

Soil Carbon Sequestration- A step towards sustainability

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.

Keywords: Agronomic Practices, Carbon Sequestration, Natural Farming, Organic Farming, Sustainable Agriculture

Introduction

Soil Carbon

The carbon stored in soils around the world is known as soil carbon. This contains carbonate minerals made from both organic and inorganic carbon found in soil. In terms of the global carbon cycle, soil carbon is a carbon sink that contributes to biogeochemistry, the mitigation of climate change, and the development of global climate models. Although the majority of the carbon on Earth is stored 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 (2000), 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. Soil carbon comprises 9% of the mitigation potential of forests, 72% for wetlands and 47% for agriculture and grasslands. Soil carbon is important to land-based efforts to prevent carbon emissions, remove atmospheric carbon dioxide and deliver ecosystem services in addition to climate mitigation. 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 CO₂ emissions.

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 buildup of greenhouse gases, which are emitted as a

result of human activity. The net removal of carbon dioxide (CO₂) from the atmosphere or the prevention of emission of carbon dioxide (CO₂) into the atmosphere by terrestrial ecosystems is referred to as carbon sequestration. All chlorophyllous plants absorb CO₂ from the atmosphere during photosynthesis as part of the elimination process. 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. Plants absorb carbon during photosynthesis and release some of it back into the atmosphere during respiration. 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. 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.

Potential of Soil Carbon Sequestration to Reduce the Impact of Global Warming

According to Ruddiman (2005), soils have lost between 140 and 150 Gt C (or 510 and 550 Gt CO₂; Sanderman et al., 2017) 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 (Lal et al., 2018). (also called negative emission technology, or carbon dioxide removal option; Smith, 2016). Nevertheless, a recent systematic assessment by Fuss et al. (2018) predicts a yearly technical capacity of 2–5 Gt CO₂/year. Worldwide estimates of soil C sequestration potential vary significantly. Economic potential estimates are at the lower end of this range (Smith, 2016; Smith et al., 2008).

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 (Guo & Gifford, 2002). 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 (Lal, 2004). 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 (Janzen, 2006). 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 (Bommarco et al. 2013). 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 (Tittonell, 2014), boosts top SOC stocks by 3.50 Mg C/ha on a worldwide average (Gattinger et al., 2012). 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 (Kirchmann et al. 2016; Leifeld & Fuhrer, 2010). However when contrasting conventional and organic farms with low manure application rates (LMR; European livestock units per hectare 1, Gattinger et al., 2012), 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 (Ponisio et al., 2014; Seufert et al. 2012). 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 (Crowther et al., 2016). 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. (2016) and Parton et al. (2007), 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 (Faucon et al. 2017). In this line, labile plant residues (e.g., greater N content) are often associated with quicker breakdown rates and consequently increased soil C losses (Cornwell et al., 2008; Garca-Palacios et al., 2016). 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 (Cotrufo et al. 2013). 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 (Faucon et al., 2017). 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 (2017), adding organic matter over a lengthy period of time boosts soil carbon sequestration. According to Li et al. (2016), 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 (Kirkby et al. 2013). 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.

Soil Carbon Sequestration in relation to Natural Farming

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

On the basis of initial investigation and observations at 180 acres of Gurukul farm Kurukshetra, it appears that natural farming may be a promising model in Indian agriculture. The analytical results from the different institutions (CCS HAU Hisar, PAU Ludhiana, IIFSR Modipuram and Kurukshetra University) have reflected that there was incredible enrichment of soils in terms of organic carbon (OC), nutrients and biological health. The results indicated that the average organic carbon in soil samples collected from Gurukul farm in June 2017 and analysed at CCS HAU, Hisar and IIFSR, Modipuram was 0.61 and 0.62%, respectively. The 19 and 30% soil samples in the analysis of IIFSR and CCS HAU were found sufficient/rich in OC (>0.75%). After one year of cropping i.e. in June 2018, soil samples were again collected and analysed at CCS HAU Hisar. It was observed that 95% soil samples were rich in OC with average OC value of 0.91% in the range of 0.82-1.12%. For confirmation of results, soil samples were further drawn in October 2018 after Kharif season and analysed at CCS HAU Hisar and PAU, Ludhiana. These results indicated that the average OC was 0.84 and 0.78% in the soil analysis reports from the respective institutes. The increase in OC by 49% (from 0.61 to 0.91%) in a period of only one year and the maintenance of average OC at the level of more than 0.75% across the season on a farm of 180 acres exhibit the impact of LBNF practices. Seasonal variation and crop management practices may exert influence on OC content of soil.

