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Review Article

Potential of carbon storage in major soil types of the Miombo woodland ecosystem, Tanzania: A review

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ABSTRACT

This review was undertaken to explore the potential of soils to sequester and store large quantities of carbon (C) in the form of soil organic carbon (SOC) from the view point of global climate change regulation and reduced CO_2 emissions. Miombo woodland forest soils are an important sink of atmospheric C. The major soils found in the Miombo woodlands include: Cambisols (Inceptisols), Leptosols, and Fluvisols (Entisols), Luvisols (Alfisols), Acrisols (Ultisols), Ferralsols (Oxisols), and Vertisols (FAO-WRB classification system and USDA-Soil Taxonomy). The soils differed in physico-chemical properties and exhibited differences in morphological characteristics, nutrient status and SOC storage, suggesting a remarkable variation in potential, constraints and management strategies for the different soil types. The review underscored the potential of soils as one among the important strategies in fighting against climate change due to the presence of soil humus that stabilizes soil organic carbon for a long period of time. Overall, Miombo woodland soils have a high potential for storing substantial SOC stocks. Miombo are composed of different tree species (average of 45 species per biome) with differences in C storage capacity. Thus, strengthening land/forest conservation could lead to build up of SOC stocks that would contribute to global climate change regulation.

Key words: Climate change, Miombo woodland ecosystems, Soil organic carbon, Land management, Tanzania.

1.0 INTRODUCTION

Carbon (C) is found in all environmental segments. It occurs in the atmosphere (as carbon dioxide (CO_2) gas), in growing vegetation, and in soils (including sediments). Large quantities of C are stored in soils. The soil C pool is comprised of two main components: soil organic carbon (SOC[1]) and soil inorganic carbon (SIC) [1, 2]. The SIC includes mineralized forms of carbon, such as calcium carbonate ($CaCO_3$) and dolomite ($CaMgCO_3$), and is estimated globally to stand at 720 Pg to the 1-m depth [2, 3]. However, SIC is usually not abundant in soils of pH 7 or lower, or in humid regions, but is more common in the more arid regions and in alkali soils [4, 5]. Moreover, the SIC is more stable than most organic forms of carbon because it is not substrate for microorganisms and therefore is not susceptible to microbially-mediated losses. But SIC quantities are much smaller than those of SOC. Therefore, studies that address dynamics of soil C usually focus mainly on SOC [5].

The SOC is the most prevalent form of C in soil, and is derived from dead plant materials (plant leaves, roots, sap and exudates) and remains of dead microorganisms and animals; and globally it is estimated to be 1500 Pg (10^{15}g) to the 1- m depth [2, 6, 7]. Most of the C enters the soil in the form of dead plant matter that is broken down by microorganisms. The microbial decomposition of these materials also releases some C back to the atmosphere because metabolism by these microorganisms eventually breaks some of the organic matter all the way down to CO_2. The net SOC accumulation in soil is controlled by (1) quantity and quality of litter inputs, (2) lower topsoil temperatures due to canopy cover, thus lower decomposition rates, (3) low decomposition rates due to decreased aeration, and (4) physico-chemical protection mechanisms by microorganisms and soil components like clay [8, 9, 10].

Different soil types contain/store different quantities of SOC/soil organic matter (SOM), with implications on their physico-chemical and biological properties and on climate change regulation. For example, studies by [7] showed that global SOC concentrations in various soils varied in this order: Histosols[2] (Histosols)[3] > Inceptisols (Cambisols) > Oxisols (Ferralsols) > Alfisols (Luvisols) > Aridisols (Solonetz) > Entisols concentrations in various soils varied in this order: Histosols (Histosols) > Inceptisols (Cambisols) > Oxisols (Ferralsols) > Alfisols (Luvisols) > Aridisols (Solonetz) > Entisols (Fluvisols/Leptosols) > Ultisols (Luvisols/Acrisols) > Spodosols (Podzols) > Mollisols (Kastanozems/Chernozems) > Andisols (Andisols) > Vertisols. Generally the minimum SOC contents are about 48 Pg in Vertisols and the maximum is about 380 Pg in Histosols, both determined to the 1- m depth. Likewise, different forest biomes differ in SOC/SOM storage. A study by [7] showed that the SOC concentrations decreased in the order: Boreal forests > Tropical forests > Temperate forests, the minimum and maximum values being 140 Pg and 340 Pg in temperate and boreal forests, respectively. Thus, globally, forest biomes and soils differ in their capacity to store C.

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[1] Soil organic carbon (SOC) is defined as the C associated with soil organic matter (SOM), and it forms 48- 58% of SOM. The SOC includes only decomposed and humified materials of SOM.

[2] Soil classification: United States Department of Agriculture- Natural Resources Conservation Services (USDA-NRCS), Soil Taxonomy system (Soil Survey Staff, 2010).

