SOIL ORGANIC MATTER CONSERVATION

Uncultivated land typically exhibits a more uniform distribution of SOM and A horizon depth compared to eroded agricultural land. In agricultural settings, the process of cultivation has led to the redistribution of organic matter-rich topsoil, particularly from upper slope positions to lower slope positions. As a result, upper slopes have become degraded, with reduced organic matter content, while lower slopes possess artificially deepened A horizons. This redistribution has significant implications for the carbon sequestration potential of soils in different landscape positions, as well as their response to further tillage interventions. Figures 1 and 2 illustrate real examples of variability in SOM within two fields of agricultural land.

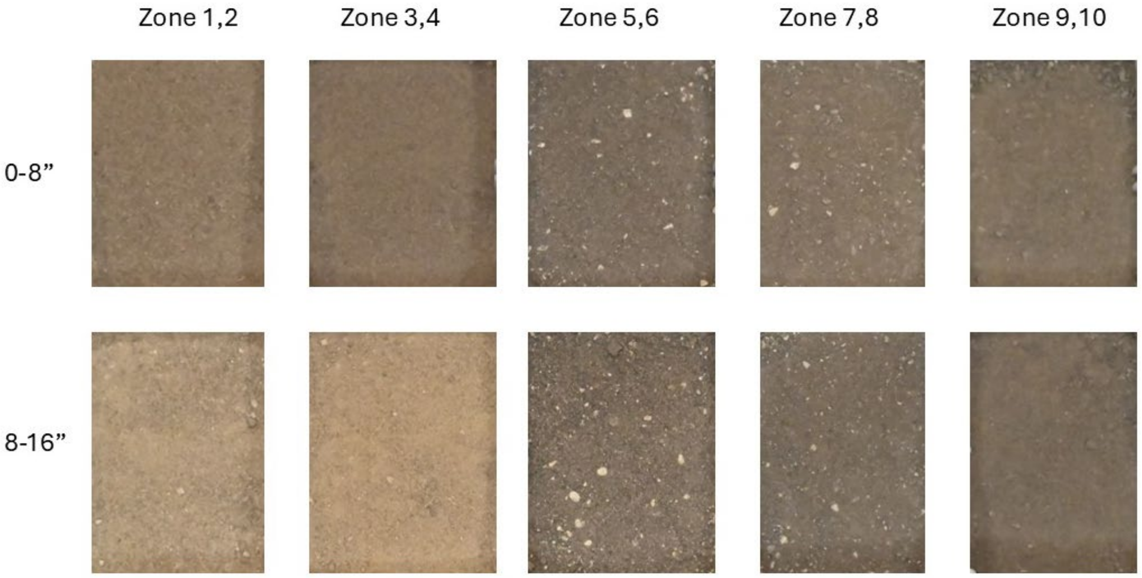

***Figure 1**. Topsoil (0-8") and subsoil (8-16") samples from five SWAT zones demonstrating variable organic matter levels within a single field. Note the dramatic change in colour from 0-8" to 0-16" zones 1-4. This indicates shallower topsoil and less total carbon.*

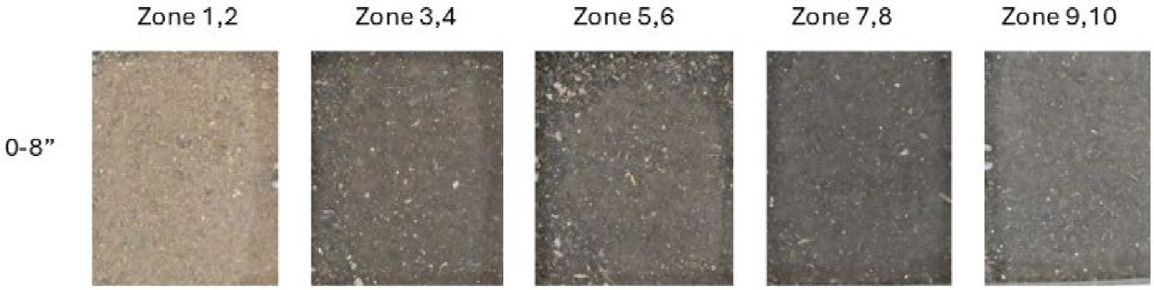

***Figure 2**. Topsoil (0-8") samples from five SWAT zones demonstrating variable organic matter levels within a single field. Note the dramatically lighter zone 1,2 topsoil indicating erosion to the point that the topsoil has largely been removed. From zone 3-8 there is a slight gradually darkening in colour as soil carbon increases. Zone 9,10 is a lighter grey colour related to the influence of trees that would have been present pre-cultivation.*

