Organic Matter in Prairie Soils

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Summary

A soil's organic matter (OM) is the product of life in and on the soil, and a supporter of the living components - the plants, microorganisms and animals. It contains a reserve store of nutrients that is released gradually to plants and microorganisms, and is an especially important repository for nitrogen, a nutrient that is not usually present in soil minerals. OM improves soil structure, making it easier for soils to accept and store water, and making soils more resistant to erosion.

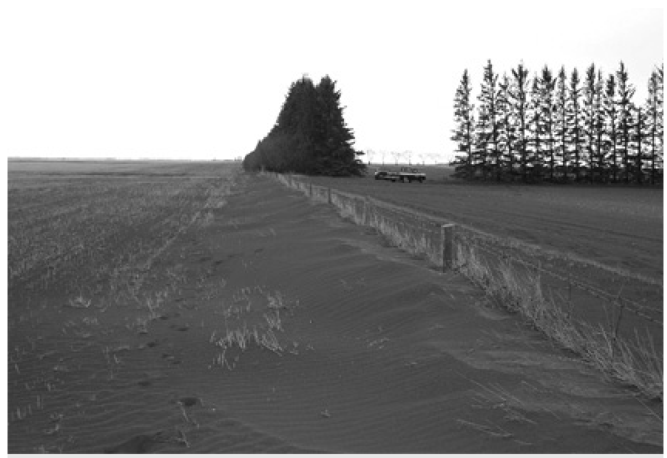
Soil OM is a large and critical pool in the global carbon cycle. This makes agriculture important, not just from a production perspective but to efforts to manage increasing atmospheric CO_2 concentrations and global climate change. Fortunately, those farming practices that make good sense production-wise are the same practices that will return or sequester more carbon to the soil.

Introduction

Soil occurs where the atmosphere and the world's water (the hydrosphere) interact with life (the biosphere) and the Earth's mineral crust (the lithosphere). Organic matter (OM) is an essential component that makes a soil a soil, a product of life in and on the land. Its rich, dark colour provides the visible evidence of the changes that happen as a soil progresses from a geological deposit to become a soil profile. Professor J.H. Ellis[2], in the "The Soils of Manitoba" wrote "For the maintenance of life through the ages since deglaciation nature evolved her own conservation policy. The living forms were maintained in equilibrium with their environment, and the soil developed by life, continues as the supporter of life." The famous Israeli soil scientist Daniel Hillel[5] drew connection between the words human and humus, both with a root meaning life. Humus, the dark, more stable component of organic matter is essentially " the stuff of life in the soil".

Soil organic matter and its functions

The terms soil OM and soil organic carbon are used almost interchangeably. Chemically, OM is just over 50% carbon, a slightly higher carbon concentration than the plant and microbial materials from which it is derived. Because organic carbon can be determined in a laboratory, organic carbon is often used as a measure of OM. Other elements are present, including the oxygen and hydrogen that are part of organic molecules, and nutrients such as nitrogen (about 5% of OM), phosphorus and sulphur (both about 0.5 to 0.8%) and several micronutrients. These numbers are more specific to prairie soils and may be somewhat different for soils of other regions.



Bare top soil is prone to wind and water erosion. As top soil is eroded from fields, it takes with it valuable soil organic matter.
Photo credit: Bill May

Most of the soil OM exists as humus - the dark, mysterious matter formed by microbes from plant residues added to soil. Because of its molecular form and adherence to particles of clay, humus decays very slowly, over centuries or longer. As a result, much of the biological carbon in the world, along with the associated nutrients, is locked up in this form. Organic matter also includes living biomass, and in a very real way brings soil to life. It's home to the microbes that shuffle carbon and nutrients about in the soil, releasing them back for re-use. Without this process of decay, the CO_2 in air would soon all be used up, halting further photosynthesis and growth.

The benefits of OM in soil has been long-recognized and are summarized as follows[11]:

1. OM is a slow-release form of nitrogen, phosphorus and sulphur for plant nutrition and microbial growth.

2. OM has considerable water-holding capacity and

thereby helps to hold water in soil.

3. OM buffers against changes in pH or acidity of a soil.

4. OM's dark colour enhances absorption of energy from the sun and helps heat the soil.

5. Organic materials are the cement that hold clay and silt particles together, thus contributing to the granular or crumb structure of the soil, resulting in both a more porous soil, and greater resistance to erosion, especially erosion by wind.

6. OM binds nutrient ions (potassium, calcium, magnesium, for example) in the soil that otherwise might be leached or lost from surface horizons.

