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Soil Carbon Sequestration: A Step towards Sustainability

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Nowadays, sustainable agriculture is a major concern of the whole world, all leading agricultural countries like China, USA and India etc. are working together in several organizations such as FAO, World Food Organisation to overcome the problem of environmental health and food security in upcoming years to meet the food demand goal in 2050 in sustainable manner. Carbon present in soil naturally is termed as soil carbon which is directly related to organic matter present in soil, higher the soil carbon more will be the crop yield. Most of the soil carbon has been released in the atmosphere due to conversion of uncultivated land into cultivated agricultural land. Bringing back that released carbon back to the soil with several methods is known as soil carbon sequestration. In this paper, relation of soil carbon sequestration has been discussed with respect to organic farming, natural farming respectively. Changes carried out in traditional agronomical practices have potential in enhancement of soil carbon sequestration. Practices such as conservation tillage, growing cover crop, proper nutrient management, residue management etc. have significant capacity to sequester carbon in the soil, along with that various challenges which are being faced during carbon sequestration are also considered in this paper. Soil carbon sequestration is a temporary solution to Carbon dioxide enrichment, but it is challenging to operationalize due to

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obstacles such as measuring the soil's carbon stock, permanence, carbon pools, separation, and the soil's propensity to approach saturation levels. This chapter aims to raise knowledge of the capability of soils to absorb and store atmospheric carbon dioxide in long-lasting pools, reducing climate change.

Keywords: Agronomic practices; carbon sequestration; natural farming; organic farming; sustainable agriculture.

1. INTRODUCTION

1.1 Soil Carbon

Soil carbon refers to the carbon that is kept in soils all over the planet. This is composed up of carbonate minerals produced from soil-found organic and inorganic carbon. In the context of the global carbon cycle, soil carbon functions as a carbon sink for biogeochemistry, climate change mitigation, and the creation of global climate models. Although the majority of the carbon on Earth exists in the seas, three times as much of it is stored in soils, which make up around 75% of the carbon pool on land. Soils are essential for maintaining a healthy global carbon cycle. According to Paustian et al. [1], around 50 Pg C are thought to have been released into the atmosphere from soils globally as a result of the conversion of natural land to cultivated agricultural land. For forests, wetlands, and farmland and grasslands, the mitigation potential from soil carbon is 9%, 72%, and 47%, respectively. In addition to helping to mitigate climate change, soil carbon is crucial to land-based initiatives to reduce atmospheric carbon dioxide, stop carbon emissions, and provide ecosystem services. Globally, soils contain three times as much carbon as the atmosphere, and scientists have known for decades that soil organic matter regulates climate. The historical loss of carbon from this pool and the potential for future accelerated loss under warming scenarios have both been noted in recent study. Thus, in response to anticipated land use change and climate change, soil organic carbon (SOC) plays a role in both repairing a carbon sink and preventing future CO_2 emissions.

1.2 Soil Carbon Sequestration

Carbon sequestration involves the long-term storage of carbon dioxide or other forms of carbon in the oceans, soils, vegetation (particularly forests), and geologic formations in order to prevent or delay global warming. It is a means of reducing the build-up of greenhouse gases, which are emitted as a result of human activity [2-4]. The net removal of carbon dioxide (CO_2) from the atmosphere or the prevention of emission of carbon dioxide (CO_2) into the atmosphere by terrestrial ecosystems is referred to as carbon sequestration. All chlorophyllous plants absorb CO_2 from the atmosphere during photosynthesis as part of the elimination process [5-7]. The soil's organic matter and the biomass of plants (their trunks, branches, leaves, and roots) are where this carbon is kept. The terrestrial carbon sequestrations are dependent on various ecosystem conditions and land use strategies that support established plants for longer periods of time. During photosynthesis, plants take in carbon, and during respiration, they release some of it back into the atmosphere [8-12]. When plants die and decay, the carbon that is still present in their plant tissue is then devoured by animals or given to the soil as litter. As soil organic matter, carbon is mostly kept in the soil (SOM). SOM is a complex mixture of carbon compounds that includes bacteria, fungi, protozoa, nematodes, decomposing plant and animal tissue, and carbon bonded to soil minerals [13-15]. Carbon can be swiftly released back into the atmosphere or can be trapped in soils for ages. The quantity and duration of carbon storage in soil are both influenced by climatic factors as well as by natural vegetation, soil texture, and drainage.

1.2.1 Potential of soil carbon sequestration to reduce the impact of global warming

According to Ruddiman [16], soils have lost between 140 and 150 Gt C (or 510 and 550 Gt CO_2; Sanderman et al., [17]) due to cultivation since the beginning of agriculture roughly 8,000 years ago. It has been argued that soil C sequestration might be a substantial greenhouse gas (GHG) removal technique because it is known that optimum management practises can restore some, if not all, of this lost carbon [18]. (also called negative emission technology, or carbon dioxide removal option; Smith, 2016). Nevertheless, a recent systematic assessment by Fuss et al. [19] predicts a yearly technical capacity of 2–5 Gt CO_2/year. Worldwide estimates of soil C sequestration potential vary significantly. Economic potential estimates are at the lower end of this range [20] (Smith et al., 2008).

