Science of Carbon Sequestration

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What is Carbon Sequestration?

Plants take carbon dioxide (CO_2) from the atmosphere and convert it organic materials that make up leaves, stems, roots, grain, etc. Plants are about 42% 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). Any change in land management that increases SOC will remove CO_2 from the atmosphere. Removing CO_2 from the atmosphere and storing it in the soil is termed **carbon sequestration**. Every pound of SOC represents 3.7 pounds of CO_2 removed from the atmosphere. The action of carbon sequestration is also called a C sink.

Basically, the rate of carbon sequestration depends on the balance between C input from crop production into the soil and C output from microbial decomposition of soil organic matter. Soil contains a vast, diverse, and adaptive population of micro-organisms whose existence depends on C input from photosynthesizing plants. Therefore, as a general rule, these microbes will decompose as much SOC to CO_2 as is added each year by plant growth. Typical values for C input and decomposition on the prairies would be 2 to 4 tonnes of C per hectare per (3 to 6 tonnes of CO_2 per acre per year). Therefore, these rates would represent the approximate limits of rates of gain or loss of SOC. Peat bogs gain about 1 tonne of C per ha per year (1.5 tonne of CO_2 per acre). As shown in peat bogs, high rates of C sequestration are associated with high rates of N immobilization and, hence, N deficiency for any plant growth. Declining SOC releases mineral N, P, and S from soil organic matter. A relatively high amount of SOC within a soil type with neither SOC loss nor gain is a highly desirable soil condition for crop production as it indicates both good nutrient cycling and good capacity to supply nutrients.

When land management is changed, the balance between SOC decomposition and C input is disrupted. Depending on how that balance is affected, the amount of SOC can either decrease or increase. Both steady SOC loss and carbon sequestration represent an abnormal soil condition. In addition, both SOC loss and carbon sequestration are unsustainable because the soil-plant system is constantly working to restore the balance between SOC decomposition and C input.

How does land management change SOC?

When soil is first broken by Europeans for crop production, an imbalance between decomposition and input was created such that decomposition exceeded inputs so SOC decreased rapidly (see Figure 1). 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_2 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).

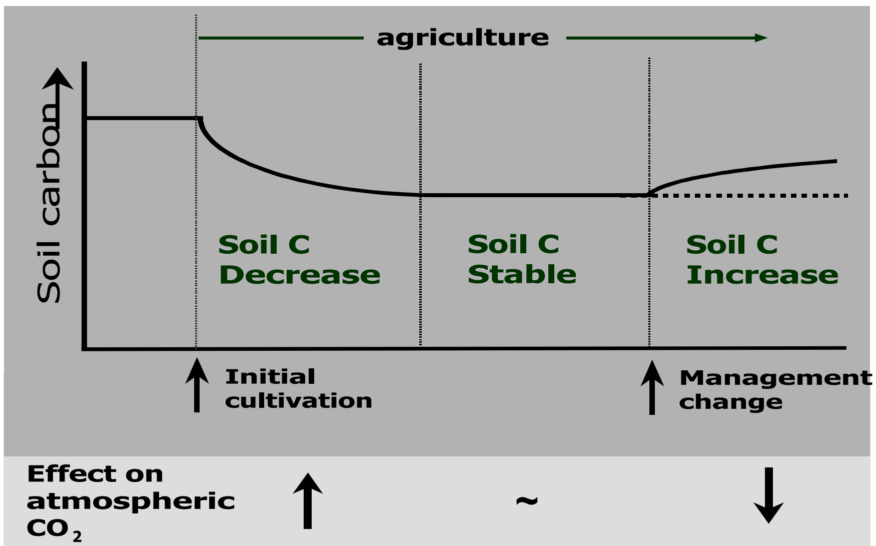

Figure 1 Agriculture effects on SOC.

How do I accomplish carbon sequestration?

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 (consider 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 also accomplishes both but works in the opposite direction and greatly decreases SOC. No new plant residues are returned during fallow and the repeated soil disturbance and warm 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.

How does weather affect C sequestration?

