Carbon Dynamics in Soil in Relation to Climate Change

Chapter · August 2023

About the Book

The book "Climate Smart Approaches Towards Sustainable Crop Production" is designed to highlight the climate-smart approaches that farmers and policymakers can adopt to enhance crop production while minimizing environmental degradation. These approaches encompass a range of strategies to address the potential benefits of climate-smart practices in terms of increased resilience, improved livelihoods, and enhanced adaptive capacity.

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Preface

We are pleased to to publish our book entitled "Climate Smart Approaches Towards Sustainable Crop Production" which delves into the critical intersection of climate change, agriculture, and sustainable crop production. This book brings together a diverse collection of scholarly contributions that explore innovative strategies, techniques, and practices aimed at mitigating the impact of climate change on crop production while fostering sustainability. The challenges posed by a changing climate are becoming increasingly evident, with rising temperatures, shifting rainfall patterns, and extreme weather events affecting agricultural systems worldwide. In this context, the need to adopt climate-smart approaches that enhance resilience, reduce greenhouse gas emissions, and promote sustainable practices has never been more pressing. This edited book serves as a comprehensive resource that addresses various dimensions of climate-smart agriculture, focusing particularly on crop production. The contributing authors, comprising esteemed researchers and experts in the field of agricultural sciences, bring together their expertise and insights to shed light on the current challenges and potential solutions. Their research findings, case studies, and practical recommendations provide valuable guidance to policymakers, practitioners, educators, and researchers engaged in the pursuit of climate-smart agriculture and sustainable crop production.

We would like to express our sincere gratitude to all the authors who have contributed their time, expertise, and research to this endeavour. Their dedication and commitment have been instrumental in shaping this book and ensuring its relevance and quality. We are also thankful to the reviewers who have provided valuable feedback and helped to enhance the rigor and coherence of the content. We hope that this edited book, "Climate Smart Approaches Towards Sustainable Crop Production" will serve as a valuable resource for all those interested in understanding and addressing the challenges posed by climate change in the context of crop production. It is our sincere desire that the knowledge shared within these pages will inspire further research, innovation, and practical interventions that promote climate resilience, sustainability, and food security in the face of a changing climate.

This book on agriculture aims to provide comprehensive information on various aspects, encouraging readers to delve deeper into the subject for further research. Its primary objective is to raise awareness about climate smart technologies that can significantly enhance crop production in era of climate change.

We are thankful to Dr. Arun Kumar, Honourable Vice Chancellor of Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan, India. Moreover, we express our gratitude to Dr. Jitendra Mehta, Vital Biotech Publication in Kota, Rajasthan for the interest and enthusiasm in producing this book.

Dated: 8-08-2023

- **Parmeswar Dayal**
- **Shivani Ranjan**
- **Sumit Sow**
- **Ram Pyare**
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Chapter 7

Carbon Dynamics in Soil in Relation to Climate Change

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In the global carbon cycle, soil carbon dynamics are of the highest importance and have significant effects on climate change. With an estimated carbon store of 1,500 to 2,500 gigatons (Gt), soil serves as a carbon source and sinks, surpassing the combined carbon content of plants and the atmosphere. Through processes like carbon fixation, which is fueled by plant photosynthesis and organic matter decomposition, carbon is deposited in the soil. Annual soil carbon sequestration ranges from 5.5 to 7.5 Gt, partially offsetting human-caused CO_2 emissions. However, the dynamics of carbon in the soil are greatly impacted by climate change. Increased soil respiration and carbon loss result from microbial activity that is accelerated by rising temperatures. Changes in precipitation patterns have an impact on carbon sequestration or loss, soil moisture, plant growth, and litter input. Predicting future climate scenarios requires careful attention due to the complex interplay between soil carbon dynamics and climate change. Furthermore, a further aspect of the dynamics of soil carbon is added by soil erosion, which is aggravated by climate-related factors. A generator or sink of atmospheric carbon, agricultural soil erosion has the potential to upset the global carbon cycle. Water quality and the carbon cycle are both impacted by how degraded soil carbon behaves in aquatic environments. Understanding and managing soil carbon dynamics in the context of climate change is crucial for reducing greenhouse gas emissions and maintaining soil health. Improved soil carbon sequestration can be achieved by implementing techniques like biochar application, organic amendments, and

sustainable land management techniques. More research is needed to evaluate the scalability and endurance of these techniques.

Keywords: *Carbon dynamics, Carbon loss, Carbon sequestration, Climate change, Soil organic carbon, Soil health.*

INTRODUCTION

The removal of tropical forests for farming, pasture, cultivation, and timber occurs on millions of hectares each year. One result of these land use changes is the emission of CO_2 due to the clearance of vegetation and soil. Even though the precise amount of this emission is uncertain, it is thought to be the second-largest source of atmospheric CO_2 after the burning of fossil fuels. It appears that tropical soils' carbon content is impacted by clearing and use to a depth of about 40 cm. To this level, tropical open forest soils have around 5.2 kg C m^{-2}, whereas tropical closed forest soils have about 6.7 kg C m^{-2}. Using tropical soils for pasture reduces their carbon content by roughly 20%, whereas cultivating them reduces it by 40% five years after clearing them. The amount of soil carbon appears to be little affected by logging in tropical forests (Cerri *et al*., 2019**)**. About 35 years after abandonment, the carbon content of soil exploited by shifting farmers reaches the level observed under primary forest.

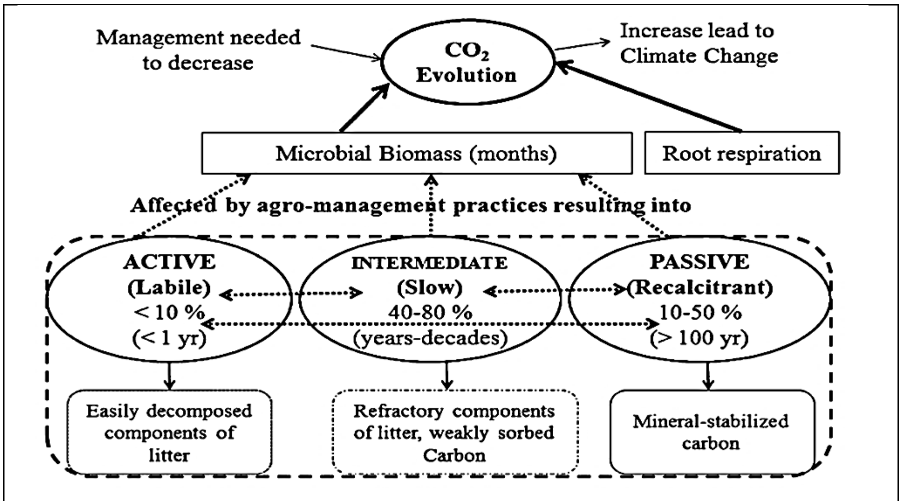

Fig. 1. Specifications of various soil organic C pools and soil CO_2 outflow (Srivastava *et al.,* 2016)

Carbon sequestration in soil is a critical process that involves capturing as well as storing carbon dioxide from the atmosphere into soil organic matter. The potential for soil carbon sequestration is enormous globally, and programs like "4 per 1000" estimate that a 0.4 percent annual increase in soil carbon stores might offset a considerable amount of world CO_2 emissions (Minasny *et al*., 2017). Various soil organic C pools and soil CO_2 outflow have been shown in Fig. 1. Agriculture, forests, wetlands, grasslands, agroforestry systems, soil management practices, land restoration and rehabilitation, as well as urban soils, all contribute to carbon sequestration in different ways. These practices and ecosystems have the capacity to sequester significant amounts of carbon, ranging from 0.1 to 2.6 Gt per year globally, depending on the context (Friedlingstein *et al*., 2019). Accurate monitoring and reporting of soil carbon stocks are crucial for evaluating the effectiveness of carbon sequestration initiatives, and recent advancements in monitoring techniques have improved our ability to estimate soil carbon stocks at regional and global scales.

