CHAPTER 2

CAN SOIL HEALTH MANAGEMENT ENHANCE CARBON SEQUESTRATION AGAINST CLIMATE CHANGE?

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1. Introduction

Soil serves not merely as a beneficial environment for plant growth. The soil is also a living storage that may function as a carbon (C) sink or source. Soil can sequestrate extra carbon dioxide (CO_2) from the atmosphere, that is making the planet warmer (Razzaghi, 2021). Taking excellent care of soil health can enhance C concentration that be could possibly be sequestrated (Razzaghi et al., 2022). Therefore, soil health management plays an essential function in addressing worldwide climatic mitigation (Meena et al., 2024).

When farmers want to enhance soil health, they use crop rotation, cover crop planting, and no-tillage, and enhance the quantity of soil organic carbon (SOC) (Razzaghi, 2021). These methods improve the soil's physical (Hubbard et al., 2013), biological (Mullen et al., 1998), and chemical (Sharma et al., 2018) properties that prepare suitable conditions where higher C content can be sequestrated in the soil. In addition, healthy soils can better combat soil erosion, which helps further increase their capacity to store C (Rojas et al., 2016).

Consequent to the above, the promotion of sustainable farming practices for increasing SOC sequestration has its most important consequence regarding climate change mitigation processes (Nazir et al., 2024). Healthy soils, with no application of chemical fertilizers in farming, link to better crop yields due to improved water usage(Lehmann et al., 2020). This aligns with Zhao et al. (2024), hence having a better effect in terms of causing more GHG reduction. In this vein, managing soil health can mitigate climate change and enhance crop yield and food security (M. Tahat et al., 2020; Timsina, 2018). This makes it a fundamental part of focusing on climate change for rural areas and farming communities (Sharma et al., 2016).

This chapter investigates various management practices in soil health that boost C sequestration in the direction of mitigating climate change. Improvement in methodology for crop rotation, cover cropping, reduced or no tillage, agroforestry, and Utilization of organic fertilizers improves soil organic matter (SOM) stock capacity, and its main fraction is named C. The chapter goes in-depth on the scientific strategies by which healthy soils act as C sinks, decreasing CO_2 concentration in the atmosphere. Furthermore, this chapter explored thoroughly other deeper ecological and agricultural benefits of these practices, which improved soil productivity, water retention, and biodiversity.

2. The Link Between Soil and Climate

2.1. Carbon Cycle and Soil

In contrast to popular belief, the majority of the C is stored in soils mainly in the manner of organic matter rather than in the atmosphere (Wu et al., 2024). In the worldwide C cycle, soil behaves as either a source or a sink. (Nazir et al., 2024). Plants absorb atmospheric CO_2 by photosynthesis, and upon dying and decomposing, a greater fraction of that C returns to the soil (Murphy, 2024). Nonetheless, human activities such as deforestation, intensive farming, and erosion-related and other types of soil degradation have accelerated C release from soils to the atmosphere and enhanced GHG emissions (Arif, 2024). The opposite happens in healthy soils when well-treated, by sequestering a high content of C and lowering the rate of atmospheric CO_2, hence mitigating climate change (Lal, 2021).

2.2. Carbon Sequestration and Soil Health

This therefore allows for higher SOC stock since healthy soils have better structure, biological activity, and organic matter (Rao, 2013). The main role of conservation agriculture through cover cropping, reduced or no-tillage, and organic fertilizers is to offer more C capture and storage in the soil (Krauss et al., 2022). It also means that food production would have to rely less on climate-sensitive areas. Sustainable soil management strategies can enhance the long-term storage of SOC and therefore, make SOC more stable through this elevated technique (Francaviglia et al., 2023). Healthy soils are also more resilient to erosion and degradation processes, as well as to their C-stock potential (Lal, 2004; Rinot et al., 2019). Improving soil health is thus crucial to reducing different aspects of climate change by improving the SOC sequestration rate.

