Measuring Soil Carbon Change on Cropland: The Prairie Soil Carbon Balance Project

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ABSTRACT

This paper discusses carbon sequestration on agricultural land, United Nations Framework Convention on Climate Change and the Kyoto Protocol, permanence of carbon sequestration, rates of carbon sequestration, and results of measuring carbon sequestration on commercial farm fields within the Prairie Soil Carbon Balance Project.

INTRODUCTION

Carbon Sequestration

Carbon sequestration refers to taking carbon dioxide (CO_2) out of the atmosphere through plants and storing that carbon in soil organic matter. Since first broken for crop production 80 to 120 years ago, prairie soils have lost about one-third of their native soil organic matter. This soil organic matter was lost because: 1) the tillage exposed the native soil organic matter to more decomposition, 2) the annual crops returned less residue than the native prairie (in particular, summerfallow added no residue except weeds), and 3) moister soil accelerated decomposition since annual crops did not keep the soil as dry as the native grass did. While the soil organic matter was being lost, the carbon in that soil organic matter was being lost to the atmosphere as CO_2. Each tonne of carbon lost from soil organic matter released 3.667 tonnes of CO_2. Similarly, each tonne of soil organic carbon increase removes 3.667 tonnes of CO_2 from the atmosphere. The process of carbon sequestration is often referred to as making the soil a *sink for* CO_2.

Presently, we estimate that the soil organic matter on cropped prairie soils is stable and at an approximate steady state where annual additions of carbon from crop residues roughly equal the amount of carbon released as CO_2 by soil microbes each year. If we change agricultural management in ways that increases soil organic matter, such as adopting direct seeding, $CO_2$is removed from the atmosphere and sequestered as soil organic matter. Hence, carbon sequestration is essentially recapturing carbon from the atmosphere that had been emitted from the soil in the past (Figure 1). Carbon sequestration does not continue indefinitely as eventually a new steady state is reached when residue inputs equal total decomposition of soil organic matter. The length of time before a new steady state soil organic carbon level is reached is uncertain but most sequestration occurs over the first 10 to 20 years after the adoption of the new management practice.

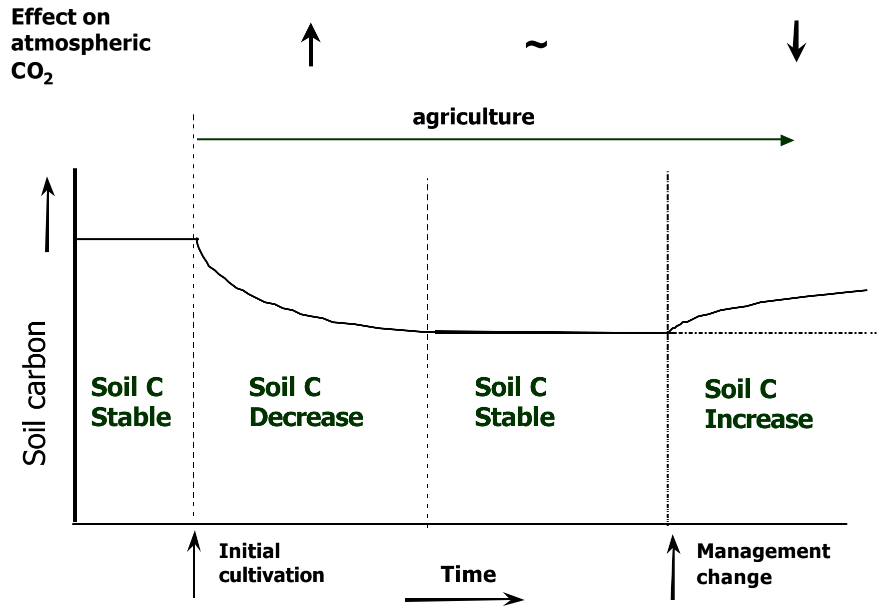

Figure 1. Soil carbon changes due to initial land conversion to agriculture, attainment of a new equilibrium, followed by adoption of management practices that sequester carbon.

United Nations Framework Convention on Climate Change

Concerns regarding climate change from increasing concentration of greenhouse gases (GHG) in the atmosphere due to human activities resulted in the United Nations Framework Convention of Climate Change (UNFCCC) that has been signed by 174 countries including Canada. The UNFCCC sets out GHG emission reduction targets for developed countries and also requires that signing countries shall "promote sustainable management, and promote ... the conservation and enhancement ... of sinks". Agricultural soil C sinks fall under article 3.4 of the yet-to-be-ratified Kyoto Protocol to the UNFCCC that call for countries to decide on "... guidelines as to how, and which, additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in agricultural soils ... shall be added to or subtracted from assigned [GHG reduction targets] ... taking into account uncertainties, transparency in reporting, [and] verifiability ". Importantly, only sinks achieved from 2008 could be considered under the Kyoto Protocol. Sinks would be quantified over 5-yr commitment periods, i.e. 2008-2012, 2013-2018, etc. Negotiations including the recent Conference of Parties to the UNFCCC in The Hague, The Netherlands, during November 2000 have failed to reach agreement on those Kyoto Protocol sink "guidelines" that would create international acceptance of agricultural soil sinks. Nevertheless, the ability to measure and verify sinks and the uncertainty of those measurements are important criteria for the acceptance of sinks as a valid offset for GHG emissions and, ultimately, for setting rewards based on the amount of soil organic carbon (SOC) sequestered for land managers who adopt practices that created the soil sink.