Land usage and soil types influence the microbial populations in the soil. It is not yet apparent how these two driving factors affect the microbial communities in soil and how they cycle carbon (C). The distribution of the bacterial population in the topsoil was controlled by land use. Effects of agriculture on soil characteristics were responsible for changes in the topsoil bacterial community structure and functional genes (Xue *et al*., 2023). The microbial community assembly in the subsurface, however, was significantly impacted by edaphic characteristics of soil types, such as pH and EC. Topsoil organic C was lower in the vineyard than in the forest, and this was related to a lower ratio of C fixation to decomposition gene abundances, which may have sped up C loss by creating an unbalanced input-output relationship. Erosion, the most prevalent form of soil degradation, is also crucial for the transfer of carbon from the atmosphere to aquatic ecosystems, has a significant impact on water quality, and affects the carbon cycle. Additionally, the random forest model predicts that erosion in basins with turbulent flows and aggregate-rich soils may produce significant carbon sources (Liu *et al*., 2023).

Agriculture production and human civilization are seriously threatened by global climate change. Increasing atmospheric CO_2 levels are connected to changes in rainfall patterns and temperature fluctuations, making agricultural civilization's Tural systems more susceptible. A large carbon sink, soil organic carbon (SOC) is essential for maintaining healthy soil. The global carbon cycle and climate change are significantly impacted by even small changes in soil carbon sequestration. Toxicologically speaking, the dynamics of SOC are influenced by several carbon pools, including dissolved organic carbon (DOC), particulate organic carbon (POC), total organic carbon (TOC), microbial biomass carbon (MBC), permanganate oxidizable carbon ($KMnO_4$-C), and mineral-associated organic carbon (MOC). By balancing carbon stocks and emission fluxes, land use and management techniques can reduce the effects of climate change (Ramesh *et al*., 2019). After applying alternative practices, labile organic carbon pools like MBC, POC, and $KMnO_4$-C are sensitive markers for determining the quality of the soil. Our knowledge of carbon sequestration and climate change mitigation techniques is improved by an understanding of SOC dynamics in various ecosystems.

Addressing the climate emergency will need dealing with the enormous accumulation of carbon dioxide in the atmosphere in addition to lowering the present pace of emissions. Fossil fuel emissions over a long period of time (and land usage) are mostly to blame for this accumulation. The total amount of fossil CO_2 emissions has surpassed 1.7 trillion tonnes. The cumulative fossil CO_2 emissions are measured in relation to 1750 (carbonation excluded). Emissions for 2022 are projected to be the same as those for 2021 and to remain steady all year (Ripple *et al*., 2023).

The problem of climate change has received a lot of attention in recent decades. Rising global temperatures are a result of an increase in the amount of greenhouse gases in the atmosphere, particularly carbon dioxide (CO_2). This has several negative effects on the environment. It is essential to comprehend the function of carbon dynamics in soil ecosystems to successfully prevent climate change. This chapter focuses on the mechanisms that affect carbon storage, release, and feedback loops that can either increase or lessen the effects of climate change. It also examines the complex link between soil carbon dynamics and climate change.

Soil Carbon: An Important Participant in the Carbon Cycle

The soil plays a crucial role in the global carbon cycle, acting as both a source and a sink of carbon dioxide (CO_2), a greenhouse gas that contributes to climate change. Soils are the largest terrestrial carbon reservoir, containing more carbon than plants and the atmosphere combined. The carbon stored in soil comes from plant residues, root exudates, and decomposed organic matter. Recent research estimates that global soil carbon stocks range from 1,500 to 2,500 Gt of carbon, which is approximately three times the amount of carbon present in the atmosphere (Minasny *et al.,* 2017).

Through the process of carbon fixation, in which atmospheric CO_2 is changed into organic carbon and deposited in the soil, soils have the capacity to sequester carbon. Carbon is delivered to the soil largely by plant photosynthesis, with help from mycorrhizal fungi, plant litter, and root turnover. According to recent studies, the world's soils store between 5.5 and 7.5 Gt of carbon yearly, offsetting a sizeable percentage of anthropogenic CO_2 emissions. (Stockmann *et al.,* 2013; Lal, 2020). Soil can also release carbon back into the atmosphere through various processes. Soil respiration, driven by microbial activity and plant root respiration, is a major source of CO_2 emissions from soils. This significant natural flux, which is now estimated to be 75 x 1015 g C/yr, is anticipated to grow as the Earth's condition changes. Rising atmospheric CO_2 levels will result in a higher flow of CO_2 from soils while also increasing the carbon stock in the soil. Without increasing the stock of soil organic matter, traditional tillage farming and rising temperatures increase the flux of CO_2 from soils. A significant increase in the soil carbon pool does not appear likely to reduce the rise in atmospheric CO_2 over the course of the next century, but it is unknown how the terrestrial biosphere will react to simultaneous changes in all these elements (Schlesinger *et al*., 2000).

Organic carbon (OC) is stored in soils more effectively attributed to biochar. OC is irregularly distributed in soils among several particle-size fractions, displaying a range of stability, structures, and functions. In soil particle size fractions of 53-250, < 53, and 250-2,000 m, the application of biochar enhanced OC by 37%, 42%, and 76%, respectively. This was confirmed by X-ray fluorescence spectroscopy research, which indicated that the addition of biochar increased the C contents by 5-56% (El-Naggar *et al*., 2018). By encouraging OC storage and fostering favourable biochar-soil interactions, long-term aged biochar may be useful to improve soil quality. Short-term nutrient turnover depends on the labile component of soil organic matter (SOM).

Microbes, including bacteria and fungi, contribute to the soil carbon pool through their biomass (Fig. 2). Microbial biomass represents an active and labile carbon pool, influenced by factors such as temperature, moisture, and nutrient availability. Recent studies suggest that microbial biomass carbon constitutes approximately 1-5% of the total soil organic carbon stock globally (Li *et al*., 2018). In terms of soil ecosystem assessments, the link between dead primary products (litter), soil organic matter (C_{org}), and soil microbial biomass (C_{mic}) has grown in importance.

