Chapter

Land Use Change Affects Soil Organic Carbon: An Indicator of Soil Health

Lucy W. Ngatia, Daniel Moriasi, Johnny M. Grace III, Riqiang Fu, Cassel S. Gardner and Robert W. Taylor

Abstract

Soil organic carbon (SOC) is a major indicator of soil health. Globally, soil contains approximately 2344 Gt of organic carbon (OC), which is the largest terrestrial pool of OC. Through plant growth, soil health is connected with the health of humans, animals, and ecosystems. Provides ecosystem services which include climate regulation, water supplies and regulation, nutrient cycling, erosion protection and enhancement of biodiversity. Global increase in land use change from natural vegetation to agricultural land has been documented as a result of intensification of agricultural practices in response to an increasing human population. Consequently, these changes have resulted in depletion of SOC stock, thereby negatively affecting agricultural productivity and provision of ecosystem services. This necessitates the need to consider technological options that promote retention of SOC stocks. Options to enhance SOC include; no-tillage/conservation agriculture, irrigation, increasing below-ground inputs, organic amendments, and integrated, and diverse cropping/farming systems. In addition, land use conversion from cropland to its natural vegetation improves soil C stocks, highlighting the importance of increasing agricultural production per unit land instead of expanding agricultural land to natural areas.

Keywords: agriculture, land use change, organic carbon, soil health

1. Introduction

The basis and essence of life on earth depends on soil health, and its main indicator is soil organic carbon (SOC) content [1, 2]. Soil health has been defined as the capacity of a soil to support ecosystem functions and sustain environmental quality and biological productivity, while promoting plant and animal health [3]. Through plant growth, soil health is connected with the health of humans, animals, and ecosystems within its domain [4]. The SOC is an indicator of soil health and is an important component of the soil ecosystem [5, 6]. Deb et al. [7] indicate that the presence of organic carbon (OC) in soil is a key determinant for soil quality and productivity. In addition, organic matter is a key influencer on physical, chemical, and biological soil attributes [8]. The SOC stock exhibit the long-term balance between additions of OC from different sources and its losses through different pathways [9].

The term SOC is defined as C in soil derived from organic origins and soil organic matter (SOM) is generally considered to contain approximately 58% SOC.

Soil organic matter is a mixture of materials including particulate organics, humus, fine plant roots, living microbial biomass as well as charcoal [10]. Two words have commonly been used in reference to SOC; C sequestration and C storage. Carbon sequestration is the process of transferring carbon dioxide (CO_2) from the atmosphere into the soil which can be achieved through plants, plant residues and other organic amendments which are retained in the soil as part of SOM [10, 11]. Carbon sequestration in soil can range from short-term to long-term [12]. However, carbon storage in soil is defined as increase in SOC stocks over time, but it is not necessarily associated with a net removal of CO_2 from the atmosphere [12]. Soil storage of OC for longer time periods is preferable in terms of greenhouse gases mitigation, however, mineralization of SOC is important in terms of soil fertility [12, 13]. Soil health reflects the capacity of a soil to support both the agricultural production and provision of other ecosystem services [14]. Therefore, evaluation of soil health is essential because soil is a critically important component of the earth's biosphere whose, functionality is critical in the production of food and fiber as well as maintenance of environmental quality [15, 16].

In the soil profile, approximately 615 Gt of OC is stored in the top 20 cm, 1500 Gt of OC stored in the first meter, and 2344 Gt of OC is stored in the top three meters of soil [17, 18]. However, approximately 9 Gt C is anthropogenically released to the atmosphere annually from fossil fuel sources and ecosystem degradation [10]. Previous studies have illustrated that conversion of forest or natural vegetation to agriculture leads to an overall loss of SOC [5, 6, 19]. Through soil supply of plant macro and micronutrients, soil health, mediated by SOC dynamics is a major determinant of global food and nutritional security [4]. The projected increase of human population by 2050 will double food demand and put immense pressure on natural resources [20]. Therefore, one of the greatest challenges will be to increase food production by maintaining ecosystem services [21].