[3] FAO-World Reference Base (WRB) for Soil Resources, FAO-WRB (2006) Classification system

In Tanzania, the Miombo[4] woodlands are one type of forest biome that has a large potential to store C in its soils. Based on the existing knowledge, Miombo woodlands cover different altitudes, which range from 230 to 2100 masl [13, 14, 15]. The areas occupied by the Miombo woodlands have different soil types and different plant species, as is the case in other Miombo woodlands elsewhere. These factors will contribute to differences in amounts of C stored in different soil types. For example, [16] reported means of 1.0% and 1.7% organic carbon (OC) in Haplic Lixisols and Chromic Luvisols, respectively, from southern African Miombo woodlands. Studies by [17] reported that African Miombos are dominated by Cambisols (Inceptisols), Ferralsols (Oxisols), Luvisols (Alfisols), Fluvisols/Leptosols (Entisols), Luvisols/Acrisols (Ultisols) and Vertisols. This study [17] did not evaluate carbon storage in those soils. However, differences in SOC storage in different soils of the Miombo woodlands can be expected.

2.0 OCCURRENCE AND SIGNIFICANCE OF MIOMBO WOODLANDS IN TANZANIA

In Africa, Miombo woodlands are a significant vegetation type which occupy about 9% of the land area, which is equivalent to about 2.7 million km^2 [18]. Miombo woodlands are found in southeastern and central Africa and form a dominant vegetation type in Angola, Zambia, Malawi, Mozambique, Zimbabwe and Tanzania [18, 19]. Tanzania has a large land area (88.6 million hectares, excluding the area covered by inland lakes), with diverse land use systems. About 40% of Tanzania's total land area is covered by Miombo woodlands [20, 21, 22]. These woodlands provide diverse ecosystem services including harbouring wildlife, acting as water catchment, providing fuelwood, fibre, charcoal, food, fodder, tourism, soil and water conservation, biodiversity, medicines, maintaining substantial carbon stocks, controlling soil erosion, providing shade, modifying hydrological cycles and maintaining soil fertility. These services support livelihoods of adjacent communities [22, 23, 24, 25]. Although these woodlands have much contribution in view of their provision of these diverse ecosystem services, the aspect of their role in climate change mitigation, with its role in the sustenance of those communities, has not received much attention in Sub-Saharan Africa (SSA) in general and Tanzania in particular. Establishing site-specific and soil-type specific C storage capacity of Miombo woodland soils in Tanzania would provide the basis on which to assess their contribution to climate change mitigation. However, the potential for C storage will be influenced by the density and species composition of the Miombo woodlands.

3.0 CARBON POOLS AND THEIR IMPLICATIONS IN GLOBAL CLIMATE CHANGE

The C and its different pools play an important role in life. All living things are made up of carbon. In addition, globally, carbon is found in the oceans (38 000 Pg), the geologic pool (coal, oil and gas) (5000 Pg), soils (1500 Pg), the atmospheric pool (760 Pg) and the biotic pool (560 Pg) [26, 27, 28]. Since these pools are interconnected, C is constantly cycling between the atmosphere, biosphere and pedosphere [29, 30, 31]. In the atmosphere, carbon is attached to oxygen in a gas called CO_2. The CO_2 is a greenhouse gas that traps heat in the

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[4] Miombo Woodland is defined as tree species belonging to the family Fabaceae, subfamily Caesalpinioideae, and genera of *Brachystegia*, *Julbernadia* and *Isoberlinia*

atmosphere [32, 33]. Without CO_2 and other greenhouse gases (nitrous oxide, methane), the earth would be a frozen planet. However, excess CO_2 in the atmosphere leads to climate change. Plants use CO_2, sunlight energy and water to make their own food for their growth. The carbon then becomes part of the plants. When the plants die, the C compounds eventually are transferred, decomposed and incorporated into the soil as SOC and vice versa. Thus, plants are the vehicle by which CO_2 is transferred from the atmosphere to soil C. It would be of interest to be able to keep more of that fixed C in the soil environment and to reduce re-emissions back to the atmosphere, where it would increase the CO_2 levels over and above normal levels, thus creating instability or change of climate [31, 33].

Earlier considerations of SOC were focused exclusively on its influence on the soil fertility and soil physical aspects that soil organic carbon/matter enhances. A soil with relatively high content of SOC/SOM has relatively higher soil fertility and improved physical properties. While this fact continues to be the case, a different dimension- the climate change regulation dimension of SOC- has of recent come into focus. Accumulation of large quantities of CO_2, e.g. due to industrial emissions into the atmosphere, has been associated with erratic changes in climate, but lower quantities of atmospheric CO_2 are associated with climate stability [33].

Because of the above considerations of the implications of SOC on soil properties, and on the potential of Miombo woodlands for climate change regulation that is currently topical, there is need for detailed analysis on the status and implications of the C stored in such forest biomes. This is now important because while extensive studies have generally been undertaken in respect of the soil fertility viewpoint, much less has been done from the viewpoint of the climate change regulation potential of SOC storage.

