Prairie Soil Carbon Balance Project - Summary

Soil Organic Carbon Change on Direct-Seeded Farmland in Saskatchewan

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Report to Saskatchewan Soil Conservation Association and Saskatchewan Pulse Growers

25 July 2013

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Executive Summary

Soil organic carbon (SOC) is a powerful indicator of soil health and increasing SOC represents a removal of greenhouse gas, CO_2, from the atmosphere. The change in soil organic carbon (SOC) was measured on a network of 137 fields throughout Saskatchewan that were converted to direct seeding in 1996 or 1997. SOC change was measured on small (2x5 m) microsites on each field. Resampling was done in 1999 (136 fields), 2005 (121 fields), and 2011 (82 fields) with small (0.5-1 m) spatial offset from previous sampling. The objectives were: 1) determine if SOC change from adoption of direct seeding can be effectively measured on individual farm field, 2) determine SOC change from direct seeding over a network of fields.

Due to large spatial variation of SOC over short distances, it is not feasible to measure SOC change on a field using single microsite. Many microsites would be required on a single field making it economically impractical.

Over groups of 25 or more fields, changes in SOC could be readily discerned from background variation. There was consistent SOC increase on these in the surface 0-10 cm depth at all the soil re-samplings.

For the 1999 re-sampling there was strong trend of increasing SOC for 0-20 and 0-30 cm depths and was significant for 0-40 cm depth.

For 2005 sampling, there was an apparent drop in SOC from 1999 to 2005 for depths below 10cm. This effect was attributed to widespread droughts during 2001-2003 when soil C balance was negative due to reduced C input.

For the 2011 sampling, there was increase in SOC to all depths from 10 to 40 cm. This sampling is considered the most reliable owing to the long period since change in cropping system so is less affected by vagaries of weather and crops. To depth of 30 cm, SOC is increasing on Saskatchewan farmland under direct seeding at a rate of 0.23 Mg C/ha/yr or up to 0.38 ton CO_2/ac/yr. The SOC is increasing at depths to at least 40 cm, and the changes are much greater than expected, particularly in the subhumid prairie (Black, Dark, Grey soil zones). This new information is expected to end controversy about SOC increase and is extremely important for claims of positive environmental performance (including a low carbon footprint).

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 is thus soil degrading while practices that increase SOC are equated with soil-improving practices. Thus the change in SOM 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 (SOC) 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 (Janzen et al. 1998; Bruce et al. 1999; McConkey et al. 2003; VandenBygaart et al. 2003; Campbell et al. 2005; 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 a;. 2008) utilizing the guidelines of the Intergovernmental Panel on Climate Change guidelines for national inventories (IPCC 2006). As a result, the Canadian Agriculture Greenhouse Gas – Monitoring Accounting and Reporting System (CanAG-MARS) was developed to annually report changes in SOC in agricultural lands for Canada's National Greenhouse Gas Inventory Report (NIR). This exercise is 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. 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.

The SOC changes from the NIR are relative changes compared to a baseline. Canada stated its reduction target in the Copenhagen Agreement as 17% below those in the base year of 2005 by 2020. These relative changes relative to a baseline are also used for calculating carbon offsets from increasing SOC.

Important questions remain as to whether or not western Canada soils are losing or gaining SOC in absolute terms (i.e. not relative to a baseline). There are also questions whether SOC change is different on commercial farm fields as in 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.

The focus of this paper is to summarize findings of the cropland portion of the "The Prairie Soil Carbon Balance" (PSCB) research project to answer some of the above questions. The cropland PSCB was a collaborative venture of Greenhouse Gas Emission Consortium (GEMCo), Agriculture and Agri-Food Canada (AAFC), and Saskatchewan Soil Conservation Association (SSCA). Established in 1996, the PSCB cropland effort, the focus of this paper, was established in part to answer long-term evaluations of SOC change. Scientists within the PSCB installed a network of 137 benchmarks on commercial farm fields in 1996. Sites which still remained in the network were resampled in 1999, 2005, and 2011 to determine the overall changes in SOC. GEMCo providing incremental funding for initial and 1999 samplings, AAFC provided incremental funding for 2005 sampling and AAFC and Saskatchewan Pulse Growers through SSCA provided incremental funding for 2011 sampling.

The main objectives of this study are to assess the soil analyses for the above years to:

- Determine whether SOC is increasing, decreasing, or exhibiting no change in western Canada soils that were converted to direct seeding in 1996 or 1997.
- Determine if it is feasible to measure SOC change on individual farm fields using one or more microsite using repeated sampling with a slight spatial displacement.

Methods

Benchmark Site Selection

The SSCA field staff compiled the list of co-operators in 1996 that had changed land from conventional tillage to direct seeding management in 1996 or 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 factors expected to affect SOC was changes in tillage and cropping intensity under rainfed conditions.

Although the criteria was 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.

The benchmark system is a network of fields across Saskatchewan (Fig. 1) containing 2 x 5 m microsites, purposefully designed to minimize the influence of spatial variability of SOC, that were sampled initially in fall of 1996. Fields included in the study had fine, medium and coarse-textured soils in the Brown, Dark Brown, Black, and Dark Grey Chernozems and the Grey Luvisols.

Sites were chosen to avoid landscape complications. For instance, microsites were placed on relatively level landscape segments to reduce soil erosion and deposition effects. The microsites typically are 100 m from either field edges or uncultivated patches and where several microsites in one field were separated by a distance of at least 200 m. Field unconformities (gullies, gravel outcrops, saline seeps, etc.) were avoided. Experienced pedologists relocated microsites if coring revealed atypical soil non-uniformity such as evidence of past physical disturbances.

Level 1 Sites

A level 1 site was one microsite in a single field. There were a total of 114 level 1 sites were established (Fig. 1).

Level 2 Sites

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. To effect the comparison between direct seeding and conventional tillage, farmer co-operators 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 (Fig. 1). After 1999, there was no more tilled strip and field managed the same.

At each of the Level 2 microsites, four one square meter crop samples were taken each fall for three years. Also, in conjunction with the soil sampling in 1999, two surface residue samples, consisting of all residue either standing or lying on the soil surface, were collected at each microsite. Because crop residues were unevenly distributed over the field, one sample was collected from the area of the combine pass and the other midway between combine passes. These crop and residue samples were taken in vicinity of, but never on, the microsites.

Level 3 and Level 4 Sites (not included in this report)

The Level 3 sites were designed to measure the changes in soil carbon at different slope positions due to the adoption of direct seeding. Only six Level 3 sites were established (Fig. 1). There proved to be too few sites to derive useful estimates of SOC change and these were not sampled after 1999.

The objective of the Level 4 sites was to assess the anticipated relationship between the adoption of direct seeding technology and increasing soil organic carbon levels over the longer term. Eleven paired-sites were selected from across the Province representing a range of soil-climate conditions (Fig. 1). Each site consisted of two adjacent or nearby fields having similar soil-landscape conditions, but with one having been in direct seeding for at least 10 years. Microsites were not established as there was no intent to resample these sites in the future. See Liang et al. 2000 for results for Level 4 sites.

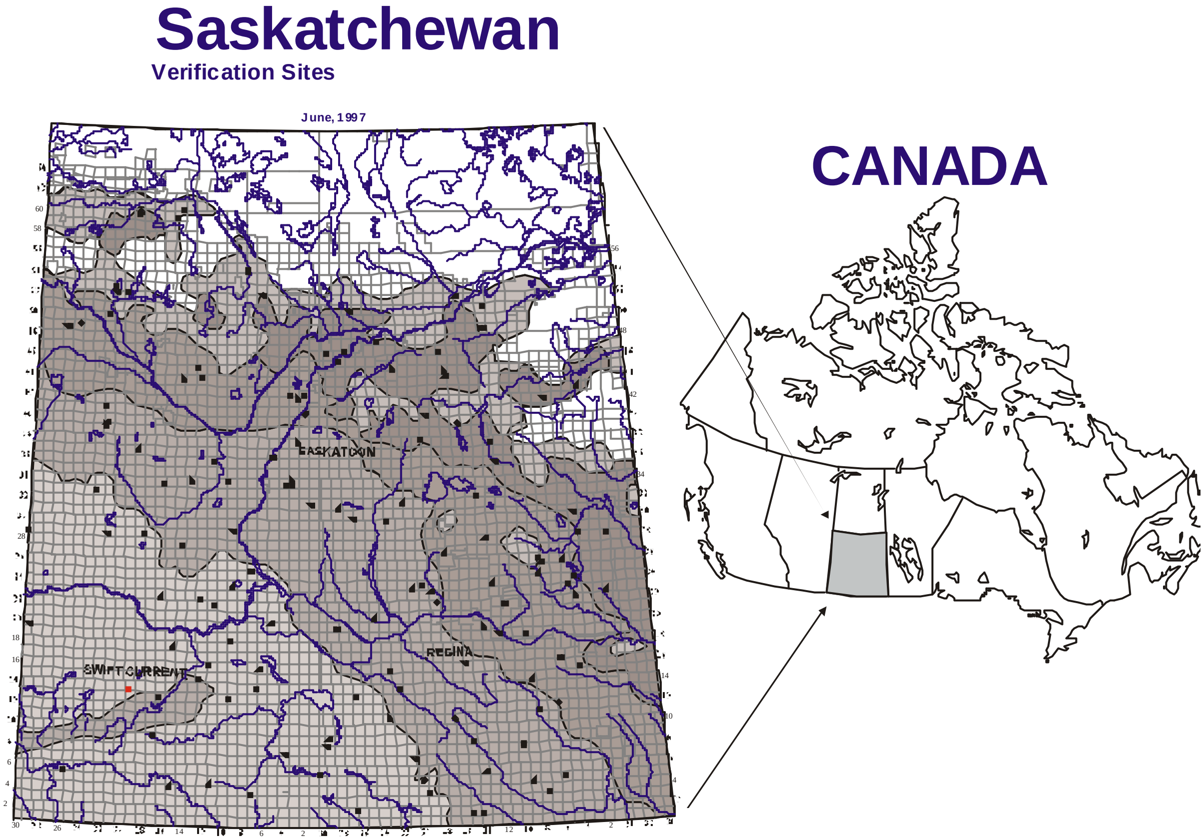

Figure 1: Location of SOC benchmark sites in Saskatchewan.

