**The Role of Organic Matter in Soil for Improving Crop Productivity and Soil Health**

**Abstract**

Soil organic matter (SOM) is one of the most important natural resources and the basis of soil fertility. The term SOM generally refers to the total organic carbon (C)-containing substances in soil. The total mass of organic C in soils has been estimated at 22 × 1014 kg, similar to the total of all other C reservoirs on the earth’s surface (21 × 1014 kg). 1 SOM contents range from less than 1% in sandy and desert soils to 1%-5% (w/w) in the surface horizons (top 15 cm) of typical mineral and agricultural soils, to almost 100% in organic soils. Even at the lowest levels, the role of SOM in all processes occurring in soil is ascertained to be highly relevant. SOM plays a crucial role in the global carbon balance that largely governs global climate change, and organic matter in soil profiles contains four to six times as much carbon as all of the world's vegetation. This dynamic component of soil has a significant impact on a variety of soil physical, chemical, and biological characteristics as well as ecosystem functions. These include enhancing soil aggregation, boosting nutrient exchange, retaining soil moisture, decreasing compaction and surface crusting, and increasing water infiltration into the soil. For the majority of soil organisms, organic matter provides them with energy and components that help them construct their bodies. The rate of herbicides applied on the surface and their impact on subsequent crops grown on the same land are also affected. Additionally, heavy metals that can harm plants or contaminate soil and lower its quality can be absorbed by organic matter. Since SOM is the best way to incorporate natural soil production, it ought to be used as a soil quality indicator. Therefore, boosting SOM pools in agricultural ecosystems is crucial for reestablishing soil health, ensuring sustainable crop production, and storing CO2 in the atmosphere. To increase the biomass production required to raise the SOM level in the soil, it is therefore crucial to implement practices like crop rotation, minimizing tillage operations, using cover crops, applying animal manures, green manures, crop residues, and composts, as well as using chemical fertilizers.

**Keywords:** Carbon, Nutrient, Compaction, Metals, Biomass

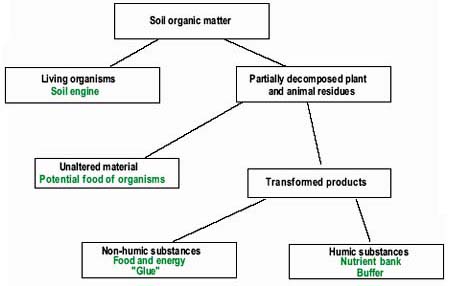
**Introduction**

Soil organic matter is any material produced originally by living organisms (plant or animal) that is returned to the soil and goes through the decomposition process. Most soil organic matter originates from plant tissue. Plant residues contain 60-90 percent moisture. The remaining dry matter consists of carbon (C), oxygen, hydrogen (H) and small amounts of sulphur (S), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). Although present in small amounts, these nutrients are very important from the viewpoint of soil fertility management.

Soil organic matter consists of a variety of components. These include, in varying proportions and many intermediate stages, an active organic fraction including microorganisms (10-40 percent), and resistant or stable organic matter (40-60 percent), also referred to as humus. Forms and classification of soil organic matter have been described by Tate (1987) and Theng (1987). For practical purposes, organic matter may be divided into aboveground and belowground fractions. Aboveground organic matter comprises plant residues and animal residues; below ground organic matter consists of living soil fauna and microflora, partially decomposed plant and animal residues, and humic substances. Doran and Parkin (1994) indicated that maintenance of soil quality, which is the capacity of soils to sustain productivity, maintain environmental quality, and promote plant and animal health, is the key to agricultural sustainability.

The C: N ratio is also used to indicate the type of material and ease of decomposition; hard woody materials with a high C: N ratio being more resilient than soft leafy materials with a low C: N ratio. The total amount and partitioning of organic matter in the soil is influenced by soil properties and by the quantity of annual inputs of plant and animal residues to the ecosystem. Soil organic matter, therefore, plays a critical role in the global C balance that largely controls global climate change (Weil and Brady, 2017). Organic matter existing on the soil surface as raw plant residues helps protect the soil from the effect of rainfall, wind and sun. Removal, incorporation or burning of residues exposes the soil to negative climatic impacts, and removal or burning deprives the soil organisms of their primary energy source. Wander et al. (1996) reported that SOM is potentially the single best integrator of inherent soil productivity and should be developed as an index of soil quality. Thus, increasing pools of soil organic carbon (SOC) in agricultural ecosystems is very critical both for restoring OM pools important to soil health and sustainable crop production as well as sequestering atmospheric CO2 (Hooker *et al*., 2005).

