The Importance of Soil Organic Matter in Cropping Systems of the Northern Great Plains

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1. Introduction

a. **Soil Organic Matter (SOM): chemical nature & fractions**
b. **SOM levels in the Northern Great Plains**

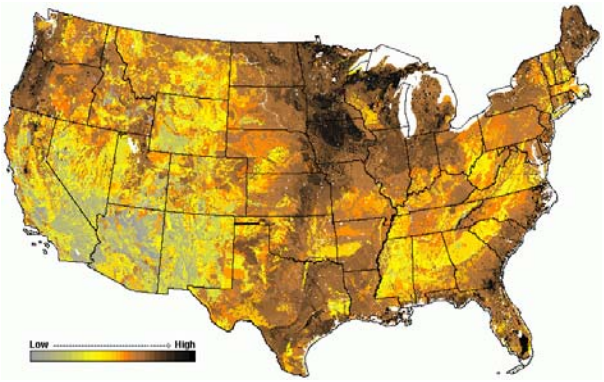
Soil organic matter (SOM) has been called "the most complex and least understood component of soils" (22). The Soil Science Society of America defines SOM as the organic fraction of soil after removing undecayed plant and animal residues (27). However, organizations and individual researchers differ in their opinion about whether undecayed plant and animal tissues (e.g. stover, dead bugs, earthworms, etc.) should be included in the definition of SOM. In this chapter, we will adopt a broader definition of SOM proposed by Magdoff (1992), which consider SOM to be the diverse organic materials, such as living organisms, slightly altered plant and animal organic residues, and well-decomposed plant and animal tissues that vary considerably in their stability and susceptibility to further degradation. Simply put, soil organic matter is any soil material that comes from the tissues of organisms (plants, animals, or microorganisms) that are currently or were once living. Soil organic matter is rich in nutrients such as nitrogen (N), phosphorus (P), sulfur (S), and micronutrients, and is comprised of approximately 50% carbon (C).

Soil organic matter is complex because it is heterogeneous (non-uniform) and, due to the biological factors under which it was formed, does not have a defined chemical or physical structure. Soil organic matter is not distributed evenly throughout the soil and breaks down at various rates by multiple agents that are influenced by the unique environmental conditions in which they are found. Soil organic matter is present in all soils all over the world. Just as all life on Earth is dependent on the processes of microorganisms, SOM is transformed and degraded as a result of soil microorganisms.

All of the transformations discussed in this chapter – decomposition, mineralization, immobilization, denitrification, and nutrient cycling - are at least in part dependent on soil organisms. The same factors that regulate the SOM pool, especially precipitation and temperature, also control the activity and community composition of soil organisms. In fact, SOM and soil organisms are so interdependent that it is difficult to discuss one without the other. As the U.S. naturalist and explorer, John Muir, said, "When we try to pick out anything by itself, we find it is tied to everything else in the universe." Soil organic matter and soil organisms are an excellent example and a testament to the wisdom of Muir's teachings.

Soil organic matter accumulates to higher levels in cool and humid regions compared to warm and arid climates (20). In addition, SOM associated with different soil textures (sand, silt, and clay), will differ in susceptibility to decomposition. Many studies have shown that SOM associated with the sand-size fraction is more susceptible to decomposition, and thus a higher turnover, than the silt- or clay-size fractions (2, 11, 29).

Figure 1. Soil organic matter content across the United States. Image: Hargrove and Luxmore (1988).



Soil organic matter has been directly and positively related to soil fertility and agricultural productivity potential. There are many advantages to increasing or maintaining a high level of SOM.

- Reduced bulk density
- Increased aggregate stability
- Resistance to soil compaction
- Enhanced fertility
- Reduced nutrient leaching
- Resistance to soil erosion
- Increased biological activity
- Reduction of greenhouse gases by soil C sequestration

In most agricultural soils, organic matter is increased by leaving residue on the soil surface, rotating crops with pasture or perennials, incorporating cover crops into the cropping rotation, or by adding organic residues such as animal manure, litter, or sewage sludge (19).

1a. Soil Organic Matter (SOM): chemical nature & fractions

The classic method of fractionating SOM into humic acid, fulvic acid, and humin has been known for hundreds of years, but is no longer considered meaningful because the fractions are artificially defined and do not exist in soils *per se* (28). Additionally, this method of fractionation does not produce chemically discrete SOM fractions, but, rather, fractions that are heterogeneous and non-reproducible.