Microsite Sampling

A soil sampling procedure was developed to measure changes in soil C at specific points (i.e. microsites) between an initial sampling and sampling in subsequent years (Ellert et al. 2001). Each microsite was a 2x5 m grid from which 6 cores were taken initially (Fig.2). Subsequent cores were offset 1 m (1999) or 0.5 m (2005 and 2011) to the initial cores (Fig. 2.). In order to determine the spatial variability within the microsite itself, at 8 of the separate Level 2 sites, soil cores were taken on a 1 m grid within the microsite.

The grids were marked via a rope template oriented to magnetic north. This orientation had advantage that the grid was at an angle, depending on the declination at the site, to the field operations that were typically either true N-S or E-W. The cores were taken at specified locations in the grid using a hydraulic, truck-mounted coring machine. The sampling locations were recorded using traditional surveying techniques from nearby fixed features and by the Global Positioning System (GPS). Electromagnetic utility markers were buried below the depth of cultivation at the northeast core.

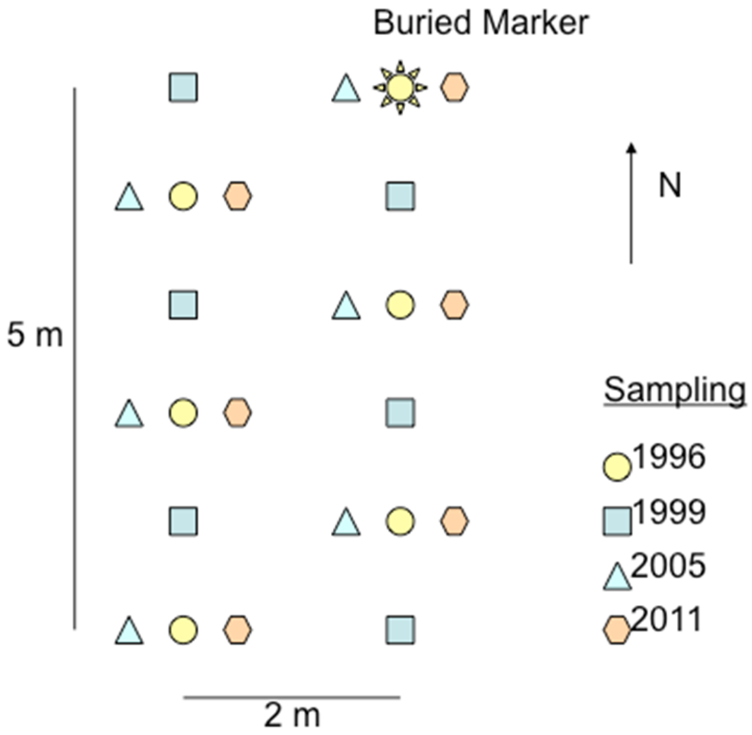

Figure 2: Microsite design and sample locations for microsite spatial variability analysis.

Soil Sampling and Processing

Sites were measured in fall 1996 (137 fields), fall 1999 (136 fields), fall 2005 (121 fields) and fall 2011 (82 fields). Soil organic carbon for an equivalent soil mass was taken from the same soil surface layer to reduce the effect of differences in soil bulk density (Ellert et al. 2001). This would also help reduce the effects of sample compaction and poor separation between soil depth increments. Cores sized 7 cm were used with a core depth about 50 cm. Soil sampling was done consistently in the fall for land accessibility and avoiding damage to crops. Soils were sampled in fall over subsequent years, as per the initial sample collection.

Extracted cores were subdivided into 10 cm segments (0 to 10, 10 to 20, 20 to 30, 30 to 40 cm). Core descriptions such as Ap horizon depth, carbonate presence, soil colour, stoniness, texture change were recorded at initial sampling. To reduce analytical cost, the six cores from each microsite were combined by profile depth increment.

Soil samples were first air-dried, crushed and passed through a 2-mm sieve, subdivided, and stored in glass jars. SOC changes were determined by analysing initial and subsequent soil samples at the same time. This methodology assumes organic C remains unchanged under proper storage conditions (dry, cool and dark).

For 2005 sampling only the three microsites that were under direct seeding during 1997-99 were resampled. For the 2011 sampling, to further reduce costs, only one microsite (arbitrarily that microsite labelled microsite “3”) was resampled.

Soils Analysis

In total, sampling was conducted in fall of 1996 (the initial condition), 1999, 2005, and 2011. The SOC was analysed using three methods. In 1999, 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. In 2005, the total carbon was also measured using dry combustion. 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 soil from 1996 was 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.

Results and Discussion

Land Management

On the Canadian prairies, approximately 32 million hectares of land are currently under annual crop production (excluding permanent pasture and forage) and account for more than 80% of total agricultural land in Canada. Historically, agricultural land use on the Canadian prairies consisted of intensive tillage for seedbed preparation and weed control. Over the years, farmers have used summerfallow to manage erratic weather conditions (especially drought), replenishing soil moisture and stabilize crop yields.

The major crops grown in Saskatchewan have seen a shift over the last 25 years, with increasing diversification from traditional grains (wheat, barley, oat) to other grains, oilseeds and pulses (Figure 3). With the advent of a greater variety of crops grown, the crop rotations used in Saskatchewan have also diversified.

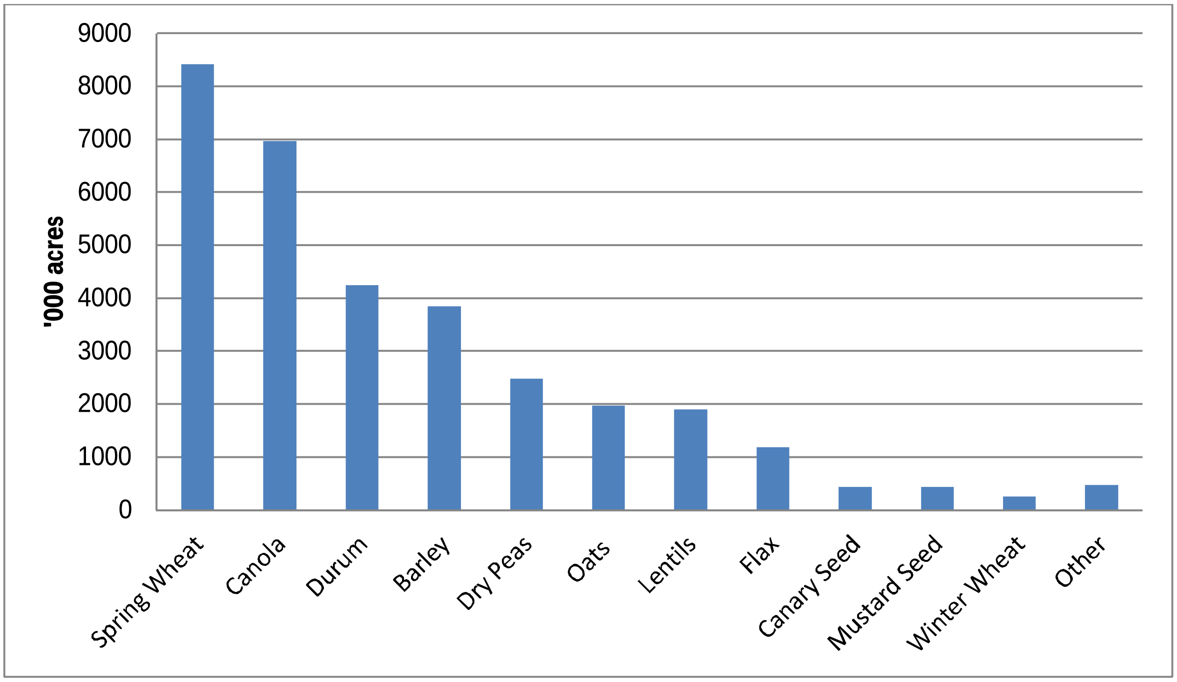

Figure 3: Average seeded acres by crop for Saskatchewan (2002-2011).

