Organic Agronomy Training

Dr. Martin Entz – University of Manitoba

Lesson 4

Soil Management for Organic Production: Putting Theory into Practice

Organic Agronomy Training

This training was developed and delivered by Martin Entz, PhD, Department of Plant Science, University of Manitoba. It is intended for private and public sector agronomists who want to respond to the growing demand from producers for more information about organic grain production. Grain farmers considering a transition to organic or current organic practitioners who want to learn the theory and latest science will also find the course valuable. The course was designed with the Prairies in mind, however agronomists in other ecoregions will learn universal principles of organic production.

The training consisted of five 75 minute live online sessions over two weeks in January 2023:

- January 5: Designing Cropping Systems with a Focus on Nutrient Management
- January 6: Crop Establishment and Seeding Systems, Tillage and Weed Control
- January 10: Pest Management with a Focus on Disease, Insects (and Weeds)
- January 12: Soil Management for Organic Production: Putting Theory into Practice
- January 13: Question & Answers

All course content (lesson recordings, presentations and notes) can be accessed on pivotandgrow.com.

The Organic Agronomy Training was developed as part of the Prairie Organic Development Fund's Canadian Organic Ingredient Strategy.

The Canadian Organic Ingredient Strategy was funded by:

CANADIAN AGRICULTURAL PARTNERSHIP

PODF PRAIRIE ORGANIC DEVELOPMENT FUND

Canada

Table of Contents

Lesson 4: Soil Management for Organic Production: Putting Theory into Practice

Soil organic matter (SOM)

A fertile and healthy soil is the basis for

- healthy plants, animals, humans and other organisms,
- productive farms with good yields throughout the crop rotation and over the long-term, and
- healthy ecosystems.

And soil organic matter is the very foundation for healthy and productive soils. We will focus on soil organic matter (SOM) in this lesson. To learn more about soil life, nutrient cycling and other aspects of soil health, check out the many great resources available.

Maintaining soil health on organic farms is a balancing act in terms of soil organic matter (SOM). To improve or even just maintain soil health, SOM must be added. This is often achieved by growing plants. On the other hand, crops need nutrients and these are supplied by the decomposition of some of that SOM. Note that SOM is about 58% carbon (C), so carbon is at the heart of SOM discussions.

Why is soil organic matter important?

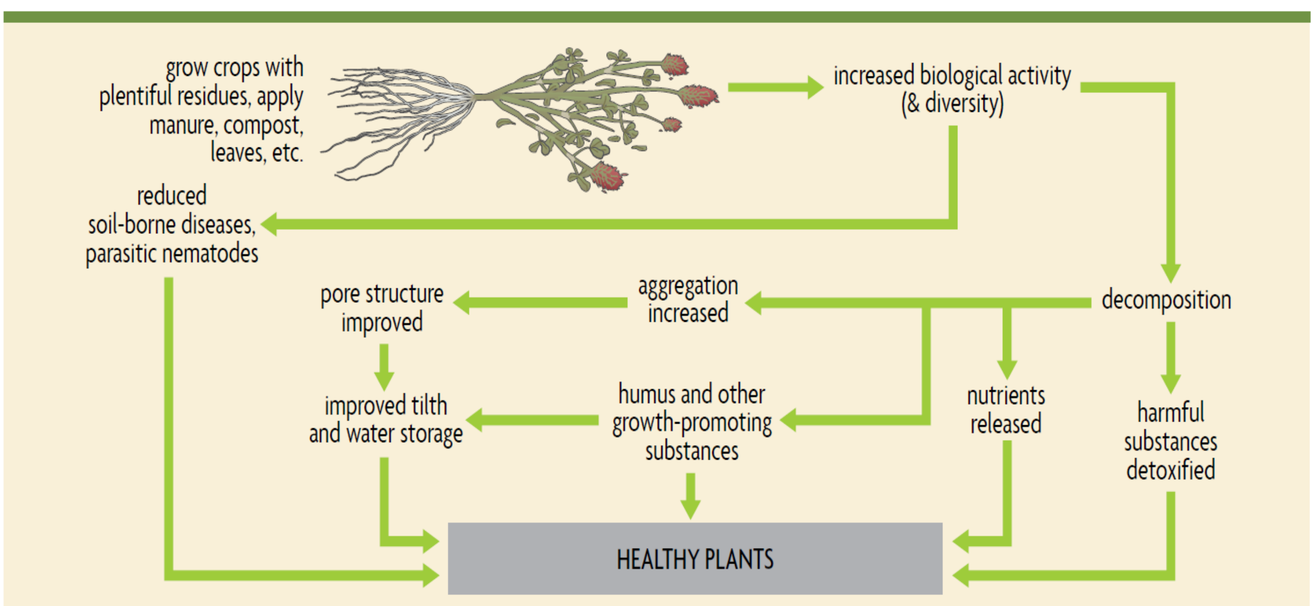


Figure 2.3. Adding organic matter results in many changes. Modified from Oshins and Drinkwater (1999).

Source: Building Soils for Better Crops: Ecological Management for Healthy Soils, Chapter 2, pg. 18

Organic matter affects many key soil properties. Soil organic matter (SOM) can improve:

- **nutrient supply and retention**. SOM can hold nutrients in the soil, protecting them from leaching, while slowly releasing nutrients as required by plants.
- **soil structure**. SOM can lead to better soil tilth and aggregation.
- **water retention**. SOM can hold water and release it as needed, similar to the effect of SOM on nutrients.
- **water infiltration rates**. SOM's positive effect on soil structure and porosity means that more water can flow into the soil rather than flow across it. So rather than losing water along with topsoil and nutrients in runoff, the water will be kept in the soil. This also helps avoid puddling on the soil surface.
- **resilience.** By improving water infiltration and retention rates, SOM helps farms cope with flooding, drought and other extreme weather events (such as prolonged heavy rain).
- **resistance to pests**. Plants grown in soils high in SOM often have fewer pest problems compared to plants in low-SOM soil. This holds true for both underground pests, such as root diseases, and aboveground pests, such as aphids. There appear to be two mechanisms for this. The SOM provides habitat for abundant and diverse life, including organisms that attack pathogens and pest insects. Also the balanced nutrient supply provided by SOM makes foliage less attractive to pests compared to plants that receive synthetic fertilizers or high levels of soluble N. See "Complex relationships between pests, beneficials, weeds and crops" in Lesson 3 - Insect and Disease Management.
- **carbon sequestration**. SOM provides a pool for carbon in the soil. As carbon dioxide is taken in by plants, some of the carbon can be held in SOM. This reduces the amount of CO2 in the atmosphere, thereby slowing the rate of climate change.