Degraded soils on upper slope positions possess a higher carbon sequestration potential than soils on lower slopes, as they are further from reaching their carbon saturation point. However, in severe cases, the low SOM content of upper slopes may limit their ability to support sufficient plant growth, which is critical for the rapid accumulation of SOM. To address this, amendments such as animal manures or green manures should be targeted to these degraded areas. Once SOM levels have been initially increased, regular cropping and appropriate fertilizer practices may become feasible for continued improvement.

In contrast, lower slope positions that have developed unnaturally deep A horizons are unlikely to benefit significantly from such amendments. In fact, applying animal manures high in soluble salts to these areas may be detrimental. The increased organic matter in these zones results in greater nutrient availability as decomposition occurs, and when combined with increased moisture, there is a higher risk of nutrient leaching and contamination of surface water bodies and groundwater.

Within the same landscape, uncultivated soils generally display minimal differences in SOM, except in depressions with poor drainage where decomposition rates are slowed by prolonged saturation. The act of cultivation—including tillage, wind, and water erosion—has led to the redistribution of SOM alongside the movement of topsoil. Tillage moves soil in all directions, but unless specifically managed to move soil upslope, the net effect is a downhill shift.

As SOM builds up through the deposition of plant residues, it becomes a larger food source for microbes, leading to increased decomposition rates. Over time, as SOM accumulates year over year, decomposition rates rise until an equilibrium is reached between accumulation and decomposition. At this point, the soil achieves SOC saturation, and net carbon sequestration slows to negligible rates. Improved management practices—including the adoption of no or conservation tillage, continuous cropping, and enhanced fertility—can result in carbon sequestration and SOM accumulation. However, the rate of SOM increase is strongly influenced by how much the current SOM concentration is below the carbon saturation point. Consequently, management practices impacting SOM will have different effects depending on the SWAT zone (landscape position) in which they are applied.

Organic matter offers numerous benefits to soil, including improved tilth, greater WHC, and enhanced nutrient supply. It sustains microbial life, facilitating nutrient cycling and additional carbon sequestration. Maintaining or increasing SOM levels is in the best interest of farmers for long-term productivity, and it also benefits society by contributing to the mitigation of rising atmospheric CO_2 levels associated with climate change.

Microbial communities require the proper combination of nutrients, water, and soil physical properties to thrive. Fertilization has a direct impact on the rate of SOM decomposition: when fertility matches plant demand, SOM can accumulate due to increased plant residue input. Conversely, if fertility exceeds plant demand, the resulting soil environment accelerates microbial activity and the decomposition of plant residues, which can ultimately reduce the total SOM stored in the long term. *Zone-specific fertility prescriptions are important not only for optimizing crop productivity but also for managing the soil carbon balance*.

For farmers, SWAT MAPS provide the information needed to identify nutrient deficiencies or pH extremes that limit crop biomass and yields, which subsequently limit carbon sequestration potential (Aulakh and Malhi, 2005; Coonan et al., 2019; Lam et al., 2013). A common example would be identifying areas where topsoil has eroded from upper landscape positions. These areas can benefit significantly from composts, manures, and specific nutrients to increase productivity, allowing the soil to increase in organic matter closer to its original state prior to cultivation.

Because SOM improves water and nutrient holding capacities of soils, composts, and animal and green manures can be particularly effective in eroded soils that are low in clay. An initial investment in increasing SOM through amendments can support plant productivity and kick off a feedback loop that drives SOM still higher as increased SOM increases plant productivity (which in turn increases SOM). It is important to understand and connect these amendments to the drainage potential, which is an inherent property of SWAT MAPS zones. Animal manures tend to be high in salts. This will have little negative effect on low EC soils with ample drainage. However, they make a poor amendment to depressions particularly if the soils there are already saline. Additionally, organic matter amendments applied to poorly drained zones already high in organic matter can increase nitrous oxide (N_2O) and methane (CH_4) emissions as well as leaching, not to mention the potential for contamination of surface water bodies and groundwater if animal manures are used.