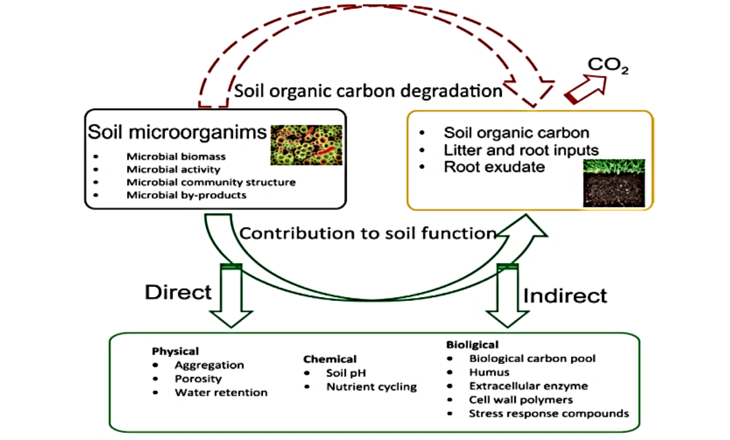

Fig. 2. Soil microorganisms in relation to soil carbon immobilization (Xu *et al.*, 2018)

To mitigate climate change and improve soil management techniques, it is essential to comprehend the importance of soil carbon pools. Increased soil carbon storage, especially in stable pools, can reduce atmospheric CO_2 levels and improve the health and productivity of the land.

Factors Influencing Soil Carbon Dynamics

Several factors influence soil carbon dynamics, including climate, land management practices, vegetation type, soil properties, and microbial activity. Climate factors, such as temperature and precipitation, have an impact on microbial activity, decomposition rates, and plant production, which all affect soil carbon dynamics. Warmer temperatures have been linked to faster microbial decomposition rates, which increases soil carbon loss. Alterations in precipitation patterns have been linked to variations in plant growth and litter input, which affects carbon sequestration (Schimel *et al.*, 1994; Wieder *et al.*, 2019). The dynamics of soil carbon are significantly influenced by land management activities, such as agriculture, forestry, and changes in land use. For instance, carbon inputs, decomposition rates, and erosion may be impacted by agricultural techniques including tillage, crop rotation, and organic additions, which in turn affect soil carbon stores. Recent studies have shown that adopting sustainable land management techniques can increase soil carbon sequestration (Lal *et al.*, 2007; Wiesmeier *et al.*, 2020).

Through the quality of the litter, root exudates, and organic matter inputs, the kind and features of the plant cover affect the dynamics of soil carbon. Different plant species have different rates of carbon intake and breakdown, which affects how much carbon is stored in the soil. Recent research has studied how various plant species affect soil carbon dynamics in diverse environments, shedding light on the function of vegetation in the carbon cycle (Wu *et al*., 2023; Jiao *et al*., 2022). By altering microbial activity, nutrient availability, and soil structure, soil characteristics including mineralogy, pH, and nutrient content have an impact on soil carbon dynamics. Recent studies have shown a connection between soil qualities and soil carbon storage in a variety of habitats and soil types, underscoring the significance of soil parameters in the carbon cycle (Rasmussen *et al*., 2018).

In general, soils with higher clay and silt content are better able to hold onto organic matter and store carbon. Clay particles can bind and keep organic matter from rotting because they have a greater surface area and cation exchange capability. Low water-holding capacity in soils with a high sand concentration can restrict microbial activity and carbon sequestration. The amount of moisture in the soil affects how active the soil microorganisms are as well as how quickly organic matter decomposes (Zhou *et al*., 2023).

The dynamics of soil carbon can be influenced by the availability of soil nutrients, notably nitrogen (N) and phosphorus (P). A sufficient supply of nutrients can promote microbial activity and the breakdown of organic materials. Nitrogen is a crucial ingredient for microbial development and controls how quickly organic matter decomposes. Nutrient availability imbalances or deficits might restrict microbial activity and, as a result, carbon turnover (Zhang *et al*., 2023). Due to their involvement in both the breakdown of organic matter and the creation of stable soil carbon, soil microbes are crucial to understanding soil carbon dynamics. Recent studies have examined the significance of microbial groups and their reactivity to environmental conditions in the microbial activities and community composition that drive soil carbon storage (Pan *et al*., 2020).

Carbon Release from Soil

Decomposition processes and carbon mineralization

The destiny of organic matter and the storage of carbon in ecosystems are influenced by decomposition processes and carbon mineralization, which are key components of the carbon cycle. Decomposition is the process through which bacteria and fungi, among other microbes, break down organic materials into simpler molecules. Complex organic molecules, such as proteins, lipids, and carbohydrates, are enzymatically broken down into simpler ones during the breakdown process. Leaching, fragmentation, chemical modification, and assimilation are the different steps of the decomposition process (Frouz, 2018). Because the microorganisms that cause decomposition need carbon as an energy source, they breathe out carbon dioxide (CO_2) into the atmosphere. How quickly organic matter decomposes is influenced by environmental factors such as temperature, moisture, oxygen availability, nutrient content, and the composition of the organic matter (Bot & Benites, 2005).

The global carbon cycle and mitigating climate change are significantly impacted by decomposition and carbon mineralization. Significant volumes of CO_2 are released into the atmosphere because of the decomposition of organic matter, which helps to contribute to greenhouse gas emissions (Kasimir-Klemedtsson *et al.*, 1997). With the removal of CO_2 from the atmosphere, carbon mineralization in soil serves as a long-term sink for atmospheric carbon. It is essential for preserving ecosystem production, nutrient cycling, and soil fertility. Carbon mineralization and carbon sequestration may be improved by using land management techniques such as the incorporation of organic amendments, conservation tillage, and reforestation (Ramesh *et al.*, 2019). Although there is a substantial body of study on carbon mineralization and decomposition processes, giving specific facts and references necessitates more context or focusing on a particular area of interest.

Impact of microbial activity on carbon release

The breakdown of organic materials and subsequent release of carbon into the atmosphere is greatly aided by microbial activity. In different ecosystems, bacteria and fungi are the main agents that cause organic matter to decompose (Romaní *et al.*, 2006). To use these smaller molecules as energy sources, microbes release enzymes that break down complex chemical compounds into simpler molecules like sugars, amino acids, and fatty acids. Through microbial respiration, the enzymatic breakdown of organic materials by bacteria produces carbon dioxide (CO_2), which contributes to the release of carbon into the atmosphere (Gougoulias *et al.*, 2014).

Microbes are essential to the carbon cycle because they fix and transfer carbon from the air to the soil. Environmental factors in the soil ecosystem have an impact on the variety and abundance of microorganisms as well as their activity. Soil carbon pools, which are significant for the global carbon cycle and have an influence on climate change, reflect many forms of carbon that have been stored. The distribution of MBC stocks and interactions with organic materials in the soil has been shown in Fig. 3 (Das *et al.*, 2023).

