

Soil Carbon Sequestration for Climate Change Mitigation and Adaptation: A Review

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ABSTRACT

Soil carbon sequestration has been recognized as a significant method for climate change mitigation and adaptation. This review investigates the multidimensional impact of soil carbon sequestration in boosting soil health, improving agricultural output, and reducing greenhouse gas emissions. Human activities, particularly intensive agricultural methods, have resulted to significant soil carbon loss, leading to global warming and worsening soil quality. By implementing sustainable agricultural techniques such as crop rotation, less tillage, and the use of cover crops, it is feasible to raise soil organic carbon levels, thereby sequestering atmospheric carbon dioxide. The research analyzes the ways via which SOC is stabilized in soils, highlighting the role of soil texture, structure, and microbial activity. It illustrates the balance between carbon inputs from plant biomass and outputs through decomposition and erosion, controlled by climatic conditions including temperature and moisture. The paper also discusses the possibilities of various land management strategies to boost soil organic carbon storage, such as agroforestry and the application of organic amendments. Despite the intricacy of soil organic carbon dynamics and the influence of regional conditions, the article highlights the worldwide potential of soil carbon sequestration to mitigate greenhouse gas emissions significantly. Furthermore, it exposes gaps in current research and advocates for more detailed, site-specific studies to maximize soil carbon sequestration technologies. Overall, this study underlines the essential role of soil in the global carbon cycle and advocates for policies and practices that increase soil carbon storage as a realistic method to mitigate climate change and enhance ecosystem resilience.

Keywords: Sustainable agriculture, Global warming, Carbon Cycling, Environmental Health, Carbon storage

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INTRODUCTION

Everyday life, tradition, technological advancements, economic growth, and farming efficiency have all seen significant changes throughout human history in parallel with the increase in population. In addition, there have been several significant shifts in agricultural productivity known as "agricultural revolutions," which have been impacted by the expansion of technological advances, culture, and humankind in general. The safety of the supply of food is impacted by a number of unfavorable effects of the remarkable population expansion that has occurred over the last 100 years, in addition to changes in environmental circumstances. The increasing demands of a growing global population are predicted to need a doubling of agricultural output worldwide by 2050, which is increasing the cost of food production (Tilman, Balzer, Hill, & Befort, 2011). The most sustainable strategy for ensuring the availability of food, according to a number of studies, is to increase agricultural output as opposed to reclaiming additional land for crop cultivation. (Godfray et al., 2010). The distribution and properties of managed and naturally occurring systems, including cryology, freshwater and marine habitats, terrestrial ecosystems, forestry, and agriculture, are greatly influenced by climate (Rosenzweig et al., 2007).

The term "climate change" refers to a persistent, significant change in factors associated with the climate, including trends in temperature, rainfall, wind, and snowfall (Pope et al., 2022). The rate of change in the climate is thought to be severely accelerated by GHG emissions and global warming (Sovacool, Griffiths, Kim, & Bazilian, 2021). The average global temperature has risen by 0.9 °C during the 19th century because of the constant increase of activity by humans, and by 2050, it is predicted to have climbed by 1.5 °C (Eftekhari, 2022). The persistent and extensive increase in greenhouse gas emissions is severely affecting land, freshwater, and marine ecosystems, resulting in significant and permanent damage (Aakko-Saksa et al., 2023). These greenhouse gases (GHGs) trap heat by

preventing the passage of infrared rays that attempt to exit the atmosphere, much like a "greenhouse" (Hergart, 2022). The primary sources of GHGs are the combustion of fossil fuels, application of nitrogen-based fertilizers, soil cultivation practices, inundated rice paddies, land use changes, biomass burning, livestock rearing, and management of animal waste (Song et al., 2022).

Agriculture is expected to be severely affected by global warming, either directly or indirectly, via impacts on agricultural products, soils, farm animals, and insects. (Hatfield et al., 2020). Even though changing the climate is a gradual process that takes a long time and involves only modest variations in rainfall and temperature, it nonetheless has an impact on a number of soil processes, especially those that are connected to soil fertility. Changes in the humidity of the soil and subsequent rises in soil temperature and carbon dioxide levels are anticipated to be the primary impacts of global warming on soils (Qiu, Shen, & Xie, 2023). The processes and characteristics of soil that are crucial for replenishing the fertility of soil and production are expected to be affected differently by the changing climate worldwide (de Alcantara, Vieira Filho, & Gasques, 2021). The primary impacts of global warming are anticipated to be elevated CO₂ levels, as well as increases in salt and temperature (Zandalinas, Balfagón, Gómez-Cadenas, & Mittler, 2022).