4.0 POTENTIAL OF MIOMBO WOODLANDS IN TANZANIA FOR CARBON STORAGE

Miombo woodlands are characterised by the dominance of the legume family Fabaceae (sub-family Caesalpinaceae), comprising the genera *Brachystegia*, *Julbernardia* and/or *Isoberlinia*, with an understory dominated by grasses, often growing in poor nutrient soils derived from acid crystalline bedrock [14, 17, 18, 22 25]. Other prominent tree species of Miombo woodlands include *Uapaca kirkiana, Erica arborea, Dalbergia lacteal, Diplorhynchus condylocarpon and Lannea schimperi*.

Studies by [14] in Kitonga Forest Reserve (KFR), Tanzania, reported a total of 45 different tree species from 26 different genera, with an average species richness of 20 species ha^{-1}**.** A study by [34] reported that in 2002 the KFR had 57 different tree species while in 2005 the species recorded were 60. A study by [35] reported 86 Miombo woodland tree species around Ihombwa village in Mikumi Division, Kilosa District, Tanzania, while [36] recorded 79 species in the Kitulanghalo Forest Reserve in Morogoro, Tanzania. The variations in the numbers of tree species within and between forest sites could be contributed by differences and changes in climatic conditions like variations in rainfall and temperature, variations in soil types in the areas, and varying levels of disturbances (deforestation, wildfires) in those forest reserves. However, the diversity of tree species in these forests presents a substantial potential for C storage in those forests. This potential is enhanced by the wide diversity of tree/vegetation species because while the plant residues of some species may be decomposed (by soil microorganisms) faster, thus losing more C, others may decompose more slowly, leading to greater accumulation of soil C. This would be the opposite if vegetation diversity was narrower and favoured the faster-decomposing plant species [9, 37].

A study by [38] in the KFR, Tanzania, showed that average SOC stocks, to 0.6 m depth varied in the order Cambisols (Inceptisols) (67.4 Mg C ha^{-1}) > Fluvisols (Entisols) (65.8 Mg C ha^{-1}) > Leptosols (Entisols) (24.4 Mg C ha^{-1}). A study conducted by NAFORMA, as presented by [39], reported average levels of the SOC to 0.1 m depth in the Miombo woodlands in Tanzania to be 37 Mg C ha^{-1} (closed Miombo) to 38 Mg C ha^{-1} (open Miombo). A study by [40], in Miombo woodland (*Brachystegia* spp) in Southestern Tanzania at 800masl with Acric Umbric Ferralsols to 1- m depth, reported SOC of 72.47 Mg ha^{-1} C. These figures can be compared with the findings of [41] which reported a value of 54 Mg C ha^{-1} for the tropical woodlands and savannas to a depth of 1 m. The capacity of the Miombo woodland soils to store C varied from one place to the other due to natural factors (climate, parent material) and human induced factors (fires, grazing and deforestation) as reported by others [31, 42] and also as observed in the Tanzanian Miombo woodland soils. In order to enhance SOC storage, proper land/forest/soil management is recommended.

Studies elsewhere revealed enormous quantities of C being stored in some forest ecosystems of the world, as follows: [43] reported SOC storage of 100 Mg ha^{-1} in the South African Miombo woodlands. A study by [44] reported highly variable SOC quantities of 30 - 140 Mg ha^{-1} in the African Savanna and woodlands. A study by [45] reported SOC variation for the Sahelian savanna soils ranging from 20 Mg ha^{-1} in Mali to 120 Mg ha^{-1} in Ghana. A study by [42] reported SOC storage to vary between 15.9 and 107 Mg ha^{-1} in Mediterranean soils of Spain. Thus, continued generation of information on carbon storage and its distribution in Miombo woodland soils in Tanzania and elsewhere will enrich the world’s knowledge base on SOC storage across different edaphic environments.

In addition to their great diversity of tree species, the soils of the Miombo woodland ecosystems would contribute to increased carbon storage due to their large area coverage and, thus, increase the potential to mitigate climate change [25, 46, 47]. Studies on C contents of the above-ground and below-ground biomass in Miombo woodland ecosystems are available, but the C, as SOC, stored in the soil component has not been studied adequately [14, 47, 48, 49, 50]. Most studies have reported OC in relation to different pools, namely above-ground, below-ground, or C in vegetation types like grasslands and shrubs. Only few studies have dealt with individual soil types as sinks of C pools in Miombo woodland ecosystems. Only general global SOC storage figures have been given by some researchers. For example, [51] gave general global SOC estimates to 1 meter soil depth (Table 1).