"...As soil organic matter decreases, it becomes increasingly difficult to grow plants, because problems with fertility, water availability, compaction, erosion, parasites, diseases and insects become more common. Ever higher levels of inputs—fertilizers, irrigation water, pesticides and machinery—are required to maintain yields in the face of organic matter depletion. But if attention is paid to proper organic matter management, the soil can support a good crop with less need for expensive fixes." [1]

According to the Canadian Organic Standards (2020), 5.4.1 "The main objective of the soil fertility and nutrient management program shall be to establish and maintain a fertile soil using practices that:
a) maintain or increase levels of soil organic matter,
b) promote an optimum balance and supply of nutrients, and
c) stimulate biological activity within the soil."
Furthermore, according to 5.4.5, "The organic matter produced on the operation shall be the basis of the nutrient cycling program."

---

[1] Building Soils for Better Crops

Voices from the Field: Our Farm

"My mantra is feed your soil and it will feed your plants," says Dennis. "If you have healthy plants, you'll have really good-tasting produce. And if the produce tastes good, it's probably very nutrient dense."

Soil health is maintained primarily by applications of compost.

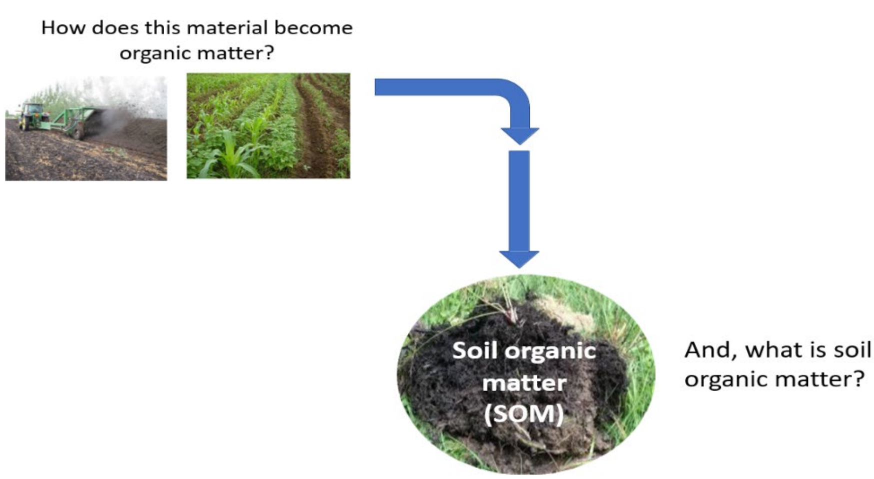
"We compost everything," Dennis laughs. "If it's not moving, we're composting it."

Each year, Our Farm makes about 20 cubic yards of compost and buys 60 cubic yards of compost which has been approved by their certification body. Dennis also uses cover crops of oats, peas, rye, wheat, buckwheat and clover in small sections of the field. Cover crops are also planted in the pathways between beds; this soil gets incorporated into the growing area when hilling potatoes or changing the bed layout.

... "After adding a lot of organic material over the years, the soil is very nice to work in. The texture is beautiful." Dennis notes that the soil texture reflects how long each bed has been worked. Eight years ago, they started with one acre, and expanded about a half-acre each year. The original garden has the best soil of all.

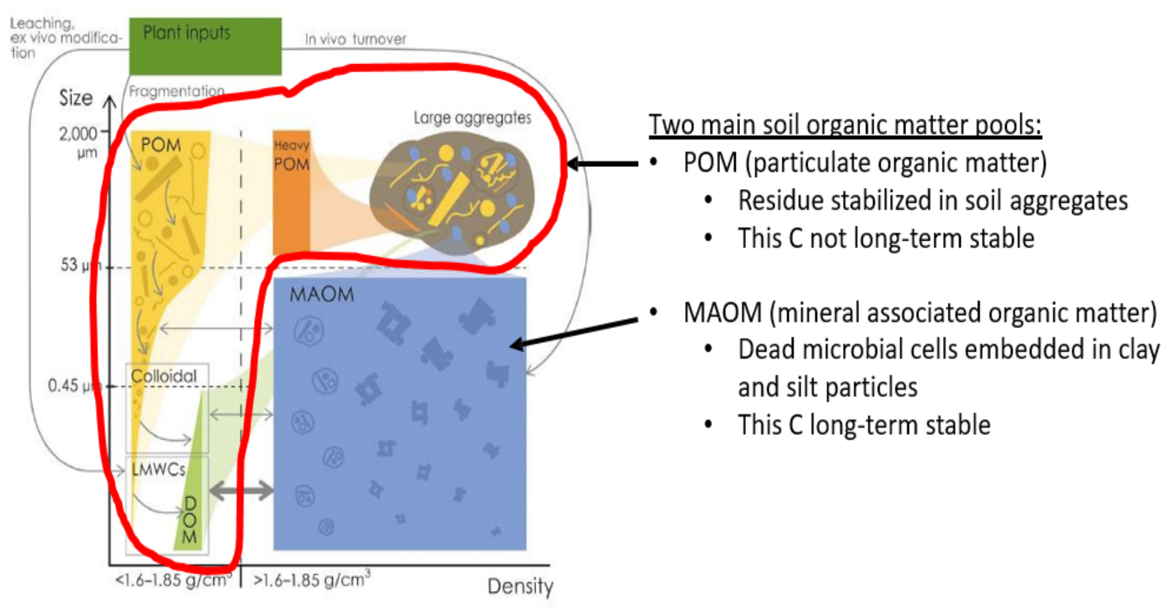
Formation of SOM: The two pathways model

The following section is quite technical. It might be helpful to refer to "Key Terms" and "Table 1" in this lesson in addition to the course glossary. After explaining the science behind the formation of soil organic matter (SOM), we describe steps growers can take to increase SOM and improve soil health.