7. Organic constituents in the humus may act as plant-growth stimulants.

A current discussion about soil OM would also include at least two other functions:

8. Soil OM is a major component of the carbon cycle, estimated globally at between 1500 and 2000 petagrams (1Pg= 1 billion tonnes). The soil pool is about twice as large as plant and atmospheric pools. Agriculture world-wide has reduced the soil carbon pool by an estimated 50 Pg[8] to perhaps 78 Pg[9] . Ironically, the losses have provided the space that adding or sequestering more carbon in soil requires.

9. Organic matter plays a major role in the soil's ability to tie up or absorb potential pollutants (including pesticides). This provides for a safe storage place where microorganisms can degrade often toxic materials over time.

Soil Organic Matter and its Effects on Crop Production

The above list of general functions of OM in soils all, to some degree, have some influence on plant growth. Two relate more closely: the role of OM as a reserve store and slow-release source of nutrients, and its positive effect on soil structure or tilth.

Nitrogen, sulphur and, to lesser degree, phosphorus are all nutrients that are stored in OM in well-drained, non-saline soils. Phosphorus, in addition to organic forms, also exists in soil as minerals. Calcium phosphates include the initial source of phosphorus, the mineral apatite, and Ca-P compounds that form in calcareous soils, like those found in the Prairies.

Complexes with iron and aluminum are more common in the more weathered soils of wetter regions.

The chemical structures of organic phosphorus are poorly understood, but we know that most of the phosphorus in surface soil is organic and that, like the OM generally, is tied to clay particles[12]. Phosphorus enters OM as phosphorus-containing plant and microbial residues are added to soil and transformed by the microorganisms. Phosphorus added as fertilizer may become organic, either by being taken up by plants, or used by the microorganisms. Storage in OM is an important way for fertilizer P not immediately used by the crop to be retained in the soil for use by subsequent crops. Some of the fertilizer P not immediately used also forms complexes with calcium and other ions, remain in the soil as a moderately available form.

Nitrogen occurs almost wholly in organic form, part of the OM. The exceptions are nitrate and ammonium ions, the plant-available forms produced by microbial decay of organic N. Nitrate is soluble and can be lost by leaching or released to the atmosphere by denitrification. Ammonium (NH_4^+) is positively charged and clings to negatively charged clay and OM components. An ideal soil has adequate organic N to supply crop needs for N by mineralization without building up high concentrations of the easily lost nitrate form.

Sulphur also occurs mainly in organic form except in subsoils that may contain sulphate salts such as gypsum, a calcium sulphate mineral. The plant-available form, sulphate (SO_4^{2-}), is formed from microbial decay of organic S.

Not all organic forms of N and S are readily converted to the plant-available form. Much of the N, and probably the S, is trapped in complex ring-like molecules that are resistant to microbial decay. Although these resistant pools are large, they release nutrients very slowly. Most of the N and S added to the OM as part of normal processes becomes part of the more easily converted fractions, namely mineralizable N and S, sometimes referred to as the labile fractions. Interestingly, for soils that have had their supplies of OM depleted by cultivation, particularly the use of tilled summer fallow, the proportion of easily mineralized N and S is low, with mainly resistant forms present. With the move away from summerfallow and the increased addition of fertilizer, the pool of readily mineralized nutrients gets larger, becoming once again an important source of nutrients to the crop.

Janzen, in a thoughtful article entitled "The soil carbon dilemma: Shall we hoard it or use it?" discusses the trade-offs between building up OM in the soil (C sequestration) and profiting from the decay of the OM and release of the nutrients tied up there[8]. Janzen considers that cropping must strive for a balance between the build up of OM, and its steady decay to supply nutrients. I wonder if an analogy of a turning wheel may be appropriate. In order to increase OM, decomposition must be slowed, or the wheel must turn more slowly. But as the size of the wheel increases (more OM is stored) the distance traveled (the release of nutrients from an enlarging pool, in this analogy) may be maintained despite the wheel's turning more slowly.

No till farming, where the seeds are planted directly into the previous crop's residues, is highly effective in protecting the top soil from erosion.
Photo credit: Guy Lafond

Soil OM Changes from Time of First Breaking

Jackson[6] in an essay entitled "Living Nets in a Prairie Sea" tells of a settler laboriously working with oxen and plough to break the prairie sod, being watched from a nearby hill by a native Sioux astride his horse. After a few furrows were ploughed, the Sioux rode down to where the settler was working, dismounted, and knelt down to observe and feel the newly-turned furrow. "Wrong side up" he commented. In a sense, the Sioux was right. Breaking of the grasslands resulted in a rapid decrease in soil OM in the first few decades, and exposed the soil to erosion.