From the farmer perspective, production is the C removed off the land in terms of pounds of grain, hay, silage, or animals. However, from the soil perspective, production is the amount of C left on or in the soil. Decomposition depends on the soil temperature and moisture, if the soil is moist, then temperature determines the rate of decomposition. Decomposition increases exponentially with temperature so even small effects on soil temperature have large effects on decomposition. If the soil is warm enough, then rate of decomposition depends on the soil moisture. A drought that is disastrous to C production to the farmer can lead to significant C sequestration since the majority of the albeit limited C production of plants is left on the fields while decomposition of SOC greatly reduced due to dry soil. Wet years that provide good crop production in terms of the amount of C removed from the land, are not necessarily good for C sequestration since decomposition is also increased. Therefore, the balance between C input to the soil and decomposition may not favour C sequestration. It is not easy to estimate the effect of weather on C sequestration. Nevertheless, one type of weather can be related to SOC loss. If weather is much wetter than normal so that crop production becomes severely limited by nutrient deficiencies, disease, delayed seeding, and/or flooding, then a net loss of SOC can be expected as decomposition will likely exceed C input from the crop.

How does crop type affect C sequestration?

Crop type itself does not affect C sequestration. Only the change from one crop type to another crop type such that the balance between input and decomposition is affected could bring about C sequestration. Crop breeding efforts often works to produce high-yielding varieties by having a larger proportion of photosynthesis allocated to grain rather than crop residue. Therefore, the C input to soil can be reduced for higher yielding varieties compared to older lower-yielding varieties. Pulse crops, although produce less C input are more effectively converted into stable SOC than non-legumes owing to the higher N concentration in plant residues of legumes. So a change to or from pulse crops from non-legume crops would not affect C sequestration greatly. The visual appearance residue left after a crop can be misleading. Canola often produces as much or more C input to soil than cereal crops. Planting perennial pasture or forage crops on land formally in annual crops almost always produces net C sequestration.

What happens if carbon sequestrating practices are stopped?

The rate of C sequestration depends on the degree of imbalance between C inputs and decomposition. If C sequestration practices are adopted, such as direct seeding on land that was regularly tilled, decomposition decreases while C inputs are similar so SOC is changed. If after some time, that land is regularly tilled again, there becomes a new imbalance between decomposition and C inputs. Decomposition increases while C inputs stay similar. SOC drops until a new balance is obtained between C inputs and decomposition. Therefore, as rough estimate it is reasonable that the rate of SOC loss from reverting to practices that existed before C sequestering practices were adopted will be similar to the rate of gain when C sequestering practices were first adopted.

Why is measuring SOC change difficult?

Measuring change in SOC is notoriously difficult. Typically change in SOC from adopting C sequestering practices would be less than 5% of the amount of SOC. Importantly, the SOC is highly variable spatially over short distances of inches. This variability would typically be at least 20% of the amount of SOC in the soil.

A good analogy to the problem of measuring SOC would be trying to weigh a 10 lb of copper block by weighing a man on a scale without the block and then weigh the man holding the block. The difference between these readings is the weight of the copper block. However, to make it like the measuring SOC, do the measurements in the back of a truck going over Saskatchewan's bumpiest highway. The weight indicated by scale could be less than, equal, or greater than the weight of the man with the block depending on the bouncing over the road. Therefore the weight of the block could be negative, zero, or positive. On the extremes, the measured block weight would be more than several times the man's weight and negative weight such that the man holding it should be floating. The method of measurement is perfectly sound but the weight of the block is lost in the variability in weights caused by the bouncing. However, if we take a large number of scale readings, the average difference between the weight with and without the block will approach the true weight of the block. The more measurements we make, the better the estimate of blocks weight. We will never know the exact weight of the block but will have an estimate with confidence limits. If we take several hundred readings, we would probably be able to say something like the mean weight of the block is 9.5 lb with 95% confidence limits of 5.1 and 13.9 lb. That is to say, our best estimate for the weight of the block is 9.5 lb with only 5% probability, given the observed variability in weight differences, that the weight of the block is less than 5.1 lb or greater than 13.9 lb. If we took thousands of weight differences, the mean difference should get very close to the true weight of the copper block and the confidence limits will get close to that mean value.

Basically, many measurements of SOC at two times are required to reliably detect the change.

What were the results from the Prairie Soil Carbon Balance Project?