“Soil organic matter, that very thin skin on the world’s terrestrial surface, serves many functions vital to humanity, such as supplying nutrients to plants and sequestering carbon. Traditional [models have] has held that the slower-decaying components of plant residues, such as fibers, help build soil organic matter. The new study suggests that the early by-products of plant residue decomposition, generally water-soluble materials, can also result in the formation of soil organic matter. The study demonstrates that these fast-decomposing materials are used more efficiently by the soil microbes, thus leaving more carbon in the soil as microbial products, which bond to the soil minerals and therefore stay in the soil for longer periods of time.”[2]

Microbial processing of organic matter appears to be much more important to long-term SOM stabilization than biochemical processing. Soil scientists have proposed the two pathways model, where SOM is contained in two major pools, particulate organic matter (POM) and mineral-associated organic matter (MAOM). A small proportion of SOM is in the form of dissolved organic matter: This represents a tiny fraction of the C but is important in controlling the formation of MAOM.



Lavallee, J.M., Soong, J.L. and Cotrufo, M.F., 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology*, *26*(1), pp.261-273.

[2] Kosovski, J. CSU study proposes new approach to retaining soil carbon. Sept. 9, 2015.

Voices from the Field: Mill Creek Organic Farm

For farmers considering transition, Alex Boersch recommends first "priming the soil." Ideally start the transition with a year of cover crops. But if you need a cash crop, he suggests fall rye underseeded with sweetclover. After harvesting the rye, let the sweetclover grow and "you have a super cheap cover crop that's super competitive. Use at least one year in transition as a cover crop year."

Key Terms

DOM: dissolved organic matter: This represents a tiny fraction of the soil C but is important in controlling the formation of MAOM.

MAOM: mineral-associated organic matter (MAOM) made mostly from dead microbes.

MAOM's greater persistence arises from the fact that the C is embedded in silt and clay particles. MAOM persists longer in the soil than POM and has a lower C:N.
Necromass: dead microbes; this forms MAOM.

POM: particulate organic matter. POM is made up of partially decomposed crop residues, stubble and other non-living C which enters the soil system. POM is less stable than MAOM.

POM is mainly stored within soil aggregates (both macro-aggregates, such as soil clumps, and micro-aggregates, clusters of soil particles).

SOM: soil organic matter.

Differences between particulate organic matter (POM) and mineral-associated organic matter (MAOM).

	POM	MAOM
Protection mechanisms	None or occlusion in large aggregates	Mineral associations (occlusion in fine aggregates, organo-mineral clusters, and micropores; sorption to mineral surfaces)
Mean residence time	<10 years - decades	Decades - centuries
Dominant formation pathway	Fragmentation, depolymerization	In vivo transformation or ex vivo modification of low molecular weight compounds
Subject to saturation?	No	Yes
Dominant chemical constituents	Plant-derived (e.g. phenols, celluloses, hemicelluloses), fungal-derived (e.g. chitin, xylanase)	Low molecular weight compounds of microbial (e.g. microbial polysaccharides, amino sugars, muramic acid) and plant origin.
C/N ratio	10-40	8-13
Nutritional role	● More complex compounds with high activation energies ● Not assimilable by plants, few or no assimilable compounds for microbes	● More simple compounds with low activation energies ● More assimilable compounds for microbes and plants

Source: Based on a table from Lavallee et al. 2020. Global Change Biology, 26(1), pp.261-273.

Mineral-associated organic matter (MAOM)

MAOM is formed after fresh plant inputs are solubilized and transformed by soil microbes, while POM is formed as a result of partial decomposition and physical fragmentation of the structural plant parts. Particulate organic matter (POM) is less stable than MAOM. Generally speaking, POM is largely made up of lightweight fragments that are relatively undecomposed. POM can be increased quite quickly in soils through practices such as increased plant growth (often associated with increased level of plant nutrients) and reduction of tillage. MAOM has a much longer persistence in soil.

The proportion of MAOM to POM varies in soils, cropping systems and soil depths. In Argentina, researchers observed about twice as much MAOM in grassland soils compared with POM (Ojeda et al., 2018). Others have reported over 10x more MAOM than POM (Gentile et al. 2005).

The general characteristics of POM and MAOM are shown in Table 1.

- POM has a high C:N ratio, which indicates that it is mostly made from plants and not microbial matter. POM persistence is mostly controlled by physical protection in soil aggregates.
- MAOM has a lower C:N ratio indicating that it is of microbial origin. Basically, MAOM is dead microbes sometimes referred to as the necromass. MAOM's greater persistence arises from the fact that the C is embedded in silt and clay particles.

In soil, MAOM is typically the largest SOM pool with the oldest carbon (Table 1). Compounds with low molecular weights (e.g., sugars, organic acids, amino acids) can become MAOM in two ways. The substances can be:

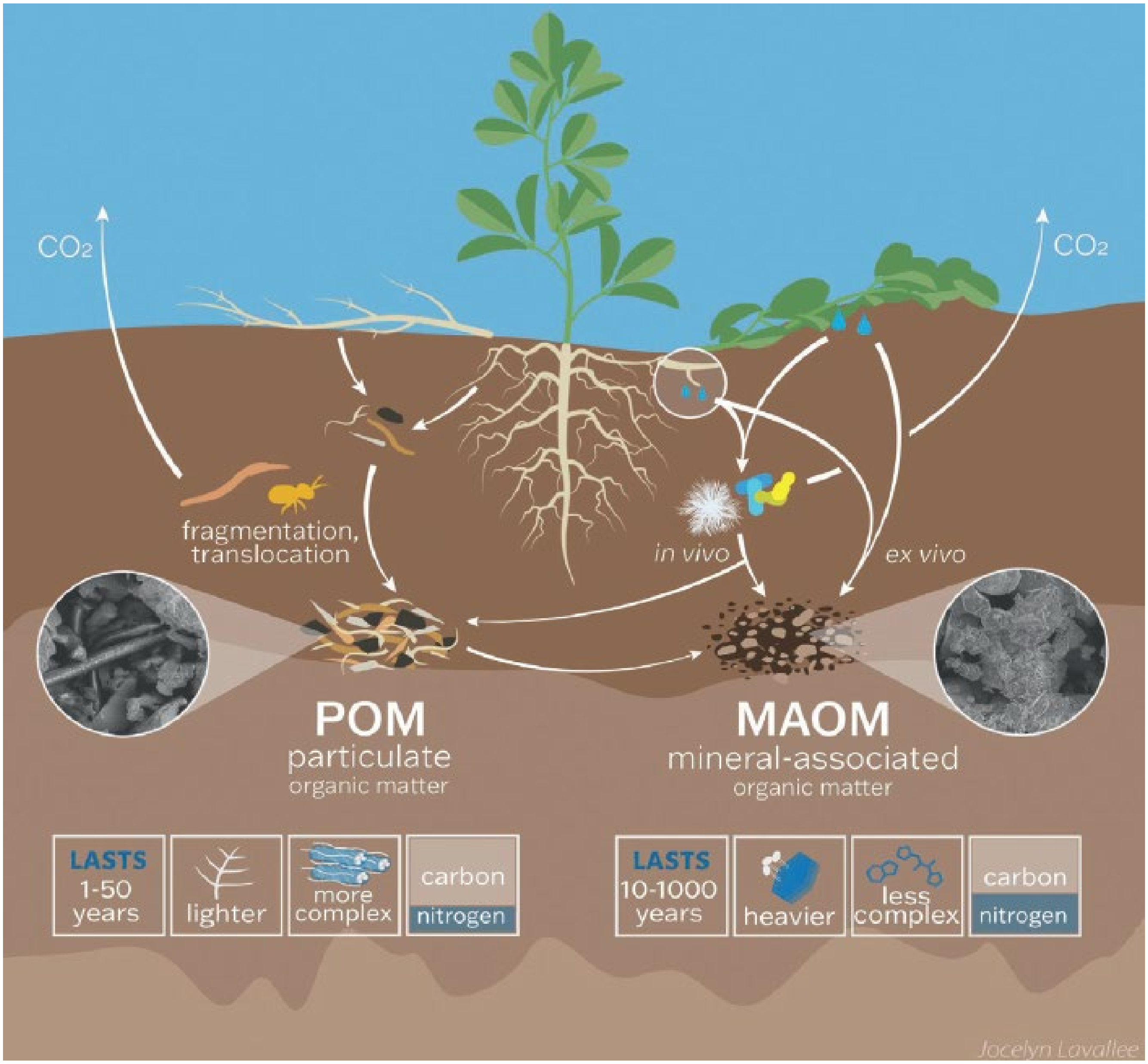
1) leached from plant roots or fresh litter and associate directly with the mineral phase in a pathway outside the microbial pool, or
2) produced by microbes decomposing and transforming organic material which then associates with soil silt and clay. This pathway that passes through the microbial pool produces dead microbial cells (necromass) that end up in clay and silt particles.

Particular organic matter (POM)

The second major form of organic matter in the soil is particulate organic matter (POM). POM is made up of crop residues, stubble and other non-living C which enters the soil system. POM is stored within soil aggregates. The persistence of POM in the soil depends on formation and maintenance of these aggregates.

One question that scientists have asked is whether POM, such as plant stubble and cover crop residues, eventually becomes MAOM. It appears not, or at least not within several years. A recent study monitored fresh plant material at 10 Canadian locations over 6 years. The researchers observed little transfer of POM to MAOM over that time period (Hatte et al. 2020).

POM appears more sensitive than MAOM to crop management practices in the short-term (2–3 years). In most studies that have shown rapid increases in SOM due to adoption of practices such as no-till, the SOM increase is due to an increase in POM.



Recent research has shown:

- Dead fungi and bacteria are the main sources of carbon (C) in the stable soil organic matter (SOM) pool.[3],[4]
- "The magnitude of the organic C reservoir in soils depends upon microbial involvement, as soil C dynamics are ultimately the consequence of microbial growth and activity."[5]

Soil pH, microbes and SOM

Microbes are very important to building SOM. How do we keep these microbes happy? There are a number of ways. One is for the soil to have a neutral pH. Organic management results in neutral pH (a good thing) while conventional systems cause a decrease in pH over time. Acidification is a consequence of long-term N fertilizer use in conventional agriculture. This acidification can slow the formation of MAOM. But microbes also require N, especially for MAOM formation because of its lower C:N ratio. Organic farmers can provide N by including legumes in the crop rotation, particularly green manures (cover crops).

Soil type, aggregation and SOM

The C in mineral-associated organic matter (MAOM) is embedded within the clay and silt particles. Therefore, soils with higher clay and silt contents have more binding sites for C, and can accumulate more C as MAOM. This begs a question: "Can sandy soils that contain neither silt or clay build up levels of MAOM?" The answer is no. Without minerals, there are no binding sites for the C and so MAOM accumulation is limited.

Particulate organic matter (POM) is mainly stored within soil aggregates (both macro-aggregates, such as soil clumps, and micro-aggregates, clusters of soil particles). Management factors that allow increased aggregation include reducing tillage, growing perennial crops and growing mycorrhizal crops. For example, in the sandy soils of PEI, a 7-year tall fescue stand increased soil C by 1 Mg/ha C per year (Carter and Gregorich, 2010).

Management practices to increase stable organic matter (specifically MAOM)

Changes in farming practices and SOM

POM appears to be more sensitive than MAOM to crop management practices in the short-term (2–3 years). In most studies that have shown rapid increases in SOM due to practices such as no-till, the type of SOM that increased was POM.