Interestingly, as discussed later, his comments foretold of our modern way of farming prairie lands using much-reduced tillage and certainly not ploughing. Janzen[7] deals with the effect of agriculture on the fertile soils of the prairie from the perspective of early scientists, who measured the startling and rapid decline in OM after just a few decades of farming. Their analyses showed that topsoil had lost between one-quarter to one-third of their OM after only two or three decades of farming. This was an ominous warning sign. It foretold not only of declining fertility and waste of nutrients, but also an increasing susceptibility of soil to erosion as the fibre in soil decreased. Agronomists faced a serious dilemma. It seemed that summer fallow, the only workable method of farming in moisture-deficient lands, was the main culprit in the loss in soil quality.

Early work and studies into the latter decades of the 20th century consistently identified summerfallow, and more specifically tilled fallow, as the main factor contributing to OM losses. Not only are no plants grown during the fallow year, and therefore no feedstocks for humus formation added to soil, but bare soils are warmer and moister, which favours the decomposition of OM. Since the soils are mixed during tillage, exposed OM trapped in aggregates and adhering on clay decays more rapidly.

Tilled fallow and bare soil also increases erosion and leads to direct loss of OM. Frequent tillage results in more tillage erosion - soil dragged down-slope by tillage, especially tillage with disks. Tillage erosion does not remove OM from the field but mostly it moves OM from the knolls where it is already scarce, to lower slopes.

A study of similar landscapes broken in 1910, 1930 and 1961, showed that most of the early loss of OM from upper slope positions occurred by decomposition (mineralization), with erosion accounting for most of the losses after a few decades[4]. Losses from lower slope soils were mainly due to mineralization, estimated at 1000 to 1500 kilograms of carbon per hectare per year. The losses were most serious where land was summerfallowed frequently.

Tillage and Cropping System Effects

The impacts of cropping systems on soil OM are exemplified by two extremes:

1. Tilled summerfallow every second year, and crop-

Save Our Soils

Every year, 2-12 million hectares or 0.3-0.8% of the world's arable land is rendered unsuitable for agricultural production through soil degradation. Wind and water erosion accounts for 84% of this degradation[1]. It is reported that that 1966 Mha of land worldwide is affected by soil degradation[4]. Thus good management to protect the soil against degradation is necessary to meet the world's future needs for food and fibre and possibly renewable energy needs as well[2]. 99% of food consumed by humans comes from the land[5]. It is therefore imperative that we do everything possible to sustain and enhance our soil resource.

The challenge for Canadian agriculture is to ensure economic viability while both satisfying society's need for safe and nutritious food and conserving or enhancing the environment for future generations[3].

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Soil Organic Matter: The Foundation of Civilization

The importance of at least maintaining and at best, replenishing the organic matter of our soils cannot be over emphasized.

As early as 1889, British scientists analyzed prairie soils and marveled at their richness relative to those of Britain. Other scientists, while agreeing on the fertility, recognized that the soils very easily "gave up their nitrogen", resulting in a net loss. In 1905, after only 22 years of cultivation, analysis of soils from the Indian Head, SK area revealed that within the top 8 inches (20 cm), about 32% of the original nitrogen had been lost. Further studies indicated that depletion of the nitrogen and organic matter continued but at a much slower rate4. By the early 1980's, it was estimated that since the advent of crop production, on average, across the prairies, 15 - 30% of the soil organic matter had been lost on non-eroded cultivated soils[3]; while eroded cultivated soils had lost 41 - 53% soil organic matter[1,2].

Great efforts have been expended by governments and farmers to reverse this process. Changes in cropping and tillage practices and the development of new technologies have been instrumental in re-building the organic matter content and natural fertility of the soil.

Soil degradation, including the loss of organic matter, has always been a product of cultivation. Modern day prairie farming is changing the course of human history by arresting soil degradation and even improving the health of our soils.

As Jim McCutcheon, a pioneer no-till farmer from Manitoba stated at the Saskatchewan Soil Conservation Association's 1994 Annual Conference, "It is important to recognize that a civilization does not develop by the intelligence of its scholars or the wisdom of its leaders, but by the ability of its farmers to produce a surplus of food".

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ping without fertilizers. This once widely used system relies completely on the mineralization of nutrients stored in OM for fertility, and exposes soil to erosion, both by tillage erosion, and wind and water.
2. Continuous cropping, under minimum tillage systems, with fertilizers added to increase yields and replace nutrients derived from the OM. This soil-conserving system is fortunately much more typical of today's farming.

