The Soil Organic Carbon Story

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What is Carbon Sequestration?

Plants take carbon dioxide (CO2) from the atmosphere and convert it organic materials that make up leaves, stems, roots, grain, etc. Plants are about 45% carbon by weight on a dry basis. The non-harvested plant parts return to the soil and become soil organic matter. Soil organic matter is about 58% carbon by weight. This carbon is called soil organic carbon (SOC) (Actually, there is no easy way to measure soil organic matter so scientists measure the SOC and divide by 58% to estimate the amount of soil organic matter.) Any change in land management that increases SOC will remove CO2 from the atmosphere. This process can have dramatic effects on atmospheric CO2 as there is more carbon in soil organic matter than there is in atmosphere. Removing CO2 from the atmosphere and storing it in the soil is termed **carbon sequestration.** Every pound of SOC represents 3.7 pounds of CO2 removed from the atmosphere.

It is important to remember that SOC is also a key indicator of soil quality and health due to its fundamental role in cycling of nutrients and producing favorable soil structure.

Why should I care about CO2?

CO2 is a greenhouse gas. This means that CO2 absorbs radiation at wavelengths that other major gases in the atmosphere (nitrogen gas, oxygen gas, and water vapor) do not absorb. Therefore, instead of being radiated into outer space, radiation at these wavelengths is absorbed by the greenhouse gases and re-radiated back to the earth, causing warming of the earth's surface. The world's rising consumption of fossil fuels (coal, petroleum, and natural gas) is greatly raising the atmospheric CO2 concentration. Figure 1 shows projections of how atmospheric CO2 will increase if nothing is done about reducing CO2 emissions including zones representing one interpretation of the danger of major climate change associated with CO2 concentration.

As a result of the concern about climate change, many people in the world have persuaded their governments to support measures to reduce the buildup of greenhouse gases in the atmosphere. This has resulted in several international conferences, including that held at Kyoto in December 1997, where the industrialized nations have pledged to reduce greenhouse gas emissions to below 1990 emissions levels (Canada's pledge was a 6% reduction during the 2008-2012 period from **1990** emissions). Even with these emission reductions accomplished, the concentration will hopefully stabilize no higher than in the "Danger Zone" shown in Figure 1. No mortal can predict the future climate but there is sufficient concern about climate change that many people are willing to incur costs now to reduce greenhouse gas emissions in the hope that will lower the risk of catastrophic climate change in the future.

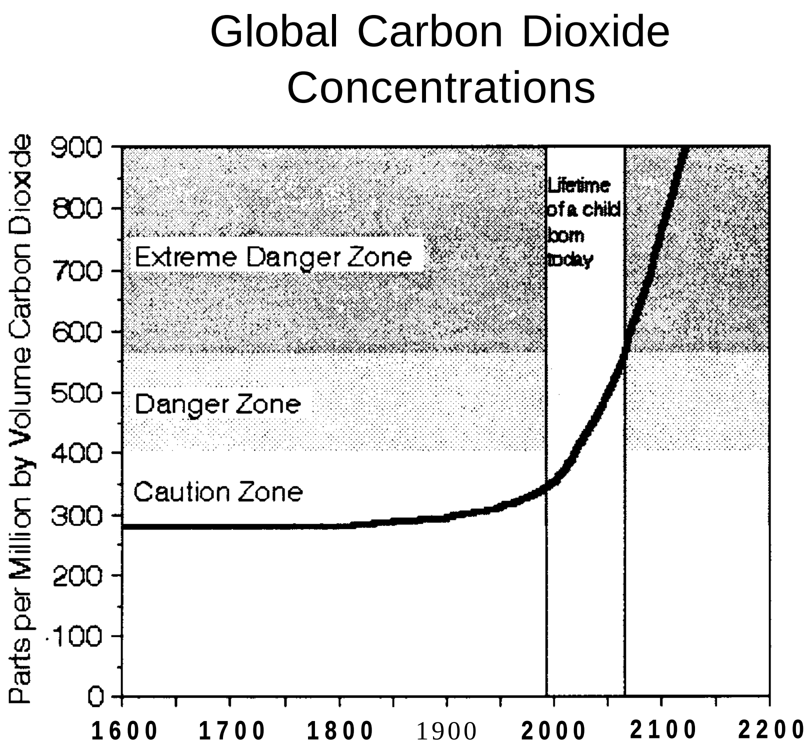

Figure 1. Projected increases in atmospheric CO2 without any emission reductions (from IPCC Working Group I. June 1990. Policymakers Summary of the Scientific Assessment on Climate Change. “Business-as-usual” scenario. Nairobi: U.N. Environment Programme. pp. 7-9.)