---

[3] Kindler, R., Miltner, A., Richnow, H.-H. & Kastner, M. Fate of gram negative bacterial biomass in soil—mineralization and contribution to SOM. Soil Biol. Biochem. 38, 2860–2870 (2006).

[4] Schweigert, M., Herrmann, S., Miltner, A., Fester, T. & Kästner, M. Fate of ectomycorrhizal fungal biomass in a soil bioreactor system and its contribution to soil organic matter formation. Soil Biol. Biochem. 88, 120–127 (2015).

[5] Liang, C., Schimel, J.P. and Jastrow, J.D., 2017. The importance of anabolism in microbial control over soil carbon storage. *Nature microbiology*, *2*(8), pp.1-6.

Plants, plants, plants...

In a nutshell, plant growth supports microbes which produce soil organic matter. Microbes add organic matter by decomposing plant matter into SOM and also their dead 'bodies' contribute to the SOM pool. Living root systems add sugars to the soil microbial community (bacteria in particular) and this stimulates microbial growth. Certain soil microorganisms, such as mycorrhizal fungi, require the presence of living roots - this highlights an advantage of keeping soil covered with living plants for as much of the year as possible.

Crop rotations vary in their ability to add organic matter. From best to worse:

- Perennial polyculture (including legumes, grasses, forbs)
- Annuals with shoulder season cover crops
- Annual diversified rotations
- Annual monoculture
- Annual monoculture with summer fallow

Voices from the Field - Upland Organics

"Once we learned about the five soil principles," explains Cody Straza of Upland Organics, "our goal became to implement as many of these as possible." Cody Straza and Allison Squires started with the "low-hanging fruit" and identified diversity as an easy first step. The more diversity above ground, they explain, the greater the diversity and health of the microorganisms below ground. Abundant, diverse soil life is key to good soil structure, retention of nutrients and water, and long-term fertility.

A simple step was expanding their cover crop by adding oats to the field peas they had been using as a green manure. Over the years, they kept adding more species and are now using cocktail mixes with up to 10 species. They also intercrop. For example, they underseed yellow sweetclover into annual crops. After the cash crop is harvested, the sweetclover will continue to grow, fix nitrogen and protect the soil from erosion.

Meanwhile, they increased the number of cash crops. Initially they grew French green lentils, flax and durum, but have since added sunflowers, camelina and various cereals including spelt, spring wheat, Kernza® and khorasan (Kamut®). Their crop rotation is more "adaptive" than rigid - they assess what a specific field needs and adapt their choice of crop rotation to the needs, rather than applying a simple formula.

"We could do much more if we had more rain," Allison says. Then she laughs and says she doesn't want to sound like she's complaining. However, their choice of crops is restricted by moisture availability.

Their desire to increase diversity continues on a large scale (now raising cattle) and small scale (soil microbes). While the couple acknowledge that having livestock is challenging, they appreciate the many benefits of incorporating cattle into the agro-ecosystem from providing fertility, "mowing" through grazing and trampling forages, and adding another income stream.

Reduce tillage?

- No-till increases POM however MAOM (the more stable, resistant organic matter) is added by an increase in plant diversity, not a lack of tillage.

Balanced nutrient supply

- An adequate supply of nutrients is required to add organic matter.
- MAOM requires more N than POM due to its lower C:N ratio – therefore it is important to have legumes in the crop rotation.
- Soils with very low soil P can result in loss of SOM because P deficiency forces soil microbes to mine the SOM for P.
- Tillage in soils with low N is particularly damaging to SOM.

Grazing

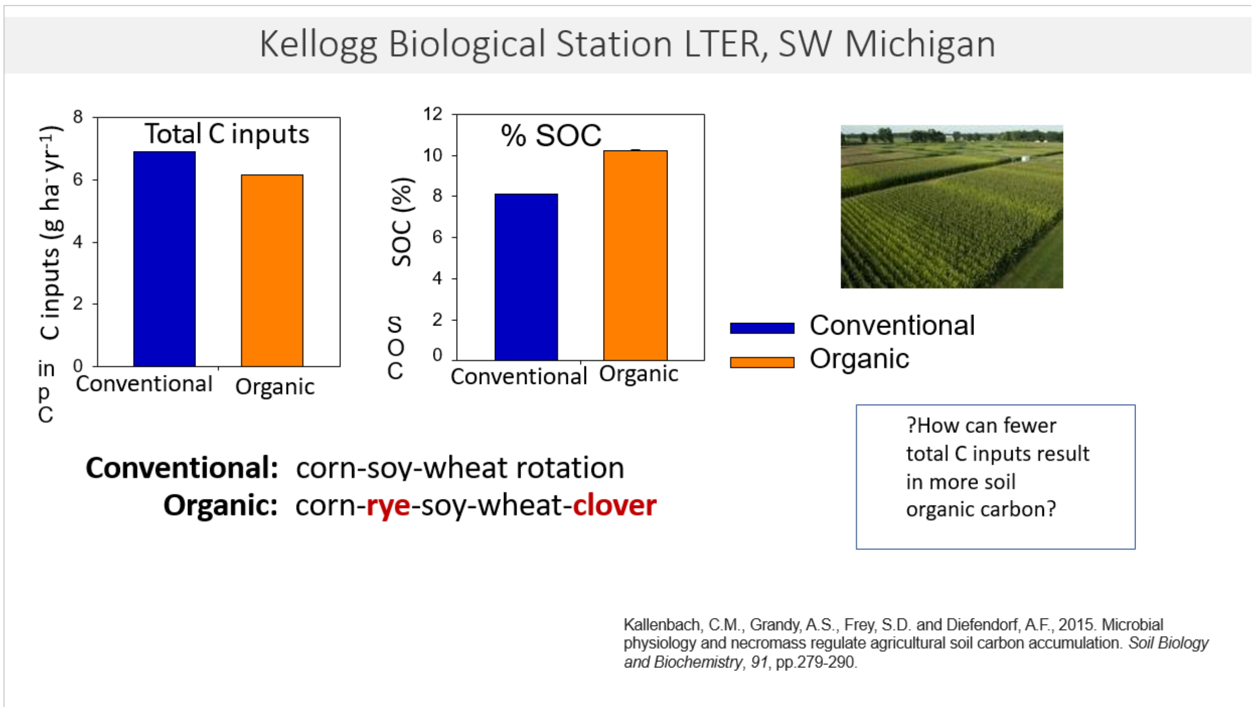
Grazing has been shown to increase SOM levels compared with unharvested forages. This may be surprising but this occurs because grazing stimulates plant root growth (provided the pasture is not overgrazed). Grazing can stimulate grassland productivity and this leads to more C in the soil, which in turn, may increase the microbial biomass and N mineralization. Research in Georgia, USA showed that grazing increased SOM accumulation during the first 5 years of a bermudagrass pasture (Franzluebbers et al. 2001). Soil C additions were 140 g/m^2 per year in the light and heavier grazing compared with 29 g/m^2 per year in the hayed and 65 g/m^2 per year in the unhayed system (where no harvests were taken). This may be surprising because it seems counterintuitive to have more SOM where forage was removed through grazing. This observation clearly suggests a higher carbon use efficiency (see * [link to next section]) in the grazed compared with the hayed and unharvested systems. Similar results have been observed by other researchers.

