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Balancing the Scales: The Complex Dynamics of Soil Carbon Sequestration

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Abstract

At present, soil pollution is a global problem, and how to control soil pollution has become a hot topic. As an important part of soil pollution control, it is necessary to discuss the importance, advantages and disadvantages of soil carbon sequestration. In the whole process of the carbon cycle, most gases need to enter the soil to complete gas exchange. Therefore, this essay provides a comprehensive analysis of soil carbon sequestration, covering its processes, environmental and economic benefits, limitations, and technological advancements. It begins by explaining soil carbon sequestration's role in mitigating climate change and enhancing soil health. Then it delves into the factors influencing carbon sequestration, including environmental conditions and soil characteristics. What is more, it acknowledges the process's limitations, such as the soil's finite carbon storage capacity and the need for widespread adoption of sustainable practices. Finally, it discusses innovative techniques in soil management and technology's role in monitoring and maximizing soil carbon sequestration. The essay concludes by emphasizing a balanced and integrated approach for effectively using soil carbon sequestration in combating climate change.

Keywords: soil carbon sequestration, advantages and disadvantages, climate change, soil science, photosynthesis

1. Introduction

Soil carbon sequestration is a crucial agricultural strategy (Bossio, D. A. et al., 2020). This natural process involves capturing atmospheric carbon dioxide and storing it in the soil, critical to the global carbon cycle. Soil carbon sequestration is essential in slowing the rise in greenhouse gas levels and enhancing soil health and fertility (Bhattacharyya, S. S. et al., 2022). It improves soil structure, enhances soil aeration, and promotes plant growth. In addition, carbon-rich soils (Zheng, J. et al., 2022) better buffer pH against acid rain and other environmental changes that can lead to soil acidification or alkalisation.

Therefore, this essay will start from the source of soil carbon sequestration, then go to the process of carbon sequestration, and finally describe the advantages and disadvantages of soil carbon sequestration.

2. Soil Carbon Sequestration

2.1 Concept and Specific Process of Soil Carbon Sequestration

In the past ten years, global attention to climate change and the greenhouse effect has been increasing, and the carbon cycle of terrestrial ecosystems and its changes in the absorption capacity of atmospheric carbon dioxide have become an important research focus (Walker, A. P. et al., 2021). As the most significant carbon storage medium in terrestrial ecosystems, soil is crucial in maintaining environmental sustainability. Furthermore, the carbon content of terrestrial vegetation is about 20% (Hibbard, K. A. et al., 2001). Soil carbon sequestration plays a crucial role in maintaining a healthy ecosystem.

Soil carbon sequestration is the natural process of plants absorbing carbon dioxide from the atmosphere through photosynthesis. Therefore, in this process, carbon dioxide could be converted into organic carbon in plant tissues, which is eventually stored in the soil. Moreover, this process is crucial in reducing atmospheric carbon dioxide levels.