What forms are there of Soil Organic Carbon?

As shown in Table 1, SOC is made up a diverse range of materials - some living and some well decomposed. Soil organic matter can be divided into many parts or fractions based on chemical or physical properties but no fractionation scheme is universally accepted. However, most soil scientists will at least conceptually divide SOC into an active, younger component that plays an important role in nutrient cycling as it is broken down by soil microbes and a less active, older component that plays a role in exchange reactions and physical structure but which itself is only very slowly broken down by soil microbes. In the Northern Great Plains up to 80% of the SOC is the well-decomposed materials that are very stable. This large proportion of more decomposed SOC gives the soils their dark color and explains why this area has more SOC than soils of many other areas.

In prairie soils, most SOC exists in the upper 10 to 30 cm of soil.

Table 1. SOC fractions

Organic Matter Fraction	Turnover Time (yr)
Living soil microbes	<3
Identifiable plant residues	<5
Partially decomposed plant residues and microbes	< 100
Well-decomposed organic materials	100-5000
Charcoal	1000s

How does agriculture change SOC?

When soil is first broken by Europeans for crop production, SOC decreased rapidly (see Figure 2). There were several factors that accounted for this initial reduction: tillage broke up the soil and exposed much more soil organic matter to microbial decomposition, fallow periods promoted microbial breakdown of SOC by leaving soil moist without any new plant material additions, erosion of topsoil removed soil organic matter, and annual crops typically produced less residue than perennial crops (remember the roots!). When SOC was decreasing in the years after conversion to arable agriculture, great quantities of CO, were released into the atmosphere that added to that released by burning fossil fuels. Generally, soil scientists believe much of the crop land in North America is now in approximate equilibrium under conventional management practices (ignoring losses of SOC in eroded sediment).

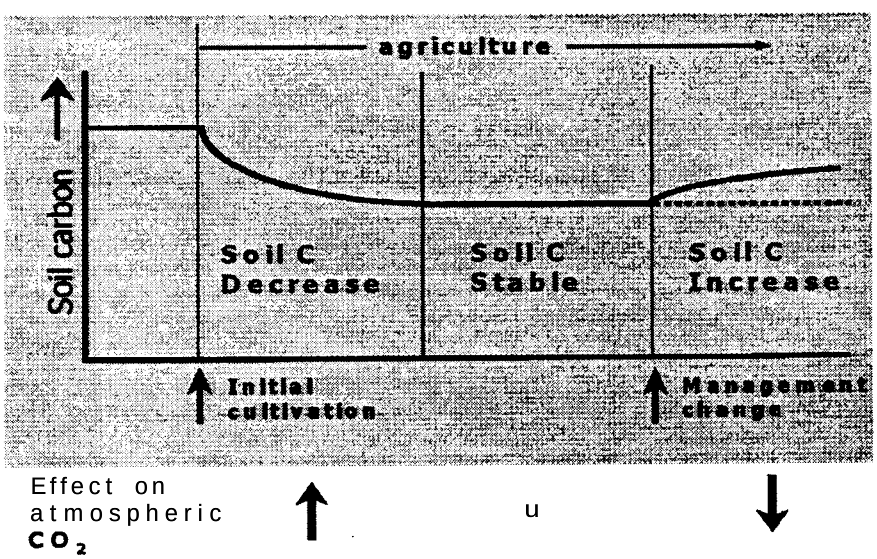

Figure 2 Agriculture effects on SOC.

What is this SOC "equilibrium" and how can I increase SOC in my soils?

Equilibrium exists when additions of new organic matter from plants just balance that lost by microbial breakdown of soil organic matter. When SOC is at equilibrium, the total amount of SOC remains about the same from year to year and as much CO_2 is removed from the atmosphere as is returned. Figure 3 shows typical annual carbon flows when SOC is at equilibrium.