1.2.2 Soil carbon sequestration in relation to organic farming

The greatest terrestrial carbon resource is represented by soil organic carbon (SOC) reserves, albeit these stocks normally drop once natural regions are converted for agricultural use [21]. As agricultural soils make up a large amount of the planet's land area, reestablishing SOC sequestration in these systems is crucial for reducing climate change [22]. Moreover, enhancing the quick cycling of particulate organic matter, a source of nutrients for crop output, may be accomplished by speeding up the sequestration of SOC [23]. The ecological intensification of agricultural systems makes the assertion that maintaining food production while boosting SOC sequestration may be achieved by optimising vital ecosystem processes like soil C cycling [24]. In fact, compared to conventional farming (CF), organic farming (OF), one of the major ecological intensification methods now in use globally in terms of surface area [25], boosts top SOC stocks by 3.50 Mg C/ha on a worldwide average [26]. The causes of this rise are unclear, but it is clearly influenced by the large rates of external C inputs (such as manure) that are generally used in OF [27,28]. However when contrasting conventional and organic farms with low manure application rates (LMR; European livestock units per hectare 1, Gattinger et al., [26]), increases in SOC stocks are also found. Additionally, because crop output is on average 20% to 25% lower in OF, C inputs to the soil via primary crop leftovers are reduced [29,30]. Hence, the higher SOC stocks observed under organic management of agricultural areas cannot be entirely explained by changes in farming systems in the quantity of C inputs entering the soil (manure and crop output).

The overall impact of long-term changes in soil carbon inputs and outputs is represented by soil organic carbon stocks [31]. As a result, variations in SOC losses from organic matter decomposition in farming systems may be changing SOC sequestration by increasing the SOC stores found under OF. According to Garca-Palacios et al. [32] and Parton et al. [33], the morphological and chemical quality of plant residues, soil decomposers, and site climate all play major roles in the breakdown of soil organic matter. The quality of plant residues (such as leaf and root N concentrations) feeding soil decomposers may be a primary driver of soil C losses when comparing SOC sequestration in OF vs. CF under the same climatic circumstances [34]. In this line, labile plant residues (e.g., greater N content) are often associated with quicker breakdown rates and consequently increased soil C losses [35,32]. Yet, the stability of biological materials might potentially have the opposite effects. According to the Microbial Efficiency-Matrix Stabilization framework, the breakdown of labile litter increases the amount of microbial residues that are chemically bound to the mineral soil matrix, enhancing the stability of the soil organic matter [36]. In order to understand the mechanisms governing SOC sequestration reactions to OF, it may be helpful to take into account crop residue features critical for decomposition [34]. To assess whether ecological intensification should be pursued as an effective land management technique helping to reduce climate change through these greater SOC sequestration rates, a thorough knowledge of the processes behind enhanced SOC sequestration is essential.

An increase in SOC could facilitate soil carbon sequestration. According to Iwasaki, Endo, and Hatano [37], adding organic matter over a lengthy period of time boosts soil carbon sequestration. According to Li et al. [38], SOC sequestration rises with addition of plant-derived C. In order to boost soil fertility, SOC sequestration must often be accompanied by increased soil P and S retention in addition to N. These are the other essential nutrients needed to create a pool of SOM that was more stable [39]. Natural farming, which entails low-input organic farming with weed cover management, has the potential to boost soil carbon sequestration, but attention must be paid to the nutrient balance for long-term management.

1.2.3 Soil carbon sequestration in relation to natural farming

Analytical report of Gurukul Farm Kurukshetra on affect of natural farming in organic carbon sequestrsation.

According to preliminary research and observations at the 180-acre Gurukul farm in Kurukshetra, natural farming may serve as a potential model for Indian agriculture. There has been a remarkable improvement of soils in respect to organic carbon (OC), nutrients, and biological health, according to the analytical findings from the several establishments (CCS HAU Hisar, PAU Ludhiana, IIFSR Modipuram, and Kurukshetra University). The analysis at CCS HAU in Hisar and IIFSR in Modipuram revealed that the average amount of organic carbon in soil samples taken from Gurukul Farm in June 2017 amounted 0.61 and 0.62%, respectively. In the IIFSR and CCS HAU analyses, the 19 and 30% soil samples were found to be suffice/rich in OC (>0.75%). In June 2018, a year after the crops had been planted, soil samples were once more taken and examined at CCS HAU Hisar. It was found that 95% of the soil samples had high OC concentrations, with a mean OC percentage of 0.91% falling within the 0.82-1.12% range. Following the Kharif season in October 2018, more soil samples were taken for analysis at CCS HAU Hisar and PAU, Ludhiana, in order to corroborate the results. These findings showed that the average OC in the soil analysis reports by the various institutes was 0.84 and 0.78%. On a 180-acre farm, the effects of LBNF practises can be seen in the 49% rise in OC (from 0.61 to 0.91%) in only one year of operation and the continual preservation of average OC at a level of over 0.75% throughout the season. On the OC content of soil, changing seasons and crop management techniques may have an impact.

Organic Carbon Content: Ten soil samples were randomly selected from Gurukul Farm and examined at CCS HAU Hisar during the summer/Kharif season of 2017. Similarly, 16 soil samples were collected by the IFSR, Modipuram scientists for study of organic carbon, macronutrients, and micronutrients. found that 19% of the soil samples examined at IIFSR and 30% of those examined at CCS HAU Hisar fell into the rich group (>0.75%) for organic carbon.

Similar findings from the respective institutions showed that 10 and 12% of the soil samples had low levels of organic carbon (0.40%). The remaining samples were classified as having a medium level of OC concentration. The two universities' combined average OC was 0.61%.