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

Table:1 Organic Carbon status of Gurukul Farm (Samples analysed at CCS HAU Hisar, Haryana)

Organic Carbon Content: In summer/Kharif season of 2017, 10 soil samples were drawn at random from Gurukul farm and got analysed at CCS HAU Hisar. Likewise 16 soil samples were taken by the scientists of IFSR, Modipuram for analysis of organic carbon, macro and micronutrients. These analytical results presented in Table 4 and 5 revealed that 30% soil samples analysed at CCS HAU Hisar and 19% of those analysed at IFSR were in rich category(>0.75%) with respect to organic carbon.

Similarly 10 and 12% soil samples represented poor status of organic carbon (<0.40% in the results registered by the respective institutions. Rest of the samples were categorised in the medium range of OC content. The average OC from both of the institutions was 0.61%.

After one year in June 2018, nineteen samples were again drawn randomly from 180 acres of Gurukul Farmland and got analysed in the soil testing laboratory of CCS HAU, Hisar. The results were incredible which depicted that 95% soil samples represented in rich category with average OC of 0.91% in the range of 0.82 to 1.12% (Table 4). Sixteen percent soil samples had OC more than 1.0%. Only one sample was in medium category with OC of 0.45%.

Again in October 2018, the soil samples were drawn at random from the farm and got analysed in soil testing labs of CCS HAU, Hisar and PAU, Ludhiana. These results again confirmed the OC status of Gurukul Farmland, although at somewhat lesser scale might be due to seasonal variations. The average OC was 0.84 and 0.78% in the samples tested at CCS HAU Hisar and PAU, Ludhiana, respectively.

The figures of the samples representing rich category (>0.75%) were 90% (CCS HAU) and 70% (PAU Ludhiana). Only one sample out of 20 samples tested at CCS HAU and PAU fall under poor category (<0.40%) whereas 30% samples analysed by both institutions had OC more than 0.90%.

Agronomic Practices followed to enhance Soil Carbon Sequestration

CO₂ is increasing at the rate of 2.3 ppm per year, which is resulting in the increase of global warming and environmental pollution. Agriculture sector is responsible for up to 30% emission of GHGs. Sustainable agriculture is essential for the survival of humankind. Adoption of different agronomic

management practices can be helpful in the sequestration of carbon. Such practices include no-tillage or reduced tillage, nutrient management, cover crops, crop rotations, green manuring, application of animal manures, agroforestry, etc. Adoption of these different agronomic practices will not only improve the crops yields but will also improve farmer's income.[Anonymus, Minnesota Board of Water and Soil Resources]

1. Conservation Tillage

Minnesota farmers are using conservation tillage more frequently than in the past, particularly in corn and soybean rotations. Soil erosion control, water quality improvement, increased nutrient retention, and lower production costs are among the many environmental and economic benefits associated with conservation tillage practices. No-till and other conservation tillage practices have proven successful in controlling soil erosion and providing other benefits. Conservation tillage practices have the additional benefit of sequestering more carbon than conventional agricultural tilling practices. There is a range of beneficial tilling practices; the most beneficial are those that disturb soils the least, including no-till and strip till.[Reicosky et al. (2015), Mbuthia et al.(2015)] Soil microbial biomass has become an indicator of soil quality and increased nutrient retention and soil structure. Additionally, studies have found that beneficial micro-organisms including bacteria and fungi are especially effective in storing carbon, and they are negatively affected by tillage.[Zuber et al.(2016), Mbuthia et al.(2015)] But conservation tillage practices alone are not the solution to greater carbon sequestration in agricultural systems. Combining conservation tillage with cover crops has been proven to significantly increase soil organic carbon in addition to benefits that include increased infiltration, nutrient retention and decreased erosion potential.[Soil Health Practices and No-till Farming Transform Landscapes(2019), Mbuthia et al.(2015)] No till and cover crop practices together provide greater benefits than either practice does individually.[Mbuthia et al.(2015)] Issues of carbon sequestration notwithstanding, BWSR encourages the use of conservation tillage and cover crops to protect soil quality, reduce soil erosion and improve water quality in local waterways.