Extreme weather events, a 30%–50% decrease in output, an increase in pests and diseases of crops, and other impacts of global warming pose threats to the farming sector and the global supply of food. The world's agricultural harvests and food security are in danger due to the growing human population and industrialization, which intensifies global warming. Two of the 21st century's biggest issues are food scarcity and global warming (Bibi & Rahman, 2023). Changes in the climate damage the soil ecosystem in addition to its immediate effects on crops. By affecting the rate of decomposition and the quantity of organic matter present in the soil, fluctuations in the air's carbon dioxide concentrations,

along with modifications in the volume, distribution, and frequency of rainfall, in addition to increasing temperatures, are transforming the soil-plant ecosystem (Pathak, 2023), (Biswal, 2023). The quantity of accessible organic carbon in the soil directly affects the number of microbes, soil health, structure, and metabolism of the soil (Pathak, 2023), (Biswal, 2023). The latest study has shown that the mechanism by which minerals are transformed into soil molecules is determined by the cumulative effects of humidity and temperature. By modifying soil moisture, climate-related changes, oscillations, and precipitation intensity also influence the

soil's hydro-physical attributes. The soil's physical traits, such as its mechanical makeup or texture, structural properties including shape and durability, overall bulk density and porosity, and the distribution of pore sizes, all play a crucial role in affecting the soil's hydrological features like hydraulic conductivity and water retention capacity (Yu et al., 2018). Together, these characteristics help the soil regulate its air, water, and heat content. These physical attributes affect both chemical and biological reactions in the soil, which significantly affects crop yield and soil fertility (**Figure 1**).

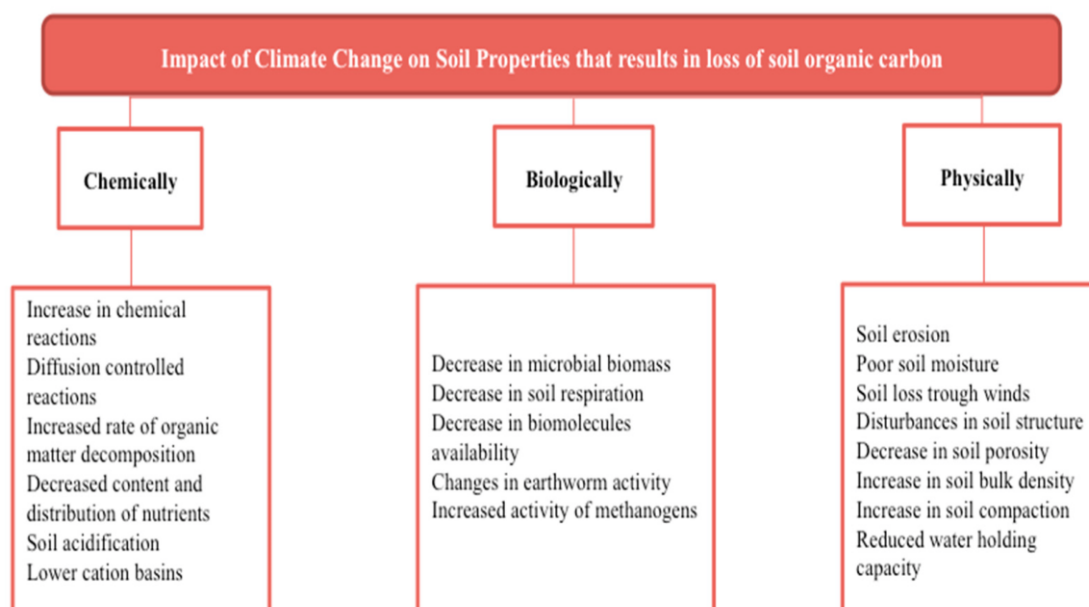


Figure 1 Deterioration of soil due to climate extremes through various mechanisms from the paper (Moreno et al., 2022)

Higher plants may benefit greatly from increased access to nutrients and uptake due to the organic matter of the soil, including its temporary and stable constituents (humic compounds). The accessibility of nutrients and storage in soils are also significantly impacted by organic matter in the soil. Soil organic matter serves as the primary source of nutrient storage for nitrogen (N), sulfur (S), and P in many soils. The accessibility of micronutrients for crops is influenced by soil organic matter. This is particularly true of iron (Fe), and copper (Cu), but to a lesser degree, zinc (Zn) (Gerke, 2022). Optimal agricultural

productivity requires sufficient availability of essential plant mineral elements, including macronutrients as well as micronutrients. The ingestion of a variety of nutrients by the underground tissues of higher plants has been deeply examined and explained by various scientific groups, including S.A. Barber's team from the USA (Barber, 1995), P.H. Nye's team from England (Tinker & Nye, 2000), and A. Jungk's team from Germany (Schwertmann, 1991). These investigations have concentrated on the function of soil accessibility and plant absorption in nutrient intake.