Table 1: Global soil organic carbon estimates in soils to the depth of 1 meter

SOURCE	**SOC AT 0-1 m DEPTH,** (Pg*)
Hiederer and Kochy (2012)	2 469
Hiederer *et al.* (2010	1 455
Henry *et al.* (2009)	1 589
Jocob *et al.* (2004)	1 600
Lal (2004)	2 500
Robert (2001)	1 500
Global Soil Task Group (2000)	1 550
IPCC (2000)	2 000
Jabbagy and Jackson (2000)	1 502
Reich (2000), NRCS- USDA)	1 463
Kasting (1998)	1 580
Batjes (1996)	1 462- 1 548
Post *et al.* (1982)	1 395

Source: Milne (2012) * Pg = Petagrammes (10^{15} grammes)

5.0 SIGNIFICANCE OF MIOMBO WOODLANDS IN CARBON STORAGE

The Miombo woodlands in Tanzania lie within the Eastern Arc Mountains (EAM), in the Udzungwa Mountains block. The Miombo woodlands are recognized, among other qualities, by having a variety of wildlife, being an important catchment to several streams that feed water into the main rivers, whose water is used for irrigation agriculture, domestic use and hydro- power generation. The Miombo woodlands are important for fuel wood provision, storage of carbon and soil protection/conservation. However, the Miombo woodlands are facing a variety of threats, including illicit timber harvesting, destructive fuel wood collection and rampant charcoal burning [14, 38]. In the long term, these threats, if not removed, will contribute to diminished quantities of C stored in this woodland/forest system.

Some researchers reported that undisturbed EAM forests could store SOC of about100 - 400 Mg $ha^{-1}$to the depth of 1 meter, as against the disturbed forests which store only about 85 Mg C ha^{-1} [52]. Studies by [25] in the African Miombo woodlands indicated that SOC in the top 5 cm was 12.1 ± 0.6 Mg C ha^{-1} and 40.1 ± 2.5 Mg C ha^{-1} to the 30 cm depth. If these were the average quantities of C stored per hectare, the total C storage over the entire area of the Miombo woodlands in Tanzania (44,760,603 ha) would be enormous (approximately 0.54 Pg C in the top 5 cm and 1.8 Pg C to the 30 cm depth), which would be a strong force for climate regulation [15]. Thus, improving the management of Miombo woodlands in ways that reduce or eliminate the cited threats could result in improvements in SOC storage that would contribute to regional and global climate change regulation.

Studies from elsewhere reported on the climate regulation potential of some forest ecosystems due to enormous quantities of SOC stored in those forests. For example, [37] reported values of SOC that ranged from 27.7 to 140.76 Mg ha^{-1} in different forest types of the Himalaya zone in India. A study by [53] reported SOC of 43 Mg

ha^{-1} in a 100 years old secondary forest in Panama. A study by [50] reported SOC of 85.7 and 99.6 Mg ha^{-1} in teak and *patula pine* forest species, respectively. Variations in SOC stocks exist among forests in different parts of the world due to elevation and climate [42, 54, 55], soil type, aspect and slope position, lithology, texture, topography [29, 31, 55], and vegetation type [31, 56]. However, globally, forests play an important role in climate change regulation. Therefore, sustainable forest management is the key to C storage and climate change regulation.

6.0 ECOLOGICAL IMPORTANCE OF SOIL ORGANIC CARBON

Soil organic carbon is a master variable determining the quality and fertility of the soils [1, 3, 5, 6]. It has a major influence on the chemical, physical and biological properties of soils and thus serves as a major determinant of soil fertility. Decomposition of SOC, in addition to improving SOM, provides an energy source for the soil micro-organisms involved in organic matter decomposition. Moreover, nutrients like nitrogen, phosphorus and a range of other nutrients vital for plant growth are released during SOM decomposition [2, 3, 57]. The SOC affects soil physical properties such as improving soil aeration, structural stability, water holding capacity, water infiltration, gaseous exchange, root growth and ease of cultivation.

The biochemical processes involving SOC include C sequestration, plant nutrient uptake, buffering activities such as sorption of toxins and heavy metals, and degradation of harmful pesticides [2, 57, 58]. Loss of SOC will, therefore, lead to a reduction in soil fertility, increased land degradation and desertification and, thus, reduction of soil quality. Soil organic carbon is stored mainly in the form of humus (or humic substances) as illustrated in Fig. 1 below.

