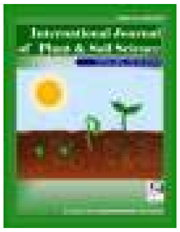

International Journal of Plant & Soil Science
2(1): 133-143, 2013; Article no. IJPSS.2013.011

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Strategies and Mechanisms of Building up and Stabilizing Organic Matter Stocks in Soils

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Authors' contributions

This paper was written in collaboration between both authors. Author KOWN developed the topic, sketched the outline and did literature review for most parts of the paper. Author JN did the editing and supplemented literature to some parts of the paper. Both authors approved the final manuscript.

Review Article

Received 22nd May 2013
Accepted 3rd July 2013
Published 18th July 2013

ABSTRACT

Soil organic matter (SOM) has very important functions in the soil. It affects the soil physical, chemical and biological properties, and eventually affecting the overall soil and crop productivity. Increase in SOM matter is associated with an increase in soil and crop productivity. It also contributes to climate change mitigation through soil carbon sequestration. This paper discusses various soil management and/or farming strategies that contribute to the building up of SOM. The paper also highlights mechanisms that stabilize organic matter in the soil and protect it from rapid decomposition and its loss from the soil. Through reviewing of various research papers, literature shows that a number of strategies provide substantial contributions to building up of SOM. These include: conservation agriculture, crop rotations, cover cropping, agroforestry and afforestation, improved fallows, well managed pastures and organic farming. Various physical, chemical and biochemical mechanisms contribute to stabilization of organic matter and protect the accumulated SOM from rapid decomposition. Quantity and quality of organic materials, soil matrix and clay minerals, organo-mineral interactions and soil management practices are all important factors in SOM stabilization. From this review it can be pointed out that research based knowledge of both SOM accumulation strategies

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and SOM stabilizing mechanisms is very beneficial in making recommendations and implementation of soil management practices that can increase and build up organic matter in the soil.

Keywords: Soil organic carbon; soil organic matter stocks; soil organic matter stabilization; soil carbon sequestration; soil management strategies.

1. INTRODUCTION

Soil organic matter is defined as any material produced originally by living organisms (plants, animal and soil biota) that is returned to the soil and goes through the decomposition processes and is biochemically altered and remains in the soil [1,2]. Its amount is easily determined through quantification of soil organic carbon (SOC). Soil organic carbon is a main constituent of soil organic matter (SOM) comprising from 48 to 58% of the total weight [3]. It is a component that is usually determined in estimating SOM through multiplying its value by a factor of 1.72 [3]. For the purposes of this paper the terms SOM and SOC will be used interchangeably.

Soil organic matter is a very important component for the productivity of soils. It is formed by the biological, chemical and physical decay of organic materials that enter the soil system from sources above ground and/or below ground [4]. Sources of SOM include leaf fall, crop residues, animal wastes and remains of roots and soil biota [4]. Functions of SOM include soil nutrient supply and reserves for metabolically active microbial community; improving soil water holding capacity; maintaining soil structure stability; enhancing chelation and bioavailability of trace elements to plants; reducing phosphorus fixation; decreasing bulk density and increasing pore space [1,4]. Processes that accumulate SOM contribute to climate change mitigation through soil carbon sequestration [5]. Soil carbon sequestration is the process of transferring carbon dioxide (CO_2) from the atmosphere into the soil through crop residues and other organic materials in a form that is not immediately reemitted [6]. In view of these functions, SOM accumulation and maintenance are of paramount importance.

Soil organic matter accumulation is mainly affected by the amount of organic inputs into the system and the rate of decomposition [5]. The rate of decomposition is affected by a number of factors including composition or quality of SOM (C:N ratios, lignin and polyphenol content), and environmental factors such as pH, moisture and aeration [4]. In tropical soils climatic factors such as temperatures have a very significant contribution in that, high tropical temperatures are associated with increased rate of decomposition thereby leading to loss of SOM as compared to temperate regions [4]. The resistance of humus to microbe-facilitated oxidation is important in maintaining SOM levels and in protecting associated nitrogen and other essential nutrients against rapid mineralization and loss from the soil [4]. Despite its resistance, it is still subjected to continuous degradation [4]. The above stated factors coupled with soil management factors contribute to the decrease or increase of organic matter in the soil. However, there are specific mechanisms that protect or stabilize SOM in the soil. SOM protective processes can be considered as the ways in which it is stabilized and get prevented from high rates of decomposition. Sollins et al. [7] defined SOM stabilization as the decrease in its potential loss through microbial respiration, erosion or leaching. Therefore the aim of this paper is to discuss the strategies for building up SOM stocks in soils. The paper also highlights the mechanisms that are involved in stabilization of organic matter in the soils.