2. Importance of soil organic carbon

Soil organic C provides ecosystem services that are essential to human well-being for example climate regulation, water supplies and regulation, nutrient cycling, erosion protection and enhancement of biodiversity [2, 22–24]. In addition, SOC exerts an influence on many soil properties, for example water holding capacity, aggregate stability, total nitrogen, pH and cation exchange capacity [5, 6]. Increasing SOC can mitigate GHG emissions, benefit agricultural productivity through improvements in soil health, and improve environmental quality [25].

Under long-term management practices SOC pools influence soil quality, C sequestration pathways, and crop productivity [9]. It has been demonstrated that high SOC levels can enhance soil fertility and health, improve water infiltration, improve soil structure, enhance moisture retention and increased crop yield [26, 27]. A positive relationship has been reported between SOC content and soil nutrient status and crop yield [28, 29]. Since SOC content influences almost all soil functions and it is easily measurable, it can be a suitable indicator of the soil capacity to supply ecosystem services [22, 23].

3. Effects of climatic conditions on soil organic carbon

Generally, SOC stocks increase with decreasing mean annual temperature [30], whereby, cold, humid climatic regions exhibit C rich soils [31]. Decomposition releases to the atmosphere most of the C added to the soil through litter deposition, only a limited fraction becomes humus [10]. Both moisture and temperature influence the rate of litter decomposition through their effects on microbial activity [32]. In addition, both moisture and temperature also exhibit strong control of humus decomposition [10].

4. Land use change affect soil organic carbon and ecosystem services

Globally, there has been increased land use change from natural vegetation to agricultural land and urban areas as well as intensification of agricultural practices [33, 34]. These changes results in large increases in energy, water, and fertilizer consumption, as well as considerable losses of biodiversity [33]. The growing human population has driven both the land use change and land use intensification in order to meet global demand for food, water and energy [35]. However, conversion of forest or natural vegetation to agriculture leads to an overall loss of SOC [2, 5, 6, 19] (**Figure 1**), resulting in efforts to restore SOC in agricultural soils [36, 37]. Once soil is cultivated for agricultural production, SOM is rapidly decomposed as a result of modifications in conditions such as aeration, water content and temperature [38]. Land use change could affect soil functions that directly or indirectly relate to SOM, as a result of its capacity to retain water and nutrients as well as provide other ecosystem services [39, 40]. For example, changes in the SOC stock could result in significant impacts on the atmospheric C concentration [10]. Carbon dioxide is the main greenhouse gas responsible for global warming [41]. Soil organic C balances