Within the Kyoto Protocol, Canada agreed to keep its average annual total GHG emissions during 2008-2012 to 6% less than the nation's emissions in 1990. Canada submitted to the UNFCCC on August 1, 2000 that it could achieve C sinks on agricultural land equalling 4 to 20

Mt of CO_2 (equivalent) per year, depending on rates of adoption of C sequestering agricultural practices including adoption of direct seeding, reduction in frequency of fallow, establishing shelterbelts, converting marginal cropland to pasture or hayland, and improved grazing management (most would come from adoption of reduced tillage and reduced summerfallow on the prairies). Agricultural soil sinks would account for no more than 15% of the expected gap between Canada's predicted emissions during 2008-2012 and the emission target under the Kyoto Protocol.

Two important issues for agricultural soil sinks are permanence and other benefits of agricultural soil sinks.

Permanence

True permanence can not be assured for reduced CO_2 emissions from burning less fossil fuel or for CO_2 removed from the atmosphere and sequestered in agricultural soils. There is no moral or practical impediment that prevents the future burning and release of CO_2 from any fossil fuel reserve that we choose not to burn at present in the interest of reducing CO_2 emissions. Similarly, there is no moral or practical impediment to prevent the future releases of CO_2 from agricultural soil sink. Both reducing emissions of CO_2 from burning less fossil fuel or sequestering atmospheric CO_2 has greatest permanency if they are the consequence of technological, economic, and attitudinal change such that there is no desire in the future to either burn the conserved fossil fuel or release the sequestered CO_2 back into the atmosphere. Regarding agricultural soils sinks, then, it is important that the practices to accomplish sinks are valued for a number of purposes so managers and owners of the agricultural SOC stocks have multiple reasons to maintain or enhance those stocks. Therefore, Canada is only proposing those activities, such as reduced tillage and improved grazing management, that have other substantial environmental and economic advantages for both the land manager and society besides carbon sequestration.

Regardless of whether agricultural soil sinks are credited as an offset for CO_2 emissions elsewhere, the issue of maintaining the SOC stock on the agricultural land remains. The current proposal from the European Union is that CO_2 emissions from agricultural SOC stock would not be counted if additions to the stock (i.e. sink) are not credited as an emission offset. Surprisingly, many environmentalists support this argument, obviously forgetting that soil degradation and associated releases of SOC from agricultural soils has been and continues to be widespread. Further, soil degradation often leads to deforestation in pursuit of new lands to replace the degraded agricultural land, further adding to CO_2 releases (only deforestation in the developed world would be counted under the Kyoto Protocol). The world's farmers control SOC stocks having CO_2 equivalent to more than 100 years of the world's current anthropogenic greenhouse gas emissions. So unless GHG-reduction policies and actions foster good land stewardship that at least maintain soil carbon stocks on agricultural land, there is a potential that emissions from those stocks could undermine other reductions in GHG emissions. For example, if a carbon tax were imposed to try to reduce fossil fuel consumption, that would increases the price of nitrogen fertilizer since that fertilizer is made from natural gas. This price increase would induce farmers to use more summerfallow to purposely reduce SOC to release the nitrogen in that soil organic matter. Unfortunately, depleting soil organic matter to release nitrogen releases about 10 times as much CO_2 as producing the nitrogen from natural gas. This example shows why sound GHG policy should explicitly include land stewardship.

Most of the increases in SOC from adoption of improved management practices are expected to occur over a time period of 10 to 20 yr after adoption. Consequently agricultural soil sinks are not a long-lived mitigation strategy. The mitigation value of sinks is that they provide net emission reductions to bridge the time until more sustainable GHG emissions reductions are accomplished by changes to technologies and fossil fuel energy use within the overall economy. Much of the interest and potential value of agricultural soil sinks is that they can be implemented relatively quickly, probably at competitive cost to other GHG mitigation strategies, thereby cost-effectively providing this bridge until the widespread adoption of newer technologies and consumer behaviours that emit less GHG.

Potential Liability for Agricultural Soil Sinks

Demanding permanency of soil organic matter in agricultural soil creates a real liability for landowners and land managers. If land management or weather changes so that SOC is released back to atmosphere, the landowner and/or land manager would be responsible for those emissions. The public concern regarding this liability is greatest if SOC increases are traded to offset GHG emissions. If the offsetting SOC is released, the offset is invalidated. To return to the same net emissions would require finding, possibly purchasing, another offset (new sink or emission reduction) in compensation.

To address the above concern the conservation tillage farm groups in the prairies, including the Alberta Conservation Tillage Society, Saskatchewan Soil Conservation Association, and Manitoba-North Dakota Zero-Tillage Farmers Association, have proposed a soil sink C bank and leasing system (Bennett and Mitchell, 2000). Under this arrangement, C sinks would be put into a CO_2 “bank” and “leased” to emitters who would be obligated to “repay” the C bank an equivalent amount of CO_2 as emission reduction in the future. For example, a major emitter may be well able to undertake large GHG emission reduction in its operations but it would take years to change its GHG-emitting infrastructure and, further, would be more cost-effectively done when that GHG emitting infrastructure is depreciated and needs to be replaced anyway. This emitter would benefit by paying the owners of the agricultural soil sink bank to “lease” a CO_2 sink from the bank for the time it takes to cost-effectively make those emission reductions. The emitter then repays the bank the “leased” CO2 sink with an equivalent amount of emission reductions (note a emission reduction is the difference between the baseline emissions and current emissions). Thus, even if the CO_2 is lost from the soil C stock, eventually, a net emission reduction is achieved to compensate for that C loss. Hence, the potential long-term liability of the contributing farmers is minimized. Further, this C bank-leasing system ensures that C sinks are used to achieve longer-lived net emission reductions and not used as a loophole to avoid actions to reduce GHG emissions.