**Chart 1 : Components of soil organic matter and their functions**



**Soil Organic Matter and Its Various Fractions**

Soil organic matter is classified as a stable humus pool when it is in a "protected" state, and as labile when it appears to be free or "unprotected." The term "labile" indicates that the C-containing materials in this pool are subject to rapid oxidation by soil organisms over periods of months to years. This is primarily because some of its component compounds are easily altered, while some of it is protected from decay by the soil environment, particularly by association with soil mineral particles and aggregates. In contrast, the C in the humus pool appears to be stabilized by various mechanisms that enable it to remain in the soil for relatively long periods (centuries or even millennia) (Weil and Brady, 2017).

The living component or biomass, macro-organic matter or light fraction, plant litter, and non-humic materials that are not bonded to soil minerals make up the labile fraction of organic matter (OM) (Theng et al., 1989; Tirol-Padre & Ladha, 2004). Carbohydrates, amino acids, peptides, amino sugars, lipids, cellulose, hemicellulose, waxes, fats, resins, and lignin are the most prevalent constituents of the labile fractions. Labile SOM fractions will offer a significant shift prior to any change in total OM since they are very sensitive to changes in C inputs to the soil (Gregorich & Janzen, 1996; Tirol-Padre and Ladha, 2004).

The stable fraction of OM (humus) includes protected bits of degraded cell walls & tissue (particulate OM), protected biomolecules, supra-molecules & degradation products, black aromatic products of fire i.e. char (Weil and Brady, 2017). Humus is highly resistant to microbial decomposition being physically adsorbed on mineral surfaces or entrapped within clay and mineral aggregates (Theng et al., 1989; Tirol-Padre and Ladha, 2004). Thus, the stable fractions of OM are probably more appropriate and representative for C sequestration characterization (Cheng and Kimble, 2001; Tirol-Padre & Ladha, 2004).

Carbon is the chief element of SOM which is readily measured quantitatively. Values for the SOC contents may be expressed as such or may be reported as total OM by multiplying the figure of OC by the conventional Van Bemmelen factor of 1.72. The use of this factor is based on the assumption that SOM contains 58% C. Organic N may also be estimated from OC values being divided by 12 for most soils (Weil and Brady, 2017). However, this conversion factor does vary depending on the origin and nature of the SOM from 1.72 to 2.0. The common convention now is to report results as SOC rather than as SOM (Baldock and Skjemstad, 1999). Generally, Histosols and Cambisols have greater C content as compared to other soil groups.

**The Connection between Organic Matter in Soil and Other Soil** **Properties**

**Effects of SOM on Soil Physical Properties**

Physical properties of soils are those characteristics, processes, or reactions of a soil that are caused by physical forces and can be described by, or expressed in physical terms or equations. Examples of physical properties are soil texture, structure or porosity, bulk density, and water-holding capacity. The soil physical properties mainly influence air–water relations in the soil, which, in turn, affect the growth of plants. The addition of OM to soil improves these physical properties. With the improvement of soil physical properties, there is an improvement in soil quality and consequently improvements in crop productivity (Stevenson, 1982; Bauer and Black, 1994).

# Soil Structural Stability

# In soils, individual soil particles typically do not stay that way. They combine in a variety of ways to create aggregates or structural units of soil. The ability of these aggregates to withstand stress from tillage, rainfall, and wetting under tension is known as aggregate stability. Because the aggregate structure can affect the bulk density, aeration, surface crusting, erosion, infiltration, water-holding capacity, and soil strength and mechanical resistance to emergence and root growth, maintaining the aggregate structure is crucial for plant production. Aggregate stability is a general indicator of the physical fertility and health of the soil, which is greatly enhanced by the existence of various functional soil attributes, even though the direct relationship between them is not always clearly defined. It is also indicated in Duiker et al. (2003) and Denef et al. (2004) that the major binding agents responsible for soil aggregate formation are the silicate clays, oxides of iron and aluminum, and OM and its biological decomposition products.