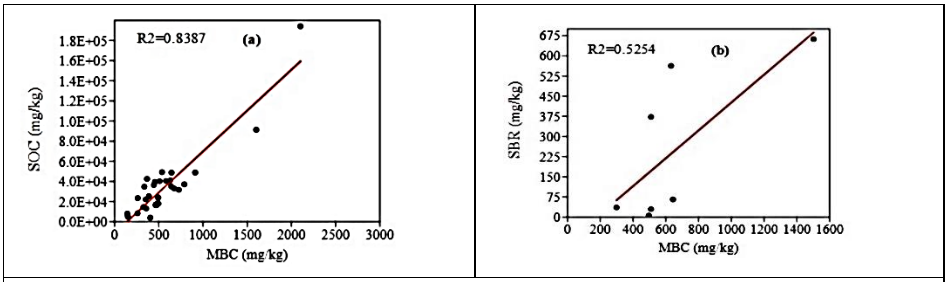

Fig. 3. Relationships between MBC storage and (a) SOC Stock and (b) Soil Basal Respiration (SBR) for key forest ecosystems (Das *et al.,* 2023)

Microbial activity and carbon release are influenced by several environmental factors, including temperature, moisture, oxygen availability, nutrient content, and pH. Warmer temperatures generally increase microbial activity and the rate of decomposition, leading to higher carbon release (Allison *et al*., 2011). Adequate moisture levels are necessary for microbial activity, as it facilitates enzyme activity and nutrient availability. Excessively dry or waterlogged conditions can limit microbial activity. Microbes can carry out decomposition under both aerobic (with oxygen) and anaerobic (without oxygen) conditions. Soil pH affects the composition and activity of microbial communities, which in turn can influence decomposition rates and carbon release (Sheng, Y., & Zhu, L., 2018).

Table1. The range of soil microbial biomass carbon ($mg\ kg^{-1}$ C) based on various environmental conditions (Das, *et al.,* 2023)

Forest types	Range of the MBC stock ($mg\ kg^{-1}$ C)
Wet & dry tropical climate	127–1453.5
Wet tropical climate	125.5–1094
Dry tropical climate	278.27–981.78
Hot humid tropical climate	262.5–2214.4
Tropical Monsoonal and humid climate	207.5–2156
Subtropical monsoon climate	161.66–1500
Subtropical humid monsoon climate	64.19–1380.86
Subtropical monsoon hot and dry climate	506.63–2102.25
Temperate climate	80–1602.16
Marine climate	58.2–724

Land-use changes, such as deforestation or conversion of natural ecosystems to agriculture, can alter microbial communities and their activity, potentially increasing carbon release from the soil. The various ranges of soil microbial biomass carbon (mg kg^{-1} C) based on various environmental conditions are mentioned in Table 1. Understanding microbial activity and its impact on carbon release is crucial for predicting carbon fluxes in ecosystems and developing effective strategies for carbon management and climate change mitigation.

Land-use changes and soil disturbance

Soil has historically lost a significant amount of carbon (C) through cultivation and disturbance, with ongoing land use change resulting in approximately 1.6 ± 0.8 Pg C y^{-1} loss, particularly in tropical regions. As soil contains more than double the C found in the atmosphere, C loss from soils impacts atmospheric CO_2 concentration and climate. While halting land-use conversion would reduce soil C losses, the growing population and changing diets may require more agricultural land. Maximizing productivity and implementing best management practices on existing agricultural land can slow or restore soil C loss, but barriers exist, particularly driven by poverty in developing countries (Smith, 2008).

Land-use changes such as deforestation and conversion of natural ecosystems to agriculture can lead to the degradation of soil organic carbon, resulting in its release as CO_2. Recent research suggests that land-use change and soil degradation contribute to the annual loss of approximately 30 Gt of carbon (Ledo *et al*., 2020). The ways in which land is managed, such as via agriculture and forestry, have a big impact on how the soil participates in the carbon cycle. For instance, using conservation tillage, cover crops, and agroforestry techniques in agriculture can improve soil carbon sequestration. According to recent studies, using soil carbon management techniques in agricultural systems can help sequester 0.4 to 1.2 Gt of carbon yearly (Smith *et al*., 2008; Minasny *et al*., 2017).

Sustainable land management practices, such as conservation agriculture, agroforestry, reforestation, and restoration of degraded land, can enhance carbon sequestration in soils and mitigate greenhouse gas emissions. Soil management strategies, including reducing soil disturbance, promoting soil organic matter inputs, and improving soil structure, can enhance soil carbon storage, improve soil fertility, and contribute to climate change mitigation efforts.

Climate change-induced soil carbon losses

Climate change is leading to significant soil carbon losses globally, impacting the carbon cycle and exacerbating climate change. Soil carbon losses are a result of various factors, including rising temperatures, altered precipitation patterns, and extreme weather events. Increased temperatures accelerate organic matter decomposition, enhancing microbial activity and releasing carbon dioxide (CO_2) into the atmosphere. Changes in precipitation patterns affect soil moisture levels, influencing microbial activity and organic matter decomposition rates, further contributing to soil carbon losses (Zeglin *et al*., 2013).

Soil carbon losses have consequences for climate change mitigation and soil fertility, impacting nutrient cycling, water retention, and overall ecosystem functioning (Ranjan *et al*., 2022). Mitigation strategies include halting land-use conversion, maximizing productivity on existing agricultural land, implementing best management practices (*e.g.,* conservation agriculture, agroforestry), and adopting sustainable land management practices. Supportive policies, such as promoting fair trade, reducing agriculture subsidies, and providing favorable loan and debt conditions, can encourage successful soil carbon management, particularly in developing countries (Smith, 2008).

Setala *et al.* (2023) found that adding twice as much aboveground tree litter to the soil resulted in a small fall in SOC of 5% and a considerable decrease in STN of 15% in the topsoil. In contrast, compared to control soils, litter clearance led to an increase in SOC and STN. Changes in SOC and STN were not related to microbial biomass or community composition despite faster leaf litter decomposition (Fig. 4). The study underscores the importance of aboveground litter's effects on PE and the function of forest soils as carbon sinks in the context of global warming.

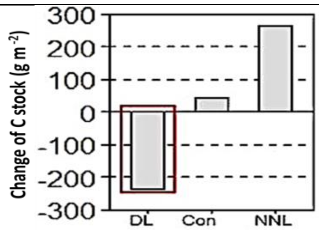

Fig. 4. Soil Priming effect in a temperate mixed forest (extra supply of aboveground tree litter reduced C content in the topsoil); DL- Double litter input, Con- Control, NNL- No new litter input (Setälä *et al.*, 2023)

Feedback Loops and Climate Change

The Paris Agreement aims to keep global warming to 2 ^{0}C, ideally 1.5 ^{0}C and has the backing of practically all countries (Jacob *et al.*, 2018). Because there is a chance that climatic feedback loops may be amplified, climate change is particularly harmful. Positive feedback loops accelerate global warming by causing more changes that result in even more warmth (Fig. 5). The impacts of climatic forcings, such as greenhouse gas concentrations, are amplified by these feedback loops. To successfully stop future warming, emissions must be rapidly reduced since even small temperature rises increase the risk of climate tipping points being crossed. These tipping points cause substantial changes in the Earth's climate system and add to the amount of amplified feedback. The acceleration of the global temperature rise brought on by these feedback loops and tipping points may still be underestimated by climate models, despite advances in their ability to consider many interacting feedbacks (Pereira & Viola, 2018).