Note that "Other" includes the following crops: Fall Rye, Mixed Grains, Triticale, and Chickpeas. **Data retrieved from: http://www.agriculture.gov.sk.ca/Default.aspx?DN=274b2ec5-4d55-4a74-9a9d-6bc1105105da.**

The pre-1997 management of the co-operating farmer's sites in the PSCB has been documented. Management of the agricultural lands in the study, post-1997, reflects a change to direct seeding, increased cropping intensity (i.e. reduced summerfallow) and more diversified crop rotations with pulses and oilseeds. This is consistent with the overall trends in summerfallow reduction in the province of Saskatchewan over the last 20 years or so (Figure 4). The adoption of direct seeding technology has provided both a mitigative approach to conserving soil moisture and an adaptive way to manage increasingly erratic weather leading to a reduction in the need for fallow. The exception to this rule, where summerfallow incidence increased in 2010 and 2011 was due to unprecedented flooding in significant portions of the agricultural area of the province and the lands were left idle for the remainder of the growing season.

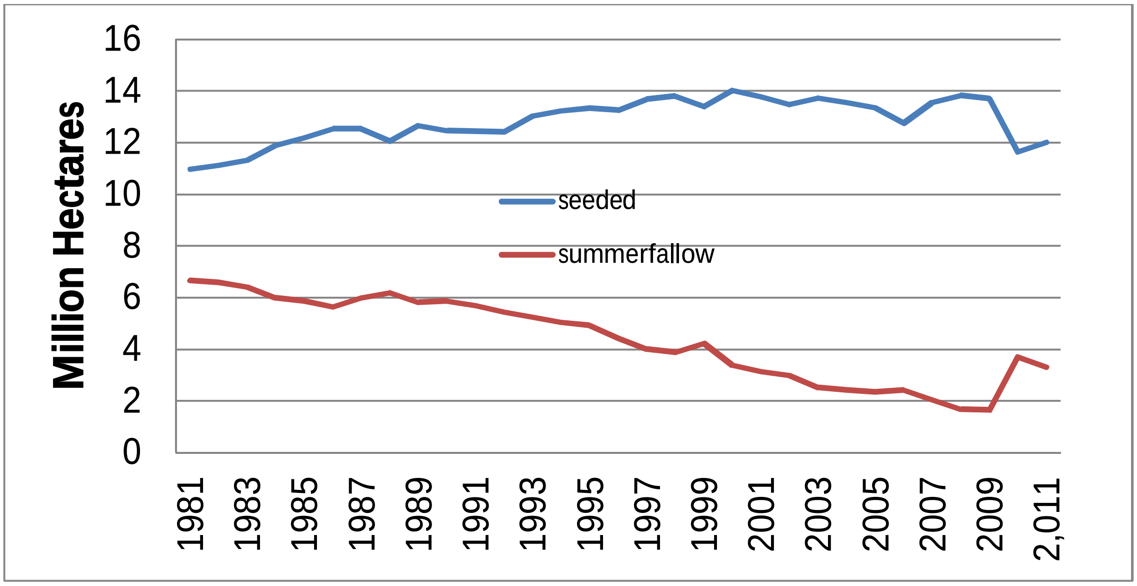

Figure 4: **Hectares seeded to crops and in summerfallow in Saskatchewan from 1981 to 2011.**
Data retrieved from: http://www.agriculture.gov.sk.ca/Default.aspx?DN=274b2ec5-4d55-4a74-9a9d-6bc1105105da

The yields for 5 major crops grown in Saskatchewan over the last 20 years, is shown in Figure 5. On average, yields have trended upwards due to improved direct seeding technologies, more precise fertilizer placement and improved crop varieties being adopted over time. However, erratic weather pattern in the form of drought from 2001 to 2003 had a significant impact on crop yields.

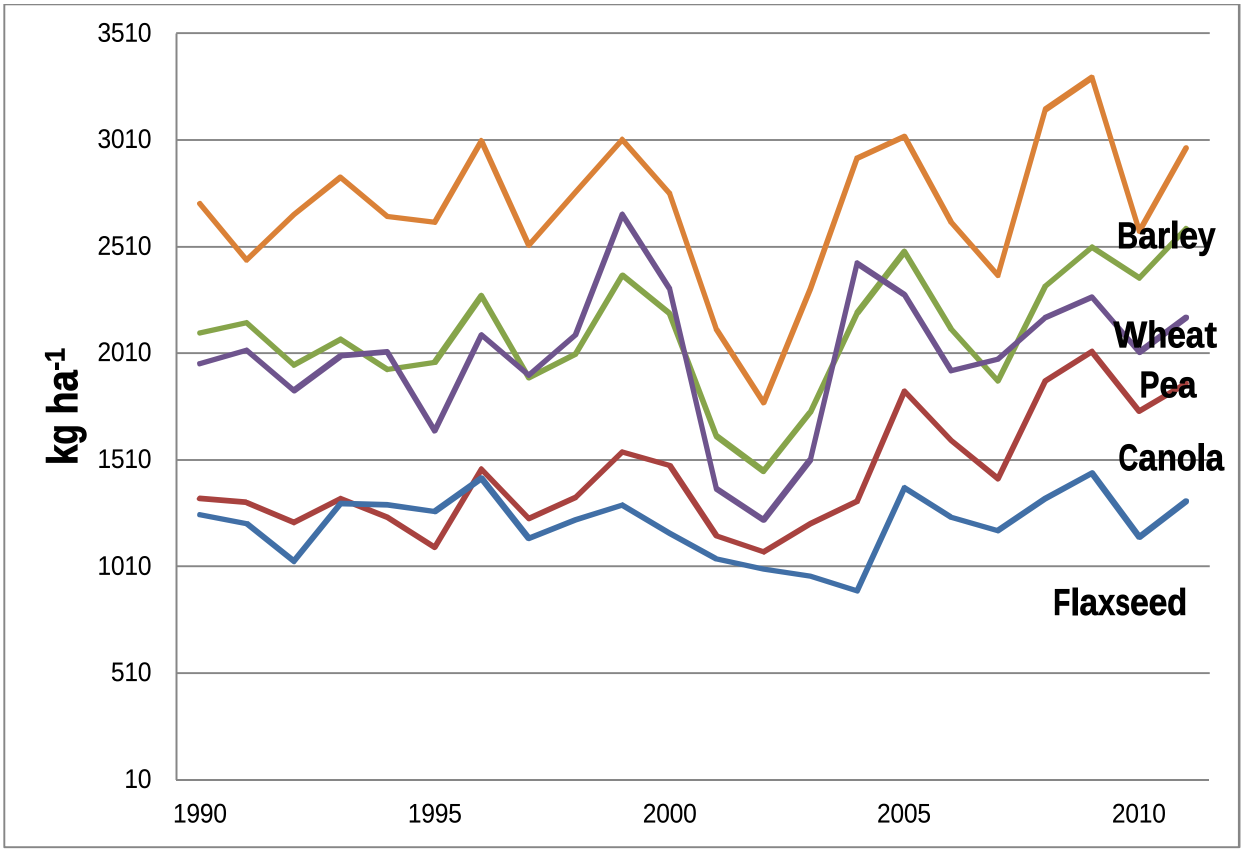

Figure 5: Average yield (kg/ha) of five major crops grown in Saskatchewan (1991-2011).

Data retrieved from Government of Saskatchewan, Ministry of Agriculture.
http://www.agriculture.gov.sk.ca/Statistics-Crops

The land managers were instructed to manage the land in their best interests (the exception was the level 2 co-operators who were asked to maintain a 5 ha strip of cultivated land for 1997 to 1999. Other than tillage, they were to manage the tilled strip the same as the remainder of the field. The level 2 co-operators were paid a modest nuisance fee for maintaining the tilled strip. The microsites had no surface marking.

Changes in land owner and/or land manager were continual over the 1997 to 2011 period. By 2011, we estimated that about half the land had changed managers. Several sites have had 3 land managers since 1997. Typically the new manager would continue with the project although some would not. Also some of the co-operators chose to drop out of the project.

Management data was obtained voluntarily from the co-operators at four times: (1) in 1997 for pre 1996; (2) 1999-2000 for 1997-99; (3) 2005-06 for 2000-2005; and (4) 2012 for 2006-2011.

Sites selected for sampling in 2011

From the 121 sites sampled in 2005, sites selected for 2011 sampling were based on the following:

1. Whether the land manager and/or land owner could be contacted to obtain permission to resample; and,
2. Whether there was at least 4 years of collected management data for the 2000-2005 (note management data for 2000-2005 had been obtained from only 108 sites.).

Of the sites meeting these conditions, those that either converted to permanent pasture by 2005, had been tilled more than three years in the 2000-2005 period, or which had had manure applied were excluded from the sampling. Some land managers and/or land owners contacted for the 2011 sampling did not want to remain involved in the project. Ultimately 82 sites were sampled in late October-early November, 2011.

The co-operators were contacted for management data for 2006-2011 for these 82 sites, with 52 responding. However data for each year was not obtained owing to discontinuous records due to gaps between changing co-operators for same land parcel or other difficulties obtaining field information for some years.