A more biologically and agriculturally meaningful method of describing soil organic matter is by dividing it into various “pools” which are sorted by how easily the material is decomposed (e.g. active or labile; slow or intermediate; and passive or stable). Pools, which have measurable organic matter components, are theoretically separate entities and are more concisely designated by fractions (28). This method of SOM classification is far more commonly used now than the outdated measurements of humic and fulvic acid separation.

Active/Labile Fraction:

In general, younger organic material, from recently deposited roots and residue, dead organisms, or waste products, is the most biologically "active" fraction of the SOM, meaning that it serves as a food source for the living soil biological community. The younger fraction is also referred to as the "labile" SOM fraction, indicating that it is more readily decomposed than the passive/stable fraction. Generally, this fraction of the SOM is less than five years old.

There are many ways to measure the active fraction but one of the most commonly used methods is to measure the particulate organic matter (POM). Particulate organic matter is defined as the microbially active fraction of soil organic matter. The reason that POM has become so frequently used is that it has been shown to have a strong response to management decisions, such as tillage, residue handling and levels, and crop rotation (1, 8, 10, 15). There are a number of different ways to measure POM, but they all rely on separation techniques that are based on size and density of the SOM material.

Passive/Stable Fraction:

Many soil organisms assist in the process of decomposing plant and animal tissues. During the process of decomposition, chemical transformations take place, creating new organic compounds in the soil. After years or decades of these transformations, the original organic materials are converted into chemically complex, nutrient-poor compounds that few microbes can degrade. These compounds are referred to as "passive" or "stabilized" and can make up a third to a half of soil organic matter. Such passive or stabilized materials are what we commonly refer to as "humus" or the "stable fraction".

The stable fraction does not contain many nutrients, and so is not directly important for soil fertility. However, the stable humus fraction of soil is very chemically reactive and contributes to the soil's net chemical charge, known as the cation exchange capacity and anion exchange capacity. In this way, humus temporarily and reversibly binds plant nutrients in the soil, preventing them from leaching, so that they are available for plant uptake. The stable fraction also modifies and "stabilizes" toxic materials so that they are less reactive and/or dangerous. Finally, the stable fraction enhances soil aggregation that reduces a soil's vulnerability to erosive forces and thereby reduces soil loss by erosion.

1b. SOM levels in the Northern Great Plains

SOM levels in mineral soils range worldwide from trace amounts up to 20%. In general, if a soil is 20% or more organic material to a depth of 16 inches, then that soil is considered organic and is taxonomically described as a Histosol. Histosols make up only about 1% of soils worldwide (5). Soils in the Northern Great Plains of the United States have some of the highest SOM levels of all mineral soils, commonly ranging from 4-7% of the total soil mass (Fig. 1).

There are several reasons to explain the higher levels of SOM in this area relative to the rest of the world. The soils of this region are relatively quite young, having only been exposed since the recession of glaciers and the drying of glacial lakes, such as Lake Agassiz in the present day Red River Valley. These soils are only 11,000-14,000 years old. Compare this with the ancient soils of the southern Appalachian Mountains in the United States, which formed during the Paleozoic

Era, somewhere between 650 and 350 million years ago. The soils of the Appalachian region have had much longer to decompose, erode, weather, and leach much of the SOM that was originally present. As a result, the SOM levels are less than 1% in most areas of southern Appalachia.

Because the northern Great Plains soils are quite young, they have not been weathered and thus stripped of their SOM and nutrients as older soils have. Additionally, the prairie vegetation that until 150 years ago covered much of the Great Plains region added large amounts of SOM to the soil. In a mixed prairie, the aboveground material may produce about 1.4 tons of biomass per acre, but the root yield is more like 4 tons of biomass per acre. The root yields of prairie grasses contributed greatly to the high SOM levels of Great Plains soil and explain why land dominated by forest vegetation is relatively lower in SOM. Soils that form under prairie vegetation commonly have SOM levels at least twice as great as soils formed under forest vegetation.

There is currently no universally accepted SOM threshold value for determining maximum agricultural productivity. Doran and Safley (13) suggested that different soil types have different organic matter levels at which they are most agriculturally productive. So, although a weathered soil in Southeastern U.S. may demonstrate maximum productivity at 1.2%, the same SOM value may indicate a degraded soil with limited soil productivity in the Northern Great Plains (19). Research suggests (18) that soil organic C levels less than 1% may be unable to attain maximum agricultural yields, regardless of the soil type.

Although the prediction of rates of SOM decomposition and release of plant nutrients is quite difficult because they are controlled by many different, yet related, physical, chemical, and biological properties, it is easy to understand how to increase SOM. When the input of organic materials into the soil exceeds the rate of loss from decomposition, erosion, and leaching, SOM will effectively increase.