Through a variety of mechanisms, soil organic carbon improves the accessibility of soil minerals and affects soil fertility. It is essential to the global cycle of carbon, which might have a big effect on atmospheric CO₂ concentrations. The amount of earth-based organic matter and humus in agricultural soils is significantly impacted by the farming methods applied in these lands. The objective is to sustain a high level of soil organic carbon (SOC), which allows for the delivery of essential nutrients like nitrogen (N) and sulfur (S) to plant roots at sufficient and potentially elevated rates. This ensures that the plants' nutritional requirements are adequately met. Therefore, it is important to get both elevated quantities of soil organic carbon (SOC) and rapid nutrient release from the decomposition of organic matter (Gerke, 2022). In addition to the significant function of soil organic carbon (SOC), particularly humic compounds, in enhancing the availability of nutrients such as nitrogen (N), sulfur (S), phosphorus (P), iron (Fe), and copper (Cu), there are other essential chemical characteristics through which SOC and primarily humic compounds may enhance the health of the soil. Humic compounds in soil have an impact on many metabolic processes in plants. They function as plant hormones (Gerke, 2021), (Canellas & Olivares, 2014), (Nardi, Ertani, & Francioso, 2017), (Urrutia et al., 2020). Humic chemicals enhance root development, the creation of hairs on root and root laterals, and the dispersion of organics by the root system (Canellas & Olivares, 2014). Sometimes, humic acids function similarly to auxins, which causes the roots to undergo mitosis and proliferate (Daniel Basilio Zandonadi, Canellas, & Façanha, 2007), (Daniel B Zandonadi et al., 2010), (Trevisan et al., 2010). The increased production of plasma membrane H⁺-ATPase is one of the main physiological processes in plants that is impacted by heat stress (HS). As a consequence, the rhizosphere becomes more acidic, which promotes the development of roots, activates nutrient transporters inside the roots, and causes the distribution of organic

acids (Pinton, Cesco, Iacoletti, Astolfi, & Varanini, 1999), (Canellas et al., 2015). Organic matter in soil affects the emissions of greenhouse gases, especially CO₂ concentrations. Limiting soil carbon is difficult because industrialized agriculture has political support. Although humic materials preserve carbon in the soil, they are politically disregarded. The importance of humic compounds may be overlooked in biochar suggestions for soil health, indicating a knowledge gap regarding soil carbon storage (Gerke, 2022).

Fundamentals of Soil Carbon Sequestration

Importance of soil carbon sequestration

Soil has a higher carbon content than all plants combined, and it plays a significant role in the global nitrogen and carbon cycle. Unfortunately, 30 to 60 percent of this carbon is lost when soils are exploited for agriculture, which negatively impacts the soil's ability to function (Kopittke et al., 2019). As released carbon dioxide reaches the atmosphere, agriculture contributes significantly to the increase in the release of greenhouse gases (IPCC, 2019). Soil carbon loss results in a decline in productivity and related ecological services (Russel, 1929), (Mann, 1986), (Davidson & Ackerman, 1993). Reversing the carbon debt from cultivation is very difficult because of the estimated 31.2 Pg C that was wasted in topsoil in more than 12,000 years (Sanderman, Hengl, & Fiske, 2017). One practical way to slow down global warming is through sequestering SOC, which balances out the releases of GHGs from human activity (Minasny et al., 2017). While there are contradictory conclusions about the possible quantity of carbon that soil may store, especially in various locations, researchers urge for scaling up ecologically sound carbon sequestration strategies worldwide (Amelung et al., 2020).