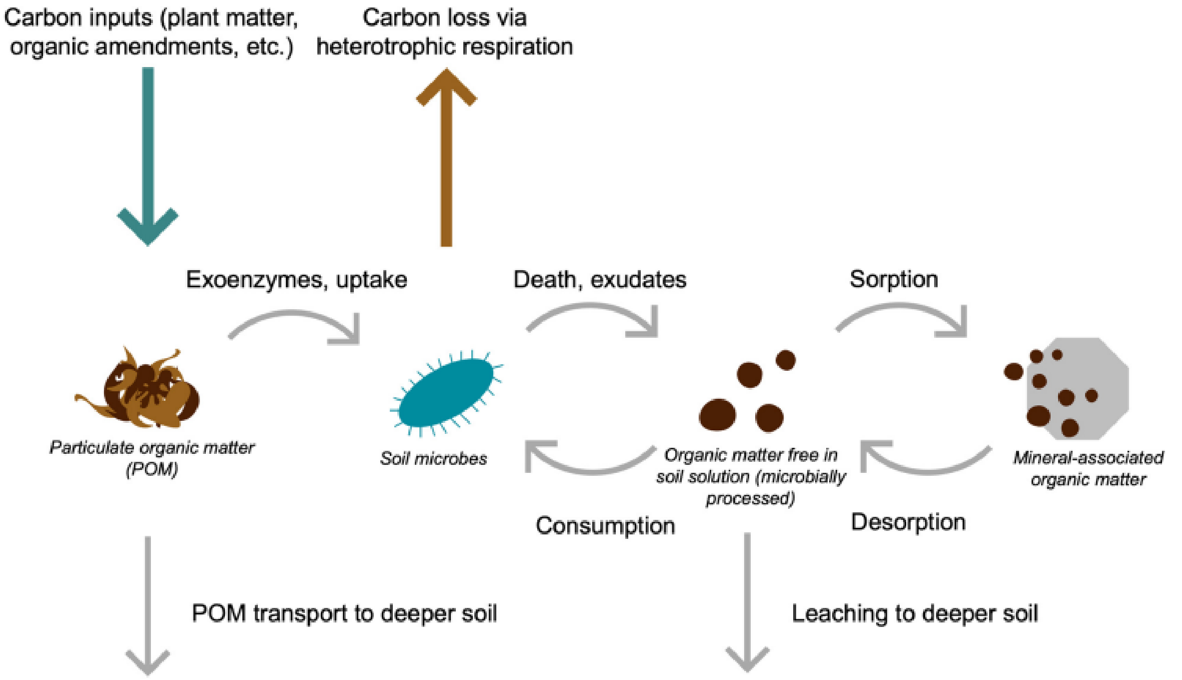

Figure 1. Flow chart of soil carbon fixation (Dynarski, K. A., Bossio, D. A. & Scow, K. M., 2020)

2.1.1 Photosynthesis

Photosynthesis is a critical ecological process for plant survival. To be specific, on the one hand, it is a collection of complex metabolic reactions that are critical to the survival of the biological world and the carbon-oxygen balance of the Earth. On the other hand, in photosynthesis, chloroplast-containing green plants use photosynthetic pigments to convert carbon dioxide and light energy into organic matter through light and carbon reactions.

Furthermore, the carbon in the carbon dioxide is fixed in the plant tissue. Two main stages of photosynthesis are light reaction and dark reaction. The reaction formula is as follows (Johnson, M. P., 2016):

Light reactions:

$2H_2O + light \rightarrow O^2 + 4H^+ + 4e^-$
$G^\circ = +317\ kJ{\cdot}mol^{-1}$

Dark reactions:

$CO_2 + 4H^+ + 4e- \rightarrow CH_2O + H_2O$
$G^\circ = +162\ kJ{\cdot}mol^{-1}$

Overall:

$H_2O + light + CO_2 \rightarrow CH_2O + O_2$
$G^\circ = +479\ kJ{\cdot}mol^{-1}$

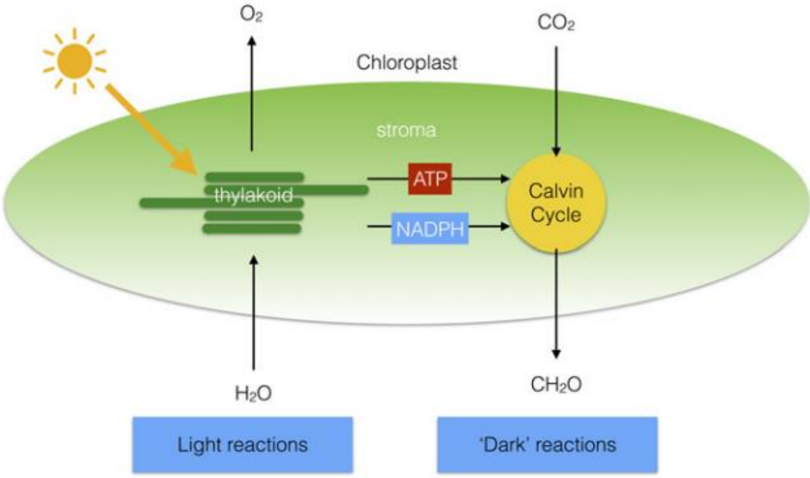

Figure 2. Schematic diagram of photosynthesis (Johnson, M. P., 2016)