In a meta-analysis of 83 grazing studies around the world, Abdalla et al. (2018) concluded that benefits of grazing to soil C and N were dependent on environmental conditions. Grazing intensity increased soil C under moist-warm environments (+7.6%) but reduced soil C by 19% under moist-cool environments. Under dry, warm conditions, only low grazing intensity increased soil C (+5.8%). Under dry, cool climates "medium" grazing pressure increased soil C by 16%.

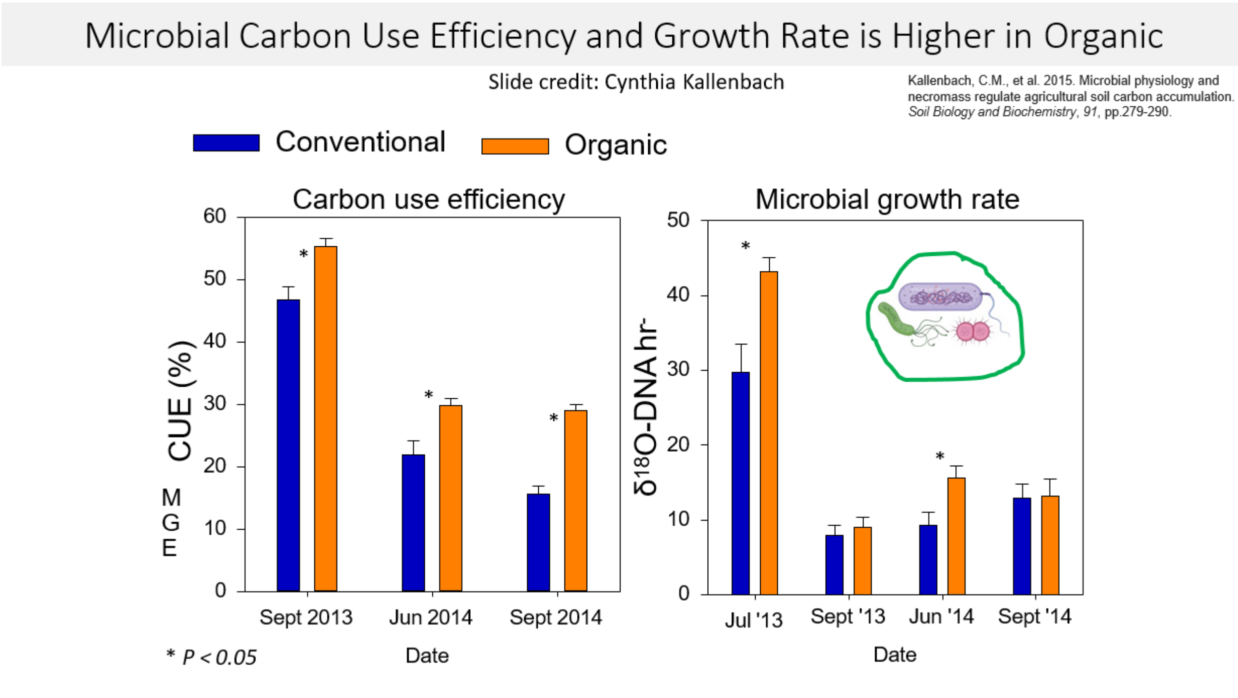
What does this mean for organic farming in the Canadian Prairies? Because the greatest benefit of grazing appeared to occur under warmer conditions, the meta-analysis data suggest that waiting until soil is warm may be an advantage. This supports the current practice of organic farmers grazing their green manure crops in mid-summer. What about fall grazing, which is popular where organic farmers have seeded late-season cover crops? Perhaps what the data are telling us is to avoid grazing if the fall conditions are very wet and cool (at least if we are trying to increase soil C).

Carbon use efficiency: more SOM with less C!

A Michigan study found that organically managed soils had higher SOM than the same rotation under conventional management, even though less carbon was added in the organic system. How can this be? It does not make logical sense.



The answer, as Kallenbach et al. (2015) discovered, was a higher carbon use efficiency (CUE) for the organic rotations.



A similar observation was made in California in the long-term tomato-corn rotation at the Russell Ranch Century experiment at UC Davis (Kong and Six, 2010). These researchers also observed that greater C storage in the organic system was not proportional to its C input. In fact, while the conventional system had 1.7 times more biomass enter the soil system than the organic system, the organic system still ended up with more SOM. The researchers also learned that preferential stabilization of belowground cover crop C inputs in the organic system was integral to its disproportionately higher total soil C sequestration (Kong and Six, 2010).

The organic system in these studies had cover crops but no manure was added to the organic rotations. The reason there was a higher CUE in the organic rotation was greater microbial growth.