2.3. The Soil Organic Carbon and Climate Change

Even so, healthy soils by enhancing water retention, assisting biodiversity, and improving nutrient cycling can mitigate climate change (Kundu & Kumar, 2024). Under dry climate conditions, a substantial concentration of SOM can store more water for crop needs, thus decreasing the requirement for irrigation (Lal, 2020). Such soils provide a home to micro- or macroorganisms, that play essential functions in nutrient cycling and the upkeep of ecosystem stability (Aqeel et al., 2023). Consequently, healthy soils

enhance the soil's buffering capability under the effect of extreme climate change (Lal, 2011). Thus, soil health contributes not only to C sequestration but also to assisting the sustainability of agricultural systems in the context of a changing climate (Kumar et al., 2017).

2.4. Sustainable Soil Management and Climate Change

The soils will need to be managed more sustainably for the full utilization of their capacity to help promote the practices that mitigate climate change on concentrations that could possibly be sequestrated (Branca et al., 2013). These paractices include scientific research that supports policies, education of farmers (Romig et al., 1995), and ultimate adoption of regenerative practices that advocate soil health (Khangura et al., 2023). The C farming incentives (Toensmeier, 2016), enhancements in land-use policies (King et al., 2016), and international cooperation are vital for upscale efforts at the global level (Bausch & Mehling, 2011). Furthermore, soil health by a natural and economically efficient method can be integrated into the mitigation of climate change (Yang et al., 2024) which will prepare food security, water management, and biodiversity preservation. Therefore, the management of soil, especially organic C, should be the primary emphasis in the combat against climate change (Lal, 2013).

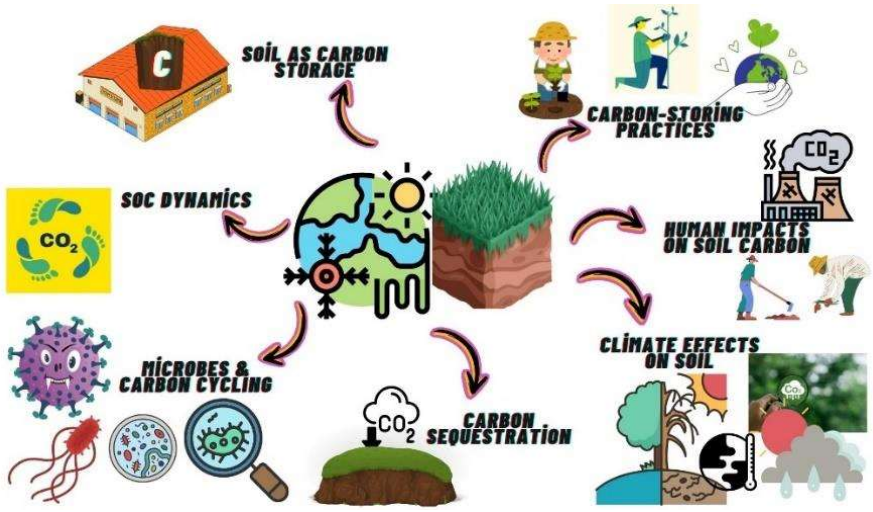


Fig. 1. "Soil and Climate: The Carbon Connection"

3. Soil Carbon Stock and Microorganisms

The microorganisms are involved in a close manner in the C cycle, since they decompose organic matter into more simple compounds, potentially affecting long-term C storage and atmospheric CO_2 emission (Mustafa et al., 2024). Moreover, microbial activity later generates stable organic molecules and governs their protection and stabilization (Paul, 2016). Soil microorganisms accomplish this by synthesizing enzymes that decompose organic substances into smaller, more stable molecules. These molecules, such as microbial necromass composed of deceased microbial cells, cannot undergo further decomposition and significantly contribute to the SOM (Sollins et al., 1996). Microbial-derived C creates enduring storage in soils and serves a crucial act in strengthening SOC sequestration (Zhou et al., 2024).