In 1996, the SSCA entered into a collaborative agreement with Agriculture and Agri-Food Canada and GEMCo to measure change in SOC on farmer fields converted to direct seeding in 1997. In this Prairie Soil Carbon Balance Project (PSCB), 134 fields across Saskatchewan were involved. A sampling benchmark was established in each field. SOC was first measured on this benchmark in fall of 1996 or spring of 1997. In the fall of 1999 and 2005 the SOC was measured again on these benchmarks. The frequency of different measured differences between the 1996/97 and 1999 measurements is shown in Figure 2. The mean difference was 1.21 tonne C per ha with 95% confident that the true means lies between 0.41 and 2.01 tonne C/ha. This mean difference is equivalent to 1.8 ±1.2 tonne of CO_2 per acre. This difference is due to adoption of direct seeding and, for majority of fields, to the elimination of frequent summerfallow.

What do measurements on individual fields tell us?

Individual measurements tell us little and can be misleading. For the PSCB project, the extreme values indicate losses or gains of C greater than 10 Mg C/ha. These amounts of SOC change are essentially biochemically impossible over three years given the management of these fields. However, these are perfectly correct measurements given the underlying variability of SOC. The situation is analogous to the measuring the weight of a block on the back of bouncing truck described earlier - occasionally unrealistically high and low weights for the block will be measured. For the copper block weight problem, we recognized that only the mean of many differences of with and without block weights was a useful indicator of weight of the copper block. About all that a single measurement of the weight of the copper block on the bouncing truck would tell us is that, perhaps, the weight of the block is not likely to 10000 or more lbs. An individual difference is most valuable as one on a collection of other measured differences. If our purpose for measuring the copper block weight was for commerce, it would be grossly unfair to base the sale on a single difference between man's weight with and without holding the block. Similarly, for the SOC change problem, a single measurement of change might indicate it is unlikely the field lost or gained 10000 tonnes of C per ha. It would be grossly unfair to base the payment of any offset on single measurements of SOC difference.

Looking at results in Figure 2, one "unlucky" field happened to have measured difference of -15 tonne C/ha (23 tonne CO_2/acre) – this would suggest a loss of SOC. Although that measurement is scientifically valid, it is not a really a fair assessment C change. The fair estimate for that field would be the mean of all the measurements – i.e. a gain of 1.21 tonne C/ha. Similarly, one "lucky" field happened to have a difference of 13 Mg C/ha (20 tonne CO_2/acre) – this would suggest a gain of SOC. Again, the fair estimate of change for that field would be the mean of the collection of the field. Based on the data, there is no reason to believe that the field with apparent loss of 15 tonne C/ha did not gain the most C of any field in the PSCB project nor reason to believe that the field with apparent 13 tonne C/ha gain did not, in actuality, lose C. Any value of rate of change assigned to these fields other than the PSCB mean of 1.21 tonne C/ha would be unquestionably biased. The PSCB project was not designed to interpret rates of SOC change for individual fields. All we know with any confidence is the mean value of SOC change for all fields. Although the PSCB project easily tells us which field in the project has largest difference in SOC between measurement times, the project, as designed, will never tell us which field had the greatest gain or loss of SOC. It would be grossly unfair if the measured differences on individual fields were used to estimate the rates of SOC change for individual participants.

What might a measurement-based system look like?

Based on the variability from the PSCB project, it takes about 100 careful measurements at two different times to detect the change in SOC. Therefore, if the farmer wants to reliably determine the change on individual field, there will need to be about 100 observations in that field. If the farmer is uninterested in SOC change on individual fields, but wants to know the change for the whole farm, there would be a need for 100 observations over that farm. If 10 farmers got together and were willing to accept the mean rate of SOC change for everyone, they would need about 100 measurements across all 10 farms. In the latter situation, if the measurements were distributed equally among farms, each farm would have 10 measurements. The question arises if these could be used to determine the relative rates among farms. The answer is NO. It is analogous to situation where you need to use a sailboat to cross the lake. However, the sailboat has 100 good sized holes in the hull. If 10 holes are patched, the sailboat won't make it. If 50 of the holes are patched, sailboat still won't make it. All 100 holes need to be patched to get the job done. Similarly, all the measurements are needed to reliably determine SOC change. Although it is tempting to use small number of measurements to estimate SOC change, it is unreliable and unfair to individual farmers. (In the sailboat analogy, if you patch 90 of the 100 holes, and you are *lucky* with good winds, it might be possible to make it across the lake fast enough before sinking. Similarly, if you had 90 measurements and you are *lucky* with low SOC variability, it might be possible to reliably detect SOC change. But if you don't patch enough holes or take enough measurements, you won't get the job done no matter how lucky you are.)