Two sites were removed from the analysis because management data was not obtained but their condition at time of sampling was different than all the other sites. One site was tilled at time of sampling and was eliminated because it was unknown how much tillage had occurred during 2006-2011. The other eliminated site was in perennial forage and it was unknown if the site had been in long-term forage production since 2006. The other 28 sampled sites without management data were assumed to have population of management practices the same as that of those sites for which management data was obtained.

Management data for 2006-2011 was collected from 52 co-operators, comprising 761 site years of management data. The focus of the analysis of management data will be on these sites because their length provides the greatest usefulness for describing the range of management.

Soil

Over the course of the study, a small increase in bulk density occurred in the 0-10 cm depth interval (Figure 6). Usage of the equivalent soil mass method for calculating SOC change results in this study would take the increase into account so not bias the statistical comparisons of SOC mass.

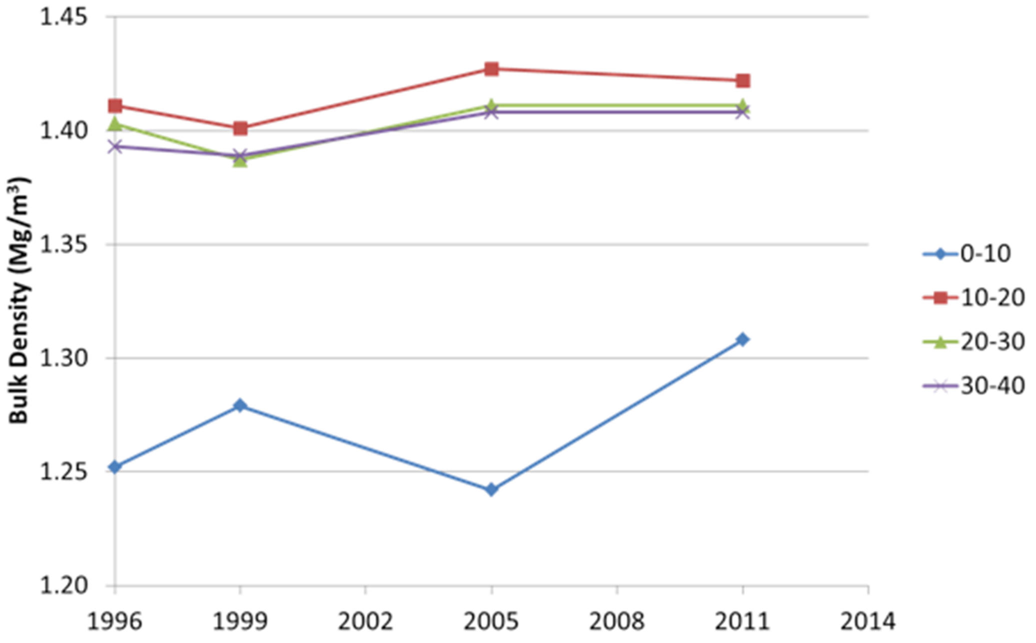

Figure 6: Saskatchewan study sites indicate a small increase in soil density at the surface, from 1996 to 2011.

Detecting SOC change on individual fields using microsites

The spatial variability of SOC at one time as measured in 8 individual microsites was large (Fig. 7). We applied the bootstrap method without replacement to the data for these 8 sites to estimate the variability of SOC differences between 100 groupings of 6 cores from within each of the 8 microsites having detailed coring. The results showed that the 95% confidence interval for 0-30 cm SOC change for one microsite was ± 3 Mg C/ha using the 6 composited cores with small spatial offset. Consequently, only large changes in SOC can be distinguished from no change using a single microsite. If it was desired to improve resolution and precision, then many microsites would be needed in a single field. Assuming the spatial variability is the same throughout the field, it would take 12 microsites in the field to have a confidence limit of ± 1 Mg C/ha and 41 microsites for a confidence limit of ± 0.5 Mg C/ha. These are likely optimistic because there would likely be extra variability introduced by variation in effects over time from place to place within the field. Clearly, the microsite method is not an effective method for precisely measuring SOC change at low cost for an individual field.

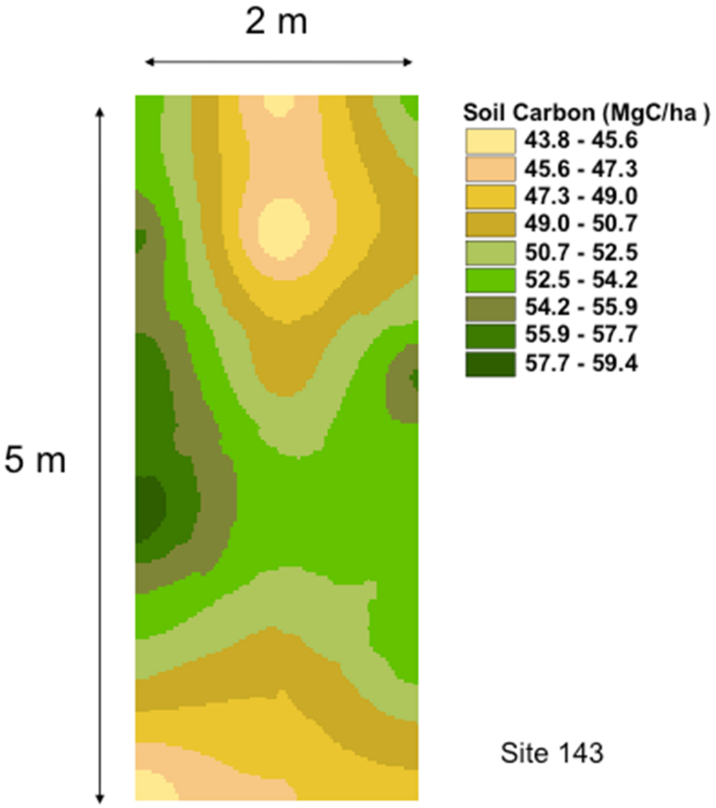

Figure 7: SOC (Mg C ha^{-1}) is highly variable in a single site location (Site 143).

1999 Sampling

For the level 2 sites, SOC increased with depth from 1996 to 1999 (Fig. 8). 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 of 0.74 Mg ha^{-1} or an average SOC change rate of 0.25 Mg ha^{-1} yr^{-1}. Despite the orders of magnitude of difference observed between the two types of crop management, this short-term study showed 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.

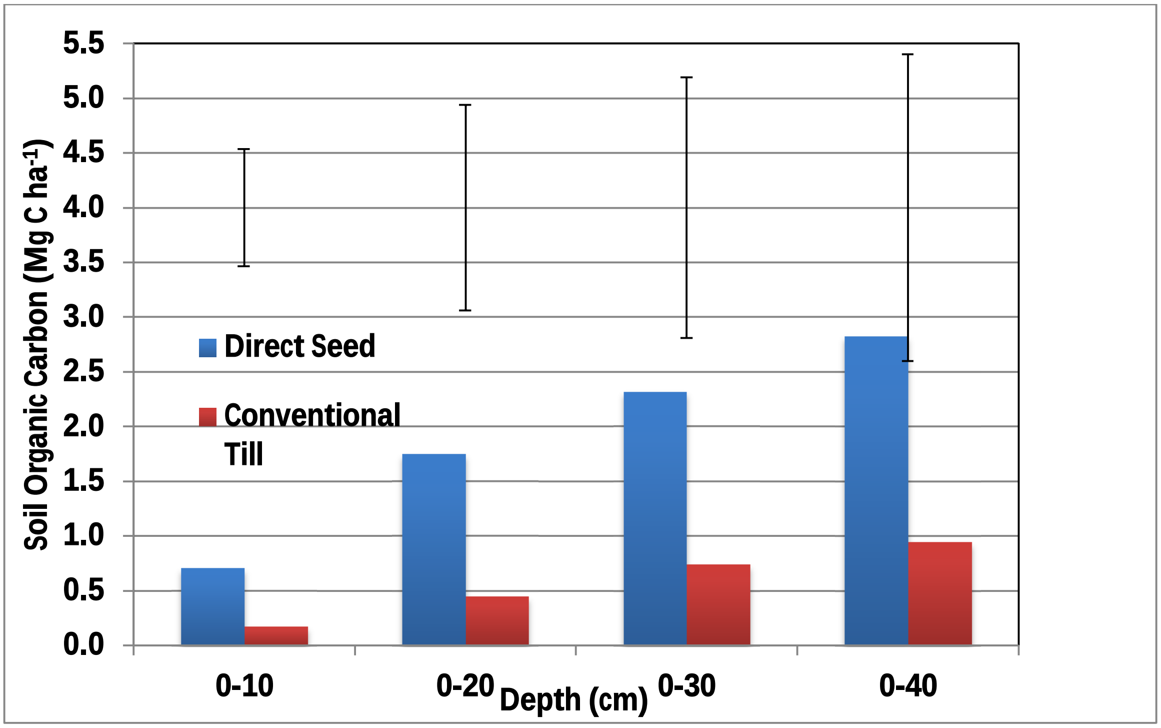

Figure 8: Soil Organic Carbon under direct seeding versus conventional tillage from 1996 to 1999 at 4 depth increments (n=22; LSD p=0.05).

As in the SOC results, direct seeded sites tended to have higher amounts of above ground production, but the differences were not statistically significant (Fig. 9).