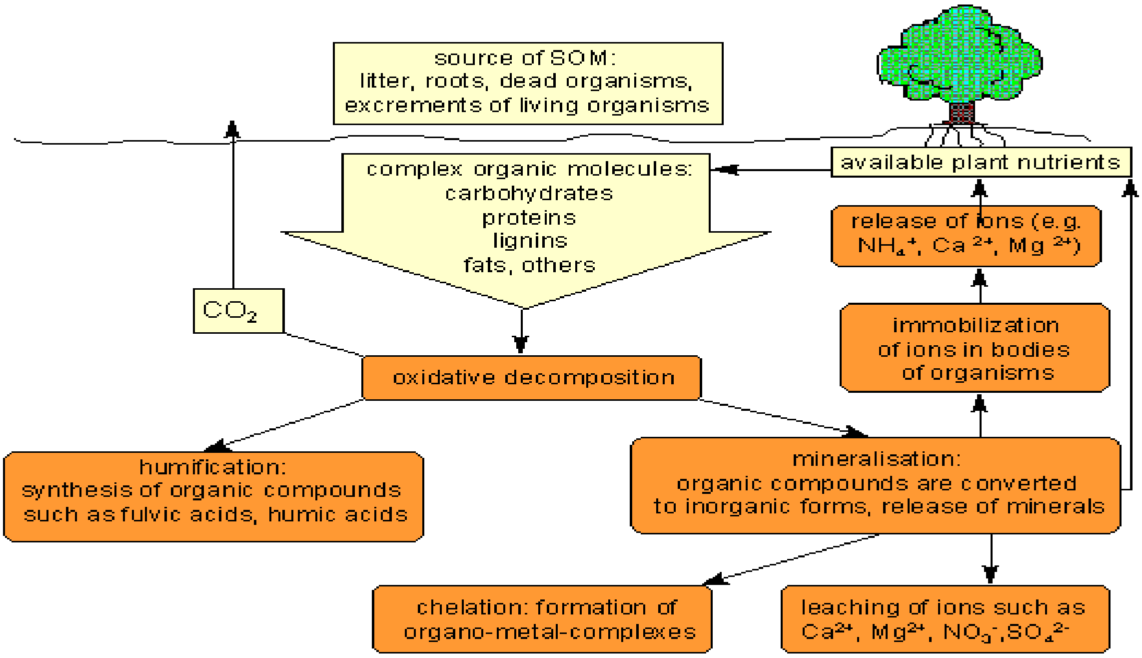

Figure 1: Soil organic carbon compounds in soils (Stockmann *et al*., 2013)

7.0 SOIL HUMIC SUBSTANCES AS STABILIZERS OF SOIL ORGANIC CARBON STOCKS

7.1 General

The decomposition of plant residues in the soil over extended periods of time finally results in the formation of a more complex form of organic products called humus, or humic substances [9, 59, 60, 61]. The non-humic substances are labile, with relatively rapid turnover in soil. They have short residence times of a few months to several years since they are more readily utilized as substrates by soil microorganisms [9, 60]. However, the humic substances are relatively more resistant to further biogradation and hence provide a long term storage sink for C in soils, with residence times of decades, centuries to millennia [5, 61, 62, 63, 64]. Humic substances represent approximately 40 - 60% of the SOM, and include three different fractions, defined according to their solubility in acid and alkali [61, 62]. Humic substances are heterogeneous, relatively large stable organic complexes in soils, with some being high molecular weight compounds that form brown to black hydrophilic, polyelectrolytes [61, 65, 66]. The three major fractions of humic substances are (1) Fulvic acids (FAs), (2) Humic acids (HAs), and (3) Humins.

7.2 Fulvic acids

The FAs are a mixture of simple chains of aliphatic and aromatic organic acids which are soluble at all pH conditions (acidic, neutral and alkaline) [60, 61]. The size of FAs is small, with molecular weights that range from approximately 1000 to 10 000 [60]. They have many carboxyl (COOH) and hydroxyl (OH) groups, which make FAs chemically reactive. The exchange capacity of FAs is high, due to the large numbers of carboxyl (COOH) groups present. The exchange capacity of carboxyl groups present in FAs ranges from 520 to 1120 cmol (H+)/kg. Fulvic acids collected from many different sources show no evidence of containing methoxy (CH_3O) groups, are low in phenols, and are less aromatic compared to humic acids from the same sources [67, 68].

7.3 Humic acids

Humic acids are a mixture of natural organic macromolecules, with many different acids, containing carboxyl and phenolate groups [60, 65]. The longer polymers of aliphatic (carbon chain) and aromatic (carbon ring) organic acids make HAs insoluble under acid conditions ($pH<2$), but are soluble under alkaline conditions ($pH>12$) [60, 65]. Humic acids are precipitated from aqueous solution when the pH is decreased to below 2. Humic acids are polydisperse because of their variable chemical features. On average 35% of the HA molecules are aromatic while the remaining components are in the form of aliphatic molecules. The molecular sizes of HAs range from approximately 10 000 to 100 000 [65, 69].

The HAs polymers readily bind to clay minerals to form stable organic-clay complexes. The HAs readily form salts with inorganic mineral elements. An analysis of extracts of naturally occurring HAs revealed the presence of over 60 different mineral elements present, bound to humic acid molecules in forms that can be readily utilized by various living organisms. As a result, the HAs function as important ion exchange and metal complexing (chelating) systems [60].