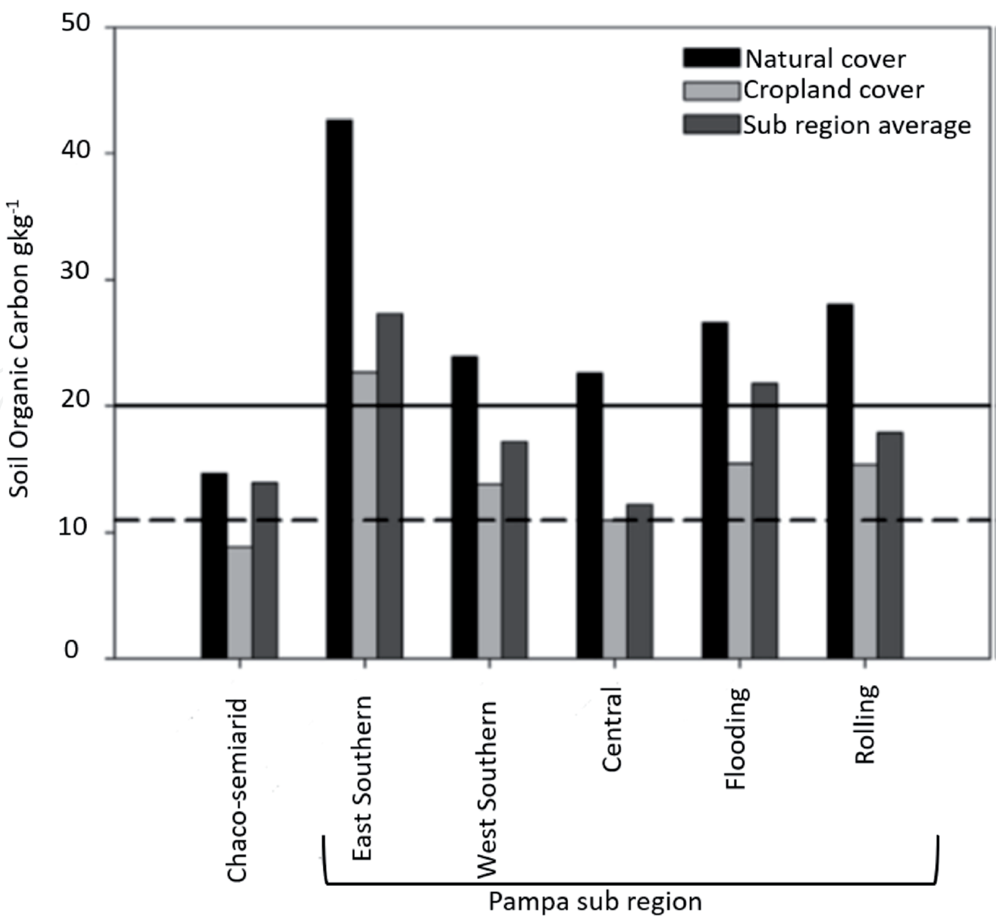

Figure 1.
Averages concentrations of soil organic carbon in semiarid Chaco and Pampa's sub-regions. Full line indicates critical thresholds proposed for temperate regions, and dashed line is for topical regions. Modified from [2].

are associated with CO_2 sequestration [36]. As a result, SOC stock is considered an intermediate ecosystem service that contributes to climate regulation [10].

Agricultural production can be increased by increasing cropland area or increasing productivity per unit area. When agricultural production increases as a result of land use change from natural cover areas to crop production agriculture, overall SOC mediated ecosystem services supply decreases [2] (**Figure 2A**). It was indicated that land use change from native forest to pasture (+8%), crop to pasture (+19%), crop to plantation (+18%), and crop to secondary forest (+53%) increased total C stocks, as well as SOC mediated ecosystem services (**Figure 2B** and **C**) whereas changes from pasture to plantation (−10%), native forest to plantation (−13%), native forest to crop (−42%), and pasture to crop (−59%) reduced total C stocks [17]. Generally, land use change from all other uses to cropping or monocultures result in losses of SOC [10]. In addition, Montgomery [42] indicated that accelerated soil erosion associated with conventional agriculture could occur at rates up to 100 times greater than the rate at which natural soil formation takes place. Additionally, peatlands have been drained for agricultural purposes [43]. Peatland store much more organic C in form of different C functional groups compared to upland. For example; in Apalachicola National Forest, the wetlands dominated by cypress (**Figure 3A**) and spikerush and water lily (**Figure 3B**) contain more alkyl, methoxyl, O-alkyl, aromatic, phenolic and carboxyl C compared to upland (**Figure 3C**). However, globally, peatland drainage causes carbon-rich peat to disappear at a rate 20 times greater than the rate at which the peat accumulated [44]. As a result, SOC affect both climate change and crop production in agricultural soils [9].

Soil management practices that sustain and enhance carbon stocks are crucial if we are to overcome near-term challenges and conserve this valuable resource for future generations. As a result of soil C loss during the past 25 years, one-quarter of the global land area has suffered a decline in productivity and the ability to provide