Under the Kyoto Protocol, the agricultural soil C bank could only contain C sinks achieved since 2008. Under a full-carbon accounting system that Canada has proposed internationally (i.e. considering all human-induced GHG emissions and sinks), Canadian farmers would be responsible for any other losses of C from agricultural soils. Also, if C was released from the sink before it had been "repaid" with emission reductions, during the commitment period of that release, the increased emissions could put Canada into non-compliance. There is no mechanism under the Kyoto Protocol for compensating for current emissions with net emission reductions in a future commitment period. Consequently, the C bank and leasing system does not really reduce liability for release of CO_2 from the portion of the agricultural soil C stock that was added since 2008 until the C "bank" has been fully "repaid" by emission reductions. Finally, there is no mechanism in the Kyoto Protocol for using sinks in a previous commitment period to offset GHG emissions in a subsequent commitment period. Within the UNFCCC process, every soil C sink accomplished is reported to the international community during the commitment period when the sink occurred. Once reported, the sink has been used as an offset against Canada's total emissions whether "leased" or not (unless it has been "leased" to an emitter in another developed country – in which case it is reported and used by that country). Hence, there is no way to bank C sinks because any C sink that was not "leased" when it occurred could not be "leased" later to offset emissions in a future commitment period. Clearly, then, there needs to be ongoing dialogue between farmers, governments, and potential "leasers" of C sinks to develop practical mechanisms for trading C sinks that fairly distributes the monetary value and risks for agricultural soil C sinks and, importantly, that also will be acceptable within the Kyoto Protocol.

Other Benefits of Agricultural Soil Carbon Sinks

SOC is a widely used and valuable indicator of the health of agricultural soils. Enhancing and maintaining SOC is thus consistent with securing healthy soil that is a essential to overall agricultural sustainability. Around the globe, much wildlife habitat is lost when it is converted to cropland to replace degraded cropland. Consequently, fostering good land stewardship that maintains or improves existing cropland is an essential step to protecting the habitats that preserve biodiversity. Climate change is predicted to makes future weather more uncertain and variable. Promoting healthy soil systems as indicated by increasing SOC helps make the agricultural system more robust against weather variability. For example, direct seeding provides better water conservation that reduces the negative impacts of droughts on crop production and provides better protection of soil with residue to protect against erosion from severe weather. Hence, many C sequestering practices to mitigate climate change are also sound practices to adapt to climate change.

Prairie Soil Carbon Balance Project

In 1996, the Prairie Soil Carbon Balance Project was initiated to determine how much carbon could be sequestered on agricultural land. The project was divided into two components: 1) annual cropping to quantify and verify the C sequestration from the adoption of direct seeding and associated concurrent intensification of cropping practices, and 2) perennial cropping to quantify the C sequestration from the adoption of better management of tame pasture and native range. This paper only discusses the annual cropping component.

The partners for the annual cropping component are Agriculture and Agri-Food Canada, SSCA

(Saskatchewan Soil Conservation Association), an organization of farmers, GEMCo (Greenhouse Emissions Management Consortium), a group of major emitters of GHG in Canada (principally coal-burning electrical utilities and natural gas transmission companies), Alberta Agriculture Food and Rural Development, and the University of Saskatchewan

The objective of this paper is to describe the quantification and verification of SOC changes due to the adoption direct seeding and concurrent reduction in fallow frequency in Saskatchewan within the annual cropping component of the Prairie Soil Carbon Balance Project.

MATERIALS AND METHODS

Paired Field Comparison

Staff of the Saskatchewan Soil Conservation Association (SSCA) identified 8 locations with paired fields representing no-till (low-disturbance direct seeding) and conventional tillage systems and crop rotations across Saskatchewan. These sites were analyzed to determine 1) if gains in SOC observed on research sites was corroborated by differences in SOC for these sites, 2) how landscape position affected apparent SOC differences between crop management systems.

At each location, a conventional-tilled field with similar soil and landscape characteristics to those of the no-till field was located nearby for comparison. Soil sampling was done on the knoll, mid-slope and where possible, on lower slope positions in both the no-till and conventional-tillage fields (it proved difficult to match soil at the lower slope at many locations). To ensure, as much as possible, comparability between the conventional and no-tillage sites, considerable care was taken to have the soil profile characteristics similar, particularly to have equal depth of topsoil. This was particularly critical at the mid-slope positions, where soil organic carbon content is strongly influenced by the relative position along the slope and by subtle differences in the shape of the slope. It is also important on the lower slopes where the amount of deposition of eroded topsoil can differ greatly from field to field. Nonetheless, it is important to remember that while considerable care was taken to ensure comparability between the no-tillage and conventional tillage fields, it is impossible to know the correctness of the assumption that soil conditions in the paired fields were identical prior to the implementation of the no-till system

Four sampling sites, or replicates, were located approximately 10 to 20 m apart at each landscape position. At each site, three individual soil profiles, each within approximately 1 m, were sampled using a hydraulically operated sampling tube of 7-cm diameter. The samples from each of the three profiles were subdivided at 0-10, 10-20, 20-30, and 30-40 cm depth increments and bulked by depth. Organic C content of soil samples was analyzed using an automated dry combustion technique (Carlo Erba™, Milan, Italy). Soil organic C in the 0-20-cm layers was calculated on the basis of an equivalent mass using SOC concentration and soil bulk density values (Ellert and Bettany, 1995).