**Bulk Density of Soil**

OM and bulk density are strongly correlated. In general, the bulk density decreases with increasing OM levels. Higher SOM levels are linked to increased aggregate stability, which raises soil porosity and lowers bulk density. According to Bockheim et al. (2003), in tundra soils in arctic Alaska, bulk density dramatically dropped in a quadratic pattern as soil OC increased. However, other soil characteristics including sodicity, exchangeable cations, clay mineral type, soil texture, and the presence of Fe and Al oxides also have an impact on bulk density. Bulk density can also be impacted by land-use history through compaction by stock, the length of time since farming began, the amount of rainfall during that time, and cultivation practices.

**Capacity for Holding Water**

One of the most important consequences of OM addition to the soil is that it modifies the soil’s water retention qualities, which is generally associated positively to crop yield. The primary cause of soil productivity loss due to erosion is thought to be a decrease in the amount of water that is available. This decrease in available water capacity is ascribed to either a decrease in the depth (thickness) of the rooting zone or modifications brought about in the soil water-holding properties of the root zone (Bauer and Black, 1994).

The plow layer of the soils often contains the majority of the organic matter   
(Fageria et al., 1991). Similar increases in soil-water retention characteristics and hydraulic conductivity were noted by Biswas and Khosla (1971) when farmyard manure was applied to soils over a 20-year period. Gupta et al. (1977) also reported that the amount of water retained at 15 bars increased linearly with the increase in sludge OM addition in a coarse sandy soil, and Scoot and Wood (1989) reported a linear increase in water retention of silt loam soil with increasing OM content. The increase in soil water retention caused by OM addition may be attributed to the following factors: (i) decreased bulk density and increased total porosity; (ii) a change in aggregate size distribution, which may alter the pore-size distribution; and (iii) an increase in the soil's absorptive capacity (Fageria and Gheyi, 1999).

# Effects of SOM on Soil Chemical Properties

# Organic matter brings many significant changes in soil chemical properties such as reducing Al toxicity and decreasing allelopathy in crop plants. It improves the availability of macro and micronutrients to crop plants. Organic matter in the soils also controls fluctuations of pH buffering capacity.

**Availability of Macro and Micronutrients**

Humus typically contributes between 50 and 90 percent of the cation-adsorbing capacity of mineral surface soils. Similar to clays, humus colloids and high surface area char hold nutrient cations (K, Ca, Mg, etc.) in easily exchangeable form that plants can use but that are not easily leached out of the profile by percolating water (Weil and Brady, 2017). Bauer and Black (1994) also noted that OM is a major indigenous source of available N, contains up to 65% of the total soil P, and provides significant amounts of sulfur (S) and other nutrients necessary for plant growth.

It is also widely acknowledged that microbes employ the C fraction as a primary source of energy for metabolic processes, which changes the availability of nutrients. Given the sharp rise in the price of N fertilizer in recent years, the ability of both OM and legumes to deliver nitrogen is very crucial in the current economy. The amount of total N in the soil can be accurately predicted from the level of organic matter. The majority of the nitrogen (93–97%) in a soil's plow layer is found in organic nitrogen compounds, with the remainder being nonexchangeable (fixed) ammonium (NH +) at any given time (Stevenson, 1982).

Small molecular weight organic acids, polysaccharides, and some polar biomolecules are particularly good at drawing cations like Fe3+, Cu2+, Zn2+, and Mn2+ from the periphery of mineral structures and chelating or binding them in stable organo-mineral complexes, according to Weil and Brady (2017). Because they are kept insoluble and in chelated form, some of these metals are more accessible to plants. According to Stevenson (1991), metal-organic complexes have the following impacts on the soil micronutrient cycle:

* Soluble OM keeps micronutrient cations in solution, which would typically precipitate at the pH levels present in most soils. Numerous biochemicals produced by microbes combine with trace elements to form water-soluble compounds. The trace element and fulvic acid (FA) complexes are likewise soluble in water.
* In some cases, using SOM to tone the skin can lower metal ion concentrations to a harmless level. This is especially true for complexes with humic acid (HA) and other high-molecular-weight components of OM, where the metal-organic complex has low solubility.
* Trace element movement to plant roots and, occasionally, to other ecosystems including lakes and streams is mediated by a variety of complexing agents.
* Through the complexion of Ca in calcareous soils and Fe and Al in acidic soils, organic materials can increase the availability of insoluble phosphates.
* The weathering of rocks and minerals and the subsequent release of plant nutrients are significantly influenced by chelation.