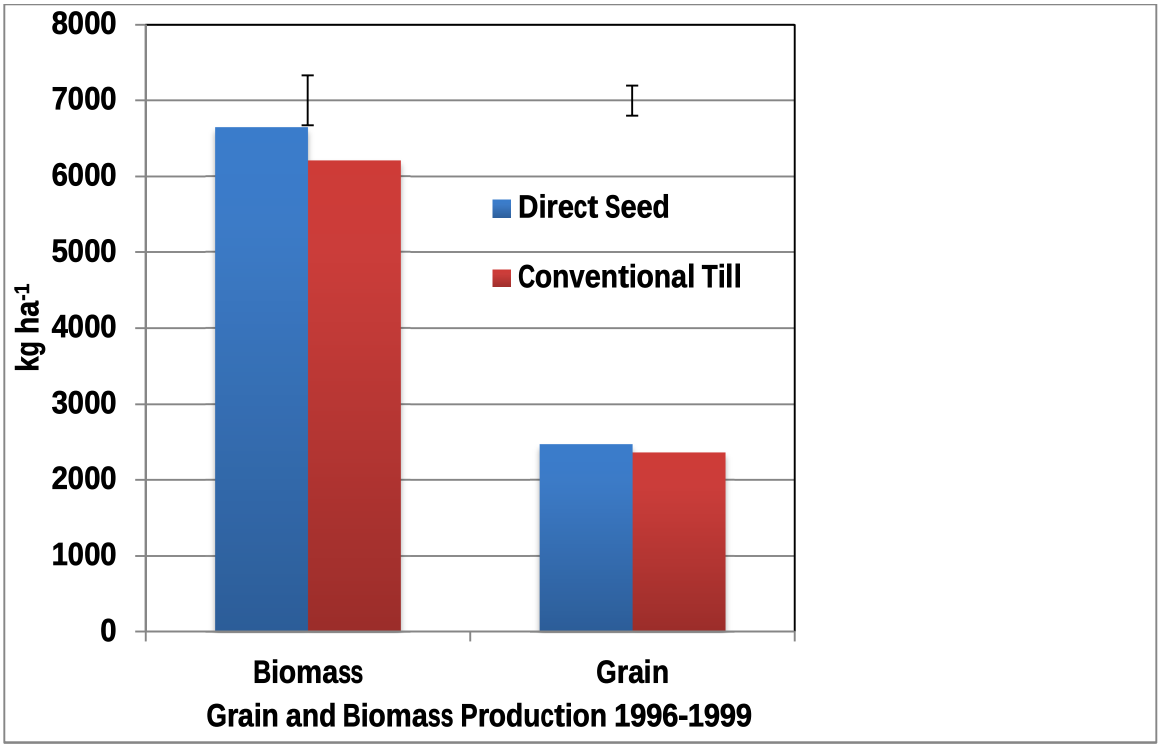

Figure 9: Changes in grain and biomass production between direct seeded and conventional tillage systems from 1996 to 1999 (n=58; LSD p=0.05)

2011 Sampling

The change in SOC over the course of the PSCB study showed an increasing amount of carbon with increasing depth, to at least 40 cm (Fig. 10).

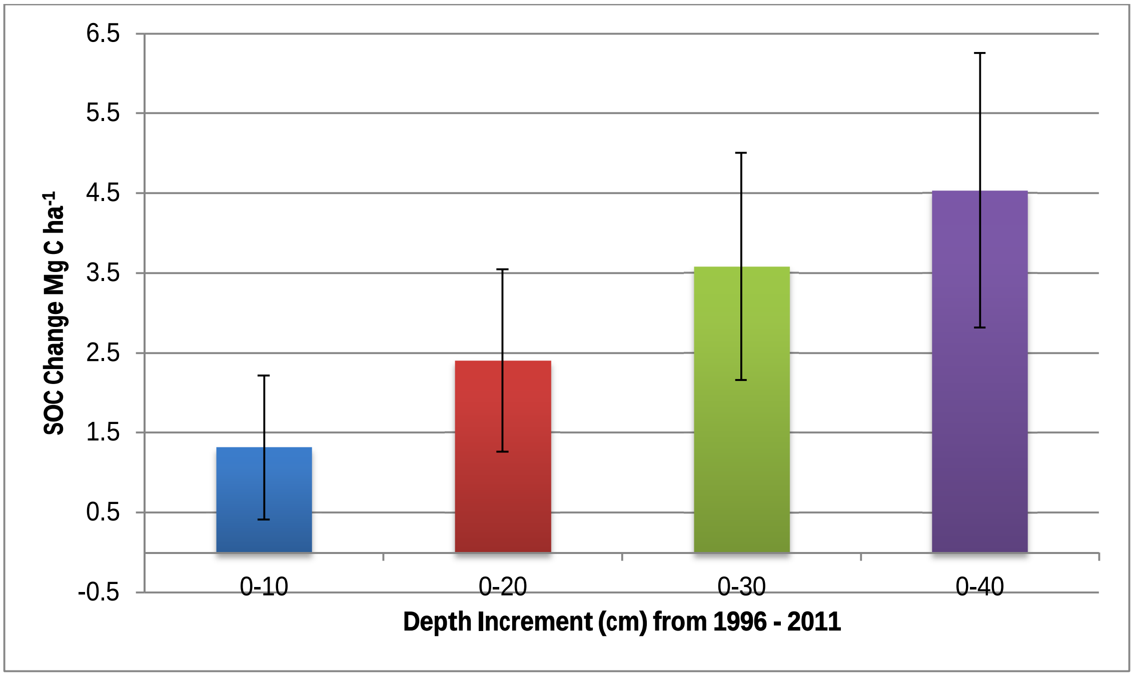

Figure 10: Soil Organic Carbon changes by depth increment averaged across all Level 1 and Level 2 sites (direct seeded) from 1996 to 2011 (n=80; statistics show 95% confidence interval for mean SOC change).

At the surface layer (0-10 cm), there was an increase in the average change in SOC over the course of the study (Fig. 11). This indicates that the SOC increase was most consistent for the surface 10 cm of soil.

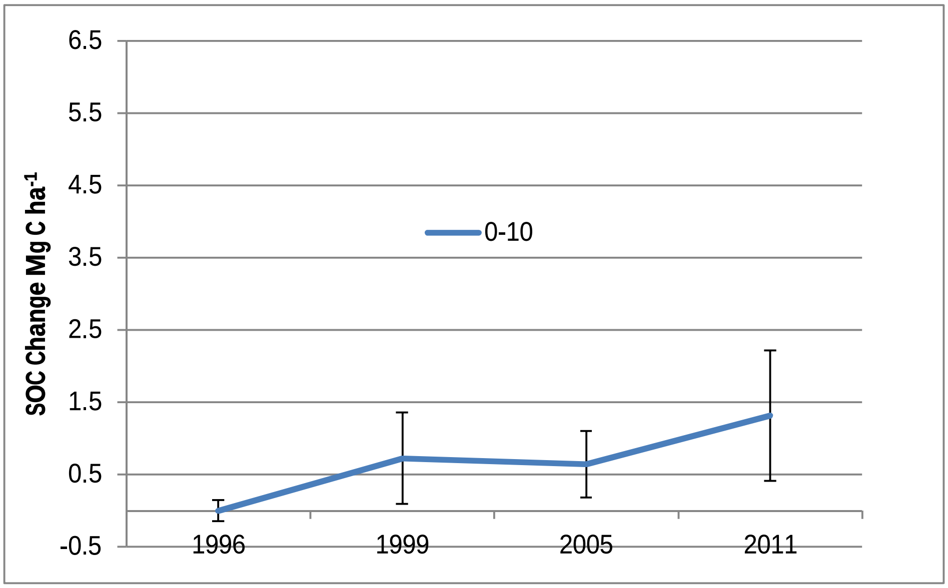

Figure 11: Changes in Soil Organic Carbon under direct seeding (2011 sampled sites only) averaged across all Level 1 and Level 2 sites (direct seeded only) from 1996-2011, for the 0-10 cm depth (n=80; statistics show 95% confidence interval for mean SOC change).

From 0-20 cm, a significant increase in the SOC change from 1996 only occurred between the initial year (1996) and 2011 (Fig. 12). A similar situation existed for 0-30 cm depth (Fig. 13).