7.4 Humins

Humins are that complex fraction of humic substances which are not soluble in alkalis (high pH) and are not soluble in acid (low pH). Humins consist of one or more of: 1) humic acids intimately and inseparably bound to mineral matter, 2) highly condensed humic matter with > 60% C, 3) fungal melanins, and/or 4) paraffinic substances (Stevenson, 1994). Humin complexes are considered to be macro-organic (very large) substances because their molecular weights (MW) range from approximately 100 000 to 10 000 000 [5, 61, 64]. The chemical and physical properties of humins are only partially understood [70]. Humins present within the soil are the most resistant to decomposition (slow to breakdown) of all the humic substances. Some of the main functions of humins within the soil are to improve the soil's water holding capacity, to improve soil structure, to maintain high soil aggregate stability, to function as a cation exchange system, and to generally improve soil fertility [33]. Because of these important functions and stability characteristics, humins can play an important role not only in soil fertility but also in climate change regulation.

7.5 Stability of Humic Substances

Studies by [70, 71] reported the residence times of the stable fractions (e.g. humic acids and humins) of SOC to be > 1000 years, making humus a much more stable C sink than living plant biomass. Neutral and alkaline soils have been reported to have large percentages of humic acids and humins, whereas sandy soils were reported to be dominated by fulvic acids [61, 70]. Thus, soil pH gives an indication of the presence and prevalence of FAs, HAs or humins of a given soil. The chemically refractory nature of humic substances contributes to their long persistence in soils [62], and this should be associated with less emissions of C (as CO_2) to the atmosphere [59]. The relationship between concentrations of HA and FA (HA/FA ratio) is indicative of the potential stability of C in the soil system. The percentages of the humic fractions which occur in humus (the humic acid/fulvic acid ratio) vary considerably from one soil type to another [5, 61, 62]. In situations where the ratio of HA/FA < 1 (signifying lability), the SOM decomposition is relatively fast whereas situations with HA/FA ratios >1 indicate slower decomposition rates due to relatively smaller quantities of the more labile FA fraction [61, 62, 64]. Thus, higher concentrations of the HAs and humins result in more stability of C in soils, and this should be an advantage in climate change regulation from the view point of less CO_2 emissions. However, recent studies by [60] reported that humic substances' molecular structure alone is not the only factor in SOC stability; they indicated that associated environmental and biological factors play a profound role. Thus, studies that integrate environmental and biological factors contributing to SOC stability will contribute more knowledge and understanding in the contribution of the C stored in soils to global/regional climate change relations.

Mid-infrared (MIR) and near-infrared (NIR) spectroscopy of soils are potential to provide a rapid method for the analysis of soil C, minerals and other soil parameters of interest [71, 72]. These techniques are considered as rapid, fast and cost-effective by reducing time and reagent use by being a non-destructive analytical technique.

However, further improvements of these techniques are still needed to improve predictions of SOC. Testing these methods in Miombo woodland soils will contribute to new knowledge in this respect.

7.6 Land Management for Maximizing the Contents of Humic Substances

Studies by [61] indicated that the humus of forest soils is characterized by high contents of fulvic acids while the humus of peat and grassland soils is high in humic acids. The turnover of SOM and, thus, SOC depends upon the chemical quality of the C compounds (labile or refractory), climate and soil properties such as clay content, soil moisture, pH and nutrient status [73, 74]. Several of these factors can be influenced by forest/soil management. Some studies [28, 74] indicated that land use changes from crops to plantations (by 18 %) or crops to secondary forests (by 53 %) increased total SOC stocks. They concluded that land use change from cropland to permanent reforestation is generally the ‘most’ efficient aggrading system in terms of SOC gains whereas the conversion (of forests) to cropland or monocultures is a common example of degrading systems. The types of permanent vegetation for reforestation purposes could, therefore, be selected to integrate those vegetation types that may contribute to increase the more stable components of humus (e.g. pine vs. broad leaf vegetation). In this way, achieving soil carbon stability may contribute to climate change regulation.

8.0 Potential of Soils in Global Climate Change Regulation

Soils are the biggest store of C in the world and, thus, they play an important role in reducing global warming and in climate change regulation [75, 76, 77, 78, 79, 80]. As already observed, about 1500 Gt C is contained in soils as SOC (to one m soil depth). The organic C stored in soils accounts for about three times the C stored in the world's vegetation, which contains/stores about 560 Gt. Furthermore, soils hold almost double the amount of C as that held in the atmosphere (760 Gt) [2, 32, 78, 79, 80]. Thus, in the terrestrial carbon cycle, soils form the largest reservoir of C [2, 77, 79, 80, 81, 82]. Thus, the Miombo woodlands, with their large areal extent and the C that they contain and could continue to capture within their soils, have a substantial potential contribution to climate change regulation. The KFR should be no exception.