2. Cover Crops Store Carbon

Cover crops are grasses, legumes and forbs planted to provide seasonal soil cover when the soil would otherwise be bare - before the main crop emerges in the spring or after fall harvest. Cover crops sequester carbon by adding biomass both on the soil surface and below-ground. Research suggests that the majority of soil organic carbon originates from root biomass. Underground carbon persists longer than above ground depositions. Cover crops encourage beneficial root-zone fungi, bacteria and invertebrates who also contribute to soil carbon and protect it over time by forming aggregates which increase overall soil health and productivity. [Mbuthia et al.(2015)]

A 12-year University of Illinois study showed that adding cover crops to all tillage treatments increased soil organic carbon stock gains by 30% for no-till, 10% for chisel plowed and 18% for moldboard-plowed plots. [Olson et al. (2014)]

Planting in late summer allows cover crops to generate substantial biomass throughout the fall and again in the spring. Winter rye is a good choice because it is more resistant to decay than other cover crops such as oats or barley.

3. Nutrient management

Chemical fertilizers are a source of emission of GHGs, especially N₂O. In addition to it, fertilizer production and its transportation are also associated with the emissions of GHGs. Judicious use of fertilizers increases crop yields and profitability, and about 50 Pg CO₂ additions to the atmosphere has been contributed by the cultivated soils [Lal R. Sequestering carbon in soils of agro-ecosystems(2011)], through the process of mineralization of soil organic carbon (SOC). The use of

fertilizers has dramatically increased agricultural productivity, but studies reveal that the chronic use of nitrogen fertilization decreases soil microbial activity [Frey SD et.al. (2014)]. Continuous use of balanced fertilizers is necessary for sustainable soil fertility and productivity of crops. Crop residues and nutrients, especially N, help in carbon sequestration up to 21.3–32.5% [Windeatt JH et.al (2014)]. However, ultimate effects of continuous nitrogen fertilization on soils are complicated and remain unclear. For example, in the long-term experiments in Canada, SOC sequestration were 50–75 g cm⁻² per year in well-fertilized soils with optimum cropping systems. Research in the Great Plains shows that SOC sequestration is improved by the application of N fertilization, but opposite to it, long-term experiments in the Northern Great Plains (ND) have also shown that N fertilizer increased crop residue returns but generally did not increase SOC sequestration Liu Enke et al. [Liu E et al. (2013)] reported the results of a long-term study which was initiated in Northwest China in 1979, to find out the effects of fertilization on SOC and SOC fractions for the whole soil profile such as (0–100 cm) soil depth. The experiment included six treatments, i.e., unfertilized (control), N fertilizer (N), nitrogen and phosphorous fertilizer (NP), straw plus N and P fertilizers (NP + S), Farmyard manure (FYM), and Farmyard manure (FYM) plus N and P fertilizers (NP+ FYM). Results showed that SOC storage in 0–60 cm in NP + FYM, NP + S, FYM, and NP treatments increased by 41.5, 32.9, 28.1, and 17.9%, respectively, as compared to control treatment. Application of organic manure plus inorganic fertilizer also enlarged labile pool in 0–60 cm soil depth. These results show that long-term applications of organic manure have the most beneficial effects in building carbon pools among the investigated types of fertilization.