Soil type, weather, use of land, and management practices are only a few of the numerous factors that affect SOC storage and dynamics. However, these factors are not fully understood on a global scale. Current estimations of SOC storage capacity often

assume a constant yearly value that comes from management guidelines, which typically cover a 20-year period based on IPCC standards (Fuss et al., 2018). While the main emphasis of modeling SOC storage is the environment, specifically weather, and rainfall (Jones et al., 2005), (Kramer & Chadwick, 2018), (Z. Shi et al., 2020). Because of other unknown limiting variables, the consequences of climate change may be overstated (Cade & Noon, 2003). Even while management techniques are important locally, there is a dearth of comprehensive worldwide data on them, and global studies often ignore them.

Soil Carbon Pools:

Soil pools, a crucial component of the global carbon cycle, hold about 2500 billion tons of soil organic carbon (SOC). This is three times more than the amount of C found in biological biomass or in the environment (Lal, 2004a), (Schmidt et al., 2011). About 60% of the bulk of soil organic matter (SOM) is made up of SOC. SOM is a collection of heterogeneous elements, ranging from freshly decomposed plant detritus, microbes, and soil animals to exudates (Pribyl, 2010). However, to meet the increasing demands for food, livestock feed, and textiles, present agricultural practices often necessitate high-intensity farming techniques (such as tillage, excessive fertilization, and chemical applications). Due to nutrient loss, soil erosion, degradation of soil composition and formation, and salinization, these activities jeopardize SOM stability and formation (Lal, 2011). For instance, worldwide agricultural soils experience 25–75% SOC deficits due to intensive agriculture (Lal, 2011), which speeds up SOM breakdown and releases 1500 Gt carbon dioxide into the environment during 1751 and 2017 (Sanderman et al., 2017), (Friedlingstein et al., 2023). Reversing this pattern and encouraging soil C sequestration may be possible through the use of improved systems and farming techniques, such as crop switching and cover crops (Lal, 2011), (Lal, Negassa, & Lorenz, 2015).

The balance between the addition of carbon (mostly from rhizodeposition and plant

biomass breakdown) and the withdrawal of carbon (mainly from weathering, leaching, and mineralization) determines how much carbon is retained in soils that support agriculture utilizing rainfall (Lal et al., 2015), (Ahkami, Amir H White III, Richard Allen Handakumbura, & Pubudu P Jansson, 2017). In varied rotational farming systems, particularly those that include crops with a variety of beneficial traits—also known as functional crops—larger carbon pools have been noticed and noted (McDaniel, Grandy, Tiemann, & Weintraub, 2014), (King & Blesh, 2018). Perennial plants with elevated levels of root secretion or cover plants—species that are not collected—that generate significant contributions of carbon residue are examples of functional plants. Unlike annual crops, these crops have special functional characteristics that promote a healthy microbial population (Faucon, Houben, & Lambers, 2017), (Pausch & Kuzyakov, 2018).

The complicated combination that makes up soil carbon is produced by the breakdown of surface biomass, root or root rhizodeposits, and the remains of living things, mostly soil microorganisms and animals (Ahkami et al., 2017). When saprotrophic fungi and animals break down litter, macromolecular components are converted to dissolved organic carbon (DOC) by means of enzymes found outside of cells and organisms. The carbon utilized in metabolism and carbon absorption in organismal biomass, whether from plants, animals, or microorganisms, is known as organismal biomass carbon (OBC). Dead organisms are called necromass carbon. The storage of soil biotic-driven carbon, such as OBC, DOC, and necromass carbon, is known as soil organic carbon (SOC). In addition, leaching and organism respiration—the main suppliers of CO₂ in terrestrial ecosystems—cause carbon losses from soil carbon stores (R. Lal et al., 2015), (Ahkami et al., 2017).

Factors influencing soil carbon sequestration:

The storage of carbon in soils may be influenced by soil properties, management

practices, and environmental features. Coarse-textured soils often mineralize carbon and nitrogen at faster rates than fine-textured soils; this is probably because fine-textured soils are better able to protect organic matter from bacterial assault. This indicates that texture is significant for sequestering carbon (Yadav, Purakayastha, Khan, & Kaushik, 2017). The carbon balance in the deeper layers of soil under different land uses, such as farmland, shrublands, and forests, is affected by the texture of the soil (Albaladejo et al., 2013). In clay-rich soils, organic carbon is physically confined within microaggregates and is fewer available to soil microbes than in sandy soils due to its chemical bonding with clay minerals (Sissoko & Kpombrekou-A, 2010). The structure of the soil and SOC are related; SOC aids in the binding of minerals and the formation of particles that shield carbon against deterioration (Lal, 2015). Lower-tillage approaches, natural environments, and fine-textured soils have higher capacities for preserving carbon than do soil aggregates with poor regularity, as those found in soils with coarse textures and heavily tilled soils (Zhang et al., 2017). Increasing carbon inputs and lowering microbial respiration can result in soil carbon reserves. For example, switching from traditional cultivation to no-tillage operations can lengthen the time that soil organic carbon (SOC) is in the soil (Chivenge, Murwira, Giller, Mapfumo, & Six, 2007). Soil organic carbon is lost as a consequence of tillage because it fractures soil aggregates, exposing carbon to mineralization, leaching as soluble carbon, and increasing runoff brought on by wind or water (Sun et al., 2016).