Global figures show that soils contain 3.5% (2500 Pg), in the top three meters of soil, of the earth's carbon reserves, compared with 1.7% (760 Pg) in the atmosphere, 8.9% (5000 Pg) in coal, oil and gas (fossil fuels), 1.0% (560 Pg) in biota and 84.9% (38 000 Pg) in the oceans [75, 77, 79, 80]. As the largest reservoir of terrestrial carbon, with much longer residence mean time than the carbon in the vegetation that the soil supports, soils act as a natural sink and mitigate climate change [32, 37, 77, 78, 80, 82]. As a natural sink, soils remove CO_2 from the atmosphere, primarily during plant photosynthesis. After harvest, crop/tree residues and other organic matter, from which CO_2 is not immediately reemitted, are returned into soil. The process of tying up C into organic/vegetation matter is known as carbon sequestration. Soil carbon sequestration can be improved by management systems that add high amounts of stable biomass to the soil, cause minimal soil disturbance, conserve soil and water, improve soil structure, and enhance soil fauna activity. Continuous no-till crop production is a prime example. As the largest pool of OC, soils have the capacity to be a stable reservoir to store C in the long term, a feature that makes soils to play an important role in climate change regulation [6, 32, 83, 77] through regulated/decreased release of CO_2 back into the atmosphere, hence regulating climate change.

9.0 Forest Soils in Global Climate Change Regulation

About 40% of the total global SOC stock resides in the forest ecosystem, with about 11% of the SOC held in forest soils [37, 80]. Therefore, forest soils are one of the major carbon sinks on earth, and play an important role in climate change regulation because of the higher amounts of organic matter stored in those soils. However, forest soils remain poorly understood due to their complexity in mechanisms of C storage and their inaccessibility, despite a significant portion of the global total carbon stock being stored and cycled under various forests. A study by [41] established the worldwide SOC storage in forest and woodland biomes (Table 2).

Table 2: Estimate of the soil carbon pool in different biomes of the world

Biome	Area (10^6 ha)	Mean Soil Carbon Content (Mg ha^{-1})
Tundra	880	218
Boreal desert	200	102
Cool desert	420	99
Warm desert	1 400	14
Tropical desert bush	120	20
Cool temperate steppe	900	133
Temperate thonne steppe	390	76
Tropical woodland and savanna	2 400	54
Boreal forest, moist	420	116
Boreal forest, wet	690	193
Temperate forest, cool	340	127
Temperate forest, warm	860	71
Temperate forest, very dry	360	61
Tropical forest, dry	240	99
Tropical forest, moist	530	114
Tropical forest, wet	410	191
Totals	10 560	1 688

Source**:** Adapted from Amundson (2001)

Forests also represent the world’s most significant terrestrial carbon store, containing an estimated 77 % of all C stored in vegetation and 39 % of all C stored in soils, twice as much C as is present in the atmosphere. Thus, good management of forests and soils will preclude excessive CO_2 emissions to the atmosphere, thus contributing to climate change regulation. The Miombo woodland ecosystem is a part of forest ecosystems, and could thus play a significant role in C storage and climate change regulation.

10.0 Factors affecting SOC across Landscapes

The SOC stocks across a landscape are very variable and are influenced by topographical features, vegetation types, climate, soil type, soil properties, soil depth and parent material [54, 81]. Therefore, the overall quantities of SOC stocks of a particular forest ecosystem, and the potential of these ecosystems to regulate climate, will depend on these influencing factors.

10.1 Topography

Numerous studies have indicated that SOC concentrations and/or stocks increase in higher mountainous terrains [31, 54, 87, 88, 89]. The greater SOC stocks at higher topographical levels are due to greater accumulation of plant litter (increased C inputs) as a result of increased precipitation, and reduced temperatures, which result in relatively low OM decomposition rates by microorganisms at those cooler temperatures. For example, in the northern temperate zone (boreal forest), where temperatures are generally low, the soils have the greatest ability to store SOC due to the low temperatures that suppress decomposition of the SOM [41] (Table 2).

Increasing altitude also has a significant effect on species richness and species composition, which increase with even a 100 m increase in altitude, as precipitation increases [78]. Topography also modifies soil moisture regimes and thus exerts an indirect control on SOC levels [54, 90, 91]. Further, slope and surface characteristics are major topographical parameters that control movement of water, sediments and nutrients, and hence modify land form, soil formation, soil depth, moisture status and, hence, biomass production and C inputs [92]. Thin soil depths are generally characteristic of steeper slopes, resulting in lower SOC stocks. However, higher soil moisture, and hence increased biomass production in down slope positions, contributes to higher SOC concentrations and stocks [93]. Overall, topography modifies temperatures and precipitation and thus exerts control of the climate parameters that effect SOC formation, accumulation and decomposition. Therefore, topography plays an important, if differential, role in SOC stocks and storage.