**Cation Exchange Capacity**

Depending on its level in the soil, organic matter can contribute significantly to the soil's cation exchange capacity (CEC). An organic method of increasing a soil's CEC is to increase its OM content, which is a slow but dependable method. Like clay particles, OM has negatively charged sites that attract and retain the cations. These negatively charged sites on OM result from the dissociation of organic acids, and this dissociation depends on the pH of the soil. For this reason, when a particular soil has a high CEC value due to its OM content, it is said to be pH dependent.

According to Kapland and Estes (1985), a comparable rise of 1.7 cmol CEC kg-1 of soil was observed for every 1% increase in SOM on a dry-weight basis. Additionally, in the surface horizon of clay-rich soils in lowland Quebec, Canada. Martel et al. (1978) found a strong correlation between CEC and OM. The findings of the experiments mentioned above have demonstrated that OM contributes significantly to the soil's CEC, although the precise amount depends on the pH of the soil.

**SOM's Impact on the Biological Properties of Soil**

The majority of the food for the community of heterotrophic soil organisms comes from soil organic matter, particularly the detritus percentage. The kind and variety of organisms that comprise the soil community can be influenced by the kind and variety of organic residues that are added to the soil (Weil and Brady, 2017). Thus, SOM concentrations have a major impact on soil biological characteristics such total microbial biomass, mycorrhizal fungi, N-mineralizing bacteria, and N-fixing bacteria. Nitrosomonas and Nitrobacter are the two most significant autotrophic bacterial genera that cause nitrification. Thus, a sufficient amount of organic matter (OM) in the soil lowers soil acidity and enhances the activity of these N-mineralizing bacteria.

Because of its greater capacity to store water, organic matter also affects the mineralization of nitrogen. Due to the fact that nitrifying bacteria are typically more susceptible to water shortages than fungi (Power, 1990). Since it sustains their life, the presence of sufficient SOM greatly favors the microbial biomass's ability to mediate numerous vital processes in soils, such as nutrient mineralization, nutrient cycling, decomposition, and SOM formation (Acosta-Martinez et al., 2004).Numerous studies have emphasized the function of microbial biomass in the breakdown of materials including plant-derived lipids and carbohydrates as well as microbial activity in enhancing soil quality (Tisdall, 1994). The efficiency of N-fixing organisms like Rhizobium and Azotobacter is increased by humic compounds that are recovered from manures. Biologically active compounds in soils, such as antibiotic and certain phenolic acids, may enhance the ability of certain plants to resist attack by pathogens (Stevenson, 1982).

**Maintenance of Organic Matter in the Soil**

Various management techniques, including crop rotation, particularly with crops that contain a lot of biomass, reduced tillage, cover crops, and a range of organic supplements, can increase the amount of organic matter in the soil. In a variety of forms and combinations, these management techniques often achieve one or more of the following objectives: boost soil-dwelling beneficial species, reduce soil-dwelling pests and diseases, and raise carbon inputs and outputs. Additionally, it improves the qualities of the soil, including more water availability, reduced compaction, improved timing of nutrient availability to crop needs, and synthesis of compounds that encourage development, which in turn helps plants establish stronger defenses against pests.

**Minimizing Tillage Operations**

According to the findings of several studies, tillage reduces the stability of soil aggregates by exposing them to more raindrop impact energy and increasing the mineralization of organic matter (Park and Smucker, 2005; Weil and Brady, 2017). According to a number of other writers, tillage causes agricultural residues to be incorporated into the soil, break down physically, and disturb macro-aggregates, all of which contribute to the loss of SOM (Paustian et al., 2000; Six et al., 2000; Wright and Hons, 2004). Conversely, conservation or no-tillage lessens soil disturbance and mixing, which permits the buildup of SOM. One tactic to lessen the loss of carbon from agricultural soils is the application of conservation tillage, which includes no-tillage

(Denef et al., 2004). Crop residues with low N concentrations typically decompose more slowly than residues with high N concentrations, but they also tend to persist longer and increase SOM over time more than residues with high N concentrations, which decompose more readily (Wright and Hons, 2004). Residue quality frequently plays a significant role in regulating long term SOM storage.