In June 2018, 19 samples were once more randomly selected from 180 acres of Gurukul Farming Land and were evaluated in the soil testing lab of CCS HAU, Hisar, after a year. The astounding findings showed that 95% of the soil samples fell into the category of rich soil, with an average OC of 0.91% in the range of 0.82 to 1.12%. One-fourteenth of the soil samples tested had OC levels above 1.0%. Only one sample, with an OC of 0.45%, fell into the medium category.

Table 1. Organic carbon status of Gurukul farm (samples analysed at CCS HAU Hisar, Haryana)

Sr. No	Organic carbon %		
	June 2017	**June 2018**	**October 2018**
1	0.82	1.12	0.82
2	0.82	1.05	0.52
3	0.75	1.05	0.82
4	0.67	0.97	0.82
5	0.60	0.97	0.75
6	0.60	0.97	1.12
7	0.52	0.97	0.82
8	0.52	0.97	0.82
9	0.45	0.97	0.97
10	0.37	0.97	0.97
11	-	0.90	-
12	-	0.90	-
13	-	0.90	-
14	-	0.90	-
15	-	0.82	-
16	-	0.82	-
17	-	0.82	-
18	-	0.82	-
19	-	0.45	-
Average	0.61	0.91	0.84

The soil samples were again randomly collected from the farm in October 2018, and they were examined at soil testing facilities run by CCS HAU in Hisar and PAU in Ludhiana. The OC state of Gurukul Farmland was once again verified by these results, though on a considerably smaller scale, which may have been caused by seasonal changes. In the samples examined at CCS HAU Hisar and PAU, Ludhiana, the average OC was 0.84 and 0.78%, respectively.

90% (CCS HAU) and 70% (PAU Ludhiana) of the samples from the wealthy category (>0.75%) respectively. Only one sample out of twenty analysed at CCS HAU and PAU falls into the low category (less than 0.40%), while 30% of samples examined by both of the universities had OC more than 0.90%.

2. AGRONOMIC PRACTICES FOLLOWED TO ENHANCE SOIL CARBON SEQUESTRATION

CO2 levels are rising at a pace of 2.3 ppm annually, which is contributing to more environmental damage and global warming. Up to 30% of GHG emissions are caused by the agricultural sector. For humanity to survive, sustainable agriculture is crucial. Utilising various agronomic management techniques can aid in the sequestration of carbon. No-till or reduced-till techniques, nitrogen management, cover crops, crop rotations, green manuring, the use of animal manures, agroforestry, etc. are some examples of these techniques. Adoption of these many agronomic techniques will increase farmer revenue in addition to crop production. [Anonymus, Minnesota Board of Water and Soil Resources].

2.1 Conservation Tillage

Especially in corn and soybean rotations, Minnesota farmers are utilising conservation tillage more often than in the past. Numerous environmental and financial advantages of conservation tillage practises include reduced production costs, improved water quality, better nutrient retention, and reduced soil erosion. No-till as well as conservation tillage techniques have been shown to be effective at reducing soil erosion and offering other advantages [2-4,40,41]. As an added bonus, conservation tillage techniques sequester more carbon than traditional agricultural tilling techniques. There are a variety of advantageous tilling techniques; the most advantageous include no-till and strip till, which disrupt soils the least [42,43]. The amount of microbial biomass in the soil has evolved into a sign of improved nutrient retention, soil structure, and soil quality. Additionally, research has shown that tillage has a negative impact on beneficial microorganisms like bacteria and fungus, which are particularly good at storing carbon [42] [Zucker et al. (2016)] The only way to increase the retention of carbon in agricultural systems, however, is through the use of conservation tillage techniques. In addition to benefits like greater infiltration, nutrient retention, and decreased erosion potential, it has been demonstrated that coupling conservation tillage and cover crops greatly increases soil organic carbon. Landscapes are transformed by soil health practises and no-till farming (2019), according to Mbuthia et al. The benefits of no-till and cover crops are greater when used jointly than when used separately.In 2015, Mbuthia et al. [42]. Despite concerns about carbon sequestration, BWSR promotes conservation tillage and cover crops to preserve soil health, prevent soil erosion, and enhance water quality in nearby streams.

2.2 Cover Crops Store Carbon

When the land would otherwise be bare, such as before the main crop appears in springtime or after the autumn harvest, cover crops are sown to offer seasonal soil cover. By generating biomass on the soil's surface and below, cover crops sequester carbon. According to research, root biomass is where the majority of the soil's organic carbon is found. Carbon buried underneath lasts longer than it does in deposits on the surface. In the long run, cover crops safeguard soil carbon by producing aggregates that improve the general health and productivity of the soil by fostering beneficial root-zone fungi, bacteria, and invertebrates that also contribute to soil carbon. In 2015, Mbuthia et al.

Introducing cover crops to all tillage treatments improved soil organic carbon stock increases by 30% for no-till, 10% for chisel ploughed plots, and 18% for moldboard ploughed plots, according to a 12-year University of Illinois study [44].

By being planted in the late summer, cover crops can produce a significant amount of biomass both in the autumn and the following spring. A suitable option is winter rye since it resists decay better compared to other cover crops like oats or barley.