Quantification and verification of carbon change

Adequate quantification and verification of agricultural soil sinks is important to their acceptance as an offset for other GHG emissions and to set any rewards for good land stewardship that produces agricultural soil sinks. The system to quantify and verify changes in soil carbon stocks on agricultural land for the Prairie Soil Carbon Balance Project is shown in Fig 2. The core of system is the model of soil C dynamics. This science of soil C dynamics is relatively well developed and several soil C models (e.g. CENTURY) have been used successfully to predict changes in soil C in a wide range of environments. The basic system involves:

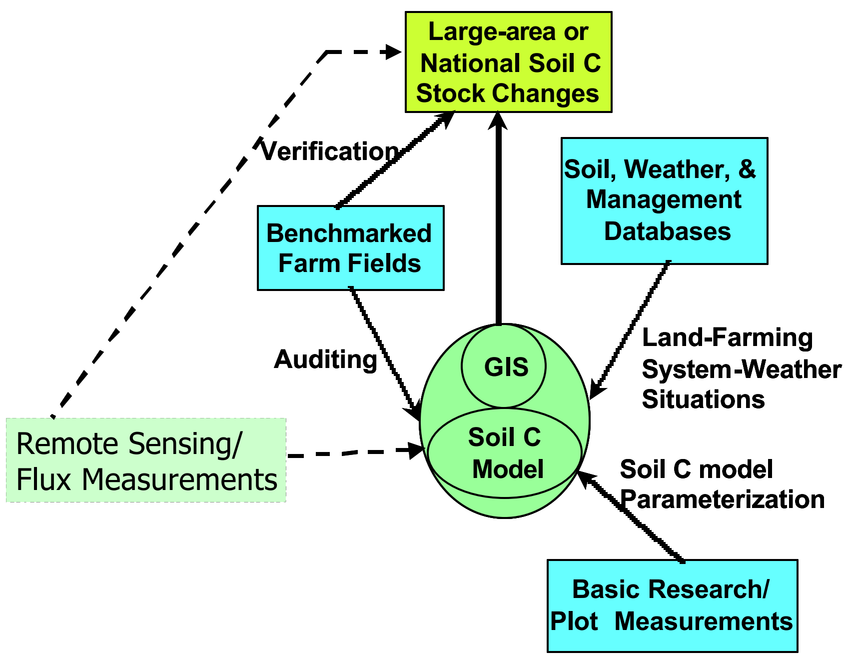

Figure 2. Schematic representation of the quantification and verification system for soil organic carbon changes.

1. Model Refinement: appropriate C model parameters are derived and the soil C model is thoroughly tested using a large set of soil C research experiments and data.
2. Define Situations: From databases of soils, landform, weather, and farm management, important situations that result from a combination of the farming system, land, and regional weather are identified. Although not used directly in the Prairie Soil Carbon Balance Project, remote sensing would supplement database information for such things as no-tillage extent and biomass production. Remote sensing will be more important when the estimation system is expanded to include soil C changes due to changes in management of pastures, farm wood lots, and other land use changes involving perennial vegetation.
3. Scaling Up: Soil C changes for these situations are predicted with the soil C model. These are integrated to make large-area or national estimates using a Geographical Information System (GIS). For the prairies, generally, soils are mapped and described into units (polygons) of similar soils and landform. To accurately estimate the C stock changes, it is first necessary to disaggregate these units into upper, mid, and lower slope positions, estimate the C change for these positions as affected by management and weather. In this process, it is also necessary to estimate SOC transferred between slope positions resulting from soil erosion by wind, water, and/or tillage. Calculating the regional estimate of soil stock change is simply the sum of the area of each soil-landform-management-weather situation multiplied by the estimated change in SOC for that situation.
4. Verification: The accuracy of the soil C model predictions is audited by comparing the predictions with the rich set of carefully measured C changes in the benchmark situations. Further, if sufficient benchmarks are available so that all important land-farming system situations are represented, an independent estimate of soil C changes is available by scaling up the benchmark soil C changes directly. Measurements of CO_2 flux (i.e. measure the actual net flow of CO_2 gas from the land), either from small-scale measurements to represent particular management-soil situations or over larger scales that pool across a number of such situations, are other potential methods for system auditing and verification.

Benchmark network

Careful measurements of SOC throughout the same small area over time are the most assured method for determining SOC changes (Ellert et al. 2001). The Prairie Soil Carbon Balance Project established a network of commercial farm fields (Figure. 3) containing small benchmark areas that would be repeatedly measured for SOC. A hierarchy of sites, based on the intensity of data collection, was used to provide the necessary quantity and quality of SOC-relevant information while minimizing network establishment and maintenance costs. This hierarchy involved level 1, 2, and 3 sites outlined below:

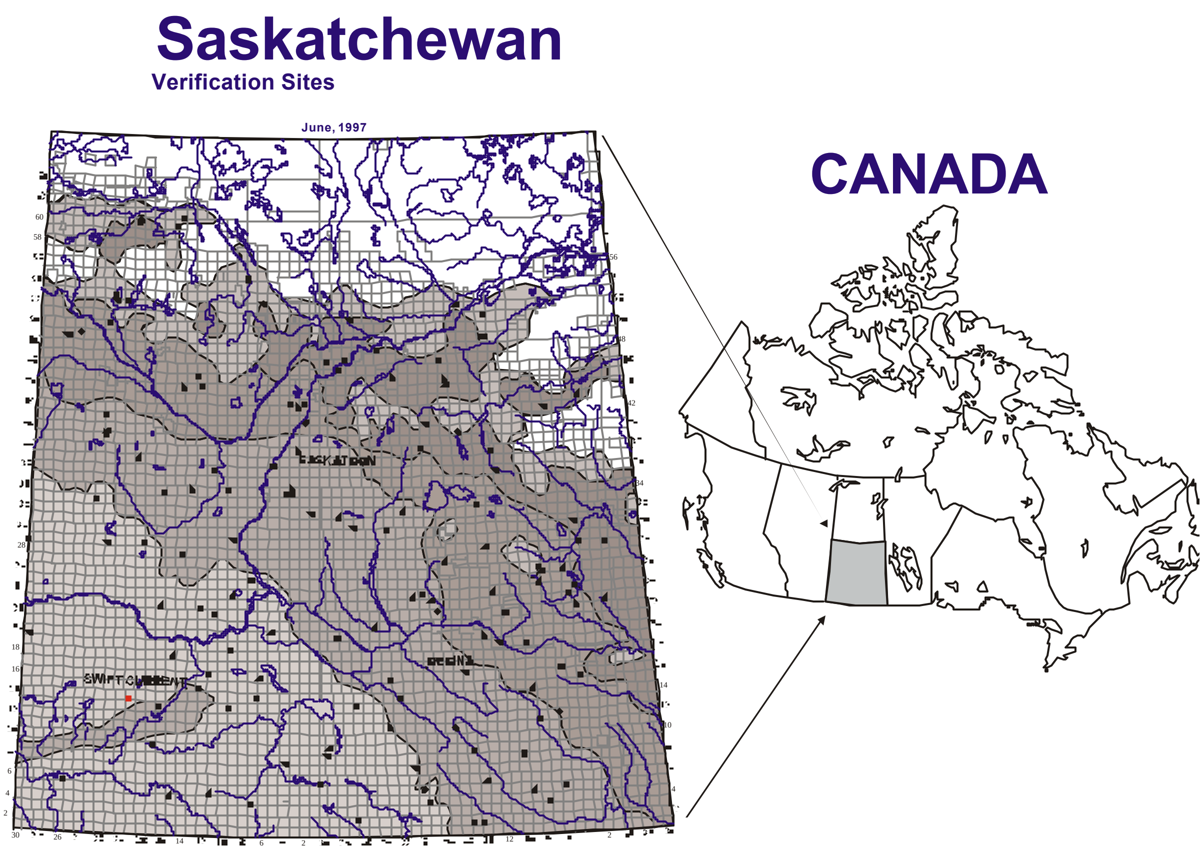

Figure 3. Network of benchmarked fields in Saskatchewan

Level 1 sites: To provide SOC data for a wide range of soil types across the agricultural portion of Saskatchewan, 115 level 1 sites were established in fall 1996 and early spring 1997. Each site consists of one 2 x 5 m benchmark microsite (Fig. 4) located in a level area of the field that was carefully documented, sampled, and marked (by buried electromagnetic markers like those use to mark underground utilities, by GPS, Global Positioning System, as well as by conventional surveying to relatively permanent objects such as power poles). The benchmark microsites allow for repeated nested sampling in the future; the first resampling was in fall 1999. These sites are on land that was being changed from conventional tillage to direct seeding. Each year the cooperating grower was contacted to for comments on crop performance, yield estimates, general weather conditions during the growing season, and seeding and cropping practices. The cooperating producers were requested to manage the field as they would any of their other fields so these level 1 sites also provide a sampling of practices used in direct seeding cropping systems. The level 1 sites were relatively low cost to establish and maintain. Because they involve only direct seeding on relatively level areas of the field, erosion from wind water or tillage would be minimal.

<u>Level 2 sites</u>: The level 1 sites provide a change in soil organic carbon over time but did not provide a direct measurement of the effect of tillage. To address this need, a network of 22 level 2 sites was established across Saskatchewan. Like level 1 sites, the fields were being converted to direct seeding in 1997. However, unlike the level 1 sites, the cooperating farmer maintained a one to three ha area within the field using conventional tillage practices. Other than tillage, the tilled area was managed like the remainder of the field, i.e. same crops, fertilizer, and herbicides, etc. Six 2 x 5 m microsites are maintained in the field: three on the conventionally tilled portion and three on the adjoining direct-seeded remainder of the field. SSC staff sampled above-ground biomass each harvest in the vicinity of the benchmarks (carefully avoiding the benchmark itself) to provide information of crop grain and residue yield. Besides total SOC, a more active and thereby sensitive component of soil organic matter was also measured. As with the level 1 sites, the cooperating producers were contacted annually to record their cropping practices and system observations. The level 2 sites provide more information than level 1 sites but fewer level 2 sites were involved owing their higher cost to maintain and monitor.

<u>Level 3 sites</u>: Benchmarks were established on the upper slope, mid, and lower slope position at six fields in Saskatchewan on land recently converted to direct seeding to provide measurements of how landscape position affected SOC change. Comparatively detailed measurements of soil environment and plant production were also measured at each position to assist with characterizing landscape differences for model development purposes.