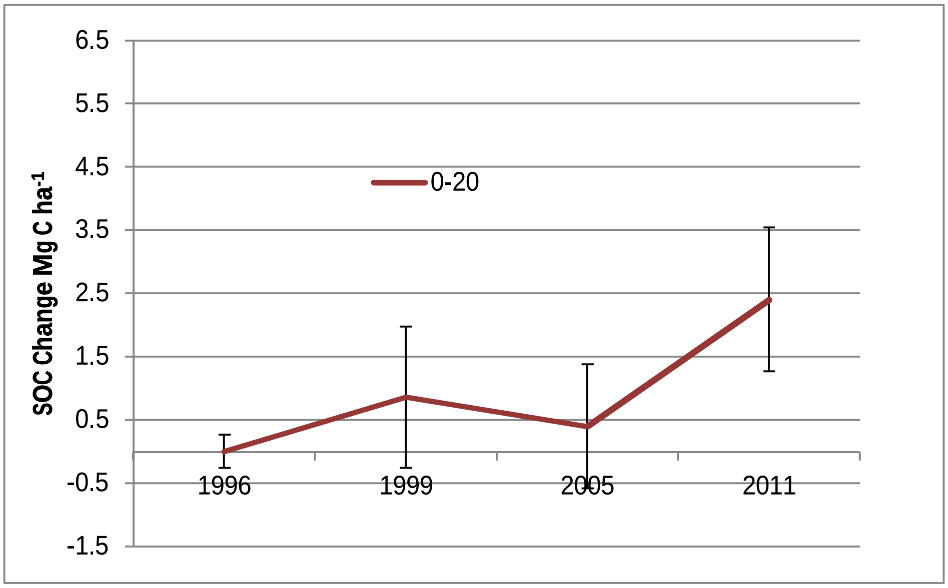

Figure 12: **Changes in Soil Organic Carbon under direct seeding (2011 sampled sites only) averaged across all Level 1 and Level 2 sites (direct seeded) from 1996-2011, for the 0-20 cm depth (n=80; statistics show 95% confidence interval for mean SOC change).**

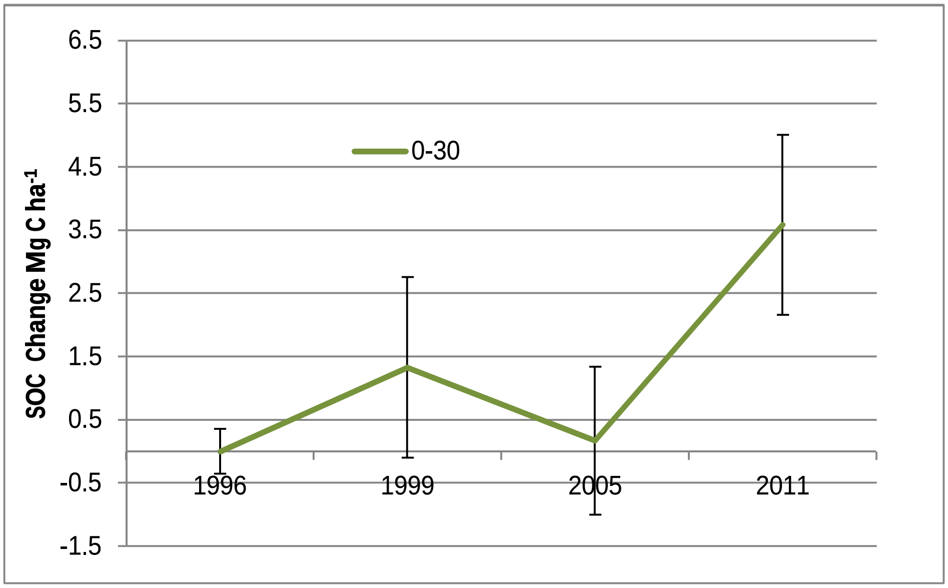

Figure 13: **Changes in Soil Organic Carbon under direct seeding (2011 sampled sites only) averaged across all Level 1 and Level 2 sites (direct seeded) from 1996-2011, for the 0-30 cm depth (n=80; statistics show 95% confidence interval for mean SOC change).**

As shown in Figure 10, the variability in SOC change increases with depth. Nevertheless, the magnitude of SOC increase was also greater for this increment so the change was significantly different from zero in 1999 and 2011. Increased SOC change below 20 cm was unexpected speaks to the benefits of more sustainable and conservation practices being adopted on the Canadian prairies over the last 15 years.

We attribute the small measured SOC change from 1996 to 2005 to the effects of the droughts of 2001-2003. These years had dramatically lower yields of crops compared to previous or following years (Fig. 5). By 2004 or 2005, more favourable weather had allowed yields to recover. However, SOC would have dropped in these prior years with lower C inputs. The SOC content of the surface soil would be first to recover as it is most responsive to a rebound in C input. This is evident as there was an increase for the 0-10 cm depth for 2005 compared to 1996 (Fig. 11) but no significant SOC change when deeper soil was included in analysis (Figs. 12-14). There was apparently not a lasting effect of the 2001-2003 drought as SOC change resumed a similar trajectory for 996-2005 period as had occurred in the 1996 to 1999 period.

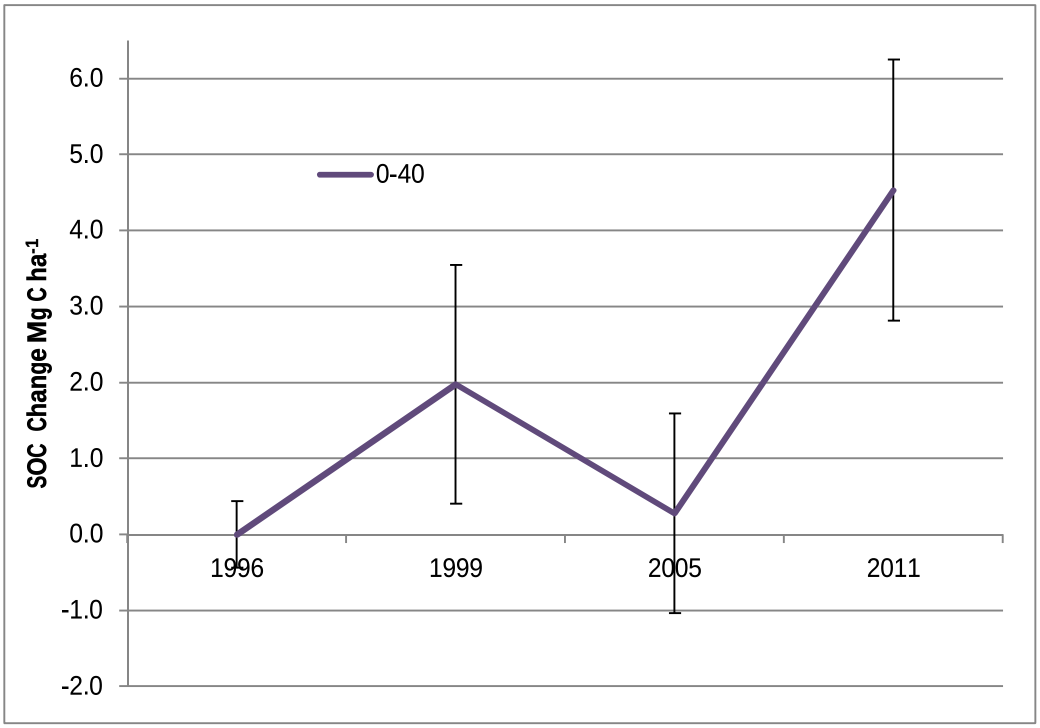

Figure 14: Changes in Soil Organic Carbon under direct seeding (2011 sampled sites only) averaged across all Level 1 and Level 2 sites (direct seeded) from 1996-2011, for the 0-40 cm depth (n=80; statistics show 95% confidence interval for mean SOC change).

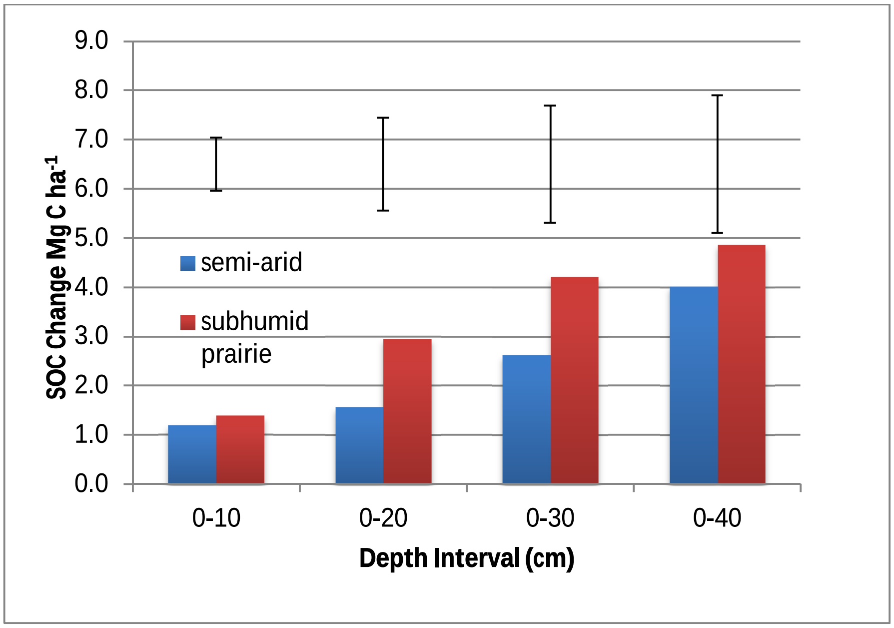

Figure 15: Soil Organic Carbon in 2011 across semiarid soil zones (Brown and Dark Brown Chernozem) versus the suhumid soil zones (Black and Dark Grey Chernozem plus Grey Luvisols) averaged across all Level 1 and Level 2 sites (direct seeded) and by depth interval, after 15 years of management change. (LSD p=0.05)

The trend was for mean SOC change within the monitored network to be smaller in the semiarid prairie compared to the subhumid prairie, as expected (Fig. 15). However, there were no significant differences between zones.