However, the diversity of soil microorganisms plays a significant role in the well's SOC sequestration (Bhattacharyya et al., 2022; Kabiri et al., 2016). By increasing the variety of microbes, techniques used in ecosystems to break down organic matter, like nutrient cycling and C stabilization, should work better and be stronger. This is because microbes have different metabolic abilities. Hence, microbial diversity is crucial in facilitating access to the full capacity of soils acting as C sinks (Dubey et al., 2019; Hu et al., 2024). In this respect, human actions that include overapplication of chemical fertilizers, intensive tillage, and monoculture help promote the deterioration of soil structure and reducing microbial diversity; hence, it is limited in storing SOC. Sustainable management practices involve the application of compost or biochar and the implementation of reduced or no-tillage practices that increase microbial activity and diversity, hence increasing C sequestration (Meng et al., 2024; Song et al., 2024). As mentioned above, only healthy soils promote a diverse microbial life that transforms organic compounds and plant residues into stable organic forms through humification. This procedure ultimately results in SOC sequestration over centuries (Walia & Kaur, 2024). Because of this, learning how SOC sequestration works and what role soil microorganisms play will make its effectiveness in mitigating climate change stand out more.

4. The Soil Health Practices for Soil Carbon Sequestration

Some of the soil health practices for soil C sequestration are outlined below (Fig. 2)

4.1. Crop Rotation

Fundamental to sustainable agriculture and ecosystem resilience is soil health improvement which assurances food security. (Lal, 2024). Healthy soils assist plant growth, improve water penetration, decrease different types of soil erosion (Turner et al., 2018), and support biodiversity (Adewara et al., 2024). The most crucial strategy for improving soil health contemplates crop rotation, where the farmers will have to plant different types of crops on the same piece of soil as their farming management practice (Aziz et al., 2011). This process reduces soil nutrient depletion (Keres et al., 2020), limits the potentiality of soil-borne diseases (Vargas Gil et al., 2008), and depending on the crop, decreases pest formation (Bullock, 1992). In addition, legumes or other nitrogen-fixing crops in rotations may replace some essential nutrients naturally, thus further reducing the necessity of utilizing synthetic fertilizers (Jensen et al., 2020).

4.2. Cover Crops

Another essential strategy adopted for soil health improvement is cover cropping. Cover crops may involve clover, rye, or legumes grown over the seasons when the major crops are not on the farm. Such crops aid in soil erosion control, restriction of weed growth, and improvement of SOM content (Razzaghi, 2021). When cover crops decompose, essential nutrients are returned to the soil, advocating the development of profitable microorganisms. Cover cropping also enhances the structure of the soil, such that the likelihood of compaction diminishes and its water retention capacity increases, which is important in drought prevention and flood management, respectively (Islam & Sherman, 2021).

4.3. Organic Fertilizers

Organic fertilizers like compost, legumes, manure, and biochar provide soil fertility. These fertilizers improve the soil structure, boost the availability of slow-releasing sources of nutrients, and improve microbial activities, which are vital for preserving fertile and healthy soils (Razzaghi, 2024). According to Yan and Gong (2010), the utilization of organic fertilizers can boost SOC and soil productivity. Furthermore, they reported that the changes in SOM and wheat yield have been significantly linearly related (Fig. 3). As mentioned

above unlike chemical fertilizers, organic fertilizers can release their nutrients more slowly, providing plant's requirements while minimizing the risk of nutrients leaching into water systems (Shaji et al., 2021). Organic amendments enhance the SOC sequestration potential; therefore, climate change is mitigated since a higher content of C is stored while there is less emission of greenhouse gases (Razzaghi, 2022). Moreover, the application of soil health practices that decrease the application of synthetic fertilizers and favors using compost and natural inputs can decrease agriculture's C footprint. In addition, healthy soils require fewer chemical inputs, which will reduce energy use and the emissions associated with fertilizer manufacture and application (Razzaghi, 2024). Healthy soil management sequesters more C by combining organic matter and optimizing nutrient cycling (Waqas et al., 2020). This approach reduces GHG associated with farming activities (Powlson et al., 2011).