Management of SOM is one part of CO_2 management at the farm level. There are many sources of CO_2 emissions in agriculture and fertilizer use has opportunity for improvement. Efficient fertilizer use is critical to minimize the environmental impact as previously discussed. Agricultural lime is also a source of CO_2 in agriculture and can be included in a similar category as fertilizers. Lime is a commonly used pH amendment in many parts of the world, used to improve acid soils that limit production. A biproduct of its chemical reaction in the soil is CO_2. For this reason, and because it is a significant cost, lime is well suited to a VR application where only areas of the field that have a low soil pH are treated (Bongiovanni and Lowenberg-DeBoer, 2000).

Decreasing tillage and increasing SOM in general has a long-term effect of improving soil structure. Tillage loosens soil temporarily but, as SOM is depleted and soil aggregates are broken, the longer-term effect is that the soil will collapse leading to compaction. However, there are instances where some types of tillage may be beneficial. In soils that are affected by high sodium and dense subsoil structures, deep ripping can be done to provide drainage channels for soil water as well as enhancing oxygenation and root penetration. This is particularly effective in sodium-affected soils if gypsum is applied to mitigate the dispersion effects of sodium. Additionally, the incorporation of manures into the topsoil can enhance the SOM within the mineral soil. This leads to better structure and more likely organo-mineral complexation leading to enhanced SOM stabilization. As discussed earlier, most tillage results in undesirable soil redistribution but targeted efforts can mitigate erosion. Harrowing to smooth out small rills can prevent the development or deeper stream channels that have more erosive power.

Metrics

Due to carbon credit and offset payment schemes, there is a broad desire to measure and track SOC levels in agriculture. This is not a simple task to do accurately and with repeatability over time. Organic carbon can vary greatly across a landscape, both horizontally and vertically (Meersmans et al., 2009; Olson and Al-Kaisi, 2015). A single point measurement in a field could yield quite different results depending on where it is taken (see Figure 3 illustrating the variable depth and amount of SOM in a single field). Over multiple years, some areas within a field could lose SOC, and other areas could gain. Not only that, but a specific point could gain SOC in the topsoil but lose in the subsoil (Olson and Al-Kaisi, 2015). For accurate tracking, the points of measurement should be based on spatial soil data considering soil texture variation and landscape position. Research has shown the complexity of influencers on SOC and soil health measurements, finding some of the best predictors include apparent EC, landscape position, wetness index, and topographic position index (Adhikari et al., 2022), which are all attributes inherent to SWAT MAPS.

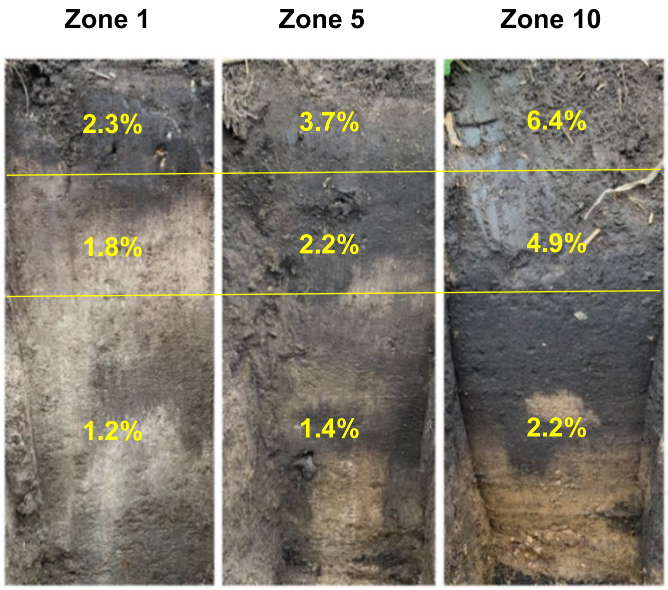

***Figure 3**. Soil profiles (0–15 cm; 15–30 cm; 30–60 cm)) from three SWAT zones demonstrating variable depth and amount of SOM.*