It can be concluded that the appropriate use of fertilizers according to the soil condition can be helpful in the maximum sequestration of carbon along with maximum crops production and in the reductions of emissions of different GHGs

4. Animal manure and compost application

Animal manure is animal's excreta which is collected from livestock farms and barnyards and is used to enrich the soil, while compost is the material which largely consists of decayed organic matter and is used for fertilizing and conditioning of agricultural soil. Application of manures is important for the maintenance of soil health and is the source of C, and its application to different crops fields has effects on C contents. As compared with the application of only NPK, application of FYM along with NPK increased C sequestration in the rice-wheat cropping system [Naresh RK et.al. (2017)], while green manuring, as compared with the application of FYM along with green manure, sequestered more C in a Maize- Wheat cropping system. Composting not only increases the net primary production but also enhances the C contents of the soil [Baldi E et al. (2018)]. It has been reported that decreasing of manures and organic fertilizers application influences not only stable organic compounds but also soil microorganisms and nutrient regimes [Ren T et al. (2014)]. Liu et al. supported the positive effect of incorporation of mineral fertilizers with organic manures. Similarly, application of different organic wastes, i.e., municipal solid waste (MSW), farm yard manure (FYM), sugar industry waste (filter cake), and maize cropping residues, at 3 t C ha⁻¹ alone and with a full or half dose of NPK mineral fertilizer showed that the addition of organic wastes (filter cake or MSW) has the best potential for improving SOC retention, WUE, and wheat yield in an irrigated maize-wheat cropping system [Shehzadi S et al. (2017)].

This all indicates that the use of animal manure, compost, etc. along with other inorganic fertilizers is beneficial for both soil health and environment.

5. Crop rotations

Crop rotations mean the sequence of crops grown in regularly recurring successions on the same area of land. The succeeding crops may be for 2 or more years. Differences in crop rotations, climates,

soils, and different crop-related management practices also affect carbon sequestration. Intensive cropping systems result in the depletion of SOM, but the use of balanced fertilization with NPK, application of organic amendments, and similarly application of crop residues can increase carbon sequestration levels to 5–10 Mg ha⁻¹ per year because these amendments contain 10.7–18% C, which can also be helpful in the sequestration of carbon [Manadal B et al.]. Different legume crops, such as peas, lentils, alfalfa, chickpea, sesbania, etc., can serve as substitute sources for nitrogen. Applications of crop rotations especially by using legume cover crops, which contain carbon compounds that are likely more resistant to microbial metabolism, can make soil carbon more stable. Syswerda et al. reported the results of a long-term study (over a 12-year period) of an organic management system that involved various crop rotations. According to them despite of extensive tillage for weed control, increase in soil carbon sequestration was recorded. The results of a long-term study, which was conducted in Dingxi, Northwest China, during 2013–2015, were shown in-spring wheat-field pea rotation in a rain-fed semi-arid environment. The treatments were: conventional tillage with stubble removed (T); no tillage with stubble removed (NT); no-till with stubble retained (NTS), and conventional tillage with stubble incorporation (TS). The SOC, microbial biomass carbon, and root biomass in NTS increased over T and NT, and similarly, average grain yield across the 3 years in NTS was better than T and NT [Yeboah S et al. (2016)]. Recently, much attention has been given to alternate tillage and cropping systems as a means to mitigate the agricultural emissions of CO₂. Different types of cropping systems, i.e., cover cropping, ratoon cropping, and companion cropping, can be helpful in carbon sequestration. Intercropping which includes row inter cropping, strip inter cropping, mixed cropping, and relay intercropping can increase the income and can also raise soil fertility.

Some of the examples of inter cropping are wheat and mustard, cotton and peanut, peanut and sunflower, wheat and chickpea, etc. [Anon, “Mixed Cropping”]. Organic farming can also improve soil organic carbon as compared with the conventional farming. Research regarding the restoration of grassland also shows that through their biotic and biotic effects, legume species have more positive effects on the restoration of grasslands as compared with the application of mineral fertilizers [De Deyn GB et al. (2011)].

This above shows that keeping in view the economic considerations, selection of appropriate crop rotations according to the soil and environmental conditions can be helpful in the sequestration of carbon, which not only improve soil fertility but also reduce the emissions of CO₂ into the atmosphere and increase farmer’s income.