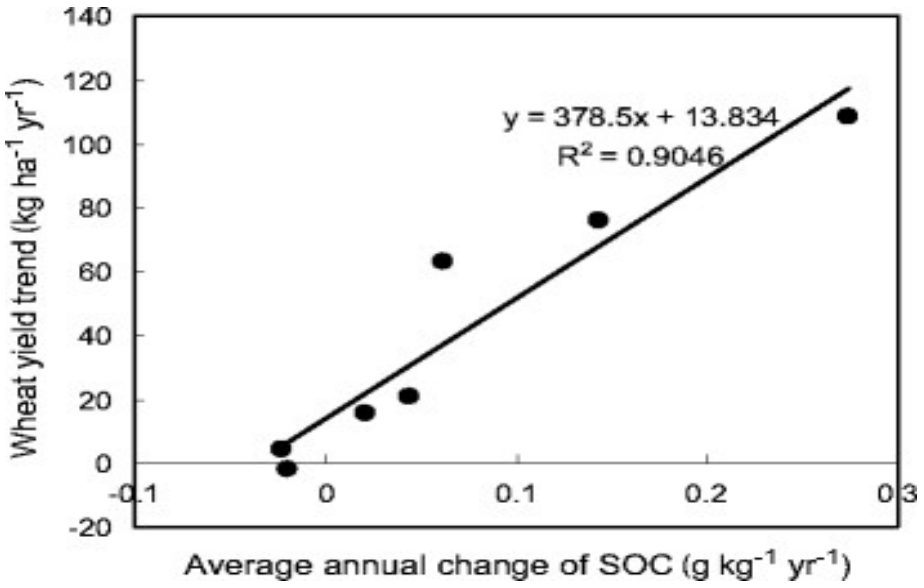


Fig. 3. The significantly linearly relation between SOC content and wheat yield (Yan & Gong, 2010)

4.4. Agroforestry

The most valuable soil health management practices are agroforestry and grazing control. Agroforestry is planting trees and shrubs among the farmland, which ensures their safety to combat erosion and boosts biodiversity and nutrient cycling via leaf litter and root interaction (Dollinger & Jose, 2018). In this method, to avoid overgrazing, farmers use rotational grazing of grasslands;

hence, the soil is not compacted to allow the growth of grass (Taylor, 2024). It is considered that these two practices, among others, are optimal management techniques for providing long-term soil health and, notably, developing agricultural resilience in response to climate change (Singh et al., 2024). According to Joshi et al. (2024), a poplar trees+wheat intercropping system could increase C sequestration compared to sole wheat or sole poplar planting in North India (Fig. 4). With such practices regarding soil health, farmers can construct more resilient ecosystems while keeping agricultural productivity at a higher rate.

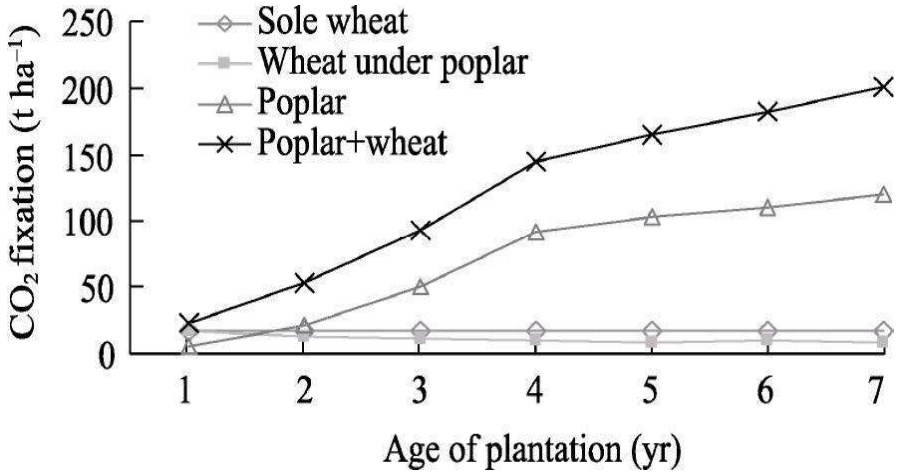


Fig. 4. The poplar-wheat intercropping system impact on Carbon sequestration (Joshi et al., 2024)