2.3 Management of the Necessary Nutrients

Chemical fertilisers, notably N2O, are a major cause of GHG emissions. In addition to this, the manufacture of fertiliser and the transportation of it are linked to GHG emissions. Using fertilisers wisely boosts crop yields and profitability, and through the process of soil organic carbon (SOC) mineralization, farmed soils have contributed roughly 50 Pg of CO_2 to the atmosphere [Lal R. Sequestering carbon in soils of agro-ecosystems (2011)]. Although studies show that nitrogen fertilisation reduces soil microbial activity over time, they also show that the use of fertilisers has significantly enhanced agricultural output [45]. For sustainable soil fertility and crop output, balanced fertilisers must be used continuously. According to Windeatt JH, et al. [46], crop residues and nutrients, particularly N, aid in the storage of up to 21.3–32.5% of carbon. The long-term impacts of nitrogen fertilisation on soils, however, are complex and still unknown. For instance, in the long-term trials conducted in Canada, SOC sequestration rates ranged from 50 to 75 g cm2 per year in soils with ideal cropping systems. Long-term tests in the Northern Great Plains (ND) have also demonstrated that N fertiliser boosted crop residue returns but generally did not increase SOC sequestration, which is the opposite of what research in the Great Plains has revealed. Liu Enke and others. A long-term study that was started in Northwest China in 1979 to determine the effects of fertilisation on SOC and SOC fractions across the entire soil profile, such as (0-100 cm) soil depth, was published by [47]. Six treatments made up the experiment: unfertilized (control), N fertiliser, NP fertiliser (nitrogen and phosphorous), straw plus N and P fertilisers (NP + S), farmyard manure (FYM), and NP fertiliser plus FYM (farmyard manure plus N and P fertilisers). As compared to the control treatment, the results showed that SOC storage in the 0–60 cm increased by 41.5, 32.9, 28.1, and 17.9% in the NP + FYM, NP + S, FYM, and NP treatments, respectively. The labile pool in the 0–60 cm of soil depth was also increased by the addition of organic manure and inorganic fertiliser. These findings demonstrate that among the forms of fertilisation under investigation, prolonged use of organic manure has the most advantageous effects on creating carbon pools.It may be inferred that the proper application of fertilisers in accordance with soil conditions can help to maximise carbon sequestration together with crop production and reduce emissions of various GHGs.

2.4 Application of Compost and Animal Manure

Compost is a substance that mostly consists of organic matter that has decomposed and is utilised to fertilise and condition agricultural soil. Animal manure is the animal excreta that is gathered from livestock ranches and barnyards and used to improve the soil. Manure application affects the C content of different agricultural fields and is crucial for maintaining the health of the soil as it is a source of carbon. Green manuring, as compared to applying a mixture of FYM along with green manure, stored more carbon in a maize-wheat cropping system, while FYM application alone increased carbon sequestration in the cropping system consisting of rice and wheat [48]. Composting improves the soil's C levels while simultaneously increasing net primary output [Baldi E et al. 2018]. According to a paper by Ren T, et al. [49], limiting the application of manures and organic fertilisers has an impact on soil microbes, nutrient regimes, and stable organic compounds in addition to stable organic compounds. The beneficial effects of mixing mineral fertilisers with organic manures were supported by Liu et al. Similarly, application of various organic materials, i.e., municipal solid waste (MSW), farm yard manure (FYM), sugar industry waste (filter cake), and maize cropping residuals, at 3 t C ha1 alone and with a full or half dose of NPK mineral fertiliser demonstrated that the utilisation of organic material (filter cake or MSW) has the best potential to improve improving SOC retention, WUE, and wheat yield in an irrigated maize-wheat cropping system [50].

All of this suggests that using organic fertilisers like compost and animal manure alongside synthetic ones is good for the environment and the health of the soil.

2.5 Performing Crop Rotations

The succession of crops cultivated in regularly occurring successions on the same plot of land is referred to as crop rotation. The subsequent crops could last for two or more years. Carbon sequestration is also impacted by variations in crop rotations, soil types, temperatures, and crop management techniques. Intensive cropping systems deplete soil organic matter (SOM), but balanced NPK fertilisation, the usage of organic amendments, and in a similar way the application of crop residues may boost carbon sequestration levels to 5-10 Mg ha1 annually as these amendments contain 10.7-18% C, which can also aid in the retention of carbon [Manadal B et al.]. Alternative sources of nitrogen include peas, lentils, alfalfa, chickpeas, sesbania, and other legume crops. Soil carbon can be stabilised by the use of crop rotations, particularly with legume cover crops, that contain carbon molecules that are probably more resistant to degradation by microbes. Syswerda et al. published the findings of a 12-year study of an organic management system which utilised different crop rotations. They claim that despite substantial weed control tillage, a rise in soil carbon sequestration was observed. The findings of a lengthy study that was carried out in Dingxi, Northwest China, between 2013 and 2015 were displayed in a rotation of spring wheat and peas in a semi-arid environment that was rain-fed. The different treatments included no-till with stubble retained (NTS), conventional tillage with stubble incorporation (TS), conventional tillage with stubble removed (T), and no-till with stubble retained (NTS). In addition, the average grain output over the course of the 3 years in NTS was higher than T and NT [51]. The SOC, microbial biomass carbon, and root biomass in NTS rose above T and NT. Alternative tillage and cropping methods have recently received a lot of interest as a way to reduce agricultural CO2 emissions. Different cropping techniques, such as cover cropping, ratoon cropping, and companion cropping, may aid in the sequestration of carbon. Row intercropping, strip intercropping, mixed cropping, and relay intercropping are all types of intercropping that can boost income and improve soil fertility.

Wheat + mustard, cotton + peanut, peanut + sunflower, wheat + chickpea, etc. are some examples of intercropping [Anon, "Mixed Cropping"]. Compared to conventional farming, organic farming may additionally boost soil organic carbon. According to research on the restoration of grasslands, legume species have more advantageous impacts on the restoration of grasslands than the use of mineral fertilisers due to their biotic and abiotic effects [52].