There are two basic ways to increase SOC:
1) increase organic carbon returned to soil
or
2) decrease microbial decomposition of soil organic matter

Some practices accomplish both. For example, converting crop land to perennial forage typically increases SOC. Perennial forages usually add more carbon to the soil than annual crops (roots!) and decrease the microbial decomposition because there is no soil disturbance once established and because the growing perennial vegetation keeps the surface soil drier for a longer period than annual crops.

Tilled fallow is an example of a practice that works in the opposite direction and greatly decreases SOC. No new plant residues are returned during fallow and the repeated soil disturbance and moist soil conditions greatly increases microbial decomposition of soil organic matter.

Direct seeding increases SOC primarily by decreasing microbial decomposition of organic materials because there is less soil disturbance. Any increase in plant residue production from direct seeding would also contribute to increasing SOC.

Therefore, practices that increase SOC include:

- putting perennial vegetation on marginal land
- shelterbelts, woodlots
- increasing crop residue production through better fertilization or varieties
- reduction in fallow
- reduction in soil disturbance (tillage)
- high intensity-short duration grazing that allows better regrowth of pasture vegetation.

As shown in Figure 2, while SOC is increasing due to a change in management practice, CO_2 is being removed from the atmosphere. Eventually, however, the SOC will reach a new equilibrium some time after the **management** change was imposed. When the new equilibrium is reached, there will again be balance between new carbon additions from plants and microbial breakdown of soil organic matter. At that time, there will be no net effect of atmospheric CO_2 and carbon sequestration stops.

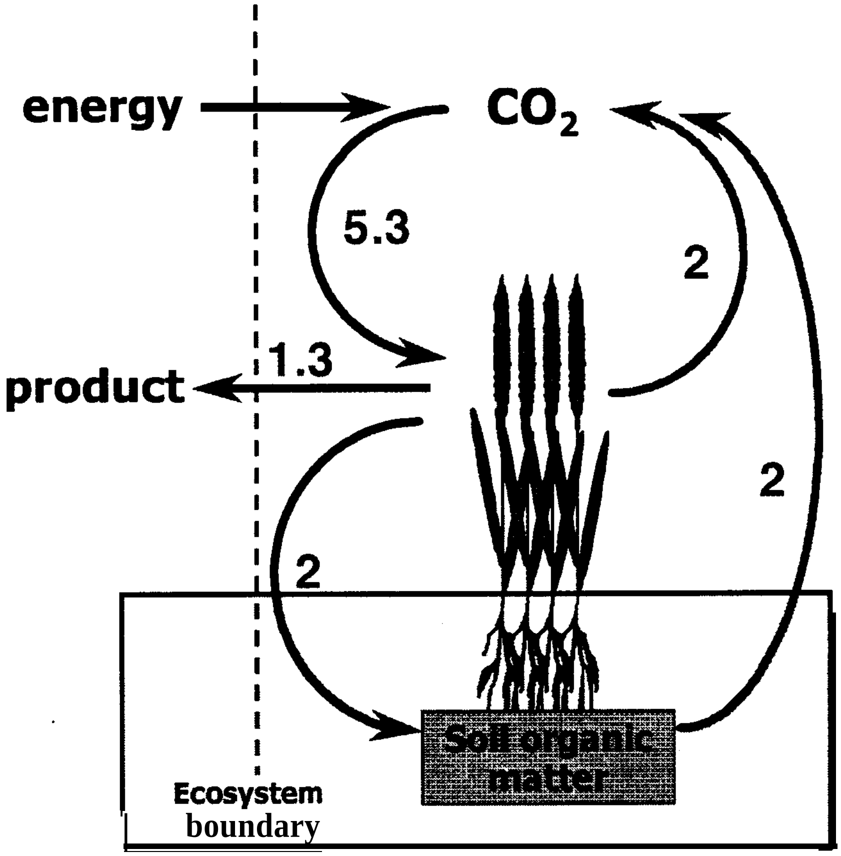

Figure 3. Annual carbon flows (t/ha) in a prairie wheat field when soil organic matter is at equilibrium.

What factors affect the equilibrium amount of SOC in my soil?

The amount SOC at equilibrium depends on many factors:

soil temperature (organic matter decomposition increases as temperature rises)
soil moisture (organic matter decomposition decreases as the soil becomes drier or when the soil is saturated)
organic matter additions and removals (increasing organic matter additions increases soil organic matter, increasing removals such as harvesting crop residue decreases SOC)
soil clay content (organic matter forms stable complexes with clay so increasing clay content increases SOC).