6. Residues management

Crop residues are detached vegetative parts of crop plants that are intentionally left to decay in agricultural fields after crop harvesting. Worldwide, the annual production of crop residues is about

3.4 × 10⁹ tones, and if 15% of these total residues are applied to the soil, it can increase the C contents of the soil, because, for example, one ton of cereal residue contains 12–20 kg N, 1–4 kg P, 7–30 kg K, 4–8 kg Ca, and 2–4 kg Mg. Mulching is detached vegetation, which includes wheat straw, compost, or may be plastic sheets, which are spread around plants to protect them from excessive evaporation and cold stress and similarly to promote SOM contents in soil.

Crop residues play an important role in the SOC management and improvement of soil quality. Mulching improves soil moisture, reduces soil erosion, and similarly reduces the loss of carbon from the soil and crop residues, which are incorporated into the soil to enhance the soil organic matter. A direct seedling mulch-based cropping system increases soil organic matter, as a result of increased carbon inputs and decreased soil disturbance. Mulch can increase soil organic matter (SOM) and carbon sequestration in the top 0–5 cm soil depth. It improves soil’s physical and chemical properties

and can increase carbon sequestration in agricultural soils up to 8–16 Mg ha⁻¹ per year. Mulch-based cropping systems enhance the buildup of soil organic matter, principally as a result of increased carbon inputs and decreased soil disturbance. Direct seedling straw mulch has the potential to ameliorate the heat stress, and it improves the infiltration rate, reduces evaporation [Lal R. Tillage in lowland rice-based cropping systems.], and similarly increases soil organic carbon and N efficiency. Increasing residues inputs to soils entails increasing net primary productivity (NPP). Many agricultural soils, which have been significantly reduced from their original C levels through cultivation, will show C gains in proportion to increases in C inputs. Soil C levels are governed by the balance between the inputs of C through plant residues and the losses of C basically through decomposition. Therefore, C can be increased in soil by increasing residues inputs and or reducing decomposition rates (i.e., heterotrophic soil respiration). Litter quality also affects rates of its decomposition. The results of a 4-month study, which was conducted in a greenhouse controlled condition and in three rates of straw residue and farm yard manure, were added to uncultivated and cropland soils. Two treatments of straw residue and farm yard manure incorporation were used into: a soil surface layer and a 0–20 cm soil depth revealed that the application of organic matter, especially the incorporation of farm yard manure, led to significant increase in the final soil organic carbon content, and higher amount of soil organic carbon were stored in the cropland soil than in the uncultivated soil. The results showed that carbon sequestration ranged farm yard manure > straw residue and cropland soil > uncultivated soil. The results revealed paying more attention to the role of organic residue management in carbon sequestration [Mahmoodabadi et al. (2014)].

This all shows that the application of mulch and the use of crop residues can improve soil microbial activity, ameliorate the heat stress, and help in water storage and improvement of soil organic carbon.

7. Use of improved crop varieties

Selection of improved varieties of different crops, which can improve both above and below ground biomass, can also improve the soil organic carbon. Machado et al. [Machado et al. (2006)] reported that crop species that have massive rooting systems have the potential to improve SOC in soils under NT. Similarly, according to Kell [Kell DB. (2012)] by improving root growth in agricultural crops, soil carbon storage can match anthropogenic emissions for the next 40 years. This all indicates that the use of improved crop varieties having extensive rootsystems and better yields can increase both yields and soil fertility.

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:

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 [Sparling et al. (2006)]. 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 practises 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. [Abdullahi et al. (2018)]

2. Permanency

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 managerial factors influence the rate of carbon loss. [Abdullahi et al. (2018)]

3. Separation

It is exceedingly challenging to identify and distinguish between the amount 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 due to natural causes. Hence, methods that can distinguish between carbon that is naturally sequestered and carbon that is captured as a result of human management are needed.

Conclusion

The extent and duration of the potential for SOC sequestration are limited. It is merely a temporary solution to the CO₂ enrichment caused by anthropogenic activity. Even with soil C sequestration, the atmospheric CO₂ concentration will keep rising. Thus, creating fossil fuel substitutes is necessary for a long-term solution. Although, theoretically this idea sounds appealing, however it is difficult to operationalize it in practice due to a number of challenges. Some of these include difficulties in measurement of soil carbon stock, permanence, carbon pools with different carbon residence times, separation, the tendency of the soil to reach saturation level when the maximum attainable carbon that could be captured is reached. Advances have been made in tackling most of these challenges, however, deliberate actions to enhance carbon capture and sequestration in the soil ecosystem is yet to get wide acceptance by practitioners and policy makers alike. This chapter is written in an attempt to create more awareness on the potential of soils in capturing and storing atmospheric CO₂ in long lived pools thereby mitigating climate change in the process. Researchers should also work assiduously in finding solutions to the challenges making widespread adoption of this initiative difficult.