4.5. Conservation Tillage

Conservation tillage is one of those farming strategies regarding minimal soil disruption via reduced or no tillage; it also performs an outstanding function in C sequestration (Hussain et al., 2021). Keeping crop residues on the field and not conducting heavy tillage enables more organic matter to remain in the soil. That organic matter stores C, avoiding the spread of it into the atmosphere as CO_2 (Aziz et al., 2013). Further, this practice consolidates the soil structure and improves microbial activities, hence SOC sequestration becomes more sustainable for longer (Zhang et al., 2021). In this context, Ur Rehman et al. (2023) reported the highest SOC sequestration rate under fellow-wheat and mungbean-wheat cropping systems in combination with no tillage

(Fig. 5). Besides improving C storage, conservation tillage enhances general soil health: it reduces erosion, improves water retention, and increases biodiversity factors that in turn further help to stabilize and sequester C (Begum et al., 2022; Fiorini et al., 2022). Conservation tillage raises the level not only of soil sustainability but also enables farmers to offset climate change by making agricultural soils serve as effective C sinks.

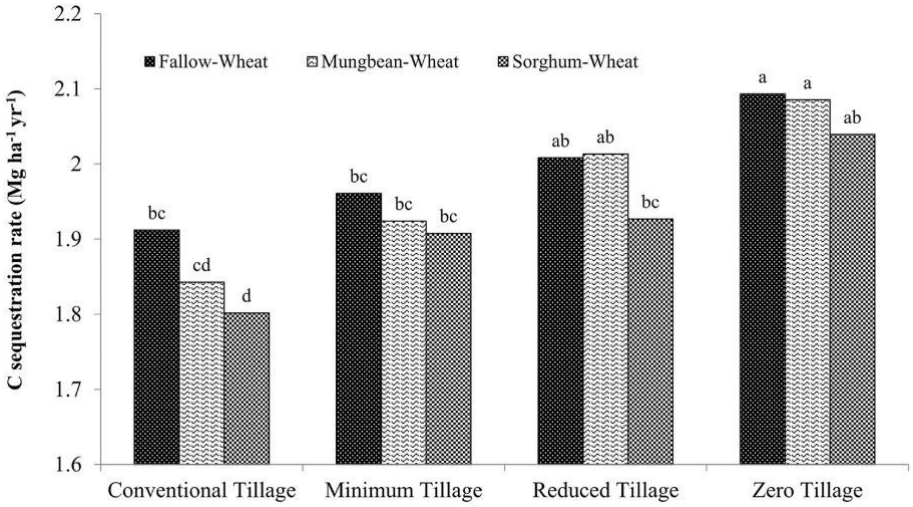


Fig. 5. SOC sequestration rate across various cropping and tillage systems (Ur Rehman et al., 2023)

4.6. Control of Soil Erosion

Management of soil health averts loss from stored C caused by the preservation of soil structure and reduction in erosion (Hussain et al., 2021). Control of soil erosion is essential in ensuring the promotion of soil health by boosting C sequestration. Wind and water erosion removes that portion of topsoil where organic matter and stored C are concentrated (Du et al., 2022). The lost topsoil releases C into the atmosphere as CO_2, subsequently contributing to increased climatic change (Yang et al., 2003). Consequently, the protection of soils from erosion will prevent this stored C from loss and guarantee its continued operation functioning as a C sink instead of a source of CO_2 emissions (Razzaghi et al., 2021). Contour farming (Farahani et al., 2016), vegetation buffers (Kavian et al., 2018), terracing, and cover cropping (Aziz et al., 2014) are some of the practices that decrease erosion and preserve the C

stored in the soils. Healthy soils with strong structures can store this C over long periods; hence, they are beneficial C sinks (Saleem & Batool, 2024).