2.2 Factors Influencing Soil Carbon Sequestration

2.2.1 Environmental Factors

(1) Climate

Temperature and humidity levels significantly affect soil carbon sequestration. Adequate moisture is essential for soil microbial activity (Bian, H. et al., 2022); besides, as Xue et al (2016) state, rising temperatures can lead to increased decomposition of soil organic matter, potentially releasing more carbon into the atmosphere. The relationship between soil carbon sequestration and temperature is as follows.

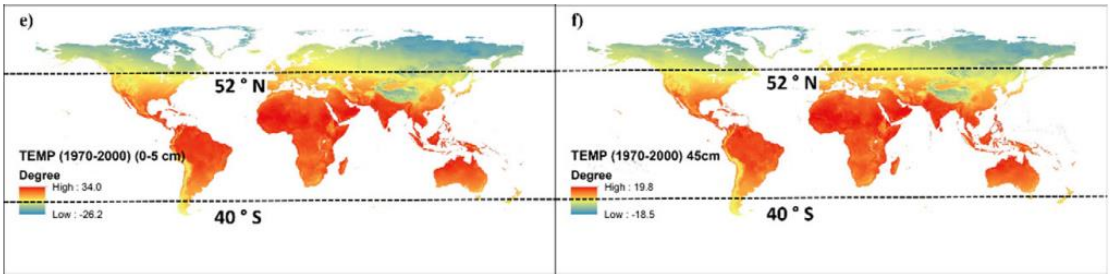

Figure 3. High and low temperatures with soil carbon (Huang, J. et al., 2018)

(2) Soil characteristics

Soil type, texture, and structure affect its ability to store carbon. For example, Prout et al. (2022) state that soils rich in clay or organic matter generally have a higher carbon storage potential than sandy soils.

Table 1. Comparison of soils rich in clay and sandy soils (Tahir, S. & Marschner, P., 2016)

	Ped size (mm)	Water-holding capacity (g water g^{-1} soil)	NH_4-N µg g^{-1} soil	Available P µg g^{-1} soil
Sandy soil	None	0.02 f	3.8 c	9.9 a
Sandy soil + 10 % clay	1	0.08 cd	4.1 bc	8.7 b
	2	0.07 de	4.1 bc	8.0 bc
	3	0.05 e	4.0 bc	8.9 ab
Sandy soil + 20 % clay	1	0.13 a	5.4 a	7.5 c
	2	0.11 b	4.6 b	7.4 c
	3	0.10 bc	4.3 bc	7.6 c

2.2.2 Biological Factors

(1) Vegetation Type and Cover

The type and density of vegetation significantly affect the input of organic matter in soil, an essential component of 'soil carbon. First, different plants, such as herbs, shrubs, and trees, have other biomass and root structures. For example, trees often have deep roots that transport carbon into deeper soil layers, while herbs primarily affect shallower soil layers.

Secondly, vegetation cover in different ecosystems affects soil carbon storage. Because of their high vegetation density and biodiversity, tropical rainforests import much organic matter into the soil yearly, making them a high-carbon storage ecosystem. In contrast, desert areas have relatively low soil carbon storage due to sparse vegetation and less organic matter input into the soil. These differences indicate the vital effect of vegetation cover on the soil carbon cycle. For example, choose a place with different vegetation, as shown in Figure 4 (WANG, Y. et al., 2020), and then the corresponding curves can be obtained through analysis and experiment.

