SOIL ORGANIC MATTER DECLINE AND MANAGEMENT

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Summary

The challenge for sustainable land management is to balance the needs for the production of food and fibre and other land uses with the necessity to minimise the adverse impact of soil degradation processes while maintaining or enhancing soil fertility and hence soil organic matter.

Past agricultural practices for food and fibre production have inevitably led to the loss of soil organic matter from soil. Until recently, both food and fibre production systems involved intensive cultivation, which resulted in lack of plant residue soil cover; which led to soil erosion, and fertility decline and declining yields.

Sustainable land and vegetation management practices are, therefore, essential for maintaining crop productivity while maintaining or enhancing organic matter in soil. Except for the introduction of grass + legume pastures or fertilised grass pastures, little is known about other soil and crop management practices to enhance organic matter in soil unless cropping land is set aside for agroforestry and forestry practices. In some soils, no-till practices may increase SOM but in the semi-arid environments in the absence of irrigation, rainfall limits the amounts of C inputs from annual crops over and above SOM losses from decomposition and other soil degradation processes.

Land clearing for grazing is still occurring in many areas, often resulting in substantial surface SOM losses especially when overgrazed. Grazing of grasslands and savannas has been practiced on an *ad hoc* basis, often incompatible with the safe carrying capacity of the land, and this is made worse by extreme climate variability in many regions. This results in overgrazing (or overstocking), and pasture degradation and disappearance of surface plant residue cover, degraded lands and thus, loss of organic C from soil.

Introduction of exotic pasture species, especially legumes have enhanced pasture productivity of grassland pastures, and often has resulted in increased organic C in soil. Improving pasture productivity through fertiliser inputs, renovation, reducing stocking rates, and eliminating or reducing fire frequency could lead to increase in pasture production and hence increase in organic C in the soil.

Studies should be undertaken to quantify the size of the aboveground biomass returned to the soil, the size of the belowground C including roots and charcoal, and the rates of turnover (C fluxes) of both below-ground and above-ground C pools. Since C components differ in their turnover rates, understanding of the nature of these components through improved techniques will lead to improved management practices and hence enhanced SOM. This approach should also lead to improved simulation of C dynamics in soils and better prediction of the short and long term consequences of land and vegetation management practices on soil organic matter management and C sequestration to mitigate greenhouse effects.

1. Introduction

Soil organic matter (SOM) is the organic fraction of soil. Temperature and moisture (net effect of rainfall and potential evapotranspiration), and radiation and nutrients are the major determinants of plant biomass production, and along with soil type determine the SOM content as well as the rate of change of SOM under different land uses and management. Since the SOM content depends upon the relative rates at which organic materials are added to the soil and lost from it primarily through decomposition, it can mathematically be expressed by Equations 1and 2:

$$d\,SOM/dt = A - k\,SOM \qquad (1)$$

Or

$$SOM_t = SOM_0 \exp(-kt) + A/k\,[1 - \exp(-kt)] \qquad (2)$$

where SOM_0 and SOM_t are the SOM contents initially ($t = 0$), and at a given time, t, respectively; A is the rate at which organic matter is returned to the soil and k is the rate of loss of SOM. When $t \rightarrow \propto$, that is when rate of addition balances the rate of decomposition, a steady concentration of organic matter in soil is attained, that is,

$$SOM_e = A/k \qquad (3)$$

where SOM_e is organic matter content at steady state after a long period of consistently similar soil management or native vegetation. The simplified form of Equations 2 and 3 is:

$$SOM_t = SOM_e + (SOM_0 - SOM_e) \exp(-kt) \qquad (4)$$

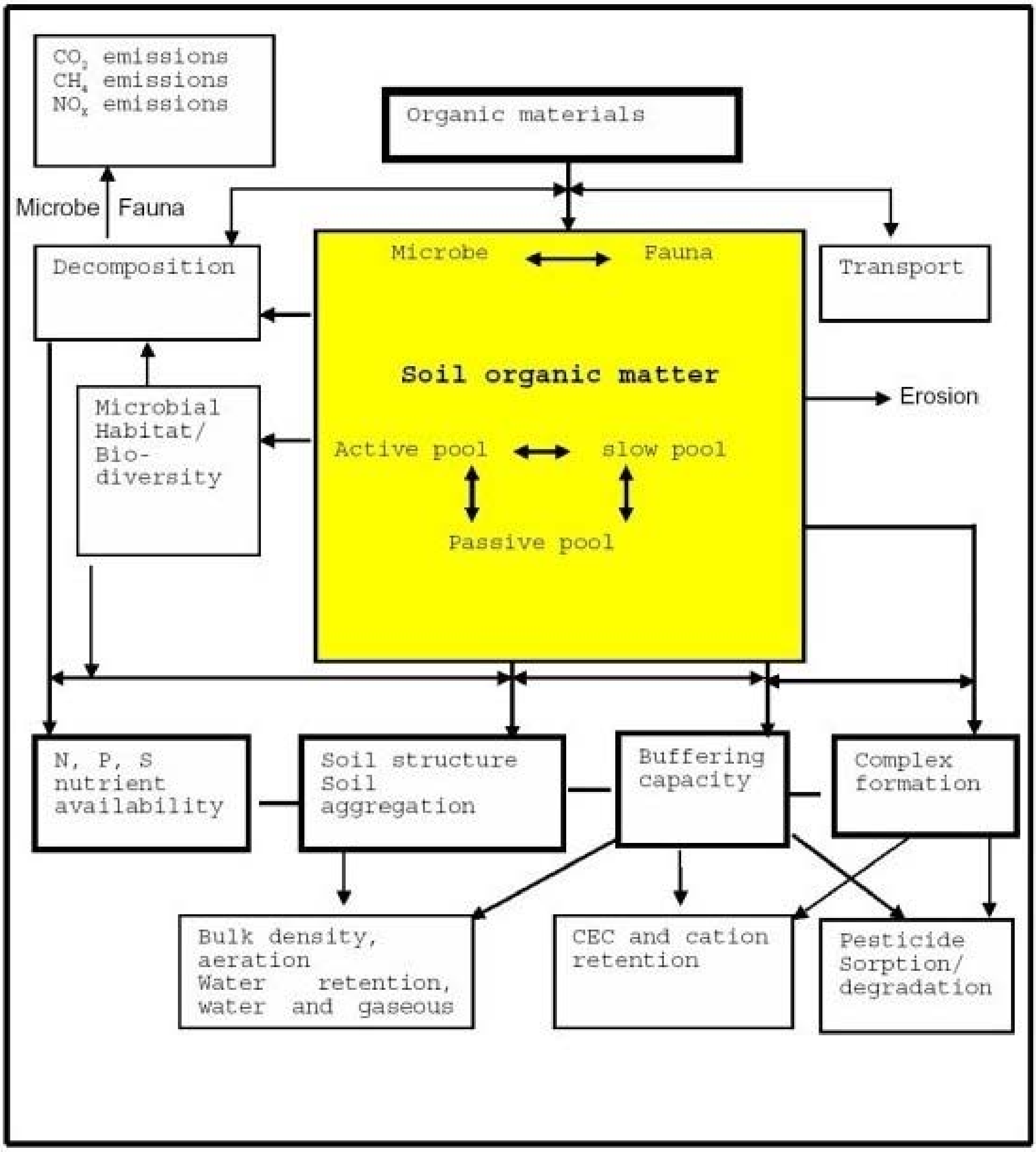

Figure 1: Functions of organic matter in soil.

The turnover period of SOM is then reciprocal of the k value. In addition, SOM dynamic models consider not only the effect of organic matter addition but also environment, soil matrix, cultural practices and some soil degradation processes such as soil erosion.

Soil organic matter is essential in maintaining physical, chemical and biological functions of soils (see Figure 1), especially those containing either low clay content or low activity clays such as kaolinite. Since turnover of SOM results in CO_2 fluxes to the atmosphere it could make significant contribution to the greenhouse effect, especially after land clearing and use of inappropriate management practices. On the other hand, soils could sequestrate significant amounts of atmospheric C and thus mitigate greenhouse effect. We present in this chapter C stocks and fluxes in soils and provide estimates of SOM decline and management practices in agricultural, pasture and rangeland soils.

2. Nature of Soil Organic Matter

Soil organic matter contains both living and nonliving organic components. The living component is soil microbial biomass and soil fauna. The nonliving components include discrete plant residues, and organic materials with varying degrees of association with the soil mineral matrix. These components of SOM are estimated either as physical separates such as density and particle size SOM or chemical separates such as humic and non-humic substances.