The overall SOC balance is impacted by variables such as humidity, climate, and air (inputs minus outputs). SOC breakdown is accelerated by its temperature, particularly at ideal or excellent humidity levels (Singh et al., 2017). In order to store carbon, the soil must have enough airflow because it promotes the growth of microbes, which in turn influences respiration rates and the cycling of carbon.

Soil Carbon Sequestration Processes and Mechanisms

Photosynthesis and carbon input to soils:

Circular plants primarily regulate the worldwide carbon cycle through photosynthetic capture of CO₂ from the air. The worldwide Carbon cycle is significantly influenced by natural environments on Earth, which serve as sinks for carbon dioxide in the atmosphere (Keenan & Williams, 2018), (Nayak, Mehrotra, & Mehrotra, 2022). There are around 3170 gigatons (Gt) of terrestrial carbon stored in the world; 2500 Gt are found in soil, 560 Gt are found in plant biomass, and 110 Gt are found in microbial biomass. Significantly, the soil carbon reservoir is over three times larger than the atmospheric carbon reservoir (760 gigatonnes), with around 950 gigatonnes of inorganic carbon and 1550 gigatonnes of organic carbon (Lal, 2004a), (Lal, 2008).

By photosynthesis, plants capture CO₂, and some of the trapped carbon is converted into SOC. Through the formation of sodium carbonates and bicarbonates, calcium, magnesium, and potassium, biomass from plants breakdown also adds to soil inorganic Carbon (Lal et al., 2018). Nearly all (approximately 99.9%) of the carbon that is present in global ecosystems is contributed by vascular plants and microbes, with very little coming from animals. The main mechanisms in carbon sequestration include producing soil inorganic Carbon and SOC and conserving stored Carbon as net ecological productivity (NEP) (Lal et al., 2018). Global gross primary production (GPP) of the agricultural system is represented by the 123 Gt yearly photosynthetic Carbon flow between the environment and ground. During photosynthesis, vascular plants absorb 60 Gt of GPP, of which about half are discharged into the environment via plant respiration (Jansson, Wullschleger, Kalluri, & Tuskan, 2010). The other half shows the overall net carbon input from soil organic matter, with bacterial respiration accounting for a large amount of the reduction. As the resistant Carbon pool, the remaining percentage (10 Gt y⁻¹), often referred to as NEP, may endure in the environment for millennia (Jansson et al.,

2010). The primary causes of carbon loss from the environment include wildfires, shifts in land use, heavy tillage, and soil deterioration (Ramesh et al., 2019), (Pellegrini et al., 2022).

Vascular plants convert CO₂ from the atmosphere into sugars by absorbing sunlight. Plants primarily absorb CO₂ in their leaves, which produces sugars that are then transferred to the stems, branches, developing seeds, and roots. The size of the photosynthetic apparatus, detection of light effectiveness, and Carbon assimilation capability all affect plant biomass

production and sequestration potential (Ontl & Schulte, 2012), (Abebe, Shiferaw Minale, Amare Sewnet Teketay, Durai Long, & Thang, 2021).

The NEP of all ecosystems on earth, including grazing land, pastures, agricultural fields, and forests, may be improved by comprehending the biology of plants and rhizosphere ecology, combining management techniques, and using techniques involving genetic engineering (**Table 1**).