4.7. Nutrient Cycling

Nutrient cycling is fundamental to soil health management practices and hence continuous supplementation of nutrients due to various natural phenomena of decompositions, mineralization, and microbial activities come back to the soil for growing better plants with structural improvement and water retention capacity (Iamjud, 2021; Singh et al.; Yousuf et al., 2022). Nutrient cycling in this respect includes the organic material from plant residues and animal manure that provide nutrient storage, decomposing through soil organisms, and providing it available to plants (Schröder et al., 2016). Besides soil fertility, nutrient cycling supports C sequestration as a very crucial strategy in the mitigation of climate change (Kirkby et al., 2013). Organic matter and plant residues broken down through nutrient cycling can keep C within the soil as stable organic materials (Razzaghi et al., 2021). Once this C gets sequestered, the atmospheric CO2 concentration will reduce, hence helping offset GHG (Razzaghi et al., 2022). Where nutrient cycling is active, healthy soils are more effective at capturing and storing C, hence acting as better C sinks (Chowdhury et al., 2021).

4.8. Organic Farming

Organic farming, as noted in organic fertilizers, has great potential to improve SOC sequestration through the improvement of soil health (Gamage et al., 2023) and the reduction of GHG emissions due to its valuable practices (Squalli & Adamkiewicz, 2023). Composting, crop rotation, manuring, and cover cropping provide a high content of SOM because of lack of synthetic fertilizers, herbicides, and pesticides (Goldan et al., 2023; Shakywal et al., 2023). Due to this high level of organic matter, the soil's capability to capture and store C increased, hence considering it a natural C sink (Mosa et al., 2023). As mentioned above, other organic farming practices, such as crop rotation, reduced tillage, and agroforestry, enhance further the soil structure, prevent erosion, and give a helping hand to biodiversity toward the sequestering of more C within plant biomass and soil. As repeatedly described in past sections, organic farming reduces climate change by decreasing GHG emissions

(Aguilera et al., 2015; Pegu et al., 2024). In addition, contrary to organic farming, conventional farming often depends on very energy-intensive input materials, such as chemical fertilizers and fossil fuels, leading to a high rate of emissions (Rosati et al., 2021; Tittonell, 2014). Organic farming also contributes to biodiversity and produces food sustainably (Underwood et al., 2011). Additionally, it makes the soil resilient to store more C for a longer period (Rohit Yadav et al., 2024). It therefore promotes food security and environmental health but also mitigates more considering climate change by C sequestration (Banerjee & Sarkar).

4.9. Precision Agriculture

The innovative tools of precision agriculture include GPS, drones, sensors, and data analytics; these enable the farmer to apply all inputs-that is, worthwhile compounds like water, fertilizers, herbicides, and pesticides-in precisely correct content to the right place; hence, diminishing waste of these costly and vital inputs (Razzaghi & Kılıç, 2024). Precision agriculture can also help C sequestration by adopting improved farming practices that drop emissions and improve the capture of more C within the soils by biomass (Balafoutis et al., 2017). Besides useful use of inputs, this type of agriculture also promotes zero tillage farming, cover cropping, and optimized crop rotations to help accumulate the SOM and develop C sequestration (Cillis et al., 2018; Handayani & Folz, 2021). As a result, this method of agriculture by appropriate soil management will increase soil fertility and soil health, SOC sequestration, and mitigation of climate change (Balasundram et al., 2023; Nath, 2024; Roy & George K, 2020; Shaheb et al., 2022).

4.10. Regenerative Agriculture

Some of the main techniques in this soil health management practice include agroforestry, holistic grazing (Cusworth et al., 2022), reduced or no-till methods of farming (Pontius & McIntosh, 2024), and cover cropping (Jordon et al., 2022) were used. These procedures can help farmers produce organic matter in soils and enhance the long-term C sequestration, decrease atmospheric emissions, and, on the other hand, improve biodiversity and enhance soil health (Sahu & Das, 2020). As previously described, C-rich Soils not only reduce atmospheric CO_2 but also enhance soil fertility and productivity

in plants by enhancing water retention and increasing resilience against climate change conditions (Victoria et al., 2012).