# Use of Crop Rotation

# Mono-cropping systems can reduce the quality of soils by loss of OM and structure because of low levels of organic inputs and regular disturbance from tillage practices. However, crop rotations have positive effects on soil properties related to the greater C inputs and diversity of plant residues to soils in comparison with continuous systems (Acosta-Martinez, et al., 2004). The levels of soil C and N were greatest in the rotation of maize–oats– clover and least in the mono-cropping of maize (Mengel et al., 2001). Wright and Hons (2004) also indicated that crop rotations under conventional tillage that provide residues with low C: N ratios stimulate decomposition of native SOM to a greater extent than rotations providing residues with high C: N ratios. Wani et al. (1994) reported that green manures and organic amendments in crop rotations systems provides a measurable increase in SOM quality and other soil quality attributes compared with continuous cereal systems.

**Use of Fertilizers and Organic Amendments**

With their distinct qualities, crop residues and organic amendments affect the biological, chemical, and physical features of soil in diverse ways. Therefore, using a range of organic materials is one of the SOM management options. For crop production, a variety of organic amendments, including composts, green manures, farmyard manures, and food processing wastes, can be applied either alone or in conjunction with chemical fertilizers to increase the SOM content.

The kind of material used to provide carbon to the soil affects SOM accumulation inm addition to the quantity of carbon added. Because manure contains highly resistant chemicals—the most readily oxidized compounds in the original plant tissue have already been broken down by the animal digestive system before its excretion—it is sometimes assumed that manure leads to higher increases in SOM. Accordingly, it has been seen that manure inputs continue to affect SOM for several years after they stop (Jenkinson and Johnson, 1977).

Similar to N, increasing SOM concentrations and, in turn, crop yields and soil quality requires the application of P at a sufficient rate. A lack of phosphorus frequently restricts crop development and can even result in crop failure, which causes farmers to clear more land in order to live. On damaged forest and savanna sites, natural plant regrowth is frequently too sluggish to stop soil erosion and SOM depletion in the absence of sufficient P application (Fageria, 2002).

**Minimizing Organic Matter Losses**

Reducing crop residue removal during harvest, erosion losses from wind and water, and carbon losses (as CO2) from rapid microbial respiration can all help to minimize the loss of SOM. Since SOM is usually richer in the topsoil, where erosion is more common than in the bulk soil, losses from erosion are greater than those from soil cultivation, which typically range from 5 to 50 Mg/ha/year (Fred and Weil, 2004). Because these soils experience fewer erosion losses and may be able to absorb SOM through sedimentation from the upslope of steeper sites, soils with less steep slopes and soils in lower landscape positions typically have higher SOM contents.

SOC losses are mostly controlled by rates of microbial respiration when there is no noticeably enhanced erosion. Temperature and alternating cycles of drying and wetting have a significant impact on the microbial activity that breaks down soil organic matter. Accelerated microbial respiration and SOM decomposition are probably caused by the increased solubility and availability of SOM when soils are wet after drying (Bartlett, 1981). In general, soil aggregates with low OM and clay contents are prone to erosion and disintegration at low rainfall intensities. Bauer and Black (1994) also observed that soil erosion in the northern Great Plains of the USA is regarded to impair soil productivity through the associated diminishing of SOM content.

**Conclusion**

A dynamic and diverse soil component with a range of molecular structures is soil organic matter. Decomposition rate, turnover time, and has a significant impact on the global C cycle and soil quality. In the long run, managing SOM is still a good way to maximize output and preserve the soil's potential for production. The physical, chemical, and biological characteristics of soil are altered by organic matter, improving soil quality and, as a result, crop yields. The mineralization of SOM satisfies a significant portion of plants' nitrogen needs. One of the main causes of OM production in soil is plant and animal waste. However, the amount and location of organic materials as well as management techniques have a significant impact on the development and accumulation of soil organic matter.