10.2 Vegetation Type

Vegetation residues are the raw materials for producing SOC. These materials include litter drop, root exudates and root mortality. The spatial distribution of plants determines the niches where SOC is accumulated. Vegetation types influence the amounts of SOC stocks through photosynthetic manufacture of organic matter, followed by low decomposition rates at low temperatures under tree canopy [78, 94]. In tropical forests, *patula pine* soil was reported to accumulate 76.1 Mg C ha^{-1} whereas the African *Tectonia grandis* stored 19 Mg C ha^{-1} (to the depth of 25 - 50 cm) [50]. Such differences may also be encountered in Miombo woodlands in Tanzania, with their wide vegetation diversity (section 4.0). In contrast, vegetation clearing, burning and the consequent erosion of bare soil are mostly responsible for decline in SOM due to physical removal of C. This C may also be emitted as CO_2 into the atmosphere, thus causing the greenhouse gas effect [2, 95].

10.3 Influence of climate on SOC stocks

Climatic conditions, specifically temperature and rainfall, may contribute to increase or decrease SOC stocks, depending on their influence on plant productivity and decomposition rates [10, 50, 95]. Higher temperatures may increase biomass production and may also lengthen the growing period, thereby increasing C additions to the soil, leading to increases in SOC stocks.

On the other hand, much higher temperatures, as encountered at low altitudes, are likely to speed up the decomposition of OM, leading to a decreases in SOC stocks [10,27, 37]. The relationship between temperature and soil organic carbon is also greatly affected by precipitation (and thus soil moisture). Thus, SOC generally increase from warmer to cooler, and from drier to wetter, locations [41]. However, excessively high soil moisture contents will lead to anaerobic conditions within the soil and decreases in decomposition rates, thus further increasing SOC storage [96].

10.4 Influence of soil type and soil properties on soil organic carbon storage

Soil type affects SOC variability due to the effect soil nutrient status of different soils has on biomass production [97]. Higher soil nutrient levels are generally observed in soil types with high contents of fine soil particles (e.g. clay). Several studies have reported a good correlation between clay contents and SOC stocks [73, 98.99]. This is so because clays provide both physical and chemical mechanisms to protect or shield SOC from microbial decomposition. The SOC can be trapped or occluded in the very small spaces between clay particles, making the carbon physically inaccessible to micro-organisms and therefore slowing down its decomposition [95]. In addition, clay provides chemical protection to SOM decomposition through adsorption of SOM onto its surfaces, which again retards SOM decomposition by microbes [95]. Therefore, different soil types differ in their SOC stocks due to variations in their physico-chemical properties, especially texture and soil moisture. Studies by [42] on different soil types under different land use types in the Mediterranean environment in Spain reported variations in SOC storage in different soils as follows: Vertisols and Calcisols stored an average of 68 Mg C ha^{-1} while Arenosols and Leptosols stored an average of 44 Mg C ha^{-1} under forest land use type. The differences in SOC storage in those soil types could be associated mainly with varying levels of clay contents, which consequently affect soil moisture retention [42, 95]. Differential C storage in Miombo woodland soils has already been highlighted (section 4.0). Thus, soils differ in C storage capacity due to their types and properties.

10.5 Distribution of SOC with soil depth

Globally, the relative distributions of SOC with soil depth have been reported to have strong association with vegetation types, soil properties and climate [42, 89, 95]. However, the rate of cycling of SOC at different depths across different vegetal cover is still not clear [76, 100]. Studies on SOC showed highest levels of C at the surface horizons, decreasing quickly with increasing soil depths and then sometimes changing slightly after a certain depth [78]. Studies of [76] reported SOC levels for the soils of the Himalayan zone in India to decrease from 24.3 g kg^{-1} in the 0-20 cm layer to 0.2 g kg^{-1} in the underlying 40-60 cm layer.

10.6 Parent material

The underlying geological material from which soils were formed can influence the amount of organic carbon that is stored in overlying layers due to influence of parent material on soil properties [101]. For example, [102] in southeastern Nigeria showed that forest soils developed over a shale lithology accumulated higher SOC stocks than soils developed from sandstone or coastal plain sands. His explanation was that the physico-chemical properties (e.g. soil texture, moisture, OM) of soils vary depending on the nature of their parent materials, and these properties can influence SOC storage.

Studies by [103] in Tanga (northern Tanzania) indicated the most important soil forming rocks in that area to be unconsolidated marine sediments, strongly weathered terrestrial sediments of the Karoo age, sandstone, limestone, dolomites, granites, gneisses of various mineral compositions, schist, ferromagnesian rocks and volcanic ash. Soils developed from those parent materials differed in their physico-chemical properties and had different quantities of carbon. Thus, different parent materials influence C storage differently.

11.0 CONCLUDING REMARKS

The analysis in of this review leads to the following major conclusions:

Miombo woodland soils differ in types, physico-chemical properties and varied potential in C storage. This is due to differences in topography, vegetation types, parent material, climate and human induced factors such as fires, grazing and deforestation. Each soil type would need specific land management and conservation strategies to stabilize SOC stocks for enhancing C storage for climate change mitigation. Enhancement of SOC stocks/storage that could contribute to climate change mitigation when forest/soil management is responsive to existing conditions in the field is recommended.

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