The exact amount of SOC at equilibrium depends on the interaction of these factors.

It is important to note that if the appropriate equilibrium SOC amount for your management practices is below existing SOC, SOC will be lost as CO_2 until the new equilibrium is reached. Hence, sequestered carbon can be lost if management practices that are less conserving of SOC are adopted, such as could occur when land is sold and/or the farm operator changes.

How much SOC can I sequester with direct seeding?

The potential amount of carbon sequestration is the difference between the current SOC and SOC when it reaches the appropriate equilibrium. In areas where grass was the native vegetation, SOC under native grass is a workable estimate on the maximum amount of SOC that could be ever expected to be sequestered. However, it is unlikely that the SOC that accumulated after many millennia under native grass would ever be achieved again with annual crops, even with good fertilization.

Figure 4 shows SOC measured for across-the-fence neighboring farm comparisons in Saskatchewan. Regardless of land use, the equilibrium SOC amounts are lower in the semiarid climate due to lower crop residue production than in the subhumid climate. Neither of the no-till farms has yet achieved the amount of SOC that existed before the land was broken. This graph also demonstrates that there is nothing unnatural about carbon sequestration - carbon sequestration is simply returning to the soil some of the carbon that was lost since original breaking.

Topography has a major effect on SOC distribution on the landscape with SOC typically increasing from the top to the bottom of the slope. Figure 5 shows the average distribution of SOC along the slope for two sets of neighboring farm comparisons in Saskatchewan. Not all the increase in SOC from the no-till system can be attributed to true carbon sequestration. Some is due to ongoing erosion, especially tillage erosion, on the conventionally tilled farms. SOC lost in erosion is not necessarily lost as CO_2 to the atmosphere - some can be effectively sequestered in at as sediments at the bottom of sloughs, reservoirs, etc. Note that decreasing soil erosion through adoption of no-till can greatly increase crop production on severely eroded areas of the fields (especially knolls) and thereby also works to increase SOC on those areas.

Clay content has a large effect on SOC amounts and carbon sequestration. Figure 6 shows that the increase in SOC, expressed as a percentage of SOC originally present in the soil, increases as clay content increases. Clay soils that have lost a lot of SOC due to past poor management have greater opportunity to sequester SOC in the short term than coarser textured soils.

For purposes of carbon sequestration, it is now standard practice to consider all carbon near the land surface including large roots, surface litter or residue (including standing stubble). In the past, soil scientists excluded surface residues and large roots that reduced the apparent amount of C sequestered. Figure 7 shows the impact including the surface litter on carbon sequestered.

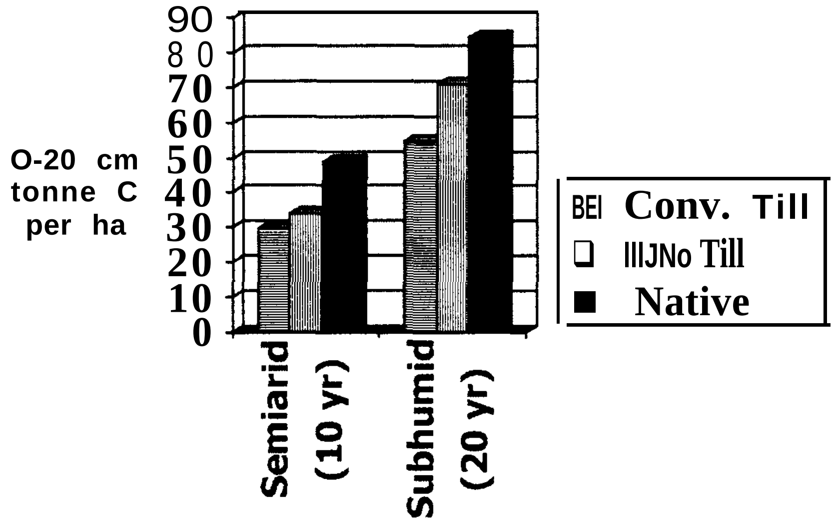

Figure 4. SOC for Conventional Till Wheat-Fallow compared with No-Till continuous cropping for 10 yr in the semiarid climate (Brown soil) and 20 yr in the subhumid climate (Black soil) of Saskatchewan.