Soil OM can be stabilized and/or improved with the use of appropriate crop and soil management techniques. These include liming acidic soils, using farmyard manure or composts, implementing conservation or minimum tillage, using appropriate crop rotation, and fertilizing crops adequately. Essential plant nutrients are gradually released by soil organic matter, which also lessens their leaching into groundwater. The health of people, animals, and agro-ecosystems is at risk due to heavy metals, which are significant environmental contaminants. Because of their higher CEC and the creation of inner-sphere complexes through surface reaction groups, they are therefore largely prevented from being adsorbed by organic colloid (humus), which reduces their toxicity to agricultural plants and prevents their leaching to groundwater.

**Reference**

Acosta-Martínez, V., Zobeck, T. M., & Allen, V. (2004). Soil microbial, chemical and physical properties in continuous cotton and integrated crop–livestock systems. Soil Science Society of America Journal, 68(6), 1875-1884.

Baldock, J.A and Skjemstad, J.O. (1999). Soil organic carbon /Soil organic matter. In Peverill, KI, Sparrow, LA and Reuter, DJ (eds). Soil Analysis - an interpretation manual. CSIRO Publishing Collingwood Australia.

Bartlett, R.J. (1981). Oxidation–reduction status of aerobic soils. In: Dowdy R.H., J.A. Ryan, V.V.Volk, and D.E. Baker (Eds.), Chemistry in the Soil Environment. American Society of Agronomy, Madison, WI, pp. 77– 102.

Bauer, A., and Black, A.L. (1994). Quantification of the effect of soil organic matter content on soil productivity. Soil Science Society of America Journal 58:15–193.

Bauer, A., and Black, A.L. (1994). Quantification of the effect of soil organic matter content on soil productivity. Soil Science Society of America Journal 58:15–193.

Bauer, A., and Black, A.L. (1994). Quantification of the effect of soil organic matter content on soil productivity. Soil Science Society of America Journal 58:15–193.

Biswas, T.D. and Khosla, B.K. (1971). Building up of organic matter status of soil and its relation to the soil physical properties. International Symposium on Soil Fertility Evaluation Proceedings, New Delhi 1:831–842.

Bockheim, J.G., Hinkel K.M., and Nelson, F.E. (2003). Predicting carbon storage in tundras soils of arctic Alaska. Soil Science Society of America Journal 67:948–950.

Denef, K. J. Six, R. Merckx, and Paustian K. (2004). Carbon sequestration in microaggregates of no-tillage soils with different clay mineralogy. Soil Science Society of America Journal 68:1935–1944.

Denef, K. J. Six, R. Merckx, and Paustian K. (2004). Carbon sequestration in microaggregates of no-tillage soils with different clay mineralogy. Soil Science Society of America Journal 68:1935–1944.

Doran, J.W. and Parkin T.B. (1994). Defining and assessing soil quality. In: Defining soil quality for a sustainable environment, ed. J.W. Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart, 3–22. Madison, Wisconsin: SSSA.

Duiker, S.W., Rhoton F.E., Torrent J., Smeck N.E., and Lal R. (2003). Iron hydroxide crystallinity effects on soil aggregation. Soil Science Society of America Journal 67:606–611.

Fageria, N.K. (2002). Soil quality versus environmentally based agricultural management practices. Communications in Soil Science and Plant Analysis 33:2301–2329.

Fageria, N.K. and Gheyi, H.R. (1999). Efficient crop production. Campina Grande, Brazil: Federal University of Paraiba.

Fageria, N.K., Wright, R.J., Baligar V.C., and Sousa, M.R. (1991). Characterization of physical and chemical properties of varzea soils of Goias State of Brazil. Communications in Soil Science and Plant Analysis 22:1631–1646.

Fred M. and Weil R.R. (2004). Soil Organic matter management strategies. Retrieved from:https://[www.researchgate.net/publication/290462906.](http://www.researchgate.net/publication/290462906)

Gregorich, E.G., and Janzen H.H. (1996). Storage of soil carbon in the light fraction and macroorganic matter. In: Structure and organic matter storage in agricultural soils, ed. M.R. Carter and D.A. Stewart, 167–190. Boca Raton, Fl.: CRC Press.