2. STRATEGIES OF BUILDING UP SOIL ORGANIC MATTER STOCKS

2.1 Conservation Agriculture

Conservation agriculture (CA) is an integrated system of farming that is aimed at managing agro-ecosystems to achieve sustained productivity, increased profits and food security by implementing and managing the following three principles: minimum soil disturbance, permanent soil cover, diversified crop associations and rotations [8,9]. Tillage systems applied in CA (No till, strip tillage, permanent ridge till) help to reduce soil disturbance. Reduction in soil disturbance slows the rate of organic matter decomposition thus, increasing soil carbon accumulation. Mulch put on the surface and cover crops reduce erosion through the reduction of the impact of rain drops, also reduction of soil temperatures and in turn slow the rate of decomposition, leading to accumulation of SOM [10]. Research conducted by Nijsingh [11] showed 32% higher organic carbon in CA as compared to conventional agriculture in Brazil. From a 10 year study on comparing no-till, minimum till and conventional tillage systems Sombrero and Benito [12] reported the following: at a depth 0-10 cm SOC was 58% and 11% higher under no-till than under convention tillage and minimum tillage respectively; SOC was 41% higher with minimum tillage than with conventional tillage; at a depth of 10-20 cm SOC was 30% higher with no-till than conventional tillage and 7% with no-till than minimum tillage. A number of authors have reported higher SOM levels in no-till systems [13,14,15].

Cover crops increase SOM through their decomposed litter. Continuous cover crops increase SOM through litter fall and prevention of soil carbon loss by erosion [16]. However, SOM building up needs both C and N but the ratios of C:N have an effect on long term accumulation of organic matter. Halvin et al. [17] noted that a C:N ratio of greater that 20:1 leads to reduced rates of mineralization. Salon [18] suggested that legume cover crops that are rotated with grasses or cereals have a higher potential of increasing SOM stocks because of relatively higher carbon input into the system. It is also noted that cover crops that are left for a long period in the field up to maturity lead to increase in C:N ratios and this has a positive contribution to long term build up of SOM [18].

Crop rotations and diversified intercropping systems with high residue crops and diversity of crops applied in CA, increase soil biomass which helps to build SOM [16]. Some rotation crops leave large quantities of residues for example grass-legume forage crops supply a lot of root biomass which can contribute to increasing SOM levels [5]. Rotations containing cover crop legumes produced significantly higher accumulations of SOC in no-till soils varying from 5 to 8 Mg ha^{-1} in comparison with conventional tillage management with 59% greater SOC accumulation down to 100 cm than to 30 cm in Brazil [19]. Maize/legume cropping systems as well provide a good balance between legume nitrogen rich material and more recalcitrant maize stover and increase both N and SOM levels [20,21].

2.2 Agroforestry and Afforestration

Agroforestry is one of the ecological practices of increasing sustainability of agricultural systems. It is an agricultural system where trees are grown together with annual crops and/or animals, resulting in enhanced complementary relations between components, and increasing multiple use of the agroecosystem [22]. It contributes to SOM accumulation through, decomposed leaf litter, decomposed prunings, root exudates, sloughed off root parts and decaying feeder roots [23,24]. Trees have a large amount of below ground biomass with an average of 20-30% with some reaching 50% of the total [23]. This offers a potential long term contribution and more materials such as root exudates going into the soil. Kunhamu et al. [25] reported 24 to 35 ton ha^{-1} soil C content in the 0-15 cm soil layer from agroforestry perennial, *Accacia mangium* in India which was significantly higher than those of plots with treeless cropping systems.

Afforestration which is the establishment of a stand of trees in an area where there were no trees is also reported to increase SOM. As shown under a discussion on agroforestry how trees contribute to SOM stocks, forest ecosystems are reported to contain more soil C per unit area than any other land use type, and their soils can contain around 40% of the total C [24]. This can be attributed to the products of the trees themselves as described earlier but also the increasing diversity that is created by forests whereby grasses and other shrubs grow within it. These lead to increased biomass contribution from root systems and eventually SOM accumulation [5].