Monitoring changes in SOM from decreasing tillage requires a long-term approach if direct measurements are to be used. As mentioned previously, whenever the soil is not frozen there is a constant balance between the decomposition and deposition of SOM. This balance shifts through time in response to environmental conditions and plant growth stage as well as the addition of any amendments. Therefore, there are cycles of accumulation and ablation of SOM. There is an annual cycle linked to the growth and senescence of plants as well as annual changes in soil temperature and moisture. There are cycles that are the length of the crop rotation as differing crops input different quantities and qualities of litter. There are also cycles that are in response to drought cycles as drought lessens productivity and therefore inputs of SOM. *This means that, for accurate descriptions of the trends of SOM accumulation and carbon sequestration to be ascertained, soils need to be analyzed for soil carbon at the same time of year, every year. They need to be analyzed year over year for the duration of these crop rotation and drought cycles as well.* Furthermore, as SOM increases so does the microbial decomposition in response such that microbial decomposition rates equal the average annual input of fresh organic matter and the soil reaches an equilibrium or carbon saturation point. As such, it is not appropriate to extrapolate a linear increase in soil carbon sequestration. For these reasons, *monitoring short term changes in carbon in soils through direct measurement is dubious and always needs to be in context.*

SOM can be quantified and characterized in many ways. For purposes of carbon sequestration, direct quantification of %C is preferable to %SOM. Microbial biomass carbon is also potentially usable as a metric for the capacity of a soil to support healthy levels of microbial activity. This is highly affected by the current conditions of the soil. Microbial biomass carbon after a standard incubation period allows for comparable results.

SWAT MAPS offer a practical way of improving the accuracy of measuring and tracking SOC over time by creating a stratified sampling protocol. Stratified sampling is especially important to tracking SOC due to the combination of spatial and temporal variability. It gives a methodology to group similar soils together for measurement, balancing cost versus accuracy. Unlike methodology using satellite imagery and modelling, SWAT MAPS are ground-truthed and either SOM or SOC is measured through accredited soil laboratories. Currently it is not practical to measure every square meter of soil, nor is it accurate to base measurements on a single point representing 100+ acres. SWAT MAPS allow a practical solution to map SOC in heterogeneous soils and give farmers insight into where and how SOC levels could be improved. More importantly, it offers a management tool to help use crop inputs more efficiently to reduce total GHG emissions per unit of production.

Recommended Metric:

- **Recurring measurement of SOC using stratified sampling protocol with ground truthing.**

Figure 4. *Uncultivated Chernozem in the Canadian Prairies illustrating a system in equilibrium (at carbon saturation) with net carbon sequestration negligible.*

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Acronym & Abbreviation Guide

CH_4 — Methane
Emitted from saturated soils; referenced in drainage and water management sections.

CO_2 — Carbon Dioxide
Discussed in relation to soil carbon sequestration and lime-related emissions.

EC — Electrical Conductivity
Measure of soluble salts in soil; used to infer salinity, texture variability, and water movement.

GHG — Greenhouse Gas
Gases whose emissions contribute to climate change (e.g., CO_2, N_2O, CH_4). Frequently discussed in relation to fertilizer and soil management.

N_2O — Nitrous Oxide
Potent GHG (265× CO_2) emitted from soils through nitrification/denitrification, especially in wet zones.

SOC — Soil Organic Carbon
Carbon component of SOM (~58% of SOM mass); key indicator of carbon sequestration potential.

SOM — Soil Organic Matter
Decomposed biological material in soil essential for fertility, structure, water retention, and long-term soil health.

SWAT — Soil, Water, and Topography
A spatial soil landscape framework for mapping stable properties that drive yield potential and environmental interactions.

SWAT MAPS
High-resolution soil, water, and topography maps forming the foundation of precision agronomy within the SWAT ECOSYSTEM.

VR — Variable Rate

Varying seed, fertilizer, or pesticide applications within a field based on mapped variability.