage operations. Unfortunately, because of years of missing management data, we do not know with confidence which fields had basically no tillage operations. A similar situation exists for residue removal. With more data on field management, these sorts of evaluations could be evaluated.

Comparison with National Inventory Estimates

The inventory provides factors of soil carbon change. These include effects of reducing fallow and reducing tillage. These factors are based on a combination of results from experiments and modelling with the Century process model of SOC dynamics. The average frequency of fallow for the subhumid sites in the 1990-96 was 16%. The average frequency for the semiarid sites was 31%. We assumed that the sites were one-half minimum tillage and one-half full tillage previously and were converted to complete no-till in 1997.

The inventory estimates fell outside the confidence limits for the 1999 and 2005 samplings (Figure 14). Specifically, the inventory factors underestimated SOC gain in 1999 and overestimated it for 2005. For 2011 and 2018, the inventory estimates were within the confidence limits of the measured values.

For 2018, the estimated SOC change for the semiarid sites was 3.53 Mg/ha while it was 3.67 Mg/ha for the subhumid sites. The semiarid sites have lower estimated C change from tillage reduction but had more due to greater fallow reduction. In contrast, the subhumid sites had more gain in SOC from tillage reduction but less from fallow reduction. The result was similar overall values. The measured values were also similar between soil zones (Table 5).

The inventory methods are general and not responsive to weather-related effects that were affecting the PSCB project sites, such as the drop in SOC from 1999 to 2005 attributed to general drought during 2001-03. Thus, there was no strong evidence PSCB SOC measurements that the inventory estimates are fundamentally incorrect.

Of interest, the inventory methods estimate there will be further increases in SOC. If the same management continues, the inventory methods estimate that the PSCB network would gain an additional 1 Mg SOC/ha from 2018 to 2028, 0.7 Mg SOC/ha from 2028 to 2038, and 0.5 Mg SOC/ha from 2038 to 2048.

The inventory estimates are also similar to the preliminary modelled results using DNDC (Figure 9).

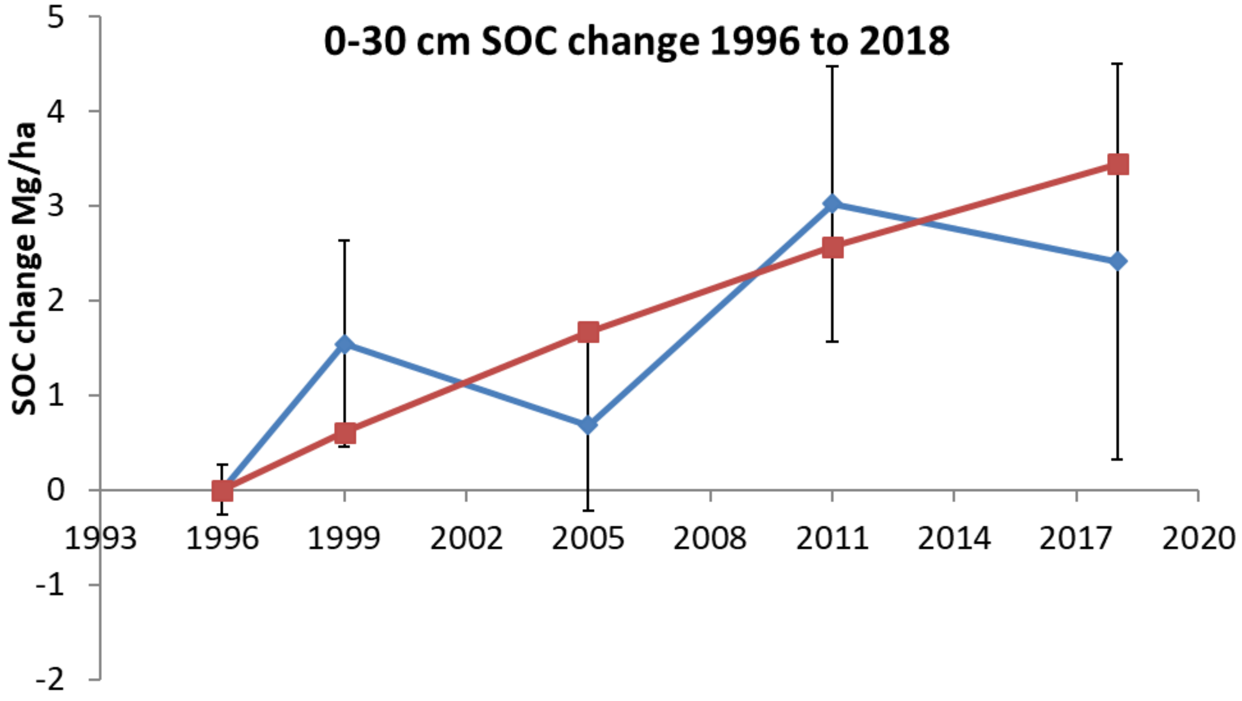


Figure 14. Measured SOC change with 95% confidence limits for PSCB sites and the estimated SOC change for the PSCB based on methods used in Canada’s national inventory.

Recommendations

Collecting more data on field management is necessary to understand the potential influence of management differences. Having fairly complete information (<5 years of missing data) on about 30 sites would be necessary. Currently we have met that completeness criteria for only six sites.

The PSCB has provided new and unique information on SOC change on commercial farm fields. Future resampling will continue to provide new data. However, as farm operators change and with problems obtaining field management information, it becomes less clear what farming systems are being measured within the PSCB.