2.1 Living Component

Soil microbial biomass and soil fauna are the agents of transformation of the added organic residues as well as SOM and a small but labile source as well as a sink of C, N, P and S. The proportions of soil organic C and N contained in microbial biomass and fauna vary widely, generally, from 1 to 5 per cent, depending on the nature of an ecosystem (forest, grassland, arable), climatic conditions, seasons, cropping, cultivation, organic residue management and fertilisation.

Soil microbial biomass includes bacteria, actinomycetes and fungi. The microbial populations within each type are not homogeneous, but are composed of tens or hundreds of species that differ in age, and physiological and metabolic state. The organic constituents bound in microbial biomass exists in two major forms: (i) cytoplasmic materials, which are labile; and (ii) cell-wall components, which are relatively resistant to decomposition.

Microorganisms are the source of many enzymes necessary for biochemical processes in soil, and are the driving agent for organic matter turnover. In most situations, fungi constitute the bulk of the microbial community in soil. The bacteria often occur as the secondary population, and the actinomycetes form a minor component. Under anaerobic conditions, bacteria play an important role in the decomposition of soil organic matter. However, anaerobic bacteria operate at low rates in both decomposition and synthesis. Usually, a small portion of the microbial population is active at any one time, while the remaining is in dormant state due to the restriction of inadequate substrate supply or unfavourable environmental conditions.

Soil fauna are also referred to as macroorganisms or invertebrates. They are composed of three size groups: microfauna, including protozoa and nematodes; mesofauna, exemplified by enchytraeidae and acari; and macrofauna, such as earthworms and termites. Soil fauna play an important role in the degradation of soil organic materials by ingesting plant residues and grazing on microorganisms and converting them into excreta. A portion of the C contained in the ingested materials is lost as a result of faunal respiration. Besides, soil fauna contribute to soil organic matter decomposition by fragmenting surface plant materials and incorporating the fragments into the soil, thus facilitating the degradation of plant residues by heterotrophic microorganisms.

2.2 Non-living Components

Plant and Animal Residues

According to the definition by Soil Science Society of America, undecomposed plant and animal residues are not considered a component of soil organic matter. However, this component plays an important role in soil C and N cycling, and sometimes also referred to as light fraction or macro organic matter.

Potentially, organic residues could contain any constituents that make up plant tissues, such as proteins, lipids, starch, carbohydrates, hemicelluloses, celluloses, lignins, polyphenols, pectins and tannins. However, their composition may vary appreciably, depending on the type and age of the plant materials, the environmental conditions under which they grow, and their decomposition stage. Generally, young plant tissues have higher content of readily mineralisable constituents like sugars, amino acids and proteins than old tissues; woody litters contain more biologically resistant compounds such as lignin. With the progress of decomposition, the relative concentration of biologically resistant components will increase and the material becomes more difficult to breakdown (recalcitrant).

The biochemical composition of plant residues determines their quality and represents a principal factor that controls the patterns of C and N mineralisation. The rate of organic matter decomposition decreases with the increase in the lignin and polyphenol contents. There is an inverse relationship between net N production and C/N ratio.

Physically Separated SOM: Density and Particle Size Fractions

Physical fractionation techniques have been developed on the hypothesis that SOM free from or associated with mineral particles of various sizes differs in composition and bioavailability. With the physical fractionation techniques, soil samples are usually first dispersed by sonication, shaking, grinding or stirring, followed by separation of soil constituents by means of flotation, sieving or sedimentation.

Fractionation of soil by flotation is based on density differences of soil particles and has been used to separate soil into a light fraction (free, particulate or macro-organic matter) and a heavy fraction. A critical density of 1.6 g/cm^3 is often used. The light fraction represents undecomposed or partially decomposed plant and animal residues and is considered to be not complexed with minerals. The heavy fraction includes the SOM in organo-mineral complexes and is more humified organic matter. Concentrations of C and N and C/N ratio are usually higher in light fraction than in heavy fraction or whole soil.