Table 1 Soil Carbon Sequestration Techniques

Practice	Country (Region)	Area	Potential Sequestration	C	References
Conservation Farming (No-till farming for Annual Crops)	Africa	142.2 million ha	130.7 Mt C y ⁻¹		(Gonzalez-Sanchez et al., 2019)
Conservation Farming with reduced soil disruption, continuous ground cover, and diverse plant varieties	Central Asia (Almalybak, Kazakhstan), north Europe (Jokioinen, Finland), south Europe (Lombriasco, Italy)	Not specified	0.4% y ⁻¹		(Valkama et al., 2020)
Afforestation (Support for riparian woodland recovery efforts)	Worldwide	Not specified	68–158 Mg C ha ⁻¹		(Dybala, Matzek, Gardali, & Seavy, 2019)
Afforestation	Europe, Asia, Africa, and America	168.4 million ha	15.7 Gt CO ₂		((IUCN). 2018)
Afforestation (shelterbelts, integrated pastures, and backyard gardens)	Worldwide	944 million ha	5.3 GtC y ⁻¹		(L. Shi, Feng, Xu, & Kuzyakov, 2018)
Enhanced grazing practices	Worldwide	Not specified	148–699 Mg t CO ₂ e y ⁻¹		(L. Shi et al., 2018)
Rehabilitating degraded pastures	Brazil	64 million ha	3445 Tg CO ₂		(De Oliveira, Maia, Freitas, & Cerri, 2022)
Incorporating legumes in pasture areas	Worldwide	Not specified	147 Mg t CO ₂ e y ⁻¹		(Bai & Cotrufo, 2022)

Soil organic matter formation and stabilization:

An essential renewable natural resource that supports ecological functions such as the supply of food and fiber, the management of the temperature and water cycle, the regeneration of fertility, and the maintenance of biodiversity is soil organic matter (Pete Smith et al., 2015). Due to increased mineralization and runoff brought on by land conversion for food production, particularly in the previous 200 years, there has been a considerable loss of SOM worldwide, with an

estimated 133 Pg of carbon (C) lost from the 2 m of topsoil (Sanderman et al., 2017). This depletion offers a chance to replenish SOM and restore lost Carbon to the soil. Massive soil carbon sequestration projects are necessary, necessitating coordinated action and the development of policies appropriate for the soil capabilities and land management potential in each location (Amelung et al., 2020). The scientific knowledge of SOM development, perseverance, and behavior should serve as the foundation for these initiatives.

Recent progress in Soil Organic Matter (SOM) research encompasses innovative theoretical models (Cotrufo, Wallenstein, Boot, Deneff, & Paul, 2013), (Daly et al., 2021), (Lehmann et al., 2020), extensive soil data collection (Harden et al., 2018), and advanced soil biogeochemical modeling techniques (Kyker-Snowman, Wieder, Frey, & Grandy, 2020), (Y. Zhang et al., 2021). The integration of these breakthroughs is necessary to attain transforming results and efficient techniques for SOM regeneration (Blankinship et al., 2018). The major target of C sequestration initiatives and SOM investigations is managed soils. Nonetheless, in both naturally occurring and maintained soils, the ecological services that SOM offers—such as reclaiming water, climate control, and soil biodiversity support—are essential. Agricultural management often modifies the dynamics, characteristics, and stocks of SOM (Ogle, Breidt, & Paustian, 2005). The most effective SOM regeneration techniques may be found by applying concepts derived from ecological system research to soils used for agriculture. We thus go over SOM processes and factors in general with the goal of giving readers a comprehensive grasp of SOM as well as a platform for further research and effective management approaches (Cotrufo & Lavalley, 2022).

While the processes of SOM creation and stabilization take place at micro-sizes (1–1000 μm), (Kravchenko & Guber, 2017), the combined effects of these activities may be seen at higher scales. We employ a simplified model for understanding Soil organic substance (SOS), dividing it into particulate organic substance (POS), mineral-associated organic substance (MAOS), and a small portion of dissolved organic substance (DOS). These categories are characterized by their physical characteristics: MAOS is heavier ($> 1.6\text{--}1.85 \text{ g cm}^{-3}$) and finer ($< 50\text{--}60 \mu\text{m}$) than POS, while DOS is water-soluble/extractable (Lavalley, Soong, & Cotrufo, 2020). Aggregates are considered a "state" in which

POM and MAOM may exist (Christensen, 2001), rather than as primary fractions in and of themselves. Aggregates are hierarchical composite structures that include both POM and MAOM. In organo-mineral complexes smaller than 60 μm , physical protection by occlusion is just as strong as chemical binding. Alternatively, MAOM may be thought of as very tiny aggregates of organic matter and minerals (Angst, Mueller, Kögel-Knabner, Freeman, & Mueller, 2017). Since various fractions develop variously, react variably to land utilization, management, and climate variability (Jilling et al., 2020), (Viscarra Rossel et al., 2019), and have distinct accrual potentials (Cotrufo, Ranalli, Haddix, Six, & Lugato, 2019), this simplified conception is based on a small number of procedurally determined physical fractions (Cotrufo et al., 2015). It is essential to know about these small-scale systems and how they affect the dynamics and processes of SO at larger scales in order to accurately predict, forecast, and monitor changes in SOM (O'Rourke, Angers, Holden, & McBratney, 2015), (Paul, 2014).