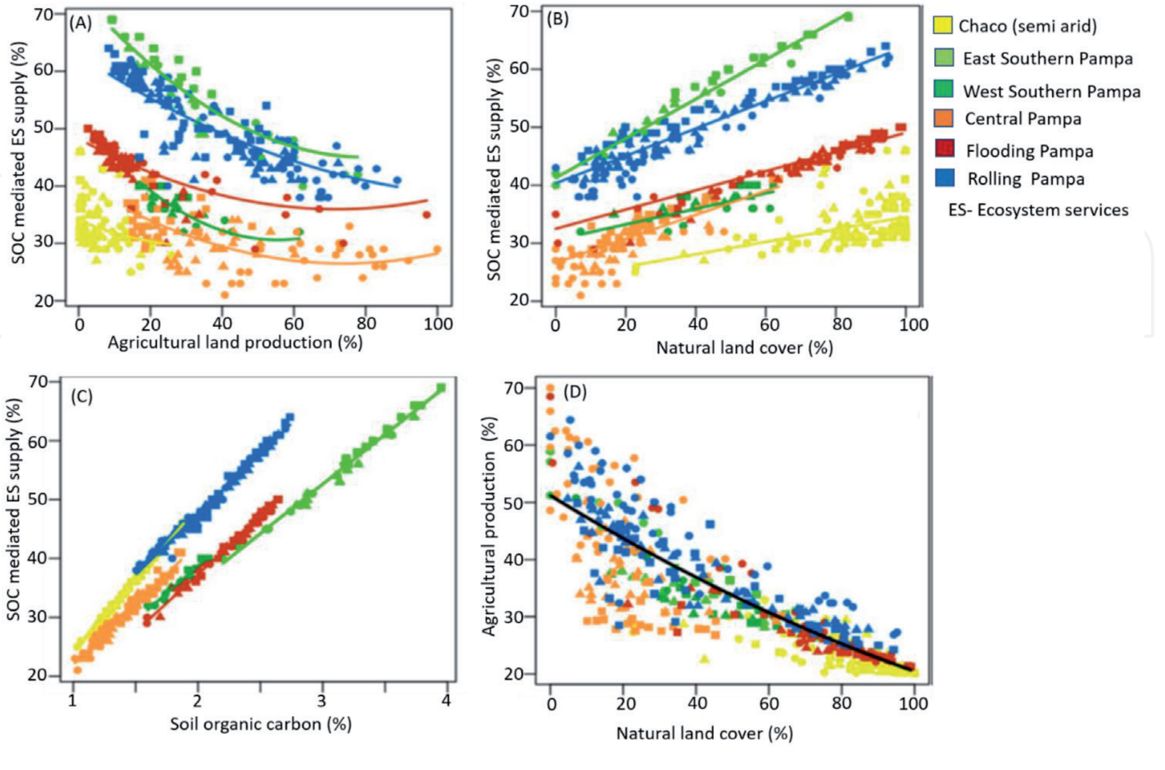

Figure 2.
Relations between ecosystem services mediated by SOC versus (A), agricultural production (B), natural cover (C), SOC and (D), relationship between agricultural production and natural cover. Modified from [2].

ecosystem services [39]. However, it has been observed that land use change from cropland to pasture or cropland to permanent forest results in the greatest gains of SOC [10] (**Table 1**). For example, Conant et al. [45] indicated that land use conversion from cropland to grassland improve soil carbon stocks. However, over time grassland area has been shrinking and arable land area expanding, indicating continued conversion of grassland to croplands [46]. In some cases where natural land cover has increased in expense of agricultural land cover, agricultural production