The PSCB provides important learnings that should be used to start any new SOC monitoring networks. Important learnings were that 40 cm is not deep enough to capture SOC change from improved management, especially for soils with deep profile development. Another was that more fields in the network would be superior from the viewpoint of measuring SOC change across the network. The benchmark design was not effective at reducing SOC variability so that the resources used to relocate and sample that benchmark could be better used by dispersing the sampling effort spatially, both to more fields and/or across the same field. Where the interest is in knowing SOC for an individual field, having about 30 distributed sampled soil profiles per field would be indicated as necessary from the PSCB results. Finally, whether PSCB is resampled in the future or a new network is started, greater attention needs to be made to having more complete sets of field management data.

Conclusions

1) The Prairie Soil Carbon Balance project has provided some new and unique information about the behaviour of SOC on commercial farm fields throughout Saskatchewan. We now have confirmation that the fields are increasing in soil carbon. We attribute these SOC increases to reduction in tillage and reduction in fallow.
2) The SOC gains were modest. The proportional SOC gain over 21 years was only 4% of the initial SOC for the 0-30 cm depth. The increase in SOC was due to small increases in bulk density and/or SOC concentration. An important new finding was that C sequestration on farm fields was occurring down to at least 40 cm. Because of the importance of bulk density on quantifying SOC, it was essential to have accurate measurements of bulk density. It is also essential to report SOC on an equivalent soil mass basis.
3) The spatial variability of SOC within benchmarks was much higher than expected. Because of the high variability the benchmark methods were not able to derive useful measured values of SOC change for individual fields. The spatial variability also limited the ability to test for statistically significant differences between subsets of fields within the PSCB. In general, a subset needs to have at least 40 fields to detect differences statistically.
4) Several influences were identified that affect the amount and nature of SOC change. First, soils with initially low SOC within the PSCB were the soils that tended to lose SOC. Second, low crop yields during drought years appeared to depress SOC gain. However, increasing yield in the last decade did not have the expected impact of raising SOC.
5) The PSCB project results did not indicate fundamental problems with the methods used to estimate SOC change in Canada’s national inventory of greenhouse gas emissions and removals.
6) More information on management of the fields is required to do additional analyses that are possible to elucidate SOC behaviour in response to management and improve model simulations.

References

Ellert, B., Janzen, H.H., Entz, T., 2002. Assessment of a method to measure temporal change in soil carbon storage. Soil Science Society of America Journal 66, 1687-1695.
Environment and Climate Change Canada, 2017. National Inventory Report 1990–2015: Greenhouse Gas Sources and Sinks in Canada. Environment and Climate Change Canada, Gatineau, QC, Canada.

Grant, B., Smith, W.N., Desjardins, R., Lemke, R., Li, C., 2004. Estimated N2O and CO2 emissions as influenced by agricultural practices in Canada. Climatic Change 65, 315-332.
Grant, B.B., Smith, W.N., Campbell, C.A., Desjardins, R.L., Lemke, R.L., Kröbel, R., McConkey, B.G., Smith, E.G., Lafond, G.P., 2015. Comparison of DayCent and DNDC Models: Case Studies Using Data from Long-Term Experiments on the Canadian Prairies. In: Del Grosso, S., Parton, W., Ahuja, L. (Eds.), Synthesis and Modeling of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forest Systems to Guide Mitigation and Adaptation, Advances in Agricultural Systems Modeling 6. American Society of Agronomy.
Guest, G., Kröbel, R., Grant, B., Smith, W., Sansoulet, J., Pattey, E., Desjardins, R., Jégo, G., Tremblay, N., Tremblay, G., 2017. Model comparison of soil processes in eastern Canada using DayCent, DNDC and STICS. Nutrient Cycling in Agroecosystems 109, 211-232.
IPCC, 2006. In: Eggleston, S., Buenida, L., Miwa, K., Ngarr, T., Tanabe, K. (Eds.), IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Agriculture, Forestry and Other Land Use. IPCC National Greenhouse Gas Inventories Programme, Hayama, Japan.
Li, C., 1996. The DNDC Model. In: Powlson, D.S., Smith, P., Smith, J.U. (Eds.), Evaluation of Soil Organic Matter Models. Springer, Berlin, pp. 263-267.
McConkey, B.G., Liang, B.C., Campbell, C.A., Curtin, D., Moulin, A.P., Brandt, S.A., Lafond, G.P., 2003. Crop rotation and tillage impact on carbon sequestration in Canadian prairie soils. Soil and Tillage Research 74, 81-90.
Qin, X., Wang, H., Li, Y., McConkey, B., Lemke, R., Li, C., Brandt, K., Gao, Q., Wan, Y., Liu, S., Liu, Y., Xu, C., 2013. A long-term sensitivity analysis of the denitrification and decomposition model. Environmental Modelling and Software 43, 26-36.
Smith, W.N., Desjardins, R.L., Grant, B., Li, C., Lemke, R.L., Rochette, P., Corre, M.D., Pennock, D.J., 2002. Testing the DNDC model using N2O emissions at two experimental sites in Canada. Canadian Journal of Soil Science 82, 365-374.
Smith, W.N., Grant, B., Desjardins, R.L., Lemke, R., Li, C., 2004. Estimates of the interannual variations of N2O emissions from agricultural soils in Canada. Nutrient Cycling in Agroecosystems 68, 37-45.
VandenBygaart, A.J., Gregorich, E.G., Angers, D.A., 2003. Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies. Canadian Journal of Soil Science 83, 363-380.
VandenBygaart, A.J., McConkey, B.G., Angers, D.A., Smith, W., de Gooijer, H., Bentham, M., Martin, T., 2008. Soil carbon change factors for the Canadian agriculture national greenhouse gas inventory. Canadian Journal of Soil Science 88, 671-680.