Microbial processes and their role in soil carbon dynamics:

It was formerly thought that plant polymers like lignin and long-chain lipids, which are resistant to processing, were the main source of stable SOM (Bhattacharyya, Ros, Furtak, Iqbal, & Parra-Saldívar, 2022). However, recent studies demonstrate the critical role soil bacteria play in the breakdown of a variety of plant compounds, given that the circumstances are favorable for microbial biomass to synthesize carbon and that the microorganisms are available (Paul, 2016). This new knowledge suggests that clay mineralogy may not be as important to SOM formation as unique microbial populations (Kallenbach, CM Grandy, Andrew Stuart Frey, SD Diefendorf, & AF, 2015). Particularly, by stabilizing SOM via a variety of mechanisms, bacterial biomass leftovers, sometimes referred to as necromass, may significantly

contribute to soil organic carbon (SOC) storage (Liang et al., 2019).

The survival of soil microorganisms is significantly influenced by the amount and quality of organic matter (Nguyen & Marschner, 2016). Necromass, which may make up more than half of the SOC pool, is a result of organic chemicals contributing to microbial cell mortality (Miltner, Bombach, Schmidt-Brücken, & Kästner, 2012). According to research employing molecular biomarkers, soil microbial communities (SMCs) are crucial contributors of organic compounds that ultimately incorporate into soil organic matter (SOM) (Schimel & Schaeffer, 2012). The process of breakdown, which involves the physical disintegration and biochemical change of organic components, integrates plant and bacterial products of decay into the soil. This process further humifies the soil (Robertson & Paul, 2000).

Due to processes that restrict their access for other microbes, support mechanisms for microbial leftovers are critical to their persistence in soil. For example, degradation rates may be efficiently lowered by forming persistent aggregates from dying cell envelope pieces (Kästner & Miltner, 2018). The complicated dynamics that control soil carbon storage are highlighted by this thorough knowledge of the microbial roles to SOM synthesis and stability. It also emphasizes the significance of regulating microbial populations to improve SOC sequestration (C. M. Kallenbach, Frey, & Grandy, 2016).

Soil Carbon Sequestration Practices and Strategies

Conservation tillage (CT) reduces the frequency of plowing and leaves crop leftovers as mulch, with an emphasis on the rotation of crops, persistent cover of soil, and little soil displacement. By using this technique, organic matter and soil organic carbon are improved. Carbon sequestration is enhanced by zero tillage practices, which also decrease CO₂ evolution and raise soil microbial biomass carbon. In dry areas, CT increases infiltration,

decreases overall density, and strengthens soil structure (Shaver et al., 2002). It may improve soil durability and condition (Blevins, Smith, Thomas, & Frye, 1983) while sequestering around 23 Tg C annually (Pete Smith, Powlson, Glendining, & Smith, 1998). CT enhances SOC content and macro-aggregation in the vicinity of the soil surface, in contrast to traditional tillage (Lai, 1989). Controlling agricultural waste raises SOC, particularly in rice-wheat systems. Burning residue raises soil pH and reduces microbial populations. Remaining leftovers as mulch may effectively store carbon, with a possible annual sequestration of 0.2×10^{15} g (Lal, 1997). The Happy Seeder saves expenses and preserves harvests by assisting with zero-planting (Y. Singh & Sidhu, 2014).

Strategies for managing crops, like alternating crops and using cover crops, enhance soil structure and contribute organic material, which aids in capturing carbon. Pulses greatly increase soil organic carbon (SOC) via biomass and nitrogen fixation (Ganeshamurthy, 2009). Research indicates that pulses, such as maize, wheat, and mungbean, raise soil organic carbon by 11% and carbon from microbial biomass by 15% in cropping settings (Venkatesh, Hazra, Ghosh, Praharaj, & Kumar, 2013). Cover crops of legumes boost soil organic carbon reservoirs and biodiversity; no-till farming methods further improve soil organic carbon (Franzluebbers, Stuedemann, & Wilkinson, 2001). Cover crops provide soil organisms with nourishment and promote ecological soil tillage. Crop rotation enhances the fertility and structure of the soil by switching between plants with deep and shallow roots. Legume-based rotations enhance carbon retention more than monocultures, according to long-term research (Gregorich, Drury, & Baldock, 2001). Compared to monocultures, crop rotations increase biomass and SOC sequestration, while green manure crops enhance soil organic matter even more (Pattnaik, Sethi, & Das, 2020).