The information above demonstrates how choosing the right crop rotations for the soil and environmental conditions can be beneficial in the storage of carbon, which not only improves soil fertility but also lowers CO2 emissions into the atmosphere and increases farmer income. This is done while keeping in mind economic considerations.

2.6 Management of Residues

Following crop harvest, crop residues—detached vegetative components of crop plants—are purposefully left in agricultural fields to decompose. A tonne of cereal residue, for example, comprises 12–20 kilogramme N, 1-4 kg P, 7–30 kg K, 4–8 kg Ca, and 2-4 kg Mg. The yearly production of agricultural residues over the world is around 3.4 109 tonnes. If 15% of these total residues are applied to the soil, it can boost the C levels of the soil. Mulching is the practise of covering plants with detachable vegetation, such as compost, wheat straw or plastic sheets, in order to shield them from excessive evaporation and cold stress as well as to increase the amount of SOM in the soil.

Crop leftovers are crucial to managing SOC and enhancing the condition of the soil. Mulching increases soil moisture, decreases soil erosion, and, in a similar manner, decreases the depletion of carbon from the soil and agricultural leftovers, which are integrated into the soil to increase its organic matter. Due to higher carbon inputs and less soil disturbance, a direct seedling mulch-based farming strategy enhances soil organic matter. In the top 0–5 cm of the soil, mulch can improve soil organic matter (SOM) and carbon sequestration. It enhances the physical and chemical characteristics of the soil and can boost the annual carbon sequestration in soils used for agriculture by 8–16 Mg ha1.

Because of higher carbon inputs and reduced soil disturbance, mulch-based cropping techniques promote the development of soil organic matter. Direct seedling straw mulch has a potential to lessen heat stress because it increases soil organic carbon and N efficiency, decreases evaporation, boosts infiltration rate, and minimises tillage in lowland rice-based cropping systems. Increased net primary productivity (NPP) results from adding more residues to the soil. Many agricultural soils will exhibit C growth proportionate to increases in C inputs, despite having had their initial C levels drastically lowered by agriculture. The equilibrium between the the inputs of C from crop residue and the losses of C, which primarily occur through decomposition, determines the amount of C in the soil.

Soil C can be raised by increasing inputs of residues or by slowing down decomposition (hétérotrophic soil respiration). Decomposition rates of litter are also impacted by its quality. Results of a 4-month study were added to uncultivated and agricultural soils over three rates of straw residue and farm yard manure under controlled greenhouse conditions. The application of organic matter, particularly the incorporation of farm yard manure, led to a significant increase in the final soil organic carbon content, and a higher amount of soil organic carbon were stored in the cropland soil than in the uncultivated soil [53-55]. Two treatments of straw residue and farm yard manure incorporation were used into: a soil surface layer and a 0-20 cm soil depth. The findings demonstrated that agricultural soil and farmyard manure were more effective at storing carbon than uncultivated soil. According to the findings [56], it is important to pay closer attention to how organic residue management affects carbon sequestration.

All of this demonstrates how using crop waste and applying mulch can enhance soil microbial activity, reduce heat stress, aid in water storage, and increase soil organic carbon.

2.7 Using Improved Crop Varieties

The soil organic carbon can be increased by choosing enhanced crop varieties that can increase both above- and below-ground biomass. According to Machado et al. [57], crop species with extensive root systems have the ability to enhance SOC in soils subject to NT. Similar to this, Kell [58] asserts that by enhancing root development in crops used in agriculture, soil carbon storage can balance greenhouse gas emissions for the ensuing 40 years. All of this suggests that using crop types with superior root systems and higher yields can boost soil fertility while also increasing agricultural yields.

3. CHALLENGES IN CARBON SEQUESTRATION

Although there are many chances to use the carbon stock and sequestration capacity of various ecosystems' soils, there are also many obstacles that make this challenging in practise. Many of these difficulties include:

3.1 Measurement and Verification

It is challenging, time-consuming, and expensive to measure the carbon stock in soils. Due to sample mistakes, small-scale variability, and difficulties with measurements and analysis, changes within the range of 10% are exceedingly challenging to detect [59]. The annual increase in soil carbon stock is quite minimal, typically between 0.25 and 1.0 t/ha [Ravindranath et al. (2007)]. Due to methodological challenges with monitoring, verification, sampling, and depth, it is particularly harder to account for tiny gains or losses in soil carbon at different scales. Even if these little adjustments It is difficult to connect such changes to management or land use practices in a specific context when (gains or losses) are found. When the soil eventually reaches a stable state, its ability to sequester and hold carbon is likewise limited.

Sequestered carbon is found in the soil in a variety of pools with variable lengths of time spent in the ecosystem. These pools consist of:

Organic carbon stored in a passive, recalcitrant, or refractory pool has an extremely long residence time, ranging from decades to thousands of years.

Carbon stored in an active, labile, or rapid pool decomposes quickly, causing it to remain in the soil for a significantly shorter time. The typical residence period is between one day and one year.

Due to the slow rate of decomposition, carbon stored in a sluggish, stable, or humus pool has a lengthy turnover time. The typical length of stay is one year to ten years [60]

3.2 Permanentity

As the sequestered carbon can be quickly released back into the atmosphere as a result of breakdown or mineralization, this presents another difficulty with carbon sequestration in soil. Sequestered carbon is regarded as a temporary solution for reducing atmospheric carbon because of this. A number of meteorological, agrarian, and managemental factors influence the rate of carbon loss [60].