References

1. Abdullahi, Ahmed Chinade, et al. 'Carbon Sequestration in Soils: The Opportunities and Challenges'. Carbon Capture, Utilization and Sequestration, InTech, Sept. 2018. Crossref, doi:10.5772/intechopen.79347.
2. Anon, "Mixed Cropping". Available from: http://Simple.wikipedia.Org/wiki/Mixed_Cropping.Html
3. Anonymus, Minnesota Board of Water and Soil Resources

4. Baldi E, Cavani L, Margon A, Quartieri M, Sorrenti G, Marzadori C, et al. Effect of compost application on the dynamics of C in a nectarine orchard ecosystem. *Science of the Total Environment*. 2018;162:239-248
5. Bommarco, R., Kleijn, D., & Potts, S. G. (2013). Ecological intensification: Harnessing ecosystem services for food security. *Trends in Ecology & Evolution*, 28, 230–238.
6. Bossio, D.A., Cook-Patton, S.C., Ellis, P.W. *et al.* The role of soil carbon in natural climate solutions. *Nat Sustain* 3, 391–398 (2020).
7. Campbell CA, Zentner RP. Soil organic matter as influenced by crop rotations and fertilization. *Soil Science Society of America Journal*. 1993;57:1034-1040
8. Cornwell, W. K., Cornelissen, J. H. C., Amatangelo, K., Dorrepaal, E., Eviner, V. T., Godoy, O., et al. (2008). Plant species traits
9. Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Deneff, K., & Paul, E. (2013). 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? *Global Change Biology*, 19, 988–995.
10. Crowther, T. W., Todd-Brown, K. E. O., Rowe, C. W., Wieder, E. R., Carey, J. C., Machmuller, M. B., ... Bradford, M. A. (2016). Quantifying global soil carbon losses in response to warming. *Nature*, 540, 104–108.
11. De Deyn GB, Shiel RS, Ostle NJ, McNamara NP, Oakley S, Young I, et al. Additional carbon sequestration benefit, of grassland diversity restoration. *Journal of Applied Ecology*. 2011;48:600-608
12. Dewi, R. K., Fukuda, M., Takashima, N., Yagioka, A., & Komatsuzaki, M. (2022). Soil carbon sequestration and soil quality change between no-tillage and conventional tillage soil management after 3 and 11 years of organic farming. *Soil Science and Plant Nutrition*, 68(1), 133-148.
13. Faucon, M. P., Houben, D., & Lambers, H. (2017). Plant functional traits: Soil and ecosystem services. *Trends in Plant Science*, 22, 385–394.
14. Faucon, M. P., Houben, D., & Lambers, H. (2017). Plant functional traits: Soil and ecosystem services. *Trends in Plant Science*, 22, 385–394.
15. 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):305-316
16. Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., ... Minx, J. C. (2018). Negative emissions – Part 2: Costs, potentials and side effects. *Environmental Research Letters*, 13, 063002. <https://doi.org/10.1088/1748-9326/aabf9f>
17. García-Palacios, P., Gattinger, A., Bracht-Jørgensen, H., Brussaard, L., Carvalho, F., Castro, H., ... & Milla, R. (2018). Crop traits drive soil carbon sequestration under organic farming. *Journal of Applied Ecology*, 55(5), 2496-2505.
18. García-Palacios, P., McKie, B. G., Handa, I. T., Frainer, A., & Hättenschwiler, S. (2016). The importance of litter traits and decomposers for litter decomposition: A comparison of aquatic and terrestrial ecosystems within and across biomes. *Functional Ecology*, 30, 819–829.
19. García-Palacios, P., McKie, B. G., Handa, I. T., Frainer, A., & Hättenschwiler, S. (2016). The importance of litter traits and decomposers for litter decomposition: A comparison of aquatic and terrestrial ecosystems within and across biomes. *Functional Ecology*, 30, 819–829.
20. Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., et al. (2012). Enhanced top soil carbon stocks under organic farming. *Proceedings of the National Academy of Sciences of the United States of America*, 109, 18226–18231.