With all 3 levels of sites there were 143 fields in the network. All important soil association type-landform combinations were present, usually with multiple sites for important combinations that represented substantial areas. Simply selecting carefully from the list of potential co-operators supplied by SSCA provided good and representative coverage of soil-landform complexess in the Brown, Dark Brown and Black soil zones. However, for the Dark Grey and Grey soil zones, to provide good coverage, additional effort was made to recruit producer co-operators as adoption of direct seeding is not as widespread in those zones.

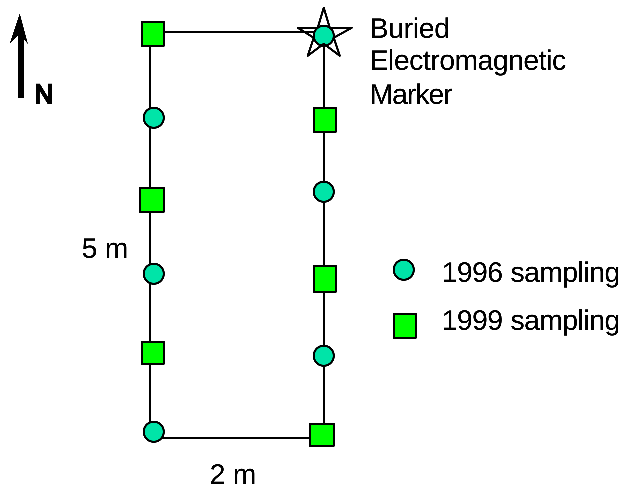

Figure 4. Plan view of benchmark microsite.

Sampling

For each benchmark, the individual soil profiles, each within approximately 1 m, were sampled using a hydraulically operated sampling tube of 7-cm diameter. The samples from each of the six cores at each sampling were subdivided at 0-10, 10-20, 20-30, and 30-40 cm depth increments and bulked according to depth. Organic C content of soil samples was analyzed using an automated dry combustion technique (Carlo Erba™, Milan, Italy). SOC was calculated on the basis of an equivalent mass using SOC concentration and soil bulk density values (Ellert and Bettany, 1995).

RESULTS AND DISCUSSION

Paired Field Comparisons

There was consistently more SOC in the direct seeded continuously cropped field than the neighbouring field under conventional management (Table 1). Some of the calculated rates of gain assuming equivalency of SOC when direct seeding was initiated are relatively high although there is no allowance for SOC lost in eroded soil. Since these losses would be expected to be much higher on the conventionally managed field but do not necessarily represent C converted to CO_2, the apparent SOC gains for the adoption of direct seeding are likely overestimates of the true rate. Between landscape positions, the greatest relative increase typically occurred on knolls while the greatest absolute difference occurred on midslopes. Several of the lower slope positions had quite small indicated changes in SOC between fields. This was expected as this slope position is often so enriched in SOC due to historical deposition of SOC-rich topsoil from upslope areas that current management is not affecting SOC amounts greatly. Further, any increased losses of SOC from tillage disturbance could be balanced from new SOC added with tillage-induced soil transfer from upslope areas.

Table 1. Amounts of soil organic C at various landscape positions of several Saskatchewan soils as influenced by tillage systems.

Soil zones	Nearby town	Texture	Years of no-tillage	Landscape position	SOC		C gains		Relative annual increase in SOC due to no-tillage
					NT	CT			
					Mg C ha^{-1}		Mg C ha^{-1}	Mg C ha^{-1} yr^{-1}	% yr^{-1}
Brown	Limerick	CL-L	8	Knoll	19.9[a]	19.2[a]	0.7	0.1	0.5
				Mid-slope	22.9[a]	18.7[b]	4.2	0.5	2.8
				Lower slope	33.4[a]	32.8[a]	0.6	0.1	0.2
	Kindersley	C-CL	8	Knoll	32.7[a]	24.4[b]	8.3	1.0	4.3
				Mid-slope	39.1[a]	33.1[b]	6.0	0.8	2.3
Dark Brown	Biggar	L-CL	7	Knoll	35.9[a]	28.1[b]	7.8	1.1	4.0
				Mid-slope	45.3[a]	43.8[a]	1.5	0.2	0.5
				Lower slope	64.1[a]	63.1[a]	1.0	0.1	0.2
	Perdue	SL	11	Knoll	42.0[a]	37.6[a]	4.4	0.4	1.1
				Level	48.5[a]	41.4[b]	7.1	0.6	1.6
	Unity	L	6	Knoll	41.4[a]	38.4[a]	3.0	0.5	1.3
				Level	69.8[a]	69.0[a]	0.8	0.1	0.2
Black	Indian Head (I)	L	21	Knoll	61.8[a]	49.8[b]	12.0	0.6	1.1
				Level	73.5[a]	57.3[b]	16.2	0.8	1.3
	Indian Head (II)	L	13	Knoll	55.1[a]	49.8[a]	5.3	0.4	0.8
				Level	65.2[a]	57.3[b]	7.9	0.6	1.1
Gray	Prince Albert	L-SL	9	Knoll	42.2[a]	40.3[a]	1.9	0.2	0.5
				Level	42.0[a]	36.6[b]	5.4	0.6	1.6
	Arbofield	L-CL	9	Knoll	58.9[a]	46.6[b]	12.3	1.4	2.9
				Mid-slope	53.0[a]	49.5[b]	3.5	0.4	0.8
				Lower slope	58.3[a]	49.6[b]	8.7	1.0	1.9

For each site different letters associated with CT and NT within the same landscape position indicate significant difference at $P<0.05$

Summary of Carbon Sequestration Potential for Direct Seeding and Reduced Fallow

McConkey et al. (1999) summarized the results from the paired field companions with other observations of SOC change due to the adoption of reduced tillage practices and less frequent summerfallow into a set of annual coefficients (Table 2). These values have been widely used for estimating the C sequestration for policy purposes.