3.3 Separation

It is exceedingly challenging to identify and distinguish between the amounts of carbon that has been naturally sunk into the soil as a result of land use or management actions. The notion of separation calls for a distinction to be made between carbon sequestered or GHG emissions avoided owing to management intervention and those that would have happened because of natural events. Hence, methodologies to distinguish between carbon that is naturally sequestered and carbon that is captured as a result of human management are needed [61-63].

4. CONCLUSION

The extent and duration of the potential for SOC sequestration are limited. It is merely a temporary solution to the CO_2 enrichment caused by anthropogenic activity. Even with soil C sequestration, the atmospheric CO_2 concentration will keep rising. Thus, creating fossil fuel substitutes is necessary for a long-term solution. Although this concept seems interesting in theory, it is challenging to operationalize in practise due to a number of obstacles. Among these are the challenges associated with measuring the soil's carbon stock, permanence, the presence of carbon pools with varying carbon residence durations, separation, and the soil's propensity to approach saturation levels once the maximum amount of carbon that can be harvested has been attained. The majority of these issues have seen progress, but deliberate initiatives to improve carbon absorption and sequestration in the soil ecosystem have not yet gained widespread recognition among practitioners and policymakers. The purpose of this chapter is to raise knowledge of the capability of soils to absorb and store atmospheric CO_2 in long-lasting pools, hence reducing climate change. Researchers must to put up a lot of effort in addressing the issues preventing the general implementation of this endeavour.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Paustian K, Six J, Elliott ET, Hunt HW. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry. 2000;48(1): 147-63.
   DOI: 10.1023/A:1006271331703
2. Lal R. Sequestering carbon in soils of agro-ecosystems. Food Policy. 2011;36: S33-9.
   DOI: 10.1016/j.foodpol.2010.12.001
3. Lal R. Tillage in lowland rice-based cropping systems. In: Soil physics and rice. Philippines: IRRI. 1985;283-307.
4. Majumder B, Mandal B, Bandyopadhyay PK, Gangopadhyay A, Mani PK, Kundu AL, et al. Organic amendments influence soil organic carbon pools and rice-wheat productivity. Soil Sci Soc Am J. 2008;72(3):775-85.
   DOI: 10.2136/sssaj2006.0378
5. Anonymous. Mixed cropping. Available:http://Simple.wikipedia.Org/wiki/Mixed_Cropping.Html
6. Anonymous, Minnesota Board of Water and Soil Resources.
7. Baldi E, Cavani L, Margon A, Quartieri M, et al. Effect of compost application on the dynamics of C in a nectarine orchard ecosystem. Sci Total Environ. 2018;162:239-48.
8. Bossio DA, Cook-Patton SC, Ellis PW, Fargione J, Sanderman J, Smith P, et al. The role of soil carbon in natural climate solutions. Nat Sustain. 2020;3(5):391-8.
   DOI: 10.1038/s41893-020-0491-z
9. Campbell CA, Zentner RP. Soil organic matter as influenced by crop rotations and fertilization. Soil Sci Soc Am J. 1993;57(4):1034-40.
   DOI:10.2136/sssaj1993.03615995005700040026x
10. Dewi RK, Fukuda M, Takashima N, Yagioka A, Komatsuzaki M. Soil carbon sequestration and soil quality change between no-tillage and conventional tillage soil management after 3 and 11 years of organic farming. Soil Sci Plant Nutr. 2022;68(1):133-48.
    DOI: 10.1080/00380768.2021.1997552
11. García-Palacios P, Gattinger A, Bracht-Jørgensen H, Brussaard L, Carvalho F, Castro H et al. Crop traits drive soil carbon sequestration under organic farming. J Appl Ecol. 2018;55(5):2496-505.
    DOI: 10.1111/1365-2664.13113
12. Halvorson AD, Wienhold BJ, Black AL. Tillage, nitrogen and cropping systems effects on soil carbon sequestration. Soil Sci Soc Am J. 2002;66(3):906-12.
    DOI: 10.2136/sssaj2002.9060
13. Kell DB. Breeding crop plants with deep roots: their role in sustainable carbon, nutrient and water sequestration. Ann Bot. 2011;108(3):407-18.

DOI: 10.1093/aob/mcr175, PMID 21813565.