21. Guo, L. B., & Gifford, R. M. (2002). Soil carbon stocks and land use change: A meta-analysis. *Global Change Biology*, 8, 345–360. <https://doi.org/10.1046/j.1354-1013.2002.00486.x>
22. Halvorson AD, Weinhold BJ, Black AL. Tillage, nitrogen and cropping systems effects on soil carbon sequestration. *Soil Science Society of America Journal*. 2002;66:906-912
23. Iwasaki, S., Y. Endo, and R. Hatano. 2017. “The Effect of Organic Matter Application on Carbon Sequestration and Soil Fertility in Upland Fields of Different Types of Andosols.” *Soil Science and Plant Nutrition* 63 (2): 200–220.
24. Janzen, H. H. (2006). The soil carbon dilemma: Shall we hoard it or use it? *Soil Biology & Biochemistry*, 38, 419–424. <https://doi.org/10.1016/j.soilbio.2005.10.008>
25. Kell DB. Breeding crop plants with deep roots: Their role in sustainable carbon, nutrient and water sequestration. *Annals of Botany*. 2011;108(93):407-418
26. Kell DB. Large scale sequestration of atmospheric via plant roots in natural and agricultural ecosystems: Why and how. *Philosophical Transactions of the Royal Society B*. 2012;367(1595):1589-1597
27. Kirchmann, H., Kätterer, T., Bergström, L., Börjesson, G., & Bolinder, M. A. (2016). Flaws and criteria for design and evaluation of comparative organic and conventional cropping systems. *Field Crops & Research*, 186, 99–106.
28. Kirkby, C. A., A. E. Richardson, L. J. Wade, G. D. Batten, C. Blanchard, and J. A. Kirkegaard. 2013. “Carbon-Nutrient Stoichiometry to Increase Soil Carbon Sequestration.” *Soil Biology and Biochemistry* 60 (May): 77–86.
29. Kowatsuzali M, Syuaib MF. Comparison of the farming systems and carbon sequestration between conventional and organic rice production in West Java, Indonesia. *Sustainability*. 2010;2:833-843
30. Lal R. Role of Mulching Techniques in Tropical Soil and Water Management. Ibadan, Nigeria: Tech. Bull ITTA; 1975
31. Lal R. Sequestering carbon in soils of agro-ecosystems. *Food Policy*. 2011;36:S33-S39
32. Lal R. Tillage in lowland rice-based cropping systems. In: *Soil Physics and Rice*. Philippines: IRRI; 1985. pp. 283-307
33. Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 305, 1623–1627. <https://doi.org/10.1126/science.1097396>
34. Lal, R., Smith, P., Jungkunst, H., Mitsch, W., Lehmann, J., Nair, P. K., ... Ravindranath, N. H. (2018). The carbon sequestration potential of terrestrial ecosystems. *Journal of Soil and Water Conservation*, 73, 145A–152A. <https://doi.org/10.2489/jswc.73.6.145A>
35. Leifeld, J., & Fuhrer, J. (2010). Organic farming and soil carbon sequestration: What do we really know about the benefits? *Ambio*, 39, 585–599.
36. Li, S., L. Youbing, L. Xiushuang, X. Tian, A. Zhao, S. Wang, S. Wang, and J. Shi. 2016. “Effect of Straw Management on Carbon Sequestration and Grain Production in a Maize-Wheat Cropping System in Anthrosol of the Guanzhong Plain.” *Soil and Tillage Research* 157 (April): 43–51.
37. 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
38. Machado S, Rhinhart K, Petrie S. Longterm cropping systems effects on carbon sequestration in eastern Oregon. *Journal of Environmental Quality*. 2006;35:1548-1553
39. Mahmoodabadi M, Heydarpour E. Sequestration of organic carbon influenced by the application of straw residue and farmyard manure in two different soils. *International Agrophysics*. 2014;28:169-176. DOI: 10.2478/intag-2014-0005