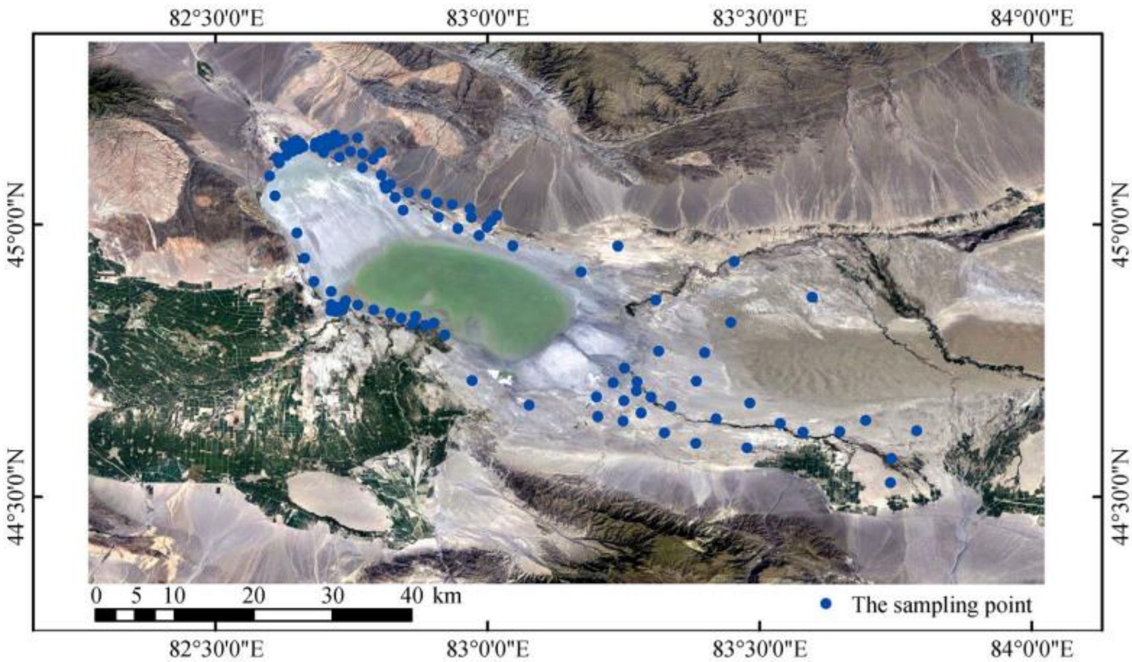

Figure 4. Different vegetation

Table 2. The type of vegetation (WANG, Y. et al., 2020)

Vegetation	Section number
Dry lakebed	16
Desert riparian forest	5
Halophyte shrub	3
Saline meadow	10
Desert shrub	11
Alpine coniferous forest	5
Microphanerophytes desert	57
Total	107