2. Role of Soil Organic Matter in Crop Productivity

- **a. Cation Exchange Capacity**
- **b. Nutrient Retention and Release**
- **c. Soil Structure and Bulk Density**
- **d. Water-Holding and Snow/Drain Catchment**
- **e. Biological Activity**

The roles of soil organic matter can be classified into three broad categories: biological, physical, and chemical. As pointed out by Krull (19), there are many and varied interactions that occur between these aspects of SOM. Additionally, the active and stable fractions will play different roles in specific SOM functions.

2a. Cation Exchange Capacity

Cation exchange capacity (CEC) is the total sum of exchangeable cations (positively charged ions) that a soil can hold (4). Cation exchange capacity determines a soil's ability to retain positively charged plant nutrients, such as NH_4^+, K^+, Ca^{2+}, Mg^{2+}, and Na^+. As CEC increases for a soil, it is able to retain more of these plant nutrients and reduces the potential for leaching. Soil CEC also influences the application rates of lime and herbicides required for optimum effectiveness. The stable fraction (humus) of SOM is the most important fraction for contributing to the CEC of a soil.

Different soil textures have differing CEC (Table 1). In most soils, organic matter contributes more to exchange capacity than the soil texture. The interaction of texture and organic matter components in soil has a tremendous influence on CEC potential (9).

Table 1. The range of CEC for each soil texture and organic matter.

Texture	CEC (cmol/kg)
Organic Matter	40-200
Sand	1-5
Sandy Loam	2-15
Silt Loam	10-25
Clay Loam/Silty Clay Loam	15-35
Clay	25-60
Vermiculite	150

2b. Nutrient Retention and Release

As stated in the previous section, humus plays an important role in regulating the retention and release of plant nutrients. Humus has a highly negatively charged soil component, and is thus capable of holding a large amount of cations. The highly charged humic fraction gives the SOM the ability to act similarly to a slow release fertilizer. Over time, as nutrients are removed from the soil cation exchange sites, they become available for plant uptake.

Predictions of the amount of nutrients released from SOM are complicated and there are no widely agreed upon methods in use. Prediction of N release to the soil from SOM is difficult but can be estimated by the pre-plant soil profile nitrate (PPNT) or pre-sidedress nitrate (PSNT) tests. Many land grant universities have conducted trials to estimate the N release from SOM for plant growth. In Minnesota, a soil with a SOM content greater than 3% will have a lower fertilizer N requirement compared to a soil with less than 3% SOM (26).

2c. Soil Structure and Bulk Density

Soil structure refers to the way that individual soil mineral particles (sand, silt, and clay) are arranged and grouped in space. Soil structure is stabilized by a variety of different binding agents. Soil organic matter is a primary factor in the development and modification of soil structure (9).

While binding forces may be of organic or inorganic origins, the organic forces are more significant for building large, stable aggregates in most soils. Examples of organic binding agents include plant- and microbially-derived polysaccharides, fungal hyphae, and plant roots. Inorganic binding agents and forces include charge attractions between mineral particles and/or organic matter and freezing/thawing and wetting/drying cycles within the soil as well as compression and deformation forces. Both the stable and the active fraction of SOM contribute to and maintain soil structure and resist compaction.

Figure 2. Water runoff on a poorly structured soil. Photo courtesy of Jodi DeJong-Hughes, UMN.

2d. Water-Holding and Snow/Drain Catchment

Increasing SOM is an effective method for increasing drought-resistance in arid areas. The effect that drought has to reduce crop yields is not only due to irregular or insufficient rainfall, but also because a large proportion of rainfall is lost from fields as a result of runoff (6) (Fig. 2). Some factors in inefficient water usage are out of a grower's hands, for example slope, rainfall intensity, soil texture, and water that moves below rooting depth. But some factors, especially those that reduce SOM, such as burning crop residues, excessive tillage, and eliminating windrows reduce water infiltration and increase water runoff. SOM affects the amount of water in a soil by influencing 1) water infiltration and percolation, 2) evaporation rates, and 3) increasing the soil water holding capacity.

Factors that reduce water infiltration and percolation are compaction in surface soils, lack of surface residue, poor soil structure, surface crusting due to salinity, and steep slopes that facilitate high volumes of water runoff. If water is running off of a field at a high velocity, it cannot overcome the lateral force of water movement and thus will not move vertically down into the soil profile. Erosion of valuable topsoil is a common result of water runoff. Surface residues physically impede water runoff, resulting in reduced velocity of water movement. As water movement across the soil surface slows down, water has more time to move downward into the soil profile, rather than across the soil surface. In this way, increasing SOM and leaving residue on the soil surface can increase water infiltration

Surface residues also slow the rate of water evaporation from the soil and improve soil structure, which helps prevent soil crusting. Crusting can result in significant losses to crop stand. Crusting is especially likely after tillage events, when the surface soils are exposed and disrupted. This happens after spring tillage events are used to prepare the seedbed. When heavy rains occur shortly after planting, the pounding effect of the raindrop impact on disturbed soils can create soil crusts up to 1 inch in thickness, which prevents adequate water infiltration and also creates a physical barrier for seedling emergence, potentially reducing plant population (Fig. 3).