Sequestration as a repeated continuous word in regenerative agriculture is a natural phenomenon that, through photosynthesis, include the uptake of CO_2 by plant and the transference of C into the soil via roots and fixed in aggregates of the soil after organic matter decomposition (Ravina Yadav et al., 2024). This balances out the emissions and, therefore, creates one of the potential solutions for mitigating climate change while restoring ecosystems (Ravina Yadav et al., 2024). Such methods in regenerative agriculture can turn the soil into a C sink to contribute to more sustainable agricultural systems in all aspects, from C sequestration to climate-friendly agriculture.

4.11. Biodiversity's Role

In the preceding sections, it was discussed widely that biodiversity in plants and micro and macroorganisms can improve soil health, which is an important part of C sequestration. As known ecosystems that will be more diverse, such as forests, grasslands, and wetlands. This diversity caused them to capture different amounts of C due to their differences in photosynthesis (Daba & Dejene, 2018). In polyculture systems, plant species with different rooting systems are more varied and are in higher depth than those in monoculture species (Lei et al., 2012). Thus, the rooting architecture strengthens soil stability and favors the transfer of C to a deeper layer of the soil (Freschet et al., 2021; Hodge et al., 2009). Ecosystems foster healthy soil microbiomes for better soil C stock through nutrient cycling. It follows that the higher the biodiversity, the more resistant the ecosystems are to disturbances, like pests and diseases, and climate changes; therefore, they are in a position to maintain C sequestration for a long period (Hartmann & Six, 2023; Prasad et al., 2021; Yadav et al., 2021). By applying soil management like crop rotation, cover cropping, polycultures, and agroforestry, we can improve biodiversity and, consequently, C sequestration due to enhancements in SOM content (Jhariya et al., 2023; Weißhuhn et al., 2017).

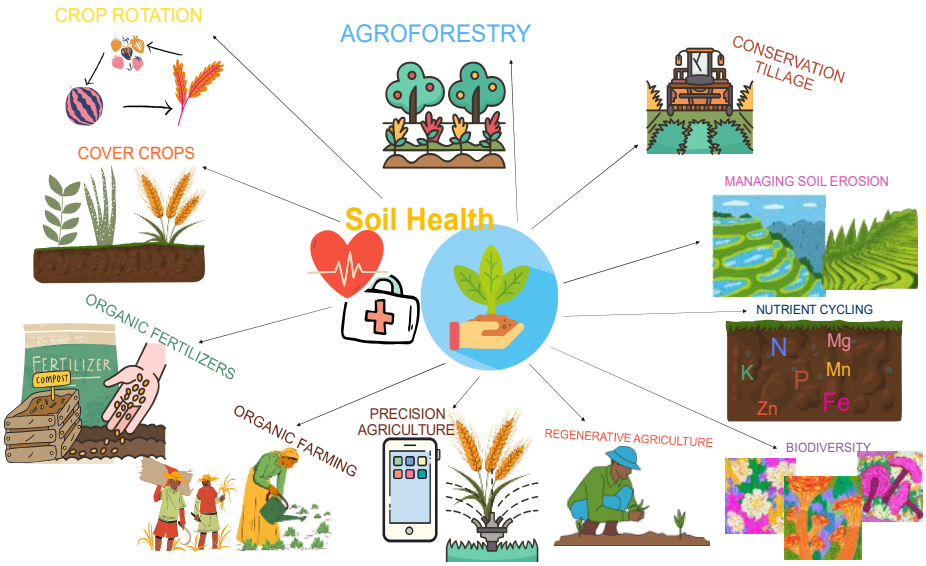


Fig. 2. The Soil Health Practices for Soil Carbon Sequestration

5. Some of the Successful Soil Health management paractices for Carbon Sequestration

Soil health management practices are essential in enhancing C sequestration for climate change mitigation. Some of the described practices that work in the recent and previous studies for improving C sequestration and climate change mitigation are listed in the table below (Table 1). The combined practice has greatly contributed to increased soil C stocks, improved soil health, and a more robust agriculture system in response to climate change.