Table 2. Expected gains in carbon sequestration for adoption of direct seeding and reduced fallow for the prairies over a 15-yr period (McConkey et al. 1999).

		Practice Adopted		
Soil Zone	Soil Texture	Low-Disturbance Direct Seeding from Conventional Tillage	High-Disturbance Direct Seeding from Conventional Tillage	Continuous Cropping from Crop-Fallow
		C gain (t/ha/yr)		
Brown	Sandy	0.1	0.1	0.2
And	Loamy	0.2	0.1	0.2
Dark Brown	Clayey	0.3	0.1	0.2
Moist Dark Brown	Sandy	0.2	0.2	0.5
And	Loamy	0.3	0.2	0.5
Thin Black	Clayey	0.4	0.2	0.5
Thick	Sandy	0.2	0.2	0.6
Black	Loamy	0.3	0.2	0.6
	Clayey	0.4	0.2	0.6
Dark Gray	Sandy	0.3	0.3	0.6
And	Loamy	0.4	0.3	0.6
Gray	Clayey	0.5	0.3	0.6

To calculate gain for other changes in fallow frequency use the following equation:
$Cgain = 2 \times Cgain_{col5,Table1} \times (FallowFreq_{old} - FallowFreq_{new})$
where $FallowFreq_{old}$ is the previous fallow frequency and $FallowFreq_{new}$ is the adopted fallow frequency.

Benchmark Network

On the level-2 fields, the average above-ground biomass, grain, and residue yields were greater for the direct seeded area than on the tilled strip (Figure 5). There were no consistent differences between the tillage effect on the yield of cereals, pulses, or oilseeds (data not shown). Assuming root mass remains a constant proportion of above-ground growth, then the adoption of direct seeding, on average, increased C inputs to the soil.

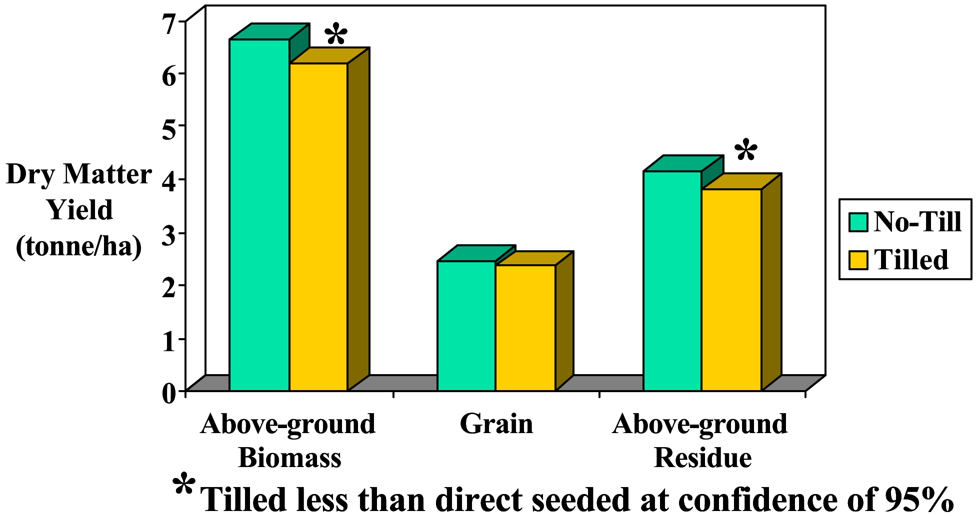

Figure 5. Average 1997-99 biomass, grain, and residue at harvest for the across level 2 sites.

Over a short time period, an individual farm field may lose or gain SOC depending on changes in crop production from the short-term variation in weather and/or crop pests and diseases. Further, even if a field, on average, is initially at an approximate steady state SOC level when management practices were changed, this steady-state condition may not apply to all small benchmarked areas in that field. Many factors can cause such non-steady state conditions on small benchmarks such as uneven residue distribution during harvesting, local flooding, weed patches, wildlife activities, etc. during the measurement period or in the years immediately before the measurement period. Hence, there remained large variability in measured SOC changes so changes must be considered statistically for groups of fields.

The observed mean SOC changes were relatively close to those expected from coefficients (Table 3) or from CENTURY version 4. For the level 2 sites involving the tillage comparisons, CENTURY predicted the direct seeded would gain 1.62 Mg C ha than the tilled whereas the actual difference was 0.53 Mg C ha.

Owing to the high variability of observed SOC changes, it is the best interest of land owners/managers to group their land so that each owner/manager can benefit from the average SOC gains over the entire SOC pool even if the closest benchmark microsite happened to lose SOC over a short measurement period. The per area cost for SOC measurement also drops quickly as more similar land is amassed.

The GIS-based prediction system for estimated SOC changes was developed and tested (Frick et al. 2000). This system includes the effects of soil transfers within the landscape for erosion by wind, water, and tillage. However, until CENTURY model of C dynamics provides better agreement with measurements, particularly better representing soil climate and tillage effects, the estimates from the CENTURY-GIS system remain preliminary.