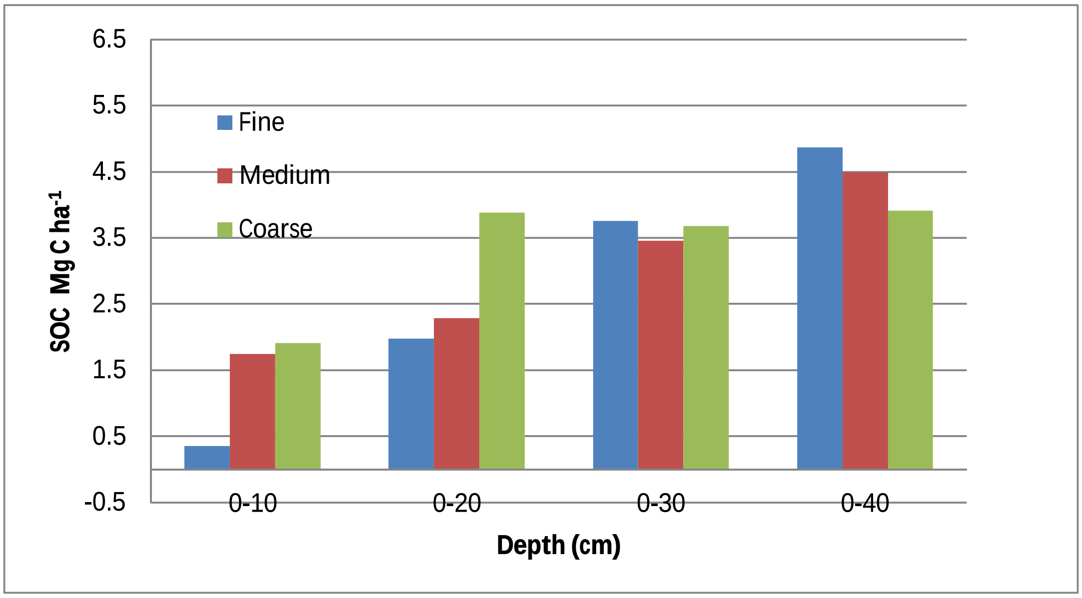

Figure 16: Soil Organic Carbon in 2011 textural classes, averaged across all Level 1 and Level 2 sites (direct seeded) and by depth interval, after 15 years of management change (n-26 for fine

textured, clay-loam to clay; n= 43 for medium textured (loam to silt-loam and n=11 for coarse textured soils, sand to sandy loam; there were no differences at p=0.05).

There was no significant effect of texture on SOC overall (Fig. 16). However the trend suggested SOC change occurred deeper in profile as texture became finer. For the coarse textured soil, all SOC change appeared to be in 0-20 cm, for finer textured soils almost all SOC change was in the 20-40 cm depth, and for medium textured soil most SOC change was in the 0-30 cm depth.

Crop Diversity and Sequences

Table 1 gives the crops grown and their prevalence. The cropping sequences were diverse. The mean number of different crops grown by each co-operator over 1997-2011period was 5 (also median=mode=5) with a maximum of 9 and minimum of 3. Fallow (no crop grown and weeds controlled) occurred 28 times. The general distribution of crop types was similar to the average situation for Saskatchewan during this time (Fig. 3). Pulse crops (pea, lentil, and chickpea) appeared more frequently in the monitored fields than their relative prevalence across all Saskatchewan cropland.

Table 1: Crop grown, species, and number of occurrences.

Crop	**Species**	**Occurrences**
wheat	*Triticum aestivum* L. (not distinguishing type or whether winter or spring growth habit)	191
canola	*Brassica napus* L. assumed, *B. rapa* L. identified once, possibly some unidentified *B. juncea* L	164
pea	*Pisum sativa* L.	93
durum	*Triticum durum* L.	76
barley	*Hordeum vulgare* L.	71
lentil	*Lens ensculenta* L.	48
flax	*Linum usitatissimum* L.	36
oat	*Avena sativa* L.	21
chickpea	*Cicer arietinum* L.	11
canary seed	*Phalaris canariensi* L.	9
mustard	*Sinapis alba L. and/or B. juncea* L. (not identified which)	6
alfalfa	*Medicago sativa* L.	2
dry bean	*Phaseolus vulgaris* L.	1
triticale	*X Triticosecale* Wittmack	1
safflower	*Carthamus tinctorius* L.	1
sunflower	*Helianthus annuus* L.	1

One co-operator followed a fixed rotation of wheat-canola-barley-pea from 1997-2011. Another co-operator had 3 consecutive cycles of that same rotation. Otherwise, over a period of at least 9 years there were no discernible rotations (even if crops in missing years were assumed to be the same as preceding or subsequent crop sequences). When the sequences were broken down into two year sequences, there were some clear patterns (Table 2). Sequences of broadleaf-cereal and cereal -broadleaf crops predominated. Broadleaf-broadleaf crop sequences were less common (occurred 44 times) than cereal - cereal sequences (occurred 57 times). Sequences of oilseed-oilseed and pulse-pulse were less common than pulse-oilseed or oilseed-pulse sequences. Cereal-cereal was the only sequence where the same crop (wheat) was seeded successively at least 1/3 of occurrences (occurred 20 times). The co-operators achieved a high degree of crop diversity on the fields. Wheat was the crop most likely to precede fallow and canola the most likely crop to be grown on fallow.

Table 2: Crop sequence occurrences.

Crop Sequence	**Occurrences**	**Most common crop sequence: Occurrences**
Cereal-oilseed	153	Wheat-canola: 65
Oilseed-cereal	149	Canola-wheat: 58
Cereal-pulse	113	Wheat-pea: 33
Pulse-cereal	113	Pea-wheat: 45
Cereal-cereal	57	Wheat-wheat: 20
Cereal-Fallow	17	Wheat-fallow: 12
Oilseed-pulse	16	Canola-pea: 6
Pulse-oilseed	13	Pea-canola: 7
Fallow-oilseed	12	Fallow-canola: 10
Oilseed-oilseed	11	Flax-canola : 4
Oilseed-fallow	7	Canola-fallow: 5
Fallow-cereal	6	Fallow-wheat: 3
Pulse-pulse	4	Lentil-pea, pea-lentil, lentil-chickpea, lentil-lentil: 1
Pea-fallow	2	
Fallow-lentil	1	
Alfalfa-alfalfa	1	
Alfalfa-pea	1	
Canola-alfalfa	1	

Other management practices and effects

Tillage

Harrowing to spread residue and a separate operation to band fertilizer before seeding with narrow knives were not considered tillage. Harrowing and/or banding were reported for 23 sites.

Tillage is defined as operation to mix and level the soil. Using this definition, land managers reported using tillage on 17 of the sites. Generally reasons for tillage were not usually included in comments except some noted it was to remove ruts from harvest traffic on wet soil or to incorporate a herbicide. Of these, 6 only used tillage once, and 5 only used tillage twice. However, tillage was used 5 or 6 times of 4 of the sites. In these latter sites with more frequent tillage, the tillage operations were always in consecutive years. In two of the sites, there was indication of change in tillage system as tillage was every fall from 2006 to 2011 in one site and every spring from 2007 to 2011 at the other. In the other two sites with frequent tillage, the tillage had occurred during the 1997-2000 period. We included the sites with apparently changed tillage systems in the analysis because it was assumed that the sites without management data would also include a similar proportion of such apparent tillage system change.

All the sites using tillage were also sites reporting using harrowing and/or banding. The majority of the sites with management data over 1997-2006, 39, did not have any soil disturbance other than that from the seeding operation.

The co-operators were asked to give the degree of soil disturbance during seeding with 20% surface disturbance being low, 20-40% being moderate, and >40% being high. Although some co-operators reported using high disturbance in initial years by 2006-2011 period all were using either moderate or low disturbance. Considering the average disturbance over the entire 1997-2011 period, we estimated that 21 had a moderate disturbance system with the remainder a low disturbance seeding system.

Residue Removal and Manure

For 16 of the sites, residue had been burned or baled and removed at least once. For 11 of those sites, this had occurred once, for four sites, twice, and for one site 5 times. Burning was reported only for flax straw.

None of the co-operators reported manure additions.

Fallow

There were 28 occurrences of fallow involving 22 sites. Hence fallow was unusual considering that average fallow frequency for these sites during 1990 to 1996 was reported by co-operators to have been 25% of years. Some co-operators noted fallow was a necessity because of land flooding in 2010 or 2011.

Weather

Co-operators had opportunity to add comments about weather and other natural factors affecting the crop. Over the 15 years, occasional hail, drought, excessive soil wetness, and disease were noted on most sites where the co-operator chose to comment. Other comments included excellent crop and undiagnosed conditions such as “poor plant stand”. Some widespread weather events such as drought during 2001-2003 period or excessive wetness in 2010-11 occurred on many sites. However, there were also occurrences of drought or excessive wetness on individual sites in other years. There were also observations of hail, disease and other factors damaging crops at individual sites. Some co-operators chose not to add comments and it is not known if that was because they experienced no major weather or other damaging effects. Basically, it was not possible to reliably separate out any subpopulation of sites that had clearly different crop growing conditions than another subpopulation.