40. Majumder B, Mandal B, Bandyopadhyay PK, Gangopadhyay A, Mani PK, et al. Organic amendments influence soil organic carbon pools and rice-wheat productivity. *Soil Science Society of America Journal*. 2008;72:775-785
41. Manadal B et al. The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. *Global Change Biology*;13:357-369
42. Mbutia, L. W. et al. Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: Implications for soil quality. *Soil Biology and Biochemistry* 89, 24–34 (2015).
43. Nair, Reena & Mehta, C. & Sharma, Shefali. (2015). Carbon sequestration in soils-A Review. *Agricultural Reviews*. 36. 10.5958/0976-0741.2015.00011.2.
44. 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. *International Journal of Chemical Studies*. 2017;5(2):221-236
45. Nivellet, E. et al. Functional response of soil microbial communities to tillage, cover crops and nitrogen fertilization. *Applied Soil Ecology* 108, 147–155 (2016).
46. Olson, K, S.A. Ebelhar and J.M. Lang. 2014. *Open Journal of Soil Science* 4: 284-292.
47. Parton, W., Silver, W. L., Burke, I. C., Grassens, L., Harmon, M. E., Currie, W. S., et al. (2007). Global-scale similarities in nitrogen release patterns during long-term decomposition. *Science*, 315, 361–364.
48. Paustian, K., Six, J., Elliott, E. T., & Hunt, H. W. (2000). Management options for reducing CO₂ emissions from agricultural soils. *Biogeochemistry*, 48, 147-163.
49. Ponisio, L. C., M'Gonigle, L. K., Mace, K., Palomino, J., de Valpine, P., & Kremen, C. (2014). Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B*, 282, 20141396.
50. Ramirez KS, Craine JM, Fierer N. Consistent effects of nitrogen amendments on soil microbial communities and processes across biomes. *Global Change Biology*. 2012;18(6):1918-1927
51. 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. pp. 99-111
52. Reicosky, D. C. Conservation tillage is not conservation agriculture. *Journal of Soil and Water Conservation* 70, 103A-108A (2015).
53. Ren T, Wang J, Chen Q, et al. 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
54. Ruddiman, W.F. 2005. *Plows, Plagues and Petroleum: How Humans Took Care of Climate*. Princeton: Princeton University Press.
55. Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences of the United States of America*, 114, 9575–9580. <https://doi.org/10.1073/pnas.1706103114>
56. Seufert, V., Ramankutty, N., & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. *Nature*, 485, 229–232.
57. Shehzadi S, Shah Z, Mohammad W. Impact of organic amendments on soil carbon sequestration, water use efficiency and yield of irrigated wheat. *Biotechnology, Agronomy, Society and Environment*. 2017;21(1):36-49
58. Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, 22, 1315–1324. <https://doi.org/10.1111/gcb.13178>

59. Smith, P., Soussana, J. F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., ... & Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology*, 26(1), 219-241.
60. Sparling GP, Wheeler D, Vesely ET, Schipper LA. What is soil organic matter worth? *Journal of Environmental Quality*. 2006;35:548-557
61. Syswerda SP, Corbin AT, Mokma DL, Kravchenko AN, Roberson GP. Agricultural management and soil carbon storage in surfaces vs deep layers. *Soil Science Society of America Journal*. 2011;75(1):92
62. Tittonell, P. (2014). Ecological intensification of agriculture — Sustainable by nature. *Current Opinion in Environmental Sustainability*, 8, 53–61.
63. 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. *Journal of Environmental Management*. 2014;146:189-197
64. Yeboah S, Zhang R, Cai L, Li L, Xie J, Lou Z, et al. Tillage effect on soil organic carbon, microbial biomass carbon and crop yield in spring wheat –field pea rotation. *Plant, Soil and Environment*. 2016;62(6):279-285
65. Zuber, S. M. & Villamil, M. B. Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. *Soil Biology and Biochemistry* 97, 176

UNDER PEER REVIEW