Table 1. Some of the successful soil health management practices affect on soil C sequestration and climate change

Soil Health Management Practice	Effect on Soil C Sequestration and Climate Change	References
Cover Cropping	↓Erosion, fix atmospheric N_2, ↓N leaching, and ↑soil health. ↑SOC most in ↓-C soils (<1% C) and after 5 yr (when cover crops created >2 Mg biomass ha^{-1}) Potential global SOC sequestration of 0.12 ± 0.03 Pg C yr^{-1} by cover cropping	(Kaye & Quemada, 2017) (Blanco-Canqui, 2022) (Poeplau & Don, 2015)

No-till or Reduced Tillage	No-till↑ ~38% SOC concent (0–5 cm depth), SOC stock ↑ by 14% or 5.4 Mg C ha^{-1} over 0–30 cm depth. SOC content was predicted to range from 1.4 - 1.7 Mg ha^{-1} (by yr 2054), and 2.3 - 3.1 Mg ha^{-1} (by yr 2100). Crop yield↓ of wheat (7.7%) and maize (2.3%), SOC sequestration↑ by 9.9%, No-till + crop residue + crop rotation ↓the negative impact of No-till on crop yield (5% to 2.44%), and ↑SOC sequestration > 12.77%.	(Mondal et al., 2023) (Sorenson et al., 2024) (Cui et al., 2024)
Organic Amendments (Compost, Manure)	Restores SOC and ↓atmospheric greenhouse gases (GHG). ↑SOC sequestration and pool and ↑soil quality ↓atmospheric GHG.	(Owusu et al., 2024; Shivangi et al., 2024) (Alvarenga et al., 2020)
Biochar Application	Globally, ↓emission reductions of 3.4–6.3 PgCO2e, with half of this amount dedicated to CO_2 removal. ↓Climate change by ↑SOC sequestration and ↓soil GHG emissions	(Lehmann et al., 2021) (Franco et al., 2024)
Agroforestry and Perennial Crops	↑ SOC sequestration rates by 5–10 times, and ↑ SOC stocks by a factor of 3–10. Agroforestry ↓the emissions of CO_2 by sequestering C from the atmosphere Agroforestry systems sequester ↑C in subsurface layers of soil near the tree	(Toensmeier, 2017) (Tefera et al., 2019) (Sow et al., 2024)
Crop Rotation and Diversification	Modifications in Finnish agricultural crop rotations, in mineral soils↓ the reduction of SOC content by 1336 Mg C $year^{-1}$, in organic soils↓ CO_2 emissions of by 10,475 Mg C $year^{-1}$.	(Kostensalo et al., 2024) (Yang et al., 2024)

	The diversified rotations » wheat–maize + sweet potato +peanut and soybean » ↑yield > 38%, ↓N_2O emissions by 39%, and ↑ the system's GHG balance by 88%. Legumes in crop rotations » ↑soil microbial activities » ↑SOC stocks by 8%, and » ↑soil health Index by 45%.	

↑= high or increased, ↓=low or less, decreased

5.5. Conclusion

Overall, from this point of view, throughout the fight against climate change, managing soil health is one of the promising techniques for C sequestration, which has huge beneficial implications both for the surrounding environment and farming. Practices in soil health enhance SOM, offer a healthy microbial ecosystem, and encourage soils to capture more C and store it longer, hence offsetting some of the GHG emissions responsible for global warming. A positive correlation exists between soil health and climate mitigation. It was demonstrated that promoting soil fertility and sustainability can reduce atmospheric CO_2 rates. Cover cropping, crop rotations, reduced tillage, and organic fertilization as accomplished practices in improving soil health present the potential of such strategies to create considerable results in enhancing C sequestration. Enhancing soil health will also minimize soil erosion, thereby enhancing soil C stock and its stability. Innovation techniques like precision agriculture and agroforestry enhance the sustainability of different soils in a wide range of agricultural ecosystems. Any accurate vision of sustainability for the future should make soil health management integral to any set of policies regarding climate change. It is, therefore, important that governments, agriculture sectors, and regional communities around the world focus their efforts on those practices that help in SOC sequestration and balance productivity with sustainability and ecological health. Enhancing operational methodologies in soil health with investment in research and training will provide a functional pathway toward mitigating climate change and protecting soil resources for future generations.

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