14. Komatsuzaki M, Syuaib MF. Comparison of the farming systems and carbon sequestration between conventional and organic rice production in west Java, Indonesia. Sustainability. 2010;2(3): 833-43.
DOI: 10.3390/su2030833
15. Lal R. Role of mulching techniques in tropical soil and water management. Ibadan, Nigeria. Tech Boll ITTA; 1975.
16. Ruddiman WF. Plows, plagues and petroleum: How humans took care of climate. Princeton: Princeton University Press; 2005.
17. Sanderman J, Hengl T, Fiske GJ. Soil carbon debt of 12,000 years of human land use. Proc Natl Acad Sci U S A. 2017; 114(36):9575-80.
DOI: 10.1073/pnas.1706103114, PMID 28827323.
18. Lal R, Smith P, Jungkunst HF, Mitsch WJ, Lehmann J, Nair PKR, et al. The carbon sequestration potential of terrestrial ecosystems. J Soil Water Conserv. 2018; 73(6):145A-52A.
DOI: 10.2489/jswc.73.6.145A
19. Fuss S, Lamb WF, Callaghan MW, Hilaire J, Creutzig F, Amann T, et al. Negative emissions – Part 2: Costs, potentials and side effects. Environ Res Lett. 2018;13(6):063002.
DOI: 10.1088/1748-9326/aabf9f
20. Smith P. Soil carbon sequestration and biochar as negative emission technologies. Glob Change Biol. 2016;22(3):1315-24.
DOI: 10.1111/gcb.13178, PMID 26732128.
21. Guo LB, Gifford RM. Soil carbon stocks and land use change: A meta-analysis. Glob Change Biol. 2002;8(4):345-60.
DOI: 10.1046/j.1354-1013.2002.00486.x
22. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science. 2004;304(5677):1623-7.
DOI: 10.1126/science.1097396, PMID 15192216.
23. Janzen HH. The soil carbon dilemma: shall we hoard it or use it? Soil Biol Biochem. 2006;38(3):419-24.
DOI: 10.1016/j.soilbio.2005.10.008
24. Bommarco R, Kleijn D, Potts SG. Ecological intensification: harnessing ecosystem services for food security. Trends Ecol Evol. 2013;28(4):230-8.
DOI: 10.1016/j.tree.2012.10.012, PMID 23153724.
25. Tittonell P. Ecological intensification of agriculture — sustainable by nature. Curr Opin Environ Sustain. 2014;8:53-61.
DOI: 10.1016/j.cosust.2014.08.006
26. Gattinger A, Muller A, Haeni M, Skinner C, Fliessbach A, Buchmann N, et al. Enhanced top soil carbon stocks under organic farming. Proc Natl Acad Sci U S A. 2012;109(44):18226-31.
DOI: 10.1073/pnas.1209429109, PMID 23071312.
27. Kirchmann H, Kätterer T, Bergström L, Börjesson G, Bolinder MA. Flaws and criteria for design and evaluation of comparative organic and conventional cropping systems. Field Crops Res. 2016;186:99-106.
DOI: 10.1016/j.fcr.2015.11.006
28. Leifeld J, Fuhrer J. Organic farming and soil carbon sequestration: What do we really know about the benefits? Ambio. 2010;39(8):585-99.
DOI: 10.1007/s13280-010-0082-8, PMID 21141778.
29. Ponisio LC, M'Gonigle LK, Mace K, Palomino J, de Valpine P, Kremen C. Diversification practices reduce organic to conventional yield gap. Proc R Soc Lond B. 2014;282:20141396.
30. Seufert V, Ramankutty N, Foley JA. Comparing the yields of organic and conventional agriculture. Nature. 2012;485(7397):229-32.
DOI: 10.1038/nature11069, PMID 22535250.
31. Crowther TW, Todd-Brown KEO, Rowe CW, Wieder WR, Carey JC, Machmuller MB, et al. Quantifying global soil carbon losses in response to warming. Nature. 2016;540(7631):104-8.
DOI: 10.1038/nature20150, PMID 27905442.
32. García-Palacios P, McKie BG, Handa IT, Frainer A, Hättenschwiler S. The importance of litter traits and decomposers for litter decomposition: A comparison of aquatic and terrestrial ecosystems within and across biomes. Funct Ecol. 2016;30(5):819-29.
DOI: 10.1111/1365-2435.12589
33. Parton W, Silver WL, Burke IC, Grassens L, Harmon ME, Currie WS, et al. Global-scale similarities in nitrogen release

patterns during long-term decomposition. Science. 2007;315(5810):361-4.
DOI: 10.1126/science.1134853, PMID 17234944.