Figure 3. Soybeans emerging through a crusted soil. Photo courtesy of USDA.

You may have observed that soils with higher SOM are "fluffier" or have better "tilth" than soils with less SOM. This is because SOM is less dense than the mineral soil particles per unit of volume, and therefore provides greater pore space for water and air to be held. The result of increasing SOM is greater soil pore space, which provides an area for water to be stored during times of drought. A unique characteristic of the pore space in SOM is that the pores are found in many different sizes. The large pores do not hold water as tightly, and thus will drain more readily. The medium and small-sized pores will hold water more tightly and for a longer period of time, so that during a dry period the soil retains moisture and a percentage of that water is made available over time for plant uptake. The benefit of leaving residue on the soil surface and increasing soil organic matter is that water infiltration is increased, soil crusting is decreased, and the soil can hold more of the water that infiltrates and will eventually make it available for plant use.

2e. Biological Activity

According to the soil formation model of Hans Jenny, the father of soil pedology, a natural body of degraded mineral or organic material cannot be considered a "soil" without soil organisms. This emphasizes the importance of soil organisms in the study of soil science.

When considering the "life" in soils, we evaluate soil microorganisms (bacteria and fungi), plants, and fauna (nematodes, springtails, mites, earthworms, and insects). While microorganisms only make up a small portion of the SOM (less than 5%) they are imperative to the formation, transformation, and functioning of the soil. In the soil, they conduct indispensable processes such as decomposition, nutrient cycling, degradation of toxic materials, N fixation, symbiotic plant relationships, and pathogen control.

About soil fauna, Jenny said, "They break up plant material, expose organic surface areas to microbes, move fragments and bacteria-rich excrement around, up, and down, and function as homogenizers of soil strata" (17). Soil fauna play an important role in the initial breakdown of complex and large pieces of organic matter, making it easier for soil microorganisms to release carbon and plant nutrients from the material as they continue the process of decomposition.

3. Effect of Agriculture on SOM

a. Carbon Sequestration
b. Tillage
c. Cropping Rotation
d. Fertilization

The loss of SOM resulting from conversion of native vegetation to farmland has been extensively studied and is one of the best-documented ecosystem consequences of our agricultural activities (25). Agriculture has affected the quality and quantity of SOM on many different levels. The greatest loss of soil organic carbon (SOC) associated with agriculture occurs during the first 25 years of cultivation, with losses of 50% being common (23). In the Midwestern United States, the majority of soils converted from natural to agricultural systems have lost 30-50% of the original SOC level, or 11-18 tons C/ac (20).

Agricultural practices contribute to the depletion of SOC through deforestation and biomass burning, drainage of wetlands, tillage, crop residue removal, summer fallow, cultivation, and overuse of pesticides and other chemicals (20). Cropland soils generally store less SOC than grazing land because cropland has greater disturbance from cultivation, lack of manure being returned to the system, has less root biomass, and less biomass returned to the soil surface (20). Many factors related to agricultural management can affect the rate and amount of C lost from the soil system.

According to Matson et al. (23) factors affecting soil C loss from agricultural soils include:

- Climate and soil type
- Tillage intensity and depth
- Crop rotation decisions
- Amount of organic inputs
- Amount of plant residue on the soil surface
- Quality of plant residues returned to the soil
- Soil biological activity
- Length and time of fallow
- Erosion

3a. Carbon Sequestration

Agriculture is thought to have developed about 12,000 years ago and since that time has changed the face of the planet in a slow but relentless transformation. However, researchers and ecologists of the 21st century have interests and concerns that were not even considered by scientists of any other time in our history. Global climate change is one of the areas receiving a great deal of attention and research effort.

Soil organic matter plays a critical role in the global C cycle. The importance of soil in the C cycle is due to its role as both a major source and sink for C in the biosphere. The total soil C pool is three times greater than the atmospheric C pool and 3.8 times greater than the biotic C pool (19). The soil C pool contains about 1.7 X 10^{12} tons of organic C and about 8.3 X 10^{11} tons of inorganic C to a depth of 3.3 feet (20).