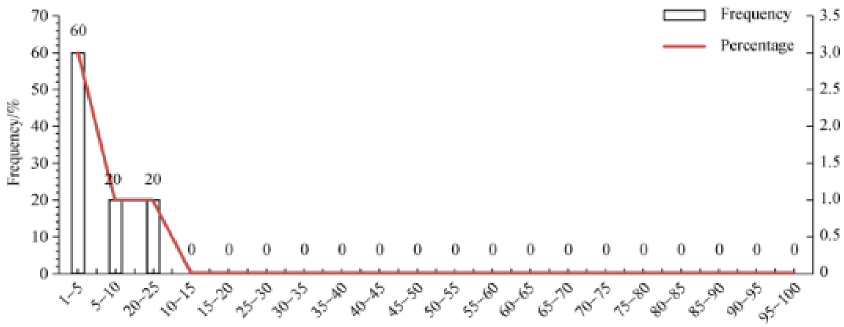

Figure 5a. Alpine coniferous forest with SCS

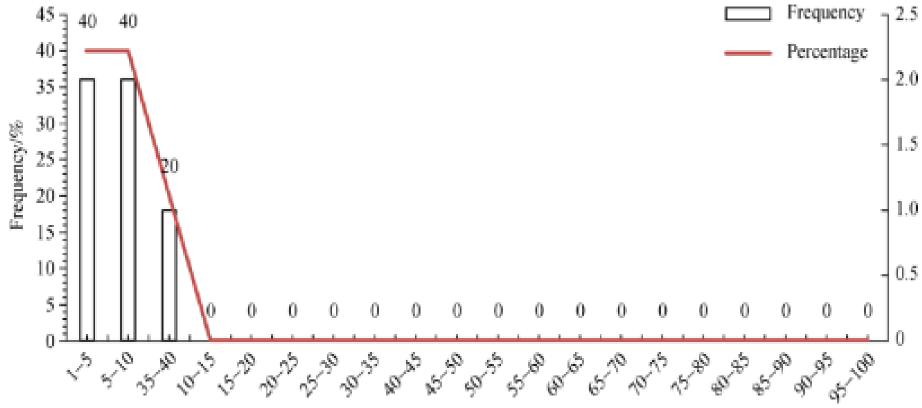

Figure 5b. Desert riparian forest with SCS

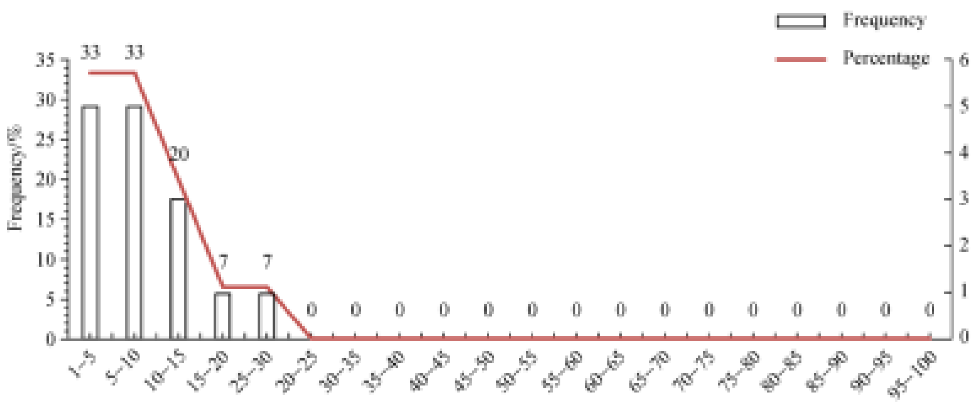

Figure 5c. Dry lakebed with SCS

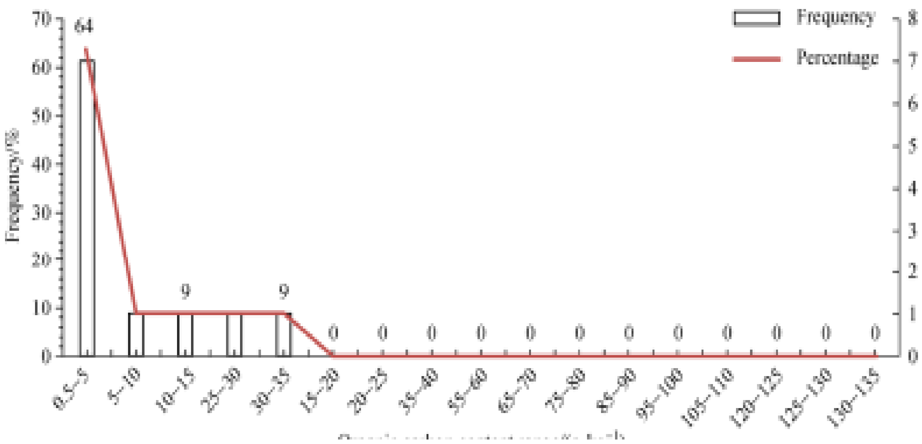

Figure 5d. Desert shrub with S

Note: SCS is Soil carbon Sequestration. (WANG, Y. et al., 2020)

Through the above four curves, it can be found that different vegetation types have various soil carbon sequestration capacities.

(2) Soil Microbes

Microbial communities in the soil play a critical role in decomposing organic matter and incorporating it into soil carbon stocks. For example, soil microbes break down complex organic compounds in plant and animal residues, such as cellulose, lignin, and proteins (López-Mondéjar, R. et al., 2016). In addition, after the initial decomposition of organic matter in the soil, microorganisms further process the material to form humus, a stable form of organic matter in the soil; humus is rich in carbon, essential for soil health and fertility.