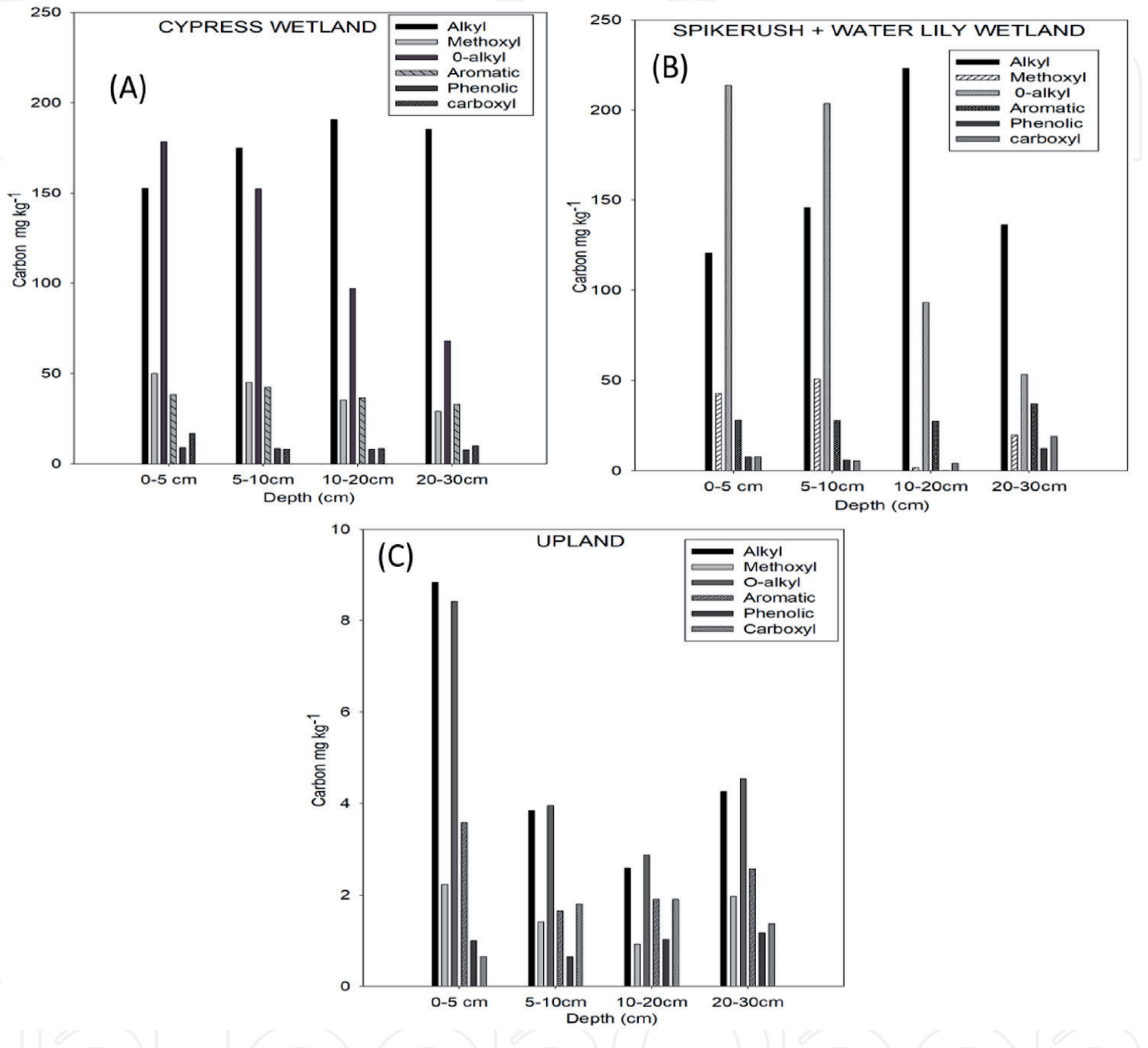

Figure 3.
Quantification of carbon functional groups in Apalachicola National Forest; which includes (A) cypress wetlands, (B) spikerush+water lily wetlands and (C) upland.

	Soil carbon change (%)		
Treatment	**Initial**	**Final**	**Change (%)**
Conversion: Cultivation to grass	0.97	1.35	39.2
Conversion: native to grass	2.97	2.55	−14
Fertilization	3.44	3.85	11.8
Grazing	2.62	2.89	9.99
Reclamation	8	15.9	98.8

Table 1.
Changes in soil carbon concentration presented by type of management change implemented. Modified from [45].

has been reported to decrease (**Figure 2D**). With increasing human population, this trend highlights the importance of increasing agricultural production by increasing crop yields per unit land area rather than expanding cropland and/or pasture over natural areas [2].

5. Increasing organic carbon stocks in agricultural soils

Agricultural systems are dependent on maintenance of four major functions; nutrients cycling, carbon transformations, soil structure maintenance, and regulation of pests and diseases [14]. Increasing SOM in agricultural soils contribute to food security and adaptation to climate change as well as mitigation of climate change [12]. SOM has a major role in soil fertility and water retention [47]. Therefore, SOM indirectly contributes to agricultural productivity and consequently to food security [12]. Management practices can influence SOC stocks by either decreasing SOC losses or increasing C inputs to soils. When OC input to a soil is larger than the OC outputs by mineralization or erosion, the SOC increases [12]. Below are technological options to manage SOC in agricultural ecosystem.