What caused the greater microbial growth rate in the organic rotation? To answer this question, let's quickly review the factors that allow soil microbes to grow efficiently:

- Neutral soil pH
- Root growth
- Diversity of plant species
- Season-long plant growth
- Adequate nutrient supply

Of these factors, the organic system in one study had the soil covered with living, growing plants for a greater part of the year than the organic system. The organic rotation also had a greater diversity of plant species. Other research has confirmed that more diversity in a crop rotation changes the soil microbial community resulting in greater carbon use efficiency. Crop rotation diversity increased soil C by 33% increase compared to monocultures at the Michigan site (Tiemann et al. 2020).

Root carbon

Carbon that arises from plant roots is incorporated into SOM more efficiently than C arising from aboveground growth. The rate of SOM formation in the organic system was about 14 times faster than in both the conventional and low-input systems. In other words, they found that root C was stored as SOM more efficiently in organic compared with conventional systems.

The greater retention of root-derived C may be due to slower decay of roots than shoots, the continuous nature of root C inputs, and physical protection of root C within soil aggregates. The theory of root vs shoot C in SOM was tested in organic agriculture by Kong and Six (2010) in the long-term plots in California. They measured the C uptake by hairy vetch in a corn-tomato rotation. By the end of the season, 52% of the root-derived C was still present in the soil, whereas only 4% of residue-derived (topgrowth) C remained in soil, thereby showing greater conservation of root vs shoot-derived C.

That was not the end of the story. They also compared root vs shoot C to SOM in organic and conventional systems. The rate of SOM formation in the organic system was about 14 times faster than in both the conventional and low-input systems. In other words, they found that root C was stored as SOM more efficiently in organic compared with conventional systems.

Deep soil profile SOM

The vast majority of past research has measured SOM only in surface soils (0 to 15 cm). But there are important reasons to consider C at greater soil depths. First, MAOM can become saturated when surface soil runs out of available binding sites for C, as was shown by Ojeda et al (2018 – see below). This may not happen anytime soon on the high clay content soils of Manitoba's Red River Valley, but it can happen on sandier soils that contain limited amounts of silt and clay (Martin Carter, AAFC, PEI, pers comm). A second reason to consider crops that add more C to the subsoil is that storing C deeper in the soil profile may allow it to be stable over time.

Grasses are important for adding C to subsoils. For example, a researcher in in eastern Canada reported that at 0–45 cm soil depth alfalfa had less total root biomass than pure stands of perennial grasses (orchardgrass, tall fescue, smooth bromegrass, reed canarygrass, timothy, perennial ryegrass and switchgrass) (Bolinder et al., 2002). Roberta Gentile, one of Dr. Martin Entz's graduate students, had the opportunity to work on deep soil C in Uruguay comparing a grain only and a pasture-grain rotation (the oldest such study in South America). Like Bolinder, Dr. Entz and Roberta observed greater subsoil root biomass for tall fescue over alfalfa (Gentile et al. 2003). They also observed that the pasture rotation had significantly greater POC at deeper in the soil (20-40 cm and 40-60 cm soil depths). When depths were combined, POC was 2.5 times greater in the pasture rotation (Gentile et al. 2005). It was also observed that MAOM was greater between 20 and 60 cm soil depth for the pasture-grain compared with the grain-only rotation.

Research in Argentina (Ojeda et al. 2018) tested the effects of different perennial forages on MAOM and POM C. Across the entire soil profile, they identified a strong relationship between root biomass and soil C stocks, mainly POM. Interestingly, the MAOM in surface soils appeared to become saturated with additions of perennial crops.

Congratulations – you did it!
Because SOM is at the heart of a successful organic farming system, it is important that you understand SOM processes. It will help you design a successful organic system.
Congratulations for getting through this lesson!

Resources

Books, webinars, podcasts and articles

- To learn more about organic soil management in general, see the free, downloadable book Building Soils for Better Crops - SARE and the *Organic Field Crop Handbook* available for sale from Canadian Organic Growers (Organic Field Crop Handbook, 3rd Edition).
- Watch a 3-minute video about the latest research into the formation of soil organic matter at https://source.colostate.edu/csu-study-proposes-new-approach-to-retaining-soil-carbon/.
- For a focus on soil health, watch the keynote talk by Francesca Cotrufo, Colorado State University at the conference "Is the Future of Agriculture perennial?" in this 37-minute video Francesca Cotrufo, Colorado State University.
- In this 43-minute podcast from the Manitoba Organic Alliance, Professor Cynthia Kallenbach talks to Scott Beaton about soil health, the different types of soil carbon and how to make deposits into both your soil chequing and savings accounts. Season 2, Episode 5-Building Soil Carbon - Manitoba Organic Alliance
- Learn more about soil health in this 54-minute video from University of Manitoba.Dr. Tenuta Coffee Shop Talk - Soil Health Scrum
- There's a 4-page article on *Tending Your Soil Life* at Organic Science Canada- Spring 2022 by OrganicScienceCanada - Issuu.
- Click here to download the 38-pp Regenerative Organic Agriculture and the Soil Carbon Solution - Rodale Institute
- Soil organic matter in cropping systems provides an excellent overview of what soil organic matter is, why it's inessential to successful, sustainable farming, and how to increase rates of SOM. The link to the printable/downloadable 18-page pdf is at the bottom of the webpage.

References

Abdalla, M., Hastings, A., Chadwick, D.R., Jones, D.L., Evans, C.D., Jones, M.B., Rees, R.M. and Smith, P., 2018. Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Agriculture, Ecosystems & Environment, 253, pp.62-81.

Bolinder, M.A., Angers, D.A., Bélanger, G., Michaud, R. and Laverdière, M.R., 2002. Root biomass and shoot to root ratios of perennial forage crops in eastern Canada. Canadian Journal of Plant Science, 82(4), pp.731-737.

Cambardella, C.A. and Elliott, E.T., 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Science Society of America Journal, 56(3), pp.777-783.

Carter, M.R. and Gregorich, E.G., 2010. Carbon and nitrogen storage by deep-rooted tall fescue (Lolium arundinaceum) in the surface and subsurface soil of a fine sandy loam in eastern Canada. Agriculture, ecosystems & environment, 136(1-2), pp.125-132.