Although the soil C cycle is complex, the concept of C sequestration for mitigating the release of greenhouse gases is relatively straightforward. Carbon stored in soils ties up C that would otherwise be released to the atmosphere as C-containing greenhouse gases, particularly carbon dioxide (CO_2) and methane (CH_4). Scientists are keenly interested in determining the extent to which atmospheric carbon can be diminished by storing C in soils.

Figure 4. Moldboard plowing reduces soil organic matter levels more than other tillage activities. Image courtesy of Jodi DeJong-Hughes, UMN.

3b. Tillage

Tillage results in the loss of SOM primarily through three mechanisms: 1) mineralization of C due to breakdown of soil aggregates and changes in temperature and moisture regimes, 2) leaching of organic C, and 3) accelerated rates of erosion (20) (Fig. 4). Even in cropping systems that return almost none of the aboveground residue back to the soil, such as silage corn production and some biofuel systems, reducing tillage intensity can result in maintaining or increasing the soil organic fraction that is most readily decomposable (3). Additionally, reduced tillage has been shown to result in increased soil microbial biomass levels before measurable changes in total soil C occur (3, 7, 12).

Tillage is responsible for substantial loss of carbon from the soil. As carbon is released from the soil as a result of tillage, it leaves in the form of carbon dioxide (CO_2). The deeper and more aggressive the tillage, the more CO_2 is released to the atmosphere. Near Jeffers, Minnesota, the USDA-ARS (14) measured the CO_2 loss from three tillage systems in a continuous corn system. The moldboard plow, the most aggressive system used, lost 579 lbs/ac of CO_2 in a 24-hour period. Disk-rip was the intermediate tillage system and it lost 271 lbs of CO_2 per acre (47% of moldboard plow). Strip tillage, a tillage system that tills less than 30% of the soil and leaves the rest undisturbed, lost 106 lbs of CO_2 per acre in a 24-hour period. Strip till lost only 18% of the carbon dioxide that the moldboard plow system lost.

3c. Cropping Rotations

Crop rotations enhance the productivity of all crops in the rotation and benefit the soil, as well. Some of the advantages of a well-managed crop rotation are improved yields, breaking plant pest cycles, maintaining soil fertility and reducing fertilizer inputs, and controlling erosion. Cover crops and green manures are also part of the crop rotation in many sustainable land management systems. A cover crop is any crop that is grown to provide soil cover, regardless of whether it is later incorporated into the soil or not. Cover crops are grown primarily to prevent soil erosion. When a cover crop is grown to reduce nutrient leaching or retrieve nutrients deep in the soil profile, it is referred to as a “catch crop.” A green manure is a crop that is grown primarily to improve soil fertility and is incorporated shortly after planting while it is still green or soon after flowering.

Crop rotations that include cover crops, perennial grasses and legumes, and reduced tillage are an important factor in SOM management and can be adapted to any cropping system. Crop rotations also affect the biological diversity of an agroecosystem. The biological diversity is important for maintaining a high-functioning, disease-resistant, and stable ecological system. Crop rotations that maximize soil C inputs and maintain a high proportion of active C are important factors in establishing a sustainable cropping system.

3d. Fertilization

With the advent of affordable N fertilizers after World War II, a new era in crop production was established. With ammonium and nitrate-based fertilizers, marginally fertile land could suddenly be cropped profitably and yields improved on land that was already fertile. How does fertilization affect SOM levels? There is no clear answer to this question since it appears that many other factors including vegetation present, soil type, and climate are factors that must also be considered. Also, different SOM fractions (the active fraction, stable fraction, etc.) are affected differently by fertilization.

Fertilization affects the soil microbial community both directly and indirectly by supplying mineral nutrients for microbial use and by allowing increased production of plant biomass to serve as a microbial food source. A larger microbial community can result in either a net C increase or decrease to the soil system, depending on how much C stays in the soil system as microbial biomass versus how much is lost as respired C gases, because of course, a greater microbial community results in a greater amount of soil respiration. All of these factors – vegetation, harvested biomass, microbial community biomass, and plant and microbial respiration – are factors that must be considered when determining if adding fertilizer will result in SOM accumulation or degradation.

4. Concluding Remarks

Despite research efforts, our understanding of the functions that SOM afford to soil quality and crop productivity still remain primarily descriptive in nature (27). The puzzle of SOM becomes even more complex given the varied responses of soil organisms to their environment and to our management efforts. It appears that increasing SOM has a host of benefits from both an agricultural and environmental standpoint. Thus, we will be well served to enhance those factors that result in SOM accumulation in the soil and, as much as possible, to moderate those factors that result in losses of SOM.

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