2.3 Fallows and Pastures

Managed fallows and pastures are some practices that are associated with increased SOM stocks. A fallow can be natural whereby land that has lost fertility is left for natural vegetation growth [26]. It can also be an improved fallow whereby some plant species such as legume trees, herbaceous cover crops and shrubs that are known to yield more biomass for a specific period, for example one to three years are planted [26]. Fallows are known to improve SOM where there is reduced exportation to off field uses of the biomass produced [27]. Plants that are grown with high density such as some cereals like wheat and grasses or pasture contribute high amounts of root biomass and this lead to increasing SOM stocks. In Germany, Soil C content rose by 10% in plots with continuous grassland whereas Soil C under potato monocrop (fertilized with synthetic fertilizer) decreased by 50% over the course of 32 years [28]. Mc Lauchlan et al. [29] reported substantial SOC increases on land that was converted from agriculture to grassland in Midwestern United States of America where SOC increased steadily by 62.0 g m^{-2} yr^{-1} in the top 10 cm regardless of type of vegetation whether C3 or C4 plants in a period of 40 years.

2.4 Organic Farming

Organic farming relies on practices such as; crop rotations, crop residues, animal manures, off-farm organic wastes, legumes, green manures and aspects of biological pest control and prohibits the use of synthetically compounded fertilizers, pesticides, growth regulators, and livestock feed additives [30]. Most of these practices are associated with SOM accumulation as noted in previous sections. Some studies indicate that organic farming emits 40-60% lower CO_2 than in inorganic farming [31]. This leads to soil carbon sequestration and accumulation of SOM in general. Some studies show that on average organic farming produced 28% higher soil carbon levels than non-organic farming in northern Europe and 20% for all countries studied (Europe, North America and Australasia) [32]. Gattinger *et al.* [33] reported from meta analysis data from 74 studies comparing organic and non-organic farming, where organic farming produced significantly higher SOC values of 0.18% for concentration, 1.08 Mg C ha^{-1} for stocks, and 0.45 Mg C $ha^{-1}yr^{-1}$ for sequestration rates than non-organic farming.

2.5 Organic Amendments and Inorganic Nutrient Application

Inorganic fertilizer is reported to increase SOM in short term through increased biomass production however, in the long term, excessive inorganic fertilizers application especially N fertilizers have been reported not to build SOC stocks because of its association with lower C:N ratios crop residues [16]. Lower C:N ratios are favorable for microbial proliferation and increased rates of decomposition leading to loss of carbon [2]. However, this is still a controversial area and needs more research as a recent finding by Gentile et al. [34] shows that stabilization of SOM is more controlled by the quantity of input and its interaction with the soil matrix compared to the effect of quality. Farm yard manure was reported to increase SOM levels because of the mix of recalcitrant material and easily mineralizable material [16]. Therefore, when compositing is done, consideration of both the quantity and quality of the organic material is important. The quantity and quality of the material used may affect its capacity to build carbon stocks.

3. SOIL ORGANIC MATTER STABILIZATION

3.1 Mechanisms of SOM stabilization

As noted in the introduction section that organic materials that accumulate in the soil may easily be lost through microbial facilitated rapid decomposition. Therefore, stabilization of SOM is very important to protect its loss. The commonly reported major mechanisms of SOM protection are based on physical, chemical and biological processes. These include: physical SOM protection, chemical stabilization or silt and clay protection of SOM and biochemical stabilization of SOM [35,36,37].

Physical protection or stabilization is a mechanism in which SOM is protected from decomposition by being inserted, occluded or obstructed within soil aggregates especially soil microaggregates [35,36]. It is considered as a spatial inaccessibility of SOM against decomposer organisms [36]. On the other hand chemical stabilization mainly describes inter-molecular interactions between organic matter and either inorganic soil components or other organic compounds that alter the rate of decomposition [36]. It is considered as the stabilization of organic matter with mineral surfaces and metal ions or protection of SOM by silt and clay particles. [35,36,37]. It is proposed that the type of clay (phyllosilicates) plays an important role because different types of clay (i.e. 1:1 and 2:1 clays) have substantial differences in cation exchange capacities (CEC) and specific surface areas, and should consequently, have different capacities to adsorb SOM materials [4]. It is noted that polyvalents such as Fe^{3+} and Al^{3+} form strong coordination complexes and bridges with organic molecules [35,36,37].

Biochemical stabilization or selective preservation of SOM occurs due to the complex chemical composition of the organic materials [35,36]. The complex chemical composition can be an inherent property of the plant material (residue quality) or be attained during decomposition through the condensation and complexation of decompositing residues (secondary biosynthesis), rendering them more resistant to subsequent decomposition [35,36]. These mechanisms are to some extent influenced by a number of factors including, soil pH, temperatures and moisture. The authors commonly referred to in this section [35,36,37] did comprehensive reviews on the subject of SOM stabilization. In this paper, only a summary of the mechanisms involved in SOM stabilization is presented in Table 1.