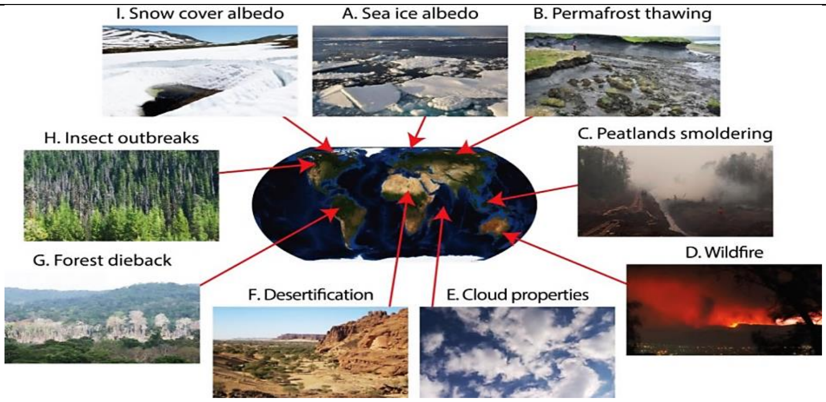

Fig. 5. Map of feedback loops (A–I) The map shows example locations where select positive feedback loops are likely operating (Ripple *et al.*, 2023)

As of 2023, it was anticipated that 260 billion metric tonnes of CO_2 would be needed to keep global warming to 1.5 ^{0}C (Tol, 2023); however, this amount may be used up in just 6.5 years. The amount of carbon budget still available may be affected by uncertainty and miscalculation of climatic feedback loops. The budget is further reduced by positive feedback loops, which increase warming per unit of CO_2 emitted. However, it is still difficult to simulate Earth system feedback, particularly positive ones. Ripple *et al.* (2023) found that for a more accurate assessment of the remaining carbon budget, it is essential to improve our knowledge of these feedback loops *viz.* 41 feedback loops in all, comprising 27 positive (reinforcing), 7 negative (balanced), and 7 unknown loops.

It is recognized that there may yet be undiscovered feedback loops, particularly in the biological category where it is conceivable for intricate interactions to occur. Positive feedback loops are more common, which implies that a lot of unidentified feedback could potentially be positive. This may mean that the amount of carbon still in the atmosphere has been overstated, which would call for achieving net-zero human emissions sooner than predicted (Ripple *et al*., 2023). Once crucial thresholds are passed, some of these tipping points are linked to severe changes of the biosphere and the global climate system, such as the slowdown of ocean circulation, disappearance of ice sheets, permafrost, and forests.

Impacts of Climate Change on Soil Carbon Dynamics

Temperature, moisture effects and radiation on carbon cycling

The transfer of carbon via various biogeochemical processes in the Earth's ecosystems is referred to as "carbon cycling," and it depends significantly on temperature and moisture. Changes in temperature and moisture content can have a significant impact on how carbon is stored, decomposed, and released. This can affect how much carbon is in the atmosphere overall. Temperature directly affects how quickly carbon is cycled. As temperatures rise, biological activity often picks up speed, hastening the breakdown of organic materials.

To comprehend its quantity and quality, the leaching of dissolved organic carbon (DOC) from the forest floor was studied. Microclimate factors such as temperature and moisture were studied for their impact on DOC production in red spruce forest material. Dry samples had an initial production rate of 1.2 mg g^{-1} in the first week, declining by 77% over 8 weeks. Unsieved, moist samples fell by less than 30%, whereas sieved samples indicated a decline of 40%. Wetter samples had an increase of 0.1 mg g^{-1} $week^{-1}$ in DOC production for every g g^{-1} increase in moisture. DOC Temperature had an exponential effect on production, and DOC composition varied depending on the circumstances. Production rates peaked in the first 2 days and then averaged 90 µg g^{-1} $week^{-1}$ (Christ & David, 1996).

The biosphere's carbon cycle is greatly influenced by temperature, which has an impact on soil-dissolved organic carbon (DOC) concentrations, primary productivity, organic matter decomposition rates, and the uptake and release of CO_2 and CH_4.

Moisture levels, particularly soil moisture, are crucial for the cycling of carbon. The availability of nutrients and microbial activity, both of which are crucial for the breakdown of organic matter, are impacted by soil moisture. Dry weather slows down microbial activity, which lowers the rate of breakdown and hence lowers carbon release. On the other hand, in wetter conditions, microbial activity rises, causing a quicker breakdown and consequent emission of carbon dioxide. Moisture content has an impact on plant production and growth as well. Dryer circumstances can inhibit plant development and decrease photosynthesis's ability to absorb carbon.

Productivity and decomposition are significantly influenced by soil moisture, especially the level of the water table in wetland soils (Liu *et al*., 2017). In general, soil moisture increases production and decomposition rates, but there is an upper limit beyond which rates drop because of how various plant species respond to it and because anaerobic conditions prevent decomposition. Through modifications in precipitation and evapotranspiration rates, land-based renewable energy (LBR) installations can directly affect soil moisture. The distribution of rainfall is thought to be impacted by large-scale wind farms on a global scale, although local effects are not anticipated. On the other hand, solar parks may not directly impact precipitation on a broad scale, but they can alter local temperatures and wind patterns, which may result in changes to rainfall. Locally, locations beneath solar panels see less rainfall, whilst places around the margins of the panels may experience more due to panel drainage.

In certain ecosystems, the combined impacts of temperature and moisture on carbon cycling can lead to complicated and occasionally divergent results. For instance, higher temperatures can accelerate decomposition rates and boost carbon release in temperate woods with relatively high moisture levels. In contrast, greater temperatures in dry areas may result in less microbial activity and carbon breakdown due to the restricted availability of moisture. Changes in temperature and precipitation patterns are predicted by climate change models, and these changes may have large effects on the carbon cycle. Increasing evapotranspiration rates might dry out some ecosystems and decrease carbon absorption in combination with shifting rainfall patterns and rising temperatures (Fig. 6).

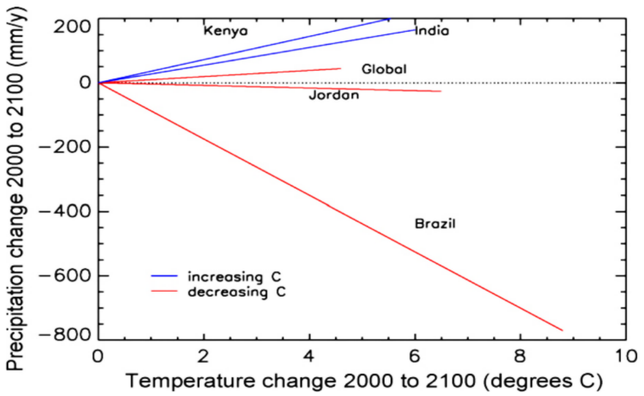

Fig. 6. For Brazil, India, Jordan, and Kenya, the HadCM3LC (C cycle Global Circulation Model) plots temperature change vs precipitation changes during the period 2000–2100. (Red lines represent losses in soil C stocks, while blue lines represent increases in soil C stocks) (Falloon *et al*., 2007)

The amount of energy available for photosynthesis depends on solar radiation, especially photosynthetically active radiation (PAR). Compared to direct sunlight, diffuse radiation speeds up photosynthetic rates and soil carbon sequestration. With only brief blade and tower shade and a minor rise in diffuse-to-direct radiation ratio, wind farms are predicted to have little impact on PAR and photosynthesis. On the other side, solar parks are expected to significantly lower PAR by the interception of direct and diffuse light, which may have an influence on photosynthesis and production (Armstrong *et al*., 2014). Reduced PAR, however, could help photosynthesis in areas with high levels of direct PAR. Rises or reductions in soil carbon sequestration are possible, with declines more likely in places with low radiation and increases more likely in areas with high radiation.