Eliminating or reducing tillage maintains the protective cover of residues from previous crops. This reduces erosion and conserves soil moisture. In addition, the decay rate of organic materials, both residues and the OM is slower. Surface residues decompose at about two-thirds the rate of buried residues. Crops and the resulting residues are produced every year, providing feedstocks for OM.

Fertilizers, at rates determined by soil testing, increase yields of both grain and residues. Returning more residues to the soil increases OM content. The increases in OM (carbon) are modest but significant. Most of the added residues continue to decompose and cycle most of the nutrients they contain. Perhaps more significantly, the additional OM in the soil is mainly in fractions that mineralize at moderate rates, releasing their nitrogen, sulphur and other nutrients to the growing crops.

Perhaps because of the build-up of this organic nitrogen, which is mineralized over the growing season, measuring nitrate in the soil in the spring as a measure of plant-available nitrogen seems not to work as well as it once did. Current research is searching for a nitrogen soil test that includes both the already soluble nitrate, and the organic forms of nitrogen that will mineralize during the growing season.

Having large amounts of nitrate in the soil is not generally a good idea. Nitrate is soluble in water and can leach easily. This results in a loss of nutrient and possible ground water contamination. Nitrate in wet soils is subject to denitrification. Specialized microorganisms use nitrate as an energy source and release nitrogen and nitrous oxide (a potent greenhouse gas) to the atmosphere. In many ways an ideal soil from a nitrogen perspective seldom contains large amounts of nitrate, but is always is able to supply adequate nitrogen to the plants growing on the soil through the mineralization of organic forms.

Likely Impacts of Bio-Energy Crops on Soil Organic Matter

Growing bio-energy crops where only the grain is harvested to produce energy, as in ethanol from cereals and bio-diesel from oilseeds, is likely to have little special impact on soil OM. Producing these crops is essentially similar to growing a food crop. However, when technologies are developed to produce cellulosic ethanol from straw or wood, it may well have significant effects on OM.

The scenario where all above-ground residues are harvested annually, as would be the case with a single purpose bio-energy crop such as switch grass is the most problematic. When cereal straw is harvested and taken from the field, and not returned in manure from livestock, there is a decrease in feedstocks for building soil OM. Despite this concern, in a long-term crop rotation experiment at Indian Head, removing straw by baling had little measureable effect on OM contents[1]. It appears that the below ground carbon additions in roots and root exudates are more important than the straw to soil OM. It should be mentioned that other studies discussed in the above paper have observed that removing straw did decrease OM, or that adding extra straw increased OM.

Fast-growing tree species such as hybrid poplar and willow are being touted as sources of bio-energy. Tree crops produce large amounts of woody material, mainly above ground, but also below ground as roots. The whole above ground tree would likely be harvested (the trunks and branches) with the roots left to grow the next generation of trees. A study of the long-term effects of growing trees on Black Chernozem soils found that OM had decreased in Ah horizons, with slight gains of OM in organic (leaf litter) layers on the soil surface and at depth in B horizons[10]. The decreased OM in Ah horizons was in comparison to pasture soils, which typically have much higher OM than cultivated soils.

Perhaps the largest conversion of grassland to forest began naturally about a century ago in the Aspen Parkland Ecoregion. Some soils, particularly more acidic soils on uplands, have been changed from Black Chernozems to Gray Luvisol soils with a marked decrease in OM in A horizons[3]. By comparison, OM contents did not go down in lowland areas with calcareous soils, and Chernozem soils remain. Although it is difficult to predict the impact that growing tree crops for energy will have on soil OM, growing trees on certain soils may well reduce soil OM storage over time.

Concluding thoughts

Adding back five centimeters (two inches) of OM-rich topsoil to severely eroded knolls increased grain yields by more than 50%[13]. This experiment in the Dark Brown Soil Zone of Saskatchewan is a practical but highly illustrative example of the importance of soil OM to crop growth. One of the key factors in increased yield was undoubtedly a better supply of plant nutrients, but other factors such as increased entry of water into the soil, better rooting environments and perhaps even plant growth stimulators in the OM are involved as well. Yields of straw were increased as well, setting in place a process that will lead eventually to a soil of higher quality, functioning well in the environment of which it is a part. But to have the time for an improved soil to rebuild, the two inches of topsoil must not be washed away again, pointing to the need for conservation tillage practices. The entire production package is important.

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