Table 3. Observed and CENTURY- and coefficient- (McConkey et al. 1999) predicted change in SOC (Mg ha^{-1}) from fall 1996 to fall 1999 for benchmark network of farm fields

	Observed		CENTURY	Coefficient
Soil Climate	0-20 cm	0-30 cm	0-20 cm	0-15 cm
Semiarid**	0.71	0.80	0.92	0.99
Subhumid**	1.25*	1.59*	0.90	1.28
All	1.01*	1.22*	0.91	1.16

*Significantly different from 0 at P=0.05
** Semiarid = Brown and Dark Brown soil zones, Subhumid = Black, Dark Grey, and Grey soil zones.

Whole Greenhouse Gas Budget for Agriculture

Although it has received the majority of public attention, CO_2 is relatively unimportant GHG for the Canadian agriculture and agri-food sector. In 1996, this sector emitted 91.3 Mt of CO_2 equivalent, about 14% of Canada's total GHG emissions of 671 Mt CO_2 equivalent. The 91.3 Mt of CO_2 equivalent includes all on-farm GHG sources as well as those from the manufacture, transportation, and retailing of farm inputs and food products. Fully 43% of those emissions are nitrous oxide (N_2O) from fertilizer and animal waste and 31% is from methane (CH_4) from cattle (and sheep) and animal waste - the remaining 26% is CO_2 and that is largely from off-farm burning of fossil fuels for manufacturing fertilizer, transportation of raw and processed food products, and food processing. Hence, efforts to reduce those on-farm N_2O and CH_4 emissions will be important over the long term for Canadian agriculture to contribute to Canadian efforts to reduce total GHG emissions.

Increasingly, whole-farm GHG budgets (Figure 6) will take on the importance of financial budgets. The impacts of all farming practices and non-food uses of farm products (e.g. biofuels, building materials) on GHG, including SOC, will have to be accounted.

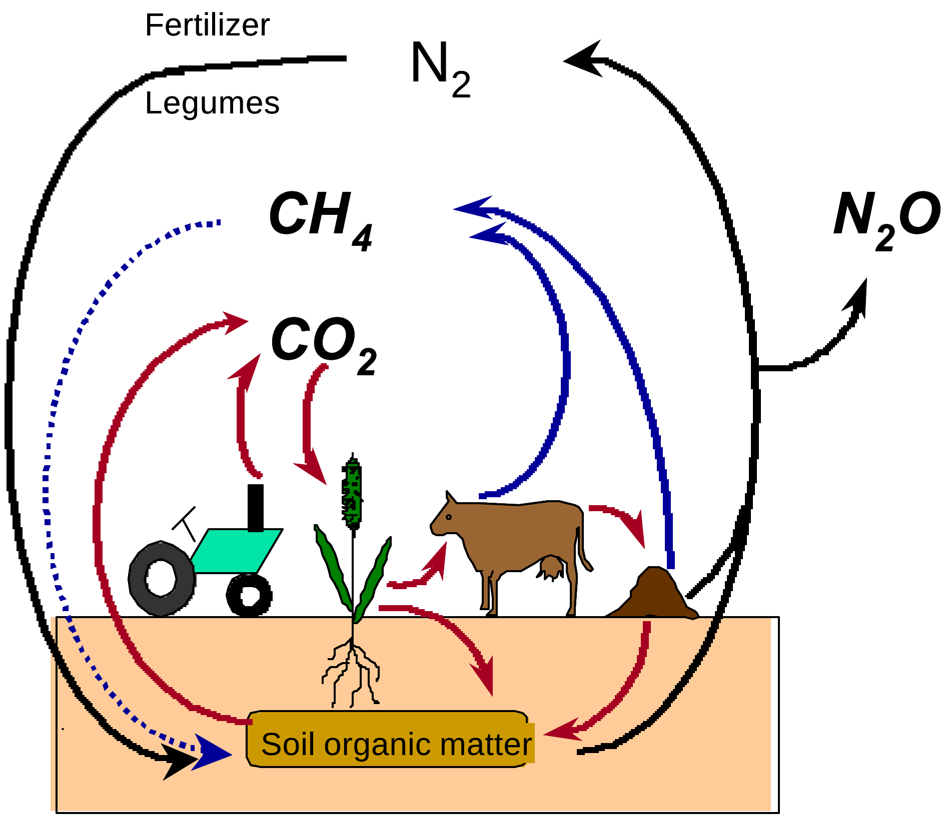

Figure 6.On-farm greenhouse gas budgets for all sources and sinks will become important in the future.

CONCLUSIONS

Measuring and verifying changes on organic carbon on agricultural lands is essential to their acceptance as an emission offset and to set any greenhouse-gas-based rewards for management practices that increase soil organic matter. The Prairie Soil Carbon Balance Project has demonstrated that it is possible to quantify and verify changes in SOC from the adoption of direct seeding and associated reductions in fallow frequency on commercial farm fields. There needs to be ongoing dialogue between farmers, governments, and potential users of agricultural soil C sinks as offsets to develop practical mechanisms for trading C sinks that fairly distributes the monetary value and risks for the C sink. Henceforth, the impacts of all farming practices and non-food uses of farm products (e.g. biofuels, building materials) on greenhouse gases, including soil organic carbon, will have to be accounted.

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