Table 1. Summary of mechanisms of SOM stabilization

Major mechanisms	Specific mechanisms	How SOM is protected	References
Physical stabilization	Occlusion	Labile (easily decomposed) SOM components are obstructed within soil aggregates especially micro-aggregates and get protected from the action of microbes and enzymes	[35,36,37, 38,39,40,41]
	Intercalation	SOM components and macromolecules such as proteins, fatty acids and organic acids can be intercalated or inserted into phyllosillicates (sheet silicate clay minerals) and get protected from decomposition processes	[36,40,42]
	Hydrophobicity	Hydrophobic properties decrease surface wettability and in turn decrease accessibility of SOM to microorganisms; increase aggregate stability	[36,43]
	Encapsulation	Labile SOM is encapsulated or shelled in a network of recalcitrant polymers	[44,40]
Chemical stabilization	Ligand exchange	Aromatic-C forms strong complexes with Al and Fe oxides in acid soils	[45]
	Polyvalent cation bridges and clay type	Polyvalents such as Fe and Al form strong coordination complexes with organic compounds; large surface area in some clays such as 2:1 type with a high degree of isomorphous substitution attracts and protects more SOM	[35,36,37]
	Weak interactions (Van der waals, H-bonding)	Van der waals create electrostatic forces; H-bonding interact with any mineral with exposed oxygen or organic matter functional groups e.g phenolic OH^-	[36]
Biochemical stabilization	Inherent or primary recalcitrance	High amount of recalcitrant components such as lignin and polyphenols decompose slowly	[35,36]
	Secondary recalcitrance	Secondary biosynthesis of organic matter renders the materials more resistant to subsequent decomposition	[35,36]

3.2 Associating SOM stabilizing mechanisms and soil management practices

Soil organic matter stabilization is affected by many factors including chemical and physical properties of the soil matrix as well as the morphology and chemical structure of organic matter [46]. The physicochemical characteristics inherent to the soils also determine the protective capacity of SOM pools by soil aggregates and clay minerals [47]. Soil management practices also have their contributions on both degradation and stabilization of organic matter [35,36]. Reports from many studies show that some mechanisms of SOM stabilization have been covered but not many studies have directly associated these mechanisms with specific soil management practices. Lutzow et al. [48] reported a conceptual model of different stabilization mechanisms of SOM related to different pools with different turnover times in four temperate soils and noted that soil management practices contribute to SOM stabilization. This section is included to provide examples where specific soil management practices can influence a SOM stabilizing mechanism. Nevertheless, using information gathered from a few studies a summary of how some soil management practices influence some specific mechanisms in SOM stabilization has been presented in Table 2.

Table 2. Soil organic matter stabilizing mechanisms as influenced by soil management practices

Mechanisms	Soil management practices	References
Occlusion	No-till: contributes to formation of stable aggregates that protect SOM	[49,50]
Hydrophobicity	Manure (some components) application; biochar/charcoal (if present): reduces wettability and protect SOM from microbial decomposition	[48]
Encapsulation	No-till: restructures the architectural system of microaggregates	[40]
Ligand exchange and polyvalent cations	Tillage can increase the importance on organo-mineral interactions	[48]
Inherent recalcitrance (biochemical)	Addition of organic materials of various types: recalcitrance affects C:N ratios and decomposer microbial community and processes	[51]

4. CONCLUSIONS

Soil organic matter is a very beneficial component of the soil, hence a need for the building up of its stocks. From this review it can be confirmed that conservation agriculture; cover crops; rotations; agroforestry; managed fallows and pastures; organic farming; and addition of crop residue and manure are some of the important strategies in building SOM stocks. The quality or composition of crop residues in terms of C:N ratios, lignin and polyphenol content and quantity of organic inputs applied have huge influences on SOM stocks. Quantity and quality of organic materials, soil matrix and clay minerals, organo-mineral interactions and soil management practices are all important factors in SOM stabilization. Understanding of mechanisms of organic matter protective or stabilizing processes is of paramount importance because it enhances good choices of soil management strategies that lead to accumulation and building up of SOM. Mainstreaming the farming practices covered in this paper, in agricultural production, accompanied by good residue management can be very good options for the tropics where rates of decomposition are high.

ACKNOWLEDGEMENTS

The authors would like to thank AGRA Soil Health Programme for funding their doctoral studies at Sokoine University of Agriculture. Prof. E. Semu and Dr. N. Amuri of the Department of Soil Science, Sokoine University of Agriculture are also thanked for their inspiration.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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