Changes in vegetation patterns and their influence on soil carbon

The amount of soil carbon stored within ecosystems is significantly impacted by changes in plant patterns. This dynamic process is greatly influenced by variables such as changes in the composition, density, and dispersion of plant communities. Different plant species have different capacities for absorbing and storing carbon, with some having deep, broad root systems that encourage the buildup of organic matter in soils and so increase carbon sequestration. Higher levels of soil carbon are often the consequence of increased vegetation biomass and density, since dense vegetation increases photosynthetic rates and adds more organic matter, enriching the soil carbon content (Falloon *et al*., 2007). The quantity of carbon intake and its breakdown in the soil are both impacted by changes in plant patterns, which also have an impact on litterfall rates and subsequent decomposition processes. Plants release root exudates into the soil, which encourage microbial activity and the breakdown of organic matter, affecting the dynamics of soil carbon. Through the loss of vegetation cover and release of stored carbon, disturbances like fires, logging, or changes in land use can have a significant impact on soil carbon. Effective management of soil carbon sequestration depends on an understanding of the interaction between plant patterns and soil carbon, and further study is required to determine the precise effects in different ecosystems and climatic circumstances.

The rhizosphere has a significant impact on several biogeochemical processes, including carbon mineralization, as well as the amounts of total nitrogen (TN), soil organic carbon (SOC), and microbial biomass. There are variances in rhizosphere effects between arid and humid regions, as well as between woody and herbaceous plant types. In order to save soil and water, vegetation covering is essential. Through several methods, including the retention of rainfall, the reduction of raindrop energy, the improvement of surface roughness, and the enhancement of infiltration, it lessens runoff and erosion. While surface litter absorbs water and lessens the effect of raindrops, plant roots directly support the soil. The presence of plants regularly lowers runoff and sediment, according to studies. With middle- and down-slope sites demonstrating increased runoff and sediment reduction, the spatial distribution of vegetation has an impact on the resistance to water flow and the ability to carry sediment. Soil carbon is redistributed because of water erosion, with runoff and sediment being the primary means of transport for soluble carbon (Shi *et al*., 2023). By boosting organic matter input, lowering soil carbon loss from erosive processes, and changing soil water penetration, vegetation restoration helps the carbon cycle. While regions with vegetation experience increased carbon flow through runoff and sediment, locations with plant cover enhance soil carbon flux via infiltration.

The position of the slope has a significant influence on both soil erosion and soil carbon redistribution. Upper slopes experience high soil carbon loss through erosion, while lower slopes accumulate soil carbon. Vegetation position plays a crucial role in runoff, sediment processes, and carbon losses. Revegetation efforts should prioritize planting suitable species at the lower slope position to reduce runoff, soil carbon losses and sediment yields. It has been discovered that grassland is more successful than forest and shrubland at preserving soil and boosting carbon levels. It is important to consider the migration and distribution of soil inorganic carbon (SIC) during the erosion process, as SIC is a significant soil carbon pool (Zamanian *et al*., 2021).

Extreme weather events and soil carbon loss

Due to climate change, extreme weather occurrences including heatwaves, storms, floods, and droughts have become more intense. This has caused soil carbon to be depleted. For the global carbon cycle and reducing climate change, soil carbon is essential. Droughts result in poorer carbon retention because they decrease plant production, restrict the input of organic matter, and impede microbial activity. Floods move sediment, degrade topsoil that is rich in carbon, and encourage the release of carbon in anaerobic environments. Intense storms damage soil carbon reserves by uprooting trees, causing erosion, and removing topsoil. Heat waves cause soil moisture to drop, microbial activity to be inhibited, plant cover to diminish, and the effects of dryness on soil carbon loss to be exacerbated. In general, it is essential for designing methods to prevent soil carbon loss and adapt to climate change to understand the consequences of extreme weather events on soil carbon dynamics, including decreased inputs, increased erosion, changed microbial activity, and changes in carbon release.

Changes in microbial physiology brought on by drought may have an impact on soil carbon cycling and the overall soil carbon balance. Foreseeing and measuring the dynamics of soil carbon requires an understanding of these influences. The chemistry of microbial necromass and release enzymes in the soil can change as a result of resource allocation trade-offs that occur during microbial responses to drought (Malik, Swenson, *et al*., 2020). The breakdown and stability of soil carbon are impacted by modifications in microbial physiology and resource distribution. Microorganisms' stress tolerance features may inhibit development and biomass, which might have an impact on the biogeochemistry of the environment. In addition to limiting substrate flow, drought can also cause biomass carbon to be allocated to other resource acquisition tactics, thereby reducing soil carbon. Changes in plant and microbial populations and their interactions have an additional impact on the chemistry of soil organic matter and the rates of carbon cycling (Malik & Bouskill, 2022). Quantifying these intricate relationships and their effects on the soil carbon cycle, however, is still difficult. Predictions may become more challenging due to nonlinear interactions between soil moisture and carbon fluxes caused by how frequently drought-precipitation cycles occur (Fig. 7). Future research is required to fully understand these microbial mechanisms and how they may affect the dynamics of soil carbon under drought.

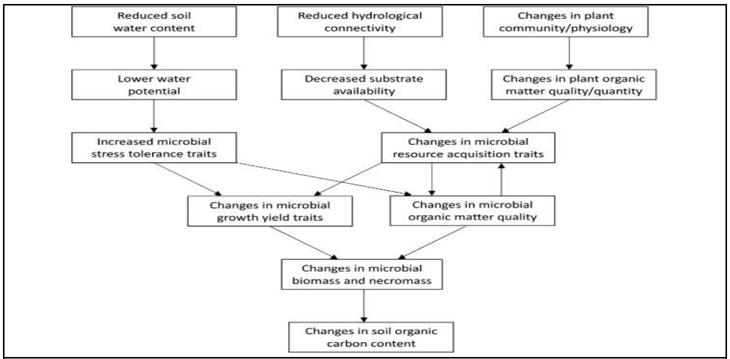

Fig. 7. Conceptual representation illustrating the long-term impacts of drought on the balance of soil carbon (Malik *et al.*, 2022)

Extreme flooding can significantly reduce soil carbon through erosion and topsoil movement. Significant amounts of carbon are lost when topsoil is washed away by floodwater power. Additionally, the silt carried by the floodwater contains organic material that has eroded from the topsoil, which adds to the loss of carbon (Khan *et al.,* 2022). Sediment deposition may build up in low-lying locations, but it frequently contains less carbon than the degraded topsoil, lowering the overall carbon stored. Organic matter is buried deeper when eroded topsoil is mixed with other sediments, which impedes decomposition and carbon sequestration. Floods can disturb soil structure, compacting the soil and lowering water penetration rates, severely influencing soil health and carbon content (Cao *et al*., 2022). Extreme flooding does, however, frequently result in large losses of soil carbon, which has a long-term impact on ecosystem health and soil fertility.