Basically then, because careful measurements are expensive, a cost-effective measurement system would involve network of measurements over a project involving a large area made up of many farmers. The project would receive credits for based on the area within the project times the total area of the projects. The fair (unbiased) method of rewarding individual producers would be to accept everyone achieved the mean value.

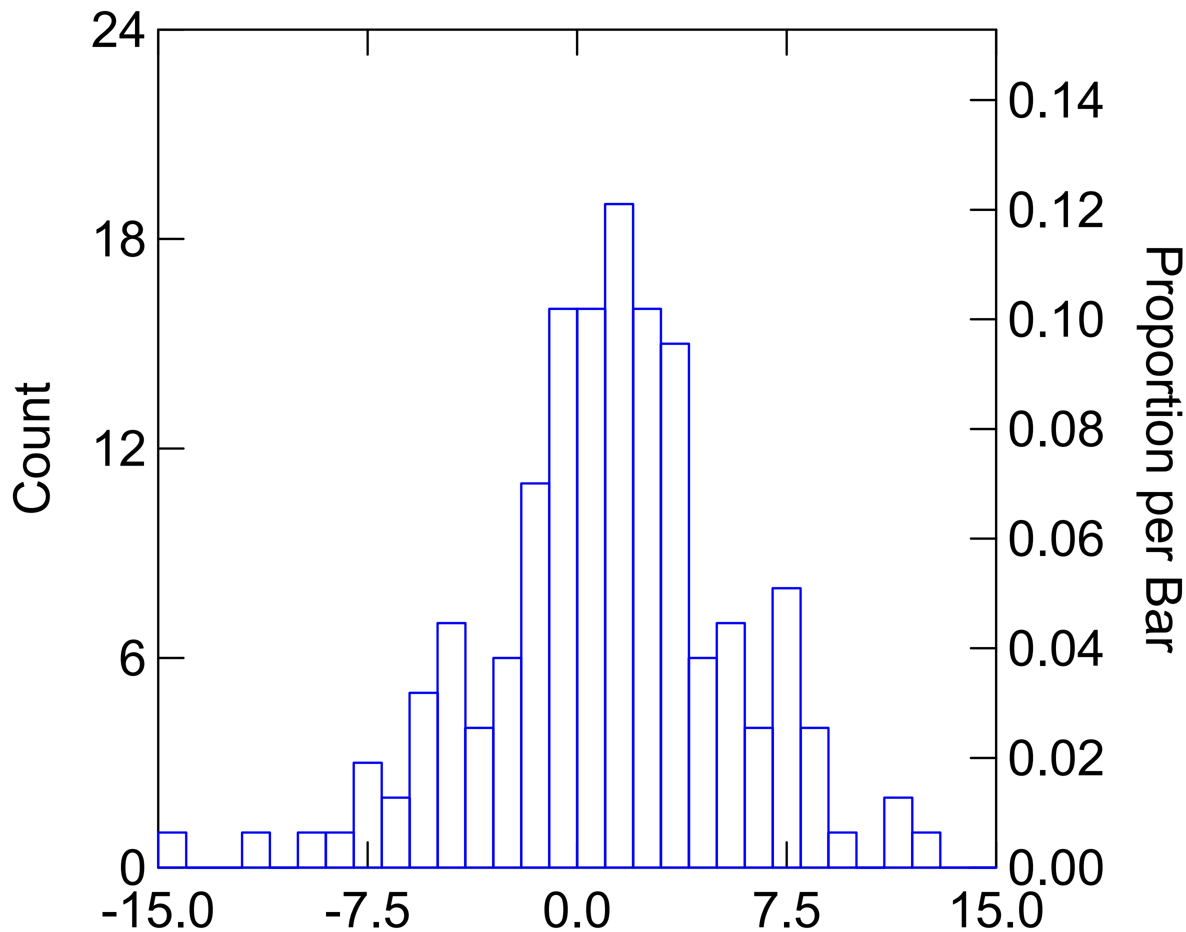

Figure 2. 0-30 cm soil organic carbon change (tonne C/ha) from 1996/97 to 1999 for the Prairie Soil Carbon Balance Project