Sieving or sedimentation can be applied to divide the whole soil or heavy fraction into different size separates. Clay is generally taken as particles < 2 μm in diameter; silt is 2--20 or 2--50 μm; and sand falls into the range of 20--2000 or 50--2000 μm. The C/N ratio of SOM in size separates declines from sand to clay particle size. Although the sand fraction usually contains most organic residues of whole soil under pasture and forest, it does not always represent a major source of mineralisable SOM in cultivated soils. In most cultivated soils, depending on the content of macro-SOM and soil texture, about 60 per cent of the mineralised C and N of whole soil comes from the clay size fraction, while some 30 per cent from silt size separates and approximately 10 per cent from sand fraction. When labelled $^{15}NH_4^+$ or ^{14}C is added to soil and incubated, most of the labelled organic N or C is recovered in the clay fraction, suggesting that a significant portion of the more recent (labile) microbial metabolites were sequestered into the clay fraction.

Chemically Separated Fractions: Humic Substances

It is technically difficult to isolate humic substances from non-humic compounds and mineral materials because of their close association. Conventionally, the chemistry of humic substances was investigated by dividing soil organic materials into three groups: (i) humin (insoluble in dilute alkali solution); (ii) humic acid (soluble in dilute alkali but precipitated when the alkaline extract is acidified); and (iii) fulvic acid (soluble when the alkaline extract is acidified). However, these procedurally identified fractions may not represent a sequence of humification due to the changes in the chemistry of humic substances during extraction since these fractions do not reflect organic matter dynamics in soil. By means of modern spectroscopic techniques (e.g. nuclear magnetic resonance and analytical pyrolysis), it is revealed that humic substances consist of a wide array of functional groups such as carbonyl, alkyl, O-alkyl and aromatic structures.

Although humic substances are considered to represent the most stable components of soil organic C and N, all major forms of organic C and N in soils are biodegradable and constantly changing as a consequence of the microbial activities. On the other hand, substantial amounts of carbohydrates and peptides, which are generally considered to be most chemically and biologically labile, have been found in the residues of soil resistant to UV photo-oxidation.

Charcoal

Charcoal occurs in soil primarily as a result of fires or burning of plant and animal residues. Since temperature varies considerably during the burns or fires, the extent of charring of these residues also vary; hence physical structure and chemical composition of charcoal in soils vary considerably. Aromatic C and pyrrolic N are the main constituents of charcoal in soil, although heterocyclic C and N groups do occur. In some soils charcoal could form as much as 30 per cent of SOM although little is known about its distribution and significance in soil. It is presumably a relatively stable SOM fraction in soil, with long turnover periods, and considered as the inert component of SOM.

Mechanism Governing SOM Turnover

Various components of SOM differ in their turnover rates; from less than 1 hr to greater than 1000 years. These are variously grouped into different conceptual pools. Besides plant residues, three main SOM pools are: active pool, with turnover period of less than 10 years, slow pool, with turnover period of 5-50 years, passive pool, with turnover period exceeding 25-50 years.

Besides temperature and moisture, the turnover periods of various SOM pools are governed by three main mechanisms: degree of accessibility to microorganisms and enzymes, extent of interaction with soil matrix such as clay and oxides of Fe and Al, and chemical and physical recalcitrance of organic compounds. One, two or all three mechanisms may be simultaneously operating for the passive pool, that is, it may have low accessibility to microorganisms due to either SOM embedded within microaggregates or spatially separated, strongly interacted with Al and Fe, and/or have high degree of recalcitrance such as lignin and charcoal. Conversely, the active pool of SOM may be easily accessible to microorganisms, have rapidly decomposable organic compounds, occurs in intra-aggregates, and have only weakly interaction with soil matrix or Al and Fe.

3. Stocks and Fluxes of Soil Organic Matter

The level of organic matter in a soil is determined by the rates of addition and oxidation of plant and animal residues and of soil organic matter. This is mathematically expressed in Equations 1-4. Table 1 gives the organic C stocks and fluxes, and turnover periods in soil under various ecosystems.

Ecosystem	Area (10^9 ha)	Total stock (C_e) Gt C	Soil Carbon t ha^{-1} m^{-1}	Annual addition/flux (A or kC) Gt C y^{-1}	Rate of turnover (k) yr^{-1}	Period of turnover (1/k) yr
Tropical forests	1.76	216	122.7	32.4	0.15	6.7
Tropical savannas	2.25	264	117.3	23.8	0.09	11.1
Temperate forests	1.04	100	96.2	7.0	0.07	14.3
Temperate grasslands	1.25	295	236.0	17.7	0.06	16.7
Tundra and Boreal forests	2.32	592	255.2	2.96	0.005	200
Deserts and semideserts	4.55	191	42.0	5.73	0.03	33.3
Wetlands	0.35	225	642.8	6.75	0.03	33.3
Croplands	1.60	128	80.0	7.68	0.06	16.7
World total	**15.12**	**2011**	**133.0**	**104.0**	**0.052**	**19.3**