3. Advantages of Soil Carbon Sequestration

3.1 Environmental Benefits

(1) Mitigating Climate Change

Climate changes, such as acid rain and the greenhouse effect, could significantly impact soil. For example, Aksulfur dioxide in acid rain may reduce soil pH and cause soil acidification. Moreover, this process of acidification disrupts the chemical balance in the soil and affects the availability of nutrients. Furthermore, warming caused by the greenhouse effect may change precipitation patterns and affect soil moisture (Yang, J. et al., 2022), as well as plant growth and soil ecosystems' stability. What is more, the ongoing climate changes may accelerate the decomposition of organic matter in soil. Besides, it may lead to the release of carbon stored in the soil into the atmosphere, creating a positive feedback loop that exacerbates the greenhouse effect.

Soil carbon sequestration can alleviate these problems by boosting carbon stocks in the soil, as well as creating a positive feedback loop (Lehmann, J. et al., 2020). In this process, healthier soils support more robust vegetation growth, allowing plants to absorb more CO_2. This not only helps enhance soil quality but also helps the overall health of ecosystems while contributing to climate change mitigation. However, the weakness of this process is the need for more consideration of extensive soil degradation on a global scale. Amelung et al. (2020) state that this uncertainty obstructs the development of a coherent global strategy for land restoration and climate mitigation due to the need for accurate data on the extent of soil degradation worldwide. This study would have been more interesting if this study had valid data on soil degradation worldwide when sequestered soil.

(2) Soil Health Improvement

Soil microorganisms are an integral part of the soil ecosystem, contributing to maintaining and enhancing soil fertility by decomposing organic matter and recycling nutrients (Abdelrahman, O. et al., 2022). However, researchers have not treated temperature in much detail in this article. For example, environmental changes caused by climate change, such as higher temperatures, may interfere with the activities of these microbes, which can affect soil health (Wang, H. et al., 2022). Higher temperatures can alter the composition of soil microbial communities, leading to the dominance of heat-tolerant species and a potential reduction in overall microbial diversity. The second is that soil carbon sequestration may indirectly improve soil health by increasing organic matter content (Baveye, P. C. et al., 2020). For example, soils rich in organic matter tend to support more vibrant and diverse microbial ecosystems. These microorganisms play a crucial role in nutrient cycling, further improving soil fertility and plant growth because organics contain functional groups such as carboxyl groups and phenols, which can retain and exchange cations (positively charged ions). When soil becomes too acidic (low pH), these functional groups can release cations like Ca^{2+}, Mg^{2+} and K^+ into the solution. This helps neutralise excess H^+ ions, raising the pH (Hartemink, A. E. & Barrow, N. J., 2023). Conversely, when the soil becomes too alkaline (high pH), these groups can bind to cations and allow more hydrogen ions to remain in the soil solution, thus lowering the pH. However, the weakness of this method is that in soils with high organic matter content, the buffering capacity can sometimes slow down the response to intentional pH adjustments. For instance, if lime is added to acidic soil to increase the pH, organic matter may slow the rate at which the pH increases (Provance-Bowley, M. C., Koppenhöfer, A. & Heckman, J., 2014). Therefore, it would have been interesting if this study considered soil and organic connections.

3.2 Economic Benefits

On an economic level, soil carbon sequestration allows farmers to create carbon credits and access financial incentives. In China, for example, the country has set targets for carbon neutrality and carbon peaking to reduce the concentration of carbon dioxide in the atmosphere. In this context, soil carbon sequestration, as an effective carbon sequestration measure, contributes to reducing atmospheric carbon dioxide content. Therefore, farmers can translate their efforts into quantified carbon reductions by adopting soil carbon sequestration practices such as no-tillage and cover crop cultivation (Poeplau, C. & Don, A., 2015). However, the weakness of this method is ignoring farmers. For example, it is a new technology that may enable farmers to learn no-till equipment and processes and how to manage crop straws. Besides, they may also learn to choose suitable cover crop varieties, understand crop growth patterns, and know when and how to plant and terminate them, which is full of expertise and knowledge. As Zambak and Tyminski (2023) stated, professional knowledge requires a relevant background; for example, in China, farmers in most areas need more wealth and expertise to do the task, which may be challenging. Therefore, this method would have been more relevant if a broader range of farmer's knowledge had been explored.