Effect of Time and Management on SOC

This project involves spatially displaced SOC measurements over time over network of fields where each field is unique in terms of soil, crops, growing conditions, weather, and exact management. Due to this nature, it is not feasible to tease out the exact factors affecting |SOC change. In simple terms the measured SOC change between time 1 and time 2 is the difference between SOC from slightly offset locations at time 1 plus the difference between total C additions and total C losses for the soil sampled at time 2. Providing a sufficient number of sites are involved (at least about 25 sites), the spatial difference due to slight spatial offset should average to approximately zero. However, the differences between C additions and C losses will be unique for each site. As C additions are from crop residues and roots while losses are from the decomposition of those residues and roots plus the decomposition of the accumulated SOC stock.

Many factors affect the SOC balance. Many of the fields in the project were added to a land base of experienced direct seeding farmers in 1996 or 1997. Consequently, in addition to changes in tillage and fallow frequency already noted, the fields will also have had changes to other aspects of cropping system management as expected with change in land manager including fertility, weed management, disease management, insect management, and the crop mix. There have also been changes to cultivars and agronomic practices generally over the 1997 to 2011. The weather is not constant so differences in weather pre 1997 and that during 1997-2011 will also affect SOC. Without strongly contrasting systems of known differences to compare, it is not possible to gain an understanding of which factors are most affecting SOC change or whether decomposition or C additions were most affected. The situation in this monitoring project of fields converted to direct seeding (with other agronomic changes) did not provide the needed strongly contrasting systems to gain that understanding. The possible exception was the tilled versus direct seeding comparison on level 2 sites for 1997-99, where strong trend suggested that direct seeding alone was important contributor to SOC increase over that period. For that latter comparison, C inputs were only marginally increased by direct seeding so reduced decomposition is assumed to be major cause of change.

In Figure 17 below, the average annual SOC rate of change between the base year of 1996 and the three sample years for the 0-30 cm depth is shown. The rate of SOC change varies from 0.443 Mg C ha^{-1} between 1996 and 1999, then decreases to 0.018 between 1996 and 2005, and then averages to 0.239 Mg C ha^{-1} between 1996 and 2011.

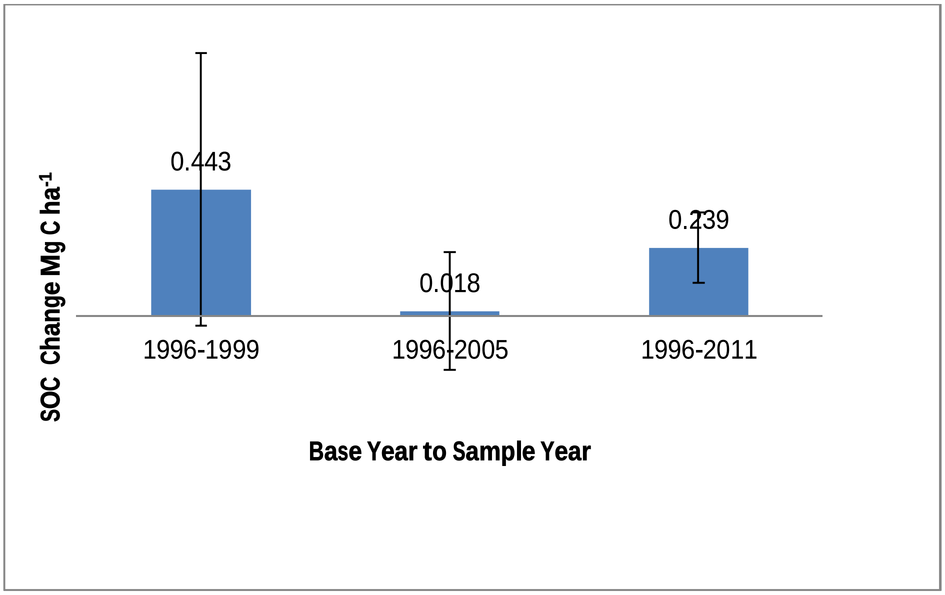

Figure 17: Average Annual Rate of Change in Soil Organic Carbon under direct seeding (2011 sampling) averaged across all Level 1 and Level 2 sites (direct seeded) for the time intervals of the study, for the 0-30 cm depth (n=80; statistics show 95% confidence interval for mean SOC change).

The small measured SOC change from 1996 to 2005 to the effects of the droughts of 2001-2003. These years had dramatically lower yields of crops compared to previous or following years (Fig. 5). By 2004 or 2005, more favourable weather had allowed yields to recover. However, SOC would have dropped in these drought years with lower C inputs. The SOC content of the surface soil would be first to recover as it is most responsive to rebound in C input. This is evident as there was an increase for the 0-10 cm depth for 2005 compared to 1996 (Fig. 11) but no significant SOC change when deeper soil was included in analysis (Figs. 12-14). There was apparently not lasting effect of the 2001-2003 drought as SOC change resumed as similar trajectory for 2005 to 1996 period as had occurred in the 1999 to 1996 period.

Generally, given the high variability of SOC change, the SOC change is only reliably interpreted for subpopulation of sites with at least 25 sites. Given the diversity of management, it was not possible to find 25 sites or more that differ from another group by only one factor. Although none had all subpopulation with 25 or more sites, those factors evaluated for effect on SOC change included tillage frequency, disturbance level, fallow frequency, oilseed vs. pulse intensive crop sequences, and residue removal. None of these had a discernible effect on SOC change (results not shown).

A variety of interesting results were found in this study. In particular, the change in SOC below the 20 cm soil depth was unexpected. A large change in SOC, below 20 cm, has been only previously observed in small plots when perennial crops introduced on land previously growing annual crops. The gain in SOC from introduction of perennial crops is related to increased C input and reduced C decomposition. By analogy, this observed SOC change for this project than is most readily explained by both increased carbon input and reduced carbon decomposition.

Overall, SOC on land converted to direct seeding in the Canadian prairies is increasing. The management shifts increasing SOC change can be classified into three main drivers. First is the reduction in summerfallow. Over the course of the study, and indicative of the major management shifts in the prairies, the average fallow frequency was 3.8% in 2011, compared to the previous time period 1990-1996 where the average frequency of fallow was 24.5%. Summerfallow frequency was probably even higher on these fields prior to 1990 consistent with historical summerfallow occurrence (Fig. 4). Second is reduced tillage intensity due to direct seeding. Reduced tillage intensity has the added benefit of slowing SOC decomposition, and increasing carbon inputs due to the way residue management is altered under this management regime. Third is assumed increased crop C input (residue+roots) from improved agronomy and cultivars for post 1996 compared to historical C inputs.

It is important to note is that SOC change to 0-40 were significant in 1999 and 2011. There was no indication of stratification of SOC change such that most SOC change increased at surface at expense of SOC losses with depth. Instead the increase was approximately linear with depth (Fig. 8 and 10). This indicates that soil sampling to detect total SOC change should be deeper than 40 cm. However, variability increases with depth so that more independent observations are generally required to detect non-zero SOC change as sampling depth increases.

Using national greenhouse gas inventory methods, the SOC change for 0-30 cm would be predicted to change at an amount of 2.3 Mg/ha for sub-humid ("parkland") prairie and 1.9 Mg/ha for semi-arid prairie relative to pre-1996 management. These changes for semiarid prairie were within 95% confidence limits but the observed mean was about 22% higher than the estimate. For the subhumid prairie the inventory estimate was less than the 95% lower confidence limit and the observed mean (4.6 Mg/ha was nearly twice the estimate). However, the inventory methods are developed to be relative to what would have occurred without change to tillage system or fallow. Therefore, it is difficult to compare with these absolute SOC change.

In summary, SOC is increasing on Saskatchewan farmland under direct seeding at a rate of 0.23 Mg C/ha/yr or up to 0.38 ton CO_2/ac/yr. The SOC is increasing at depths to at least 40 cm, and the changes are much greater than expected. This new information is expected to end controversy about SOC increase and is extremely important for claims of positive environmental performance (including a low carbon footprint).

Resampling of the PSCB sites in future would further clarify the rates of SOC change over longer periods and, more importantly, provide new information on the duration of C sequestration.

Conclusion

The PSCB has been success in proving that adoption of direct seeding increases SOC on Canadian prairies. The SOC increases were both substantial and greater than expected. Unfortunately, it proved impractical to measure SOC change on individual farm fields. The new information supports documentation of reduced C footprint for direct seeded cropland on Canadian prairies because increasing SOC represents removal of CO_2 from the atmosphere. The results also support, indirectly, carbon offsets from adoption of direct seeding.

Acknowledgements

This project would not have been possible without the involvement of dozens of people over many years. It is therefore difficult to properly acknowledge everyone. All SSCA staff from 1996 onwards and current Board of Directors were instrumental to the success of the project. Numerous AAFC staff also provided essential contributions. Particular thanks are owed to Glenn Padbury for spearheading initial samplings and to Alvin Anderson for ensuring sampling integrity throughout the entire project.

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