Table1: Amount of organic C (C_e), annual addition or flux (A or kC), and rate of loss (k) and period of turnover (1/k) of organic C in soil under various ecosystems

3.1 Forest Soils

Tropical forests occupy an area of 1760 Mha and contain 216 Gt (1 Gt = 10^{15}g) organic C in their soils down to 1m depths (122.7 t ha^{-1}). While Tundra and Boreal forest soils contain organic C more than two times that of tropical forests, annual addition to or CO_2-equivalent flux from the former is less than 10 percent that from the latter. This is reflected in the overall period of turnover of soil organic C; less than seven years for the tropical forest soils but over 200 years for the Tundra and Boreal forests.

Temperate forest soils contain about 100 Gt C in 1040 Mha (96.2 t ha^{-1}). The rate of turnover of soil organic C is less than half that of tropical forest soils. Annual CO_2-equivalent flux is 7 Gt C; about 20 percent that of tropical forests. The tropical and temperate forests and Tundra and Boreal forest soils contain almost half of the total organic C stocks in soil and contribute to about 40 percent of the terrestrial C cycling (sink/flux), and provide net C sink for another one Gt C y^{-1}.

However, continuing deforestation, mainly in tropical and subtropical regions, have reduced the soil organic C stocks and increased CO_2 fluxes from these soils. As a result, approximately, 1.5 Gt C y^{-1} is contributing to the total CO_2 emissions into the atmosphere. Deforestation also reduces the soil organic C stock due to reduced plant residue input from soil erosion, fertility decline, and other land degradation processes, besides changes in temperature and moisture regimes. Clearing a forest considerably alters microclimate and results in more solar radiation reaching ground level during daylight. Measurement of changes in microclimate shows that soil surface (0-0.02m) temperatures increase by as much as 3°C. This increase in temperature alone could increase the rates of organic matter decomposition although drier moisture regime would moderate the temperature effects. Reforestation and afforestation reverses these trends as well as increase soil organic matter in soil.

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Bibliography

Carter, M.R. and Stewart, B.A. Eds. (1996). Structure and Organic Matter Storage in Agricultural Soils. Advances in Soil Science, Lewis Publishers, New York. [This book provides a thorough understanding of role of organic matter in maintaining soil structure]

Dalal, R.C. and Chan, K.Y. (2001). Soil organic matter in rainfed cropping systems of the Australian cereal belt. *Australian Journal of Soil Research* **39**, 3. 000 (in press). [This paper reviews the current understanding and management practices of soil organic matter in cropping soils and consequences for greenhouse gases]

Lal, R., Kimble, J.M., Follett, R.F. and Stewart, B.A. (1998). Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, Florida. [This book brings together the research on mitigating the greenhouse effects using soil as a C sink]

Powlson, D.S., Smith, P. and Smith, J. Eds. (1996). Evaluation of Soil Organic Matter Models using Long-Term Experiments. Springer-Verlag, Berlin, Germany. [This volume reviews the current models used in simulating organic matter in soil]

Rasmussen, P.E. and H.P. Collins. 1991. Long-term impacts of tillage, fertilisation, and crop residues on soil organic matter in temperate semi-arid regions. *Adv. Agron* 45:93-134. (This review contains the impact of no-till practices on soil organic matter management]

Scurlock, J.M.O. and Hall, D.O. (1998). The global carbon sink: a grassland perspective. *Global Change Biology* **4:** 229-233.

Singh, G, Singh, N.T. and Abrol, I.P. (1994). Agroforestry techniques for the rehabilitation of degraded salt-affected land. *Land Degradation Development* **5**, 223-242.

Stevenson F. J. (1982). Humic Chemistry, Genesis, Composition and Reactions. New York: John Wiley

& Sons, Inc. [This book contains detailed information on soil organic matter formation, composition and transformation]

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J.and Dokken, D.J. Eds. (2000). *Land Use, Land-use Change, and Forestry: A Special Report of the IPCC.* Cambridge University Press. [This publication presents current information on soil carbon stocks and fluxes following land use, land use change and forestry, and their impact on greenhouse gases and global change.