Permafrost thaw - release of stored carbon

Rising temperatures in the Arctic and sub-Arctic can cause permafrost to melt, releasing stored carbon from organic materials. A large amount of carbon has collected and been retained in permafrost over time. As temperatures rise, either from the surface or through the melting of ice-rich strata, thawing happens. When organic material that had been frozen is exposed to higher temperatures, bacteria decompose it and release greenhouse gases like methane and carbon dioxide. This carbon release may result in a positive feedback loop that accelerates global warming and permafrost thawing (Xie *et al*., 2023). Methane emissions, which are produced in low-oxygen environments, aggravate climate change. Although the precise rates of carbon storage and release are unknown, the magnitude of the potential emissions highlights the need for continued study and observation to better understand permafrost dynamics and its effect on the global carbon cycle (Page *et al.*, 2022).

Mitigation Strategies for Enhancing Soil Carbon Sequestration

Conservation agriculture and reduced tillage practices

By reducing soil disturbance, preserving organic matter, increasing carbon inputs through cover crops, enhancing soil health, facilitating long-term carbon sequestration, and aiding in climate change mitigation, conservation agriculture and reduced tillage practices are effective in enhancing soil carbon sequestration (Fig. 8). These procedures safeguard soil structure, stop erosion, and preserve the consistency of soil aggregates. Due to their persistence on the soil's surface, crop by-products act as both a barrier and a source of organic carbon. By introducing more organic matter through the application of cover crops, microbial activity and carbon sequestration are encouraged (Bai *et al.*, 2019). A healthier soil environment encourages the stable organic matter that stores carbon. These procedures progressively increase soil carbon over time, which reduces greenhouse gas emissions. For environmentally friendly farming and long-term carbon storage in agricultural soils that contribute to climate change mitigation, it is critical to adopt conservation agriculture and decreased tillage methods.

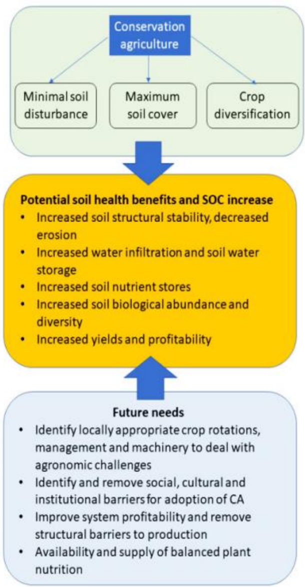

Fig. 8. Principles of conservation agriculture, advantages of raising SOC, and requirements for the future (Francaviglia *et al.*, 2023)

Conservation tillage (CT) techniques seek to reduce soil deterioration while preserving agricultural yields and the stability of agroecosystems. The Conservation Tillage Information Center defines CT as lowering ploughing depth, utilizing shallower tillage instruments, and reducing seedbed preparation intensity while making sure that crop residues cover at least 30% of the soil surface. No-tillage, minimum tillage, reduced tillage, and mulch tillage are just a few of the practices that are included in CT (Claassen *et al*., 2018). After the Dust Bowl incidents in the 1930s, interest in CT systems increased on a global scale because they were perceived as a solution to soil erosion and water conservation. According to extensive studies, implementing CT systems has several positive effects on the environment, including raising the amount of soil organic carbon, maintaining agricultural production, and cutting back on the time, fuel, and equipment needed to prepare seedbeds (Lal, 1993). Additionally, CT lowers evapotranspiration, enhances water penetration, and inhibits weed development by leaving crop residues on the soil's surface.

It has been shown that soil organic carbon (SOC) content has increased because of the global switch from conventional, intense tillage to conservation tillage (CT). However, the rates of SOC sequestration differ amongst research because of elements including climatic conditions, soil properties, beginning SOC levels, crop variety, management techniques, and experiment length. SOC sequestration rates in Mediterranean woody cropping systems ranged from 0.27 to 1.1 t ha^{-1} yr^{-1}, according to meta-analyses and modeling studies (Pardo *et al*., 2017). In the Mediterranean, woody crops sequester SOC at a rate that is almost five times higher than that of arable crops. Regardless of the crop variety, SOC sequestration rates in tropical circumstances range from 0.12 to 1.56 t ha^{-1} yr^{-1}, with greater rates in moist compared to dry conditions. However, in tropical environments, arable crops often sequester more SOC than woody crops. In the boreal region, local research put the sequestration rates of SOC for various soil types at 0.28 and 0.39 t ha^{-1} yr^{-1} (Gonzalez-Sanchez *et al*., 2019).

Agroforestry and afforestation programs

Agroforestry and afforestation programs successfully boost soil carbon sequestration by integrating trees and other plants into agricultural systems. These techniques enhance the input of organic matter, nutrient cycling, and soil structure. Through photosynthesis and the buildup of biomass, trees and other flora improve the sequestration of carbon. Trees with deep root systems help to store soil organic carbon and encourage microbial activity and nutrient cycling. By preventing soil erosion and preserving soil moisture, agroforestry and afforestation also safeguard and rehabilitate damaged soils. As trees store carbon for many years, these programs have a significant long-term carbon sequestration potential. They also help the preservation of biodiversity and offer ecological services. However, several things affect efficacy. Overall, carbon sequestration, climate change mitigation, and promoting sustainable land management can all be accomplished through agroforestry and afforestation.

According to Guo *et al*., 2020 agroforestry and afforestation systems usually raised SOC stocks over the whole soil profile, with the GW (ginkgo and wheat agroforestry system) having the largest SOC stock (111.6 t hm^{-2}) and the M (pure metasequoia seedling nursery system) having the lowest (42.9 t hm^{-2}). Across all soil layers, the G (pure ginkgo plantation system) and GW (ginkgo and metasequoia seedling agroforestry) systems had much greater SOC stocks than the W (wheat–corn rotation field system), M, and GM systems. About half of the total SOC stocks were kept in the top 20 cm of soil in the W and M systems, compared to only 35 to 41% in the top 20 cm of soil in the G, GW, and GM systems. The 40-60 cm and 60-100 cm layers in the G, GW, and GM systems made up 45–50% of the total SOC stocks in the deeper soil profile (Fig. 9).