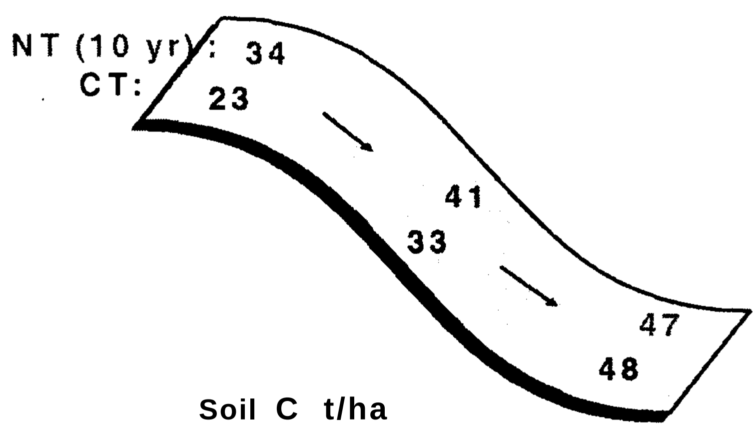

Figure 5. SOC in upper 20 cm of soil for neighboring farm comparisons after 10 yr of no-till (NT) continuously cropped compared with conventional till (CT) wheat- fallow.

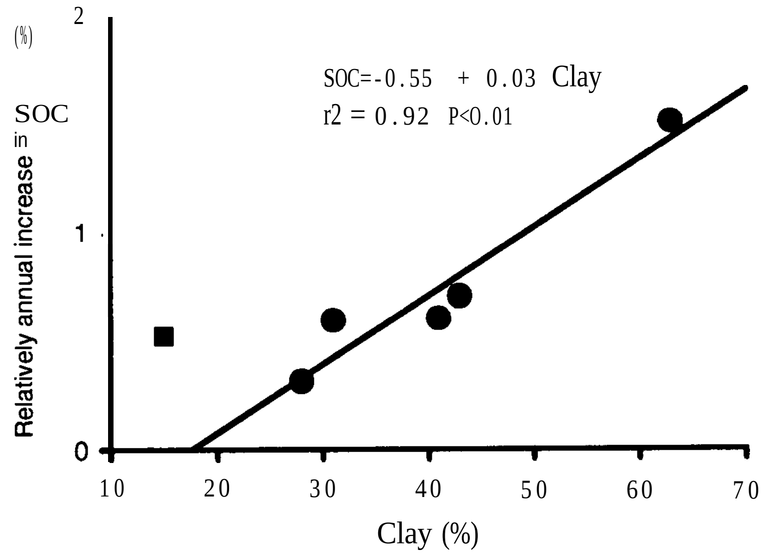

Figure 6. Relative annual increase in SOC as function of clay content for long-term research plots in Saskatchewan. Carbon sequestered in sandy soil (shown with a square) was increased due to observed wind erosion on the tilled plots and was not used in regression.