Gupta, S.C., Dowdy, R.H., and Larson, W.E. (1977). Hydraulic and thermal properties of a sandy soil as influenced by incorporation of sewage sludge. Soil Science Society of America Journal 41:601–605.

Hooker, B.A., Morris, T.F., Peters R., and Cardon Z.G. (2005). Long-term effects of tillage and corn stalk return on soil carbon dynamics. Soil Science Society of America Journal 69:188–196.

Jenkinson, D.S. and Johnson, A.E. (1977). Soil organic matter in the Hoosfield barley experiment. In Annual Report 1976. Rothamstead Experiment Station, Reading, UK, pp. 87–102.

Kapland, D.I. and Estes, G.O. (1985). Organic matter relationship to soil nutrient status and aluminum toxicity in alfalfa. Agronomy Journal 77(5), 735–738.

Martel, Y.A., De Kimpe, C. R., & Laverdiere, M.R. (1978). Cation-exchange Capacity of Clay-rich Soils in Relation to Organic Matter, Mineral Composition, and Surface Area 1. Soil Science Society of America Journal, 42(5), 764-767.

Mengel, K., Kirkby, E.A., Kosegarten, H. and Appel, T. (2001). Principles of plant nutrition, 5th ed. Dordrecht, the Netherlands: Kluwer Academic.

Park, E.J., and A.J. Smucker, M. (2005). Saturated hydraulic conductivity and porosity within macro- aggregates modified by tillage. Soil Science Society of America Journal, 69:38–45.

Paustian, K., Six J., Elliott, E.T., and Hunt, H.W. (2000). Management options for reducing CO2 emissions from agricultural soils. Biochemistry, 48:147–163.

Power, J. F. (1990). Fertility management and nutrient cycling. In: Advanced Soil Science, 13:131–149.

Scoot, H.D. and Wood L.S. (1989). Impact of crop production on the physical status of a typic Albaqualf. Soil Science Society of America Journal 53:1819–1825.

Six, J., Elliott, E.T., and Paustian, K. (2000). Soil microaggregate turnover and microaggregate formation: A mechanism for C sequestration under no- tillage agriculture. Soil Biology Biochemistry, 32:2099– 2013.

Stevenson, F.J. (1982). Humus chemistry: Genesis, composition, reactions. New York: John Wiley & Sons.

Stevenson, F.J. (1991). Organic matter–micronutrient reactions in soil. In: Micronutrients in agriculture, 2nd ed., ed. R. R. Mortvedt, 145–186. Madison, Wisconsin.

Tate, R.L.1987. *Soil organic matter: biological and ecological effects*. New York, USA, John Wiley & Sons. 291 pp.

Theng, B.K., Tate, K.R. and Sollins, P. (1989). Constituents of organic matter in temperate and tropical soils. In: Dynamics of soil organic matter in tropical ecosystems, ed. D.C. Coleman et al., 5-31. Honolulu, Hawaii: University of Hawaii Press.

Theng, B.K.G.1987. Clay-humic interactions and soil aggregate stability. *In*P. Rengasamy, ed. *Soil structure and aggregate stability,*pp. 32-73. Proc. Institute of Irrigation and Salinity Research. Tatura, Australia.

Tirol-Padre, A., and Ladha, J.K. (2004). Assessing the reliability of permanganate-oxidizable carbon as an index of soil labile carbon. Soil Science Society of America Journal, 68(3), 969-978.

Tisdall, J.M. (1994). Possible role of soil microorganisms in aggregation in soils. Plant and Soil, 159 (1), 115– 121.

Wander, M.M., Dudley, R.B., Traina, S.J., Kaufman, S.J., Stinner, B.R., and Sims G.K. (1996). Acetate fate in organic and conventionally managed soils. *Soil Science Society of America Journal* 60:1110–1116.

Wani, S.P., McGill,W.B., Haugen-Kozyra, K.L., Robertson, J.A., and Thurston, J.J. (1994). Improved soil quality and barley yields with faba beans, manure, forages, and crop rotation on a Gray Luvisol. Canadian Journal of Soil Science, 74:75–84.

Wright, A.L., and Hons, F.M. (2004). Soil aggregation and carbon and nitrogen storage under soybean cropping sequences. Soil Science Society of America Journal, 68:507–513.