5.1 No-tillage and conservation agriculture

Soil organic matter is considered an important indicator of soil quality and health, which can be impacted by crop production practices such as tillage [48]. Tillage has the potential to increase the rate of C mineralization through breaking larger macro aggregates, mixing crop residues and exposing protected SOC in the aggregates to soil microorganisms [5, 6, 49, 50]. In general, tillage is considered to increase SOC mineralization as a result of mechanical and rain induced disruption of soil aggregates and the consequent release of CO_2. Hence, conservation tillage/no-tillage has been considered as a suitable practice to maintain or increase SOC stocks compared to conventional tillage [12, 51, 52]. Conservation tillage practices such as no till can enhance assimilation of SOC by decreasing soil disturbance and increasing crop residue accumulation in comparison to conventional tillage [12, 25, 48, 53]. For example; Blanco-Canqui and Lal [54] indicated an increase in SOC with increasing crop residue retention, whereby 16.0 t C ha^{-1} of SOC was reported without straw additions, 25.3 t SOC ha^{-1} with 8 t ha^{-1} of straw added and 104.9 t C ha^{-1} with 16 t ha^{-1} of straw added.

Global meta-analyses and reviews have recently confirmed that SOC stock increases in the upper soil layers (0–15 or 0–20 cm) under no tillage, but generally has low to non-significant effects on SOC stocks over 30 cm depth or deeper [51, 55–58] (**Figure 4**). In addition to carbon sequestration, conservation tillage can reduce CO_2 emissions [60]. Accumulation of SOC exhibit a positive correlation with the sequestration of atmospheric CO_2, while oxidation of SOC, as a result of practices such as tillage, can contribute to CO_2 emission from agricultural fields [48]. For example, CO_2 emission in conventional tillage was 29% greater than in no till in a loamy soil as reported by Bista et al. [61].

5.2 Irrigation

Irrigation may have similar effects on SOC decomposition in varying scenarios, but, its effects on primary production are likely to be much higher in arid and semi-arid areas compared to humid regions with dry summers [62]. It is reported that irrigation exhibited strong positive effects on SOC stocks in desert soils, positive effects in semi-arid areas, but no consistent trend was observed in humid areas [12, 62]. Further, it is emphasized that SOC stocks are dependent on climate and initial SOC content [62].

5.3 Increasing below-ground inputs

Below ground OC inputs, which includes roots and associated inputs, contribute more to SOC compared with above ground inputs [59, 63, 64] (**Figure 5**). For example, Kätterer et al., [63] reported long-term experimental results which indicated that root derived C was 2.3 times higher than that derived from above ground plant residue. Rasse et al. [64] estimated that mean residence time in soils of root derived C is 2.4 times compared with that of shoot derived C, indicating that root C has a longer residence time in soil compared to the shoot C.