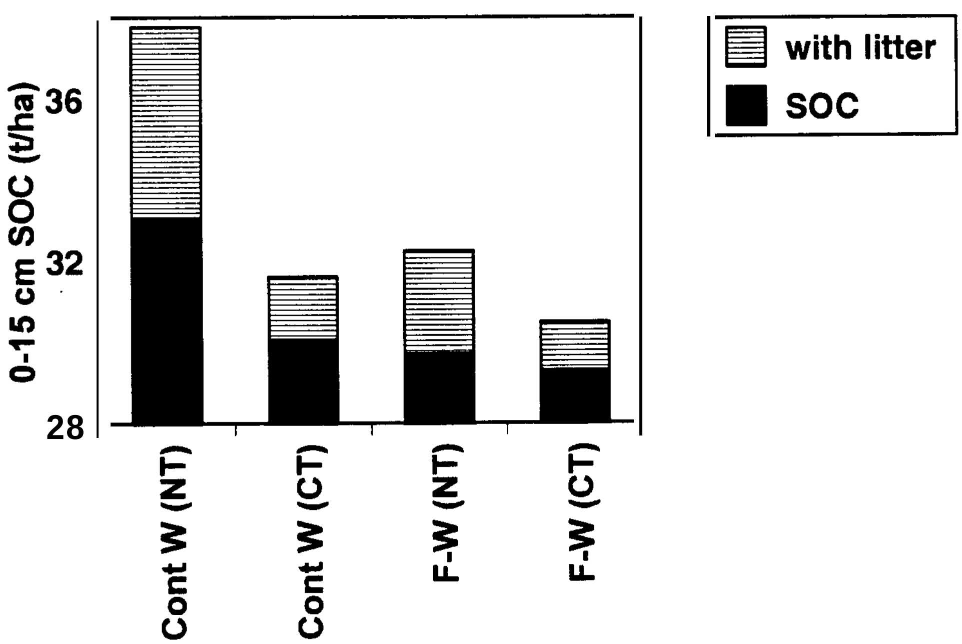

Figure 7. SOC and surface litter carbon after 13 years of continuous wheat (Cont W) with no-till (NT) and conventional tillage (CT) and for fallow-wheat (F-W) with NT and CT at Swift Current, SK. (F-W average of both rotation phases)

How much is SOC worth?

Soil organic matter has a value to agricultural land in terms of improving soil structure and nutrient cycling independent of any value associated with reduction in atmospheric CO_2. Nevertheless, if agricultural soils are accepted as a tradeable CO, sink, then emitters of greenhouse gases will be willing to buy the SOC to offset their emissions.

The dollar value of SOC will be determined in the marketplace based on the competing costs of achieving those emission reductions through technological improvements that lower emissions directly or from competing sink offsets such as growing forests. Estimates of the value of SOC range from less than CAN$l to CAN$400 per tonne. Current trades in emission reduction offset are toward the low end of that range. The higher end of the range is unlikely because it implies drastic effects on the economy. For example, at CAN$400 per tonne, a power company could cost effectively buy feed grains to burn instead of coal to make electricity (such biomass fuels add no new CO_2 to the atmosphere).

Farmers are also emitters of greenhouse gases - the major ones being CO_2 from fossil fuels, nitrous oxide (N20) from inefficiencies in nitrogen use, and methane (CH_4) from ruminants (cattle and sheep) and manure storage and disposal. Therefore, in a situation where there are taxes on emissions, farmers may need their SOC increases to offset their own emissions, especially if they have a substantial cattle operation.

How important is carbon sequestration to overall greenhouse gas emissions?

Carbon sequestering practices on agricultural land could have a large impact on North American greenhouse gas emissions. For example, using relatively conservative estimates of carbon sequestration potential, carbon sequestration could make up 8 to 18% of Canada's greenhouse gas emissions by 2008, depending on the extent of adoption of carbon sequestering practices (Bruce, J., Frome, M., Haites, E., Janzen, H., Lal, R, and Paustian, K. 1998. Carbon sequestration in soils. Discussion paper by the Soil and Water Conservation Society with input from praticipants ia a workshop on Carbon Sequestration in Soils, Calgary, May 21-22. 1998.)

What will a system to quantify SOC credits look like?

The Kyoto Protocol on greenhouse gas emissions requires a transparent (i.e. clear, scientifically valid) and verifiable system to quantify any CO_2 sinks. With support from a consortium of Canadian industrial greenhouse gas emitters (GEMCo), a pilot project to develop such a system is being undertaken in Saskatchewan. Figure 8 shows a schematic representation of this system.

The basis of the system is the carbon model which will be a refined version of the CENTURY model. Estimates from this model will be made for thousands of soil-climate-cropping system combinations, these SOC estimates multiplied by the appropriate area, and totalled to produce regional estimates of SOC. There are about 140 benchmarks established across Saskatchewan (see below) to verify estimates of carbon change. The same general system could be used to develop SOC estimates and changes for an individual farm, although the system would have no rigorous method of verification for an individual farm unless the farm happened to have one of the benchmarks on the major soil type present on the farm.

Verification Benchmarks:

<u>Level I sites</u>: 114 level 1 sites were established in fall 1996 and early spring 1997 to provide soil organic C data for a wide range of soil types across the agricultural portion of Saskatchewan. Each site consists of one 2 x 5 m benchmark microsite in a level area that is carefully documented, sampled, and marked (GPS). The microsites are designed so that they can be sampled repeatedly in the future with the first scheduled resampling in fall 1999. These sites are on land that was being changed from conventional tillage to low-disturbance direct seeding (no-till). Each year the cooperating grower is contacted to for comments on crop performance, yield estimates, general weather conditions during the growing season, and seeding and cropping practices. Growers are requested to manage the field as they would any of their other fields so level 1 sites also provide a sampling of practices used in direct seeding cropping systems. The level 1 sites are relatively low cost to establish and maintain.