Cotrufo, M.F., Soong, J.L., Horton, A.J., Campbell, E.E., Haddix, M.L., Wall, D.H. and Parton, W.J., 2015. Formation of soil organic matter via biochemical and physical pathways of litter mass loss. Nature Geoscience, 8(10), pp.776-779.

Denef, K., Roobroeck, D., Wadu, M.C.M., Lootens, P. and Boeckx, P., 2009. Microbial community composition and rhizodeposit-carbon assimilation in differently managed temperate grassland soils. Soil Biology and Biochemistry, 41(1), pp.144-153.

Drinkwater, L.E., Wagoner, P. and Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature, 396(6708), pp.262-265.

Frank, D.A., McNaughton, S.J. and Tracy, B.F., 1998. The ecology of the earth's grazing ecosystems. BioScience, 48(7), pp.513-521.

Franzluebbers, A.J., Stuedemann, J.A. and Wilkinson, S.R., 2001. Bermudagrass management in the Southern Piedmont USA: I. Soil and surface residue carbon and sulfur. Soil Science Society of America Journal, 65(3), pp.834-841.

Guan, X.K., Turner, N.C., Song, L., Gu, Y.J., Wang, T.C. and Li, F.M., 2016. Soil carbon sequestration by three perennial legume pastures is greater in deeper soil layers than in the surface soil. Biogeosciences Discussions, 12(13).

Gentile, R.M., Martino, D.L. and Entz, M.H., 2003. Root characterization of three forage species grown in southwestern Uruguay. Canadian Journal of Plant Science, 83(4), pp.785-788.

Gentile, R.M., Martino, D.L. and Entz, M.H., 2005. Influence of perennial forages on subsoil organic carbon in a long-term rotation study in Uruguay. Agriculture, Ecosystems & Environment, 105(1-2), pp.419-423.

Haddix, M.L., Gregorich, E.G., Helgason, B.L., Janzen, H., Ellert, B.H. and Cotrufo, M.F., 2020. Climate, carbon content, and soil texture control the independent formation and persistence of particulate and mineral-associated organic matter in soil. Geoderma, 363, p.114160.

Hamilton III, E.W., Frank, D.A., Hinchey, P.M. and Murray, T.R., 2008. Defoliation induces root exudation and triggers positive rhizospheric feedbacks in a temperate grassland. Soil Biology and Biochemistry, 40(11), pp.2865-2873.

Janzen, H.H., 2001. Soil science on the Canadian prairies-Peering into the future from a century ago. Canadian Journal of Soil Science, 81(4), pp.489-503.

Jastrow, J.D., Amonette, J.E. and Bailey, V.L., 2007. Mechanisms controlling soil carbon turnover and their potential application for enhancing carbon sequestration. Climatic Change, 80(1-2), pp.5-23.

Kallenbach, C.M., Grandy, A.S., Frey, S.D. and Diefendorf, A.F., 2015. Microbial physiology and necromass regulate agricultural soil carbon accumulation. Soil Biology and Biochemistry, 91, pp.279-290.

Kong, A.Y. and Six, J., 2010. Tracing root vs. residue carbon into soils from conventional and alternative cropping systems. Soil Science Society of America Journal, 74(4), pp.1201-1210.

Lavallee, J.M., Soong, J.L. and Cotrufo, M.F., 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Global Change Biology, 26(1), pp.261-273.

Lützow, M.V., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B. and Flessa, H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions–a review. European journal of soil science, 57(4), pp.426-445.

McDaniel, M.D., Tiemann, L.K. and Grandy, A.S., 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecological Applications, 24(3), pp.560-570.

Ojeda, J.J., Caviglia, O.P. and Agnusdei, M.G., 2018. Vertical distribution of root biomass and soil carbon stocks in forage cropping systems. Plant and soil, 423(1-2), pp.175-191.

Rasse, D.P., Rumpel, C. and Dignac, M.F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant and soil, 269(1-2), pp.341-356.

Samson, M.É., Chantigny, M.H., Vanasse, A., Menasseri-Aubry, S. and Angers, D.A., 2020. Coarse mineral-associated organic matter is a pivotal fraction for SOM formation and is sensitive to the quality of organic inputs. Soil Biology and Biochemistry, 149, p.107935.

Six, J., Bossuyt, H., Degryze, S. and Denef, K., 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil and Tillage Research, 79(1), pp.7-31.

Tiemann, L.K., Grandy, A.S., Atkinson, E.E., Marin-Spiotta, E. and McDaniel, M.D., 2015. Crop rotational diversity enhances belowground communities and functions in an agroecosystem. Ecology letters, 18(8), pp.761-771.

PODF
PRAIRIE ORGANIC DEVELOPMENT FUND

Platinum Sponsors

Grain Millers

SaskWheat Development Commission

Silver Sponsors

Nature's Path Organic

The Bauta Family Initiative on Canadian Seed Security

PHS Prairie Heritage Seeds

Friend

F.W. Cobs Company Growing Together

The Canadian Organic Ingredient Strategy is funded by

Canadian Agricultural Partnership

Canada

To learn more about the Prairie Organic Development Fund www.organicdevelopmentfund.org

For more Organic Production Resources www.pivotandgrow.com

PODF
PRAIRIE ORGANIC DEVELOPMENT FUND

The Prairie Organic Development Fund (PODF) is an investment platform established to develop organic agriculture and marketing in the Canadian Prairies. PODF builds resilience by investing in organic provincial associations (Capacity Fund) and high impact programs (Innovation Fund) related to marketing, research, policy, education and capacity development that have broad public benefit to the organic sector. The fund is directed by a board made up of organic producers, grain buyers, organic brands, researchers and provincial organizations.

The **Canadian Organic Ingredient Strategy (COIS)** provides farmers with tools and support to incorporate organic farming practices that help meet the growing demand for organic foods in Canada. The tools developed as part of this project will help Canadian farmers benefit from increased knowledge and skills in organic farming methods, which can improve soil health and boost farm resilience in the face of changing markets and climate change.

Visit www.pivotandgrow.com to learn more about the tools created as part of COIS.