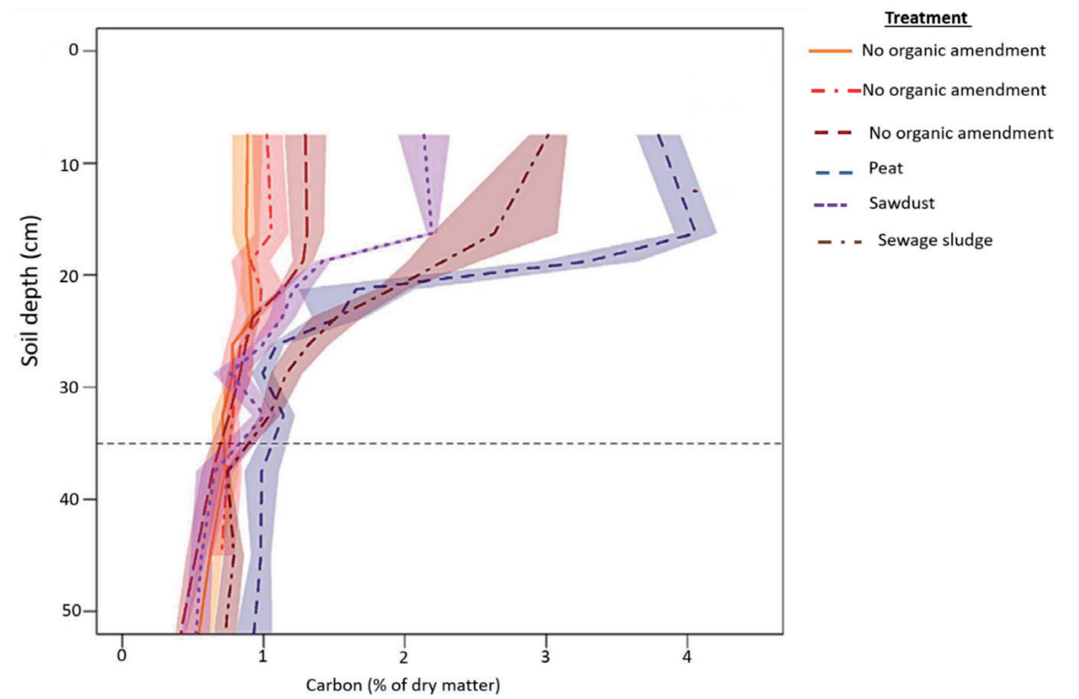

Figure 4.
Soil carbon content with depth. Shaded areas represent standard error of the mean. Data from long-term field experiment in Ultuna. Modified from [59].

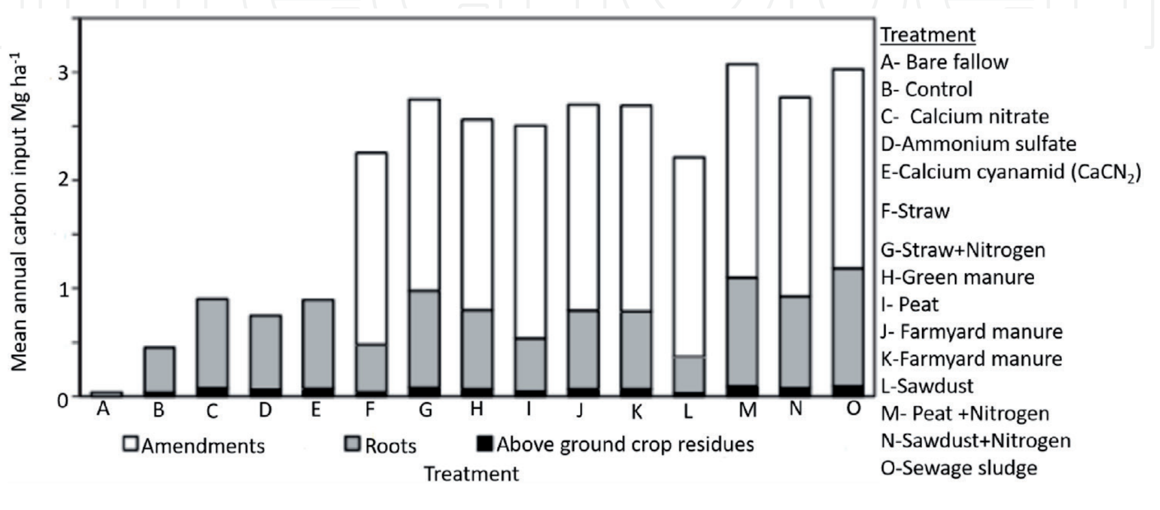

Figure 5.
Mean annual carbon inputs through above-ground crop residues, roots including rhizodeposition to equivalent topsoil depth (1957–2008), and organic amendments (1956–2008). Modified from [63].