*<u>Level 2 **sites**</u>*: The level 1 sites provide a change in soil organic carbon over time but do not provide a direct measurement of the effect of tillage To address this need, a network of 23 level 2 sites were established across Saskatchewan. Like level 1 sites, the fields were being converted to direct seeding. However, unlike the level 1 sites, the cooperating grower maintains about a 1 ha area within the field using his conventional tillage practices. Other than tillage, the 1 ha area is to be managed like the remainder of the field. Six 2 x 5 m microsites are maintained in the field: 3 on the conventionally tilled portion and 3 on the adjoining direct-seeded remainder of the field. Aboveground biomass samples are taken each harvest in the vicinity of the benchmarks so good estimates of residue production are available. The smaller number of level 2 sites compared with level 1 reflects their higher cost to maintain and monitor.

In addition, we have benchmark microsites established on the upper slope, midslope, and lower slope position at six fields throughout Saskatchewan on land recently converted to direct seeding to provide measurements of how landscape position affects soil organic carbon change. We are also resampling of selected long-term (>lO yr) cropping and tillage system experiments within the prairies to provide more complete observations of how management has affected soil organic carbon contents and other soil quality indicators over time. We have 10 comparisons of long-term (> 6 yr) tillage system effects using adjacent paired fields throughout Saskatchewan. These comparisons give an opportunity to investigate tillage effects on the soil quality for soil types and landscapes not represented in existing research plots. These comparisons also include erosion effects that are also minimized on small and level research plots. At each paired-field site, soil quality under native grass is also measured.

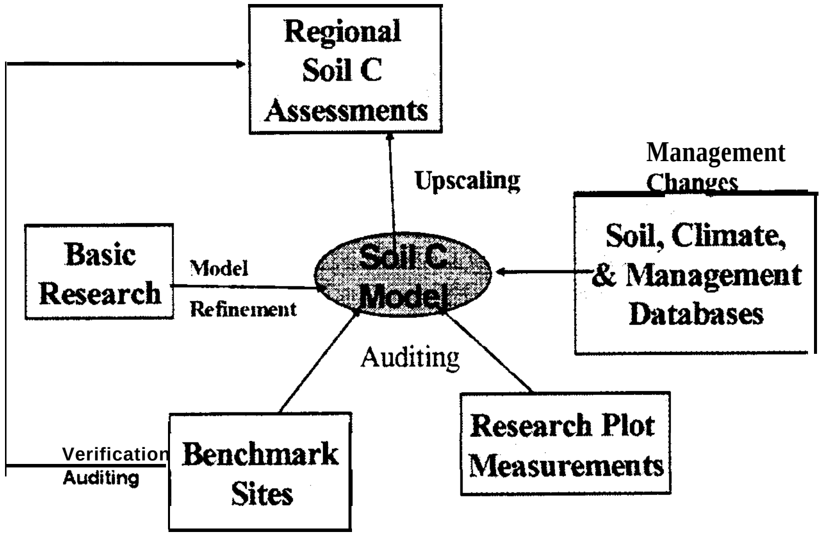

Figure 8. Schematic representation of Saskatchewan project to develop a system for quantifying SOC changes.

Why can't I just measure SOC amount on my farm directly rather than using a computer model to estimate it?

SOC is typically one of the most spatially variable soil attributes so is difficult and thus costly to quantify on a field or larger area basis from actual measurement (likely greater cost than the SOC is worth). Benchmarks (specific small areas that are sampled over time), like those used in the Saskatchewan project, remove a lot of the effects of spatial variability. However, benchmarks are really only valuable for verifying the model, the model still has to be used to estimate SOC in the rest of field outside of the benchmark area.