34. Faucon MP, Houben D, Lambers H. Plant functional traits: Soil and ecosystem services. Trends Plant Sci. 2017;22(5):385-94.
DOI: 10.1016/j.tplants.2017.01.005, PMID 28209328.
35. Cornwell WK, Cornelissen JHC, Amatangelo K, Dorrepaal E, Eviner VT, Godoy O, et al. Plant species traits; 2008.
36. Cotrufo MF, Wallenstein MD, Boot CM, Denef K, Paul E. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? Glob Change Biol. 2013;19(4): 988-95.
DOI: 10.1111/gcb.12113, PMID 23504877.
37. Iwasaki S, Endo Y, Hatano R. The effect of organic matter application on carbon sequestration and soil fertility in upland fields of different types of andosols. Soil Sci Plant Nutr. 2017;63(2):200-20.
DOI: 10.1080/00380768.2017.1309255
38. Li S, Li Y, Li X, Tian X, Zhao A, Wang S, et al. Effect of straw management on carbon sequestration and grain production in a maize-wheat cropping system in anthrosol of the Guanzhong Plain. Soil Till Res. 2016;157(April):43-51.
DOI: 10.1016/j.still.2015.11.002
39. Kirkby CA, Richardson AE, Wade LJ, Batten GD, Blanchard C, Kirkegaard JA. Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biol Biochem. 2013;60(May):77-86.
DOI: 10.1016/j.soilbio.2013.01.011
40. Mandal B, Majumder B, Bandyopadhyay PK, Hazra GC, Gangopadhyay A, Samantaray RN, et al. The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. Glob Change Biol. 2007;13(2):357-69.
DOI: 10.1111/j.1365-2486.2006.01309.x
41. Nair R, Mehta CR, Sharma S. Carbon sequestration in soils-A Review. Agric Rev. 2015;36(2).
DOI: 10.5958/0976-0741.2015.00011.2
42. Mbuthia LW, Acosta-Martínez V, DeBruyn J, Schaeffer S, Tyler D, Odoi E, et al. Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: implications for soil quality. Soil Biol Biochem. 2015;89:24-34.
DOI: 10.1016/j.soilbio.2015.06.016
43. Reicosky DC. Conservation tillage is not conservation agriculture. J Soil Water Conserv. 2015;70(5):103A-8A.
DOI: 10.2489/jswc.70.5.103A
44. Olson K, Ebelhar SA, Lang JM. Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration. Open J Soil Sci. 2014;04(8):284-92.
DOI: 10.4236/ojss.2014.48030
45. Frey SD, Ollinger S, Nadelhoffer K, Bowden R, Brzostek E, Burton A, et al. Chronic nitrogen addition suppress decomposition and sequester soil carbon in temperate forests. Biogeochemistry. 2014;121(2):305-16.
DOI: 10.1007/s10533-014-0004-0
46. Windeatt JH, Ross AB, Williams PT, Forster PM, Nahil MA, Singh S. Characteristics of Bs from crop residues: potential for C sequestration and soil amendment. J Environ Manage. 2014;146:189-97.
DOI: 10.1016/j.jenvman.2014.08.003, PMID 25173727.
47. Liu E, Yan C, Mei X, Zhang Y, Fan T. Long-term effect of manure and fertilizer on soil organic carbon pools in dryland farming in Northwest China. PLOS ONE. 2013;8(2):e56536.
DOI: 10.1371/journal.pone.0056536. PMID 23437161.
48. Naresh RK, Gupta RK, Minhas PS, Rathore RS, Ashish D, Purushottam V. Climate change and challenges of water and food security for smallholder farmers of Uttar Pradesh and mitigation through C sequestration in agricultural lands: an overview. Int J Chem Stud. 2017;5(2):221-36.
49. Ren T, Wang J, Chen Q, Zhang F, Lu S. The effects of manure and nitrogen fertilizer application on soil organic carbon and nitrogen in a high input cropping system. PLOS ONE. 2014;9(5): e97732.
DOI: 10.1371/journal.pone.0097732. PMID 24830463.
50. Shehzadi S, Shah Z, Mohammad W. Impact of organic amendments on soil carbon sequestration, water use efficiency and yield of irrigated wheat. Biotechnol Agron Soc Environ. 2017;21(1):36-49.

DOI: 10.25518/1780-4507.13435

51. Yeboah S, Zhang R, Cai L, Li L, Xie J, Luo Z, et al. Tillage effect on soil organic carbon, microbial biomass carbon and crop yield in spring wheat –field pea rotation. Plant Soil Environ. 2016;62(6): 279-85.
DOI: 10.17221/66/2016-PSE
52. De Deyn GB, Shiel RS, Ostle NJ, McNamara NP, Oakley S, Young I, et al. Additional carbon sequestration benefit, of grassland diversity restoration. J Appl Ecol. 2011;48(3):600-8.
DOI: 10.1111/j.1365-2664.2010.01925.x
53. Nivelle E, Verzeaux J, Habbib H, Kuzyakov Y, Decocq G, Roger D, et al. Functional response of soil microbial communities to tillage, cover crops and nitrogen fertilization. Appl Soil Ecol. 2016;108:147-55.
DOI: 10.1016/j.apsoil.2016.08.004
54. Ramirez KS, Craine JM, Fierer N. Consistent effects of nitrogen amendments on soil microbial communities and processes across biomes. Glob Change Biol. 2012;18(6):1918-27.
DOI: 10.1111/j.1365-2486.2012.02639.x
55. Ravindranath NH, Ostwald M. Generic methods for inventory of carbon pools. In: Carbon inventory methods: handbook for greenhouse gas inventory, carbon mitigation and roundwood production projects. Netherlands: Springer. 2008; 99-111.
56. Mahmoodabadi M, Heydarpour E. Sequestration of organic carbon influenced by the application of straw residue and farmyard manure in two different soils. Int Agrophys. 2014;28(2):169-76.
DOI: 10.2478/intag-2014-0005
57. Machado S, Rhinhart K, Petrie S. Longterm cropping systems effects on carbon sequestration in eastern Oregon. J Environ Qual. 2006;35(4):1548-53.
DOI: 10.2134/jeq2005.0201, PMID 16825475.
58. Kell DB. Large scale sequestration of atmospheric via plant roots in natural and agricultural ecosystems: why and how. Philos Trans R Soc Lond B Biol Sci. 2012;367(1595):1589-97.
DOI: 10.1098/rstb.2011.0244, PMID 22527402.
59. Sparling GP, Wheeler D, Vesely ET, Schipper LA. What is soil organic matter worth? J Environ Qual. 2006;35(2):548-57.
DOI: 10.2134/jeq2005.0230, PMID 16510699.
60. Abdullahi AC, et al. Carbon sequestration in soils: The opportunities and challenges. Carbon capture, utilization and sequestration. InTech; 2018.
DOI: Crossref
61. Smith P, Soussana JF, Angers D, Schipper L, Chenu C, Rasse DP, et al. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Glob Change Biol. 2020;26(1):219-41.
DOI: 10.1111/gcb.14815,
PMID 31469216.
62. Syswerda SP, Corbin AT, Mokma DL, Kravchenko AN, Robertson GP. Agricultural management and soil carbon storage in surfaces vs deep layers. Soil Sci Soc Am J. 2011;75(1):92-101.
DOI: 10.2136/sssaj2009.0414
63. Zuber SM, Villamil MB. Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. Soil Biol Biochem. 2016;97:176-87.
DOI: 10.1016/j.soilbio.2016.03.011

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