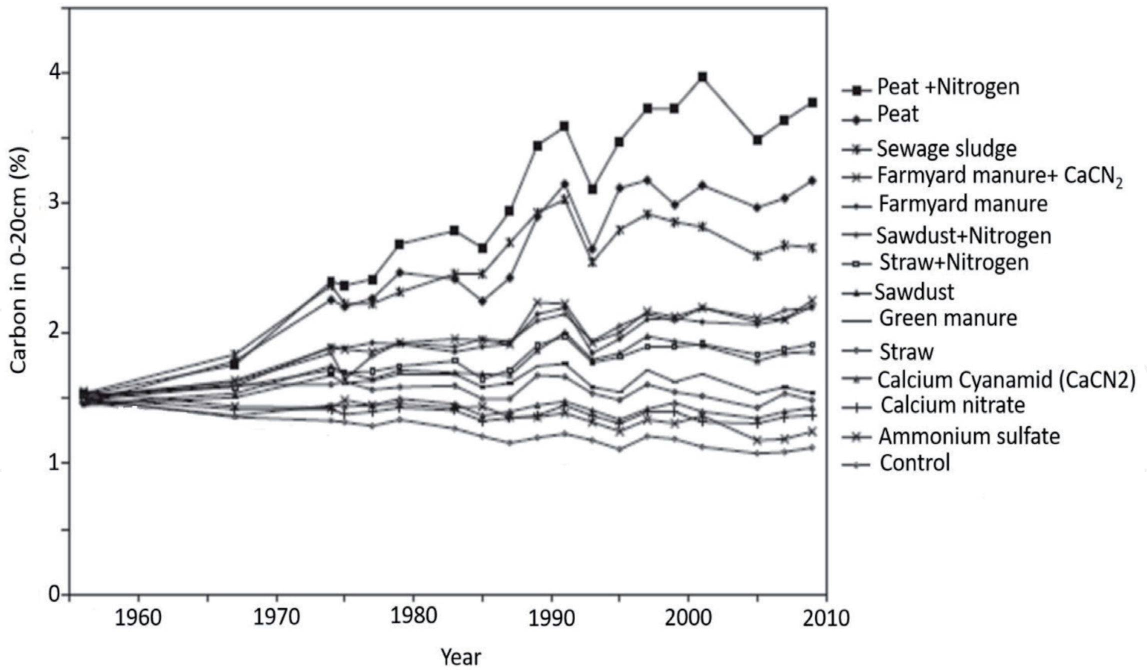

Figure 6.
Topsoil carbon concentrations over time in the Ultuna long-term soil organic matter experiment. Modified from [63].

5.4 Organic amendments

Organic amendment inputs can promote a buildup of SOM and hence SOC [65] (**Figure 6**). Menichetti et al. [59] reported that application of organic amendments affected SOC in the topsoil resulting in fourfold increases in C stock. Organic residues and wastes can be applied to soil, as fresh organic matter, after composting, methanisation, or pyrolysis [12]. However, the effects of residue quality on long term SOC is still a matter of debate [12]. Previous studies have indicated that the most labile and easily degradable compounds contribute more to SOM in the long term than recalcitrant materials such as lignin, this is especially common in clayey soil [66]. There are three explanations to this finding, which include: 1) long lasting SOM are mainly derived from microbial materials [67, 68]; 2) substrates that are easily degradable are processed with a high microbial C use efficiency [69], and 3) soluble compounds could be protected between mineral surfaces [12].

5.5 Integrated, and diverse cropping/farming systems

Compared with monoculture, introduction of crop diversity increases SOC which improves soil health [70]. Whereby, a combination of diversification within a cropping system and no-till soil management can help to improve SOC [71]. Increased plant diversity can enhance positive soil feedbacks on residue decomposition and soil SOM stabilization and may contribute to C accumulation in soils with rotated crops [72]. Further, Maiga et al. [71] demonstrated that use of diverse 4-year crop rotations for longer duration (>24 years) enhanced SOC, overall C and nitrogen fractions, and soil aggregation in comparison with those under 2-year corn–soybean rotations.

6. Conclusion

Soil organic C is an important indicator of soil health. Soil health is a major component of one health, which encompasses human, animal, and environmental health [73].

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Soil organic C promotes land productivity and provides ecosystem services. Since SOC content influences almost all soil functions and is easily measurable, it can be a suitable indicator of the soil capacity to supply ecosystem services. This hypothesis reinforces the suitability of SOC as an appropriate indicator for soil management decisions, land use planning, and regulation. However, the rapidly increasing global human population is exerting enormous pressure on natural resources, as a result of the need to provide food and fiber to supply demands from this growing population. Consequently, there has been conversion of natural land areas to agricultural land globally in pursuit of meeting the human demand for food and fiber. This land use change has resulted in losses of SOC, which negatively affects productivity and diminish ecosystem services. Previous work has demonstrated that conversion of agricultural land to its natural cover provides positive feedback in terms of increasing soil C stocks. This finding highlights the importance of increasing agricultural production by increasing crop yields per unit area rather than expanding cropland and/or pasture to natural areas for long-term sustainability. In addition, there is need to invest in technological options that enhance SOC stocks in agricultural land. These options include no-tillage/conservation agriculture, irrigation, increasing below-ground inputs, organic amendments and integrated, diverse cropping/farming systems.

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