From the perspective of SOC for emissions reduction credits, it is the change in SOC that is important, not the total amount. This means that with direct measurement only carbon sequestered after initial sampling could be counted as, without a model, there would be no way to estimate SOC before initial sampling. Further, only SOC changes relative to some baseline would be considered as an offset credit. So to measure SOC changes directly, you would also have to measure that baseline. Although we used neighboring farm comparisons in the Saskatchewan, these are only supplements to, not replacements for, more exacting measurements using benchmarks and research plots. Importantly, to use the neighboring farm approach as the sole determinant of SOC changes, it would be necessary to account for all SOC lost to erosion on both fields. This is a difficult, almost impossible, to do by direct measurement when there has been appreciable erosion. Also, the neighboring field would have to have had the identical amount of SOC when you converted to direct seeding - an uncertain assumption to make. It is highly unlikely that carbon sequestration determined by neighboring farm comparisons would be accepted as valid offset credits.

What is happening in international negotiations regarding carbon sequestration?

At Kyoto, Canada was the only vocal supporter of agricultural soils as sink for CO, and succeeded in having agricultural soils not explicitly excluded as an eligible sink. In subsequent scientific negotiations at Bonn in June 1998, several other countries, including the U.S., joined Canada in support of agricultural soils as sinks. The European Union has been vigorous opponents of agricultural soils as sinks because they claim that it is an unfair advantage for North America, sequestered carbon is fragile and difficult to quantify, and carbon sequestration only delays the reduction in fossil fuel burning. Nevertheless, at a more recent international climate change meeting in Buenos Aires, there was growing international support for considering agricultural soils as a CO_2 sink. A decision on the eligibility of agricultural soil sinks by the international community is expected in 2000 or 2001.

What about agricultural greenhouse gas emissions?

If agricultural soils are accepted as greenhouse gas sinks then the entire greenhouse gas balance needs to be considered.

Methane (CH) is generally seen as the most important farm-related greenhouse gas emission. CH_4, is produced mostly in the rumen of cattle and sheep with some also produced in wet manure whether stockpiled or recently spread. The importance of CH_4 is related to the fact that it is a more potent greenhouse gas than CO_2. One pound of CH_4 is considered the same as 21 pounds of CO_2 from the perspective of the greenhouse effect. Through better feed and manure handling it is possible to reduce CH_4 emissions somewhat but most CH_4 emissions have to be considered as unavoidable part of livestock rearing.

Nitrous oxide (N_2O) is generally considered the second most important farm-related greenhouse gas emission. The amounts of N_2O released are relatively small but N_2O is a very potent greenhouse gas. One pound of N_2O is considered the equivalent to about 310 pounds of CO_2. N20 is mainly produced by microbes during denitrification when nitrate and readily decomposable organic matter are present without oxygen - most commonly occurring when the soil is saturated, even for a short time, with water. Usually only a small portion of nitrate that is denitrified transforms to N_2O with most nitrate ending up as nitrogen gas (N_2) that is not a greenhouse gas. However, when temperatures are slightly above freezing, most nitrate is transformed into N_2O.

Some N_2O is produced during the conversion of ammonia to nitrate (nitrification) but the amounts are uncertain. Regardless of the form of nitrogen fertilizer, most free nitrogen in the soil will usually be converted to nitrate. To reduce N_2O emissions, it is important to minimize the amount of nitrate in the soil, especially at time of spring thaw. Practices such as fallow are particularly bad for N_2O emissions because the soil typically wet at time of spring thaw with abundant soil nitrate that accumulated during the fallow year from the break down of soil organic matter. It is also important to minimize the amount of soil nitrate in areas of the field are subject to even short-term flooding during heavy rains. Some denitrification, and hence some N_2O emission, also occurs within wet manure and has also been linked to incorporation of legume residues into the soil.

CO_2 is a relatively small proportion of farm-related greenhouse gas emissions. Nitrogen fertilizer is made from natural gas and often represents the largest single farm-related CO_2 emission although actual emissions occur during manufacture. Therefore, improving the efficiency of nitrogen fertilizer use will accomplish the largest reduction in farm-related CO_2 emissions. Note that improving nitrogen use efficiency could also reduce N_2O emissions. Fossil fuels used for machinery, vehicles, and space heating is typically the second largest farm-related CO_2 emission. Fossil fuel use associated with machinery manufacture and maintenance and for buildings manufacture and maintenance are the typically the third largest source of farm-related CO_2 emissions although most of these emissions occur off-farm.