Governments can give tax subsidies to those who implement soil carbon sequestration. Tax subsidies have significant effort for farmers (Piñeiro, V. et al., 2020); for example, through this incentive, farmers can pay less tax so that more money can be invested in the family, such as medical care for parents or education for children. However, the weakness of this method is ignoring unfair competition with tax subsidies. For instance, large agribusinesses may have dedicated teams to manage grant applications and compliance, giving them an advantage when obtaining tax benefits. In contrast, small family farms may lack the workforce or knowledge to apply for these subsidies effectively; this disparity could result in larger farms strengthening their operations and increasing profits while smaller farms struggle to compete, potentially widening economic inequality in the agricultural sector (Farm Progress, 2017). Therefore, it would be meaningful if this method considers competition between large and small farms.

Overall, soil carbon sequestration brings dual economic benefits to farmers and countries: income generation through carbon credits and environmental protection through implementing sustainable agricultural practices.

4. Shortcomings of Soil Carbon Fixation

Soil carbon sequestration can slow global warming by fixing carbon dioxide from the atmosphere into the soil (Lehmann, J. et al., 2020). However, there are some limitations and drawbacks to this process. First, the soil's carbon storage capacity is limited. Over time, the soil may reach a "saturated" state where it can no longer absorb more carbon. This is because most carbon in soil exists as organic matter, with its capacity to store carbon limited by the initial content and growth rate of said matter (Matus, F. J., 2021). However, the most crucial disadvantage is that Matus failed to note that he ignores the cumulative effect. Despite the limited capacity, the cumulative impact of soil carbon sequestration worldwide could be significant. For example, if sustainable practices such as no-till farming, cover cropping, agroforestry and organic agriculture are adopted on a large scale (El-Ramady, H. et al., 2023), the cumulative effect of increased soil carbon storage could be very significant for the global carbon budget, to decrease climate change. Therefore, before the soil carbon sequestration capacity reaches saturation, it can be accumulated to mitigate climate change and improve soil fertility.

5. Technological and Methodological Advances

5.1 Innovations in Soil Management

First, one of the key innovations is biochar, a high-carbon material produced through the thermal decomposition of organic matter without oxygen. Incorporating biochar into the soil can increase carbon fixation while improving soil quality (Amoah-Antwi, C. et al., 2021), followed by adopting no-till or low-till farming practices. In contrast to traditional farming methods, which often release stored carbon back into the atmosphere, no-till farming preserves soil structure, reduces erosion, and helps retain carbon.

5.2 Role of Technology in Monitoring Soil Carbon

Satellites and drones with advanced sensors can monitor soil health and carbon sequestration levels over large areas, providing valuable data for carbon sequestration projects. Second, innovations in soil sampling methods and laboratory analysis can more accurately measure soil carbon content (Sánchez-Reparaz, M. et al., 2020), critical to verifying carbon sequestration and qualifying for carbon credits. Finally, based on the model, scientists can estimate and predict the level of soil carbon sequestration.

6. Conclusion

Soil carbon sequestration is an effective climate change mitigation measure that helps mitigate global warming by reducing atmospheric carbon dioxide concentrations and storing atmospheric carbon dioxide in the soil. Moreover, the process can also improve soil fertility and crop yield, significantly benefiting agricultural practices. However, soil carbon sequestration also has some disadvantages, such as hurting soil fertility. Therefore, people should have a more balanced and integrated approach when using soil carbon sequestration to combat climate change. It may include considering the characteristics of soil types in different areas, and people can maximise the benefits of soil carbon sequestration.

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