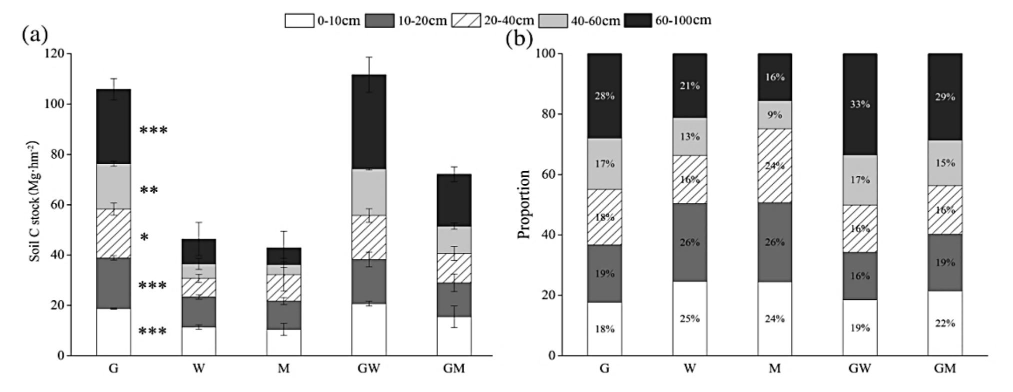

Fig. 9. Stocks of soil organic carbon (a) and their proportions in each soil layer (b) for the five planting systems (Source: Guo *et al*. 2020)

Organic waste management and Composting

By avoiding landfills and using organic waste instead for composting, organic waste management and composting are efficient methods for increasing soil carbon sequestration (Hodge *et al*., 2016). Organic materials are transformed into stable, carbon-rich organic matter that may be applied to soil through the controlled breakdown process of composting. By adding organic matter to the soil, compost enhances the soil's structure, nutrient availability, and water-holding capacity. Long-term carbon storage in the soil results from the stable organic matter in compost's resistance to degradation. Additionally, compost increases microbial activity and nutrient cycling, which promotes additional carbon sequestration (Wei *et al.,* 2022). Compost may also be used in land restoration efforts and aids in preserving soil organic matter and preventing erosion. By following the best methods for managing organic waste and composting, carbon from organic waste is efficiently deposited in the soil, enhancing soil health, and assisting in sustainable land management techniques.

Organic solid waste (OSW), including various types of waste, can be categorized based on composition. During composting, OSW undergoes a process where non-structural compounds are initially utilized by microbial biomass, followed by the degradation of proteins, fats, lignin, and cellulose. In the early stages, microorganisms break down labile protein and fat compounds, releasing by-products like ammonia, hydrogen sulfide, and organic acids. As composting progresses, the focus shifts to degrading refractory organic carbon such as cellulose, hemicellulose, and lignin (Zhao *et al*., 2019). Extracellular enzymes play a vital role in breaking down these compounds. However, some residues may remain undecomposed and not easily assimilated by microorganisms. Ongoing organic matter degradation during composting can hinder organic carbon retention. Enhancing microbial biomass and metabolites is crucial for promoting organic carbon sequestration. Understanding CO_2 release pathways is key in regulating microbial metabolism to reduce emissions (Hu *et al*., 2019). While controlling the tricarboxylic acid cycle (TCA) can limit CO_2 emissions, finding a balance between reducing emissions and promoting microbial activity presents a challenge.

Soil Amendments and biochar application

Soil amendments and the use of biochar are effective methods for boosting soil carbon sequestration because they improve soil quality and promote the retention of carbon in the soil (Hansen *et al*., 2015). When applied as soil supplements, organic materials and mineral-based additions improve soil structure, nutrient availability, and microbial activity, which increases carbon sequestration. Organic matter addition boosts the soil's carbon content and encourages the synthesis of stable carbon molecules (Dhaliwal *et al*., 2019). When added to the soil, biochar, a highly porous type of charcoal, creates a home for soil microorganisms, improves water and nutrient retention, and results in long-term carbon storage. These techniques enhance the soil's fertility, microbial activity, productivity, and nutrient cycling, which increases plant biomass and carbon sequestration. Effective implementation requires careful consideration of variables including amendment type, application rates, and regional conditions (Moinet *et al.,* 2023). Improved soil health, greater agricultural output, and climate change mitigation are all supported using soil additives and biochar.

Soil Carbon Monitoring and Modeling

Understanding and managing the dynamics of soil carbon stocks, fluxes, and their effects on climate change depends heavily on soil carbon monitoring and modeling (Makipaa *et al*., 2023). In order to estimate the carbon content of the soil, soil samples are frequently taken from different depths and locations. To get representative samples, methods such as bulk density measurements, soil coring, and soil profile description are utilized. For instance, to evaluate carbon stocks and geographic variability, researchers may gather soil samples in agricultural areas using a grid or transect-based technique (Regassa *et al.,* 2023). To determine the amount of carbon in soil samples, a laboratory analysis is performed. Dry combustion (such as the Walkley-Black method), loss-on-ignition, and infrared spectroscopy are typical techniques. Estimates of total organic carbon, carbon fractions (such as labile and stable carbon), and carbon isotopic composition are provided by these techniques. Characterizing soil carbon pools and their stability over time is aided by laboratory analysis.

Geospatial and temporal data on the dynamics of soil carbon may be obtained *via* remote sensing techniques, such as satellite images and aerial photography. Rapid determination of the soil carbon content across significant regions is made possible by proximal sensing techniques like electromagnetic induction and visible-near-infrared spectroscopy (Das *et al.,* 2023). Examples include estimating the amount of soil organic carbon present in agricultural landscapes and tracking changes in carbon stocks over time using satellite-based remote sensing. To simulate soil carbon dynamics and forecast changes under various land management scenarios and climatic conditions, mathematical models are used. To simulate carbon inputs, losses, and storage in soils, models incorporate a variety of factors, including climate, vegetation, soil properties, and land use practices. The RothC (Rothamsted Carbon) model, CENTURY model, and DNDC (DeNitrification-DeComposition) model are a few examples of popular soil carbon models (Ahmed *et al*., 2022).

Approaches for monitoring and modeling soil carbon have been used in several investigations. For instance, to evaluate the effects of deforestation and land-use change on soil carbon stocks, research in a tropical forest environment used both field measurements and modeling (Lippe *et al*., 2022).

Another research in agricultural settings examined the impact of cover crops and tillage on soil carbon dynamics using soil sampling and modeling methods (Babu *et al*., 2023). Our understanding of regional and global soil carbon dynamics is improved by integrating soil carbon data from many sources, including field observations, remote sensing, and modeling outputs. Upscaling techniques make it possible to calculate soil carbon stocks and fluxes at greater geographical scales, which helps with estimates of the world's carbon budget and the formulation of policies for reducing climate change.

CONCLUSION

This chapter offers insightful information on the intricate relationships between soil carbon cycles and climate change. The mechanisms that affect carbon storage and release in soils are highlighted in this chapter, along with elements including temperature fluctuations, precipitation patterns, and changes in land use. It focuses on the feedback loops that might aggravate or mitigate climate change, where changes in soil carbon can either serve as a carbon sink or contribute to increased greenhouse gas emissions. The dynamics of soil carbon are significantly impacted by climate change, with possible repercussions for soil organic matter, nutrient cycling, and ecosystem health. Through the emission of carbon dioxide and other greenhouse gases, these changes in soil carbon can further affect climate change. For climate change consequences to be reduced, soil carbon sequestration mitigation measures are essential. A variety of sustainable land management strategies including agroforestry, conservation agriculture, and the use of organic fertilizers have been discussed. These techniques could enhance soil health, increase soil carbon storage, and aid in the fight against climate change. Thus, understanding and controlling soil carbon dynamics in the context of climate change requires ongoing study, observation, and the use of sustainable land management methods.

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