Careful nutrition control is necessary to sequester SOC. Composting and organic waste improve SOC more successfully than inorganic fertilizers (Gregorich et al., 2001). Continuously manure application improves soil cohesiveness and soil organic carbon (Gilley & Risse, 2000). Organic additions are beneficial for conservation farming (Hao et al., 2002). Adding manure to agricultural land raises SOC more than pastures do; in the EU, this might contribute up to 6.8 Tg C annually (Pete Smith et al., 1998). Long-term research indicates that using fertilizer correctly improves SOC (Kimble, Follett, & Cole, 1998). Soil organic matter is greatly increased through integrated management of nutrients, which includes crop leftovers, green manure, and farmyard waste. Agroforestry fights poverty, hunger, malnutrition, and environmental damage by combining multifunctional trees with crops (Garrity, 2004). It improves the efficiency of land, reduces deterioration, increases SOC via litterfall, and diversifies agricultural revenue. Trees increase the soil's capacity to hold moisture and reduce runoff (Pattnaik et al., 2020). Positive relationships may sometimes outweigh negative ones, even in the face of obstacles like rivalry for space and resources and possible pest hosting (Jose, Gillespie, Seifert, & Biehle, 2000). By capturing carbon from soil and biomass, agroforestry helps to mitigate climate change (Albrecht & Kandji, 2003). Significant SOC sequestration occurs in agroforestry systems, according to decades of study (Swamy & Puri, 2005). Both organic and inorganic soil additions increase soil fertility. Crop leftovers may be used as amendments to improve fertility as they break down. Composted agricultural byproducts, wood ash, soil ash, animal manures, municipal biosolids, and composted biosolids are examples of common additives. These substances enhance soil-holding capacity, raise organic matter levels, restore microbial populations, lower compaction of the soil, and regulate pH of the soil. They also inhibit the

emissions of methane and CO₂. Specifically, it has been shown that biochar improves the physical characteristics of soil, encourages crop development, and increases water and nutrient retention (Pattnaik et al., 2020).

Impacts and Co-benefits of Soil Carbon Sequestration

Climate change mitigation potential:

Life on Earth is being transformed by climate change, primarily driven by the emission of GHGs, which represents the greatest threat to humanity (Hu et al., 2022). Every year, manmade sources release 8.7 Gt of carbon into the environment worldwide (Lal, 2008), (Stockmann et al., 2013). The significant regulating ability of carbon reservoirs is shown by the atmospheric rise of about 3.8 Gt of carbon annually (Stockmann et al., 2013). In this context, scientific research discusses SOC's ability to absorb CO₂ from the atmosphere in great depth. This is in light of growing concerns over possible climate change effects on soil processes. This worry is accompanied by the desire to create policies that improve carbon sequestration, support empirical studies, and create theoretical frameworks (Lal, 2004b), (Guo & Gifford, 2002), (Post & Kwon, 2000), (Post et al., 2004), (Lal, 2008). By the storage of SOC, soils offer a tremendous deal of potential to counteract global warming (Raza et al., 2021). Soil carbon stores at depths more than 1 m (~1600 Gt) are projected to be twice as large as the carbon in the atmosphere (~800 Gt) (Lal, Monger, Nave, & Smith, 2021), (Batjes, 2014), (Le Quéré et al., 2016).

The impacts of GHGs and the change of climate might be lessened by minor rises in soil organic carbon (SOC) (Lal, 2004b), which entails the elimination of atmospheric CO₂ by crops and the preservation of carbon that is fixed as soil organic material (Wang, Tao, Chen, & Yin, 2022), (Pete Smith, 2012). In addition, maintaining and increasing SOC deposits is essential for fertility, soil health, agricultural production, and lowering the release of GHGs (Wang et al., 2022).

However, factors related to climate change have a significant impact on both biotic and abiotic processes that contribute to soil carbon alterations, which might destabilize SOC stores. These factors include rainfall, temperature, levels of CO₂ in the atmosphere, and periods of severe drought (Lal, 2004b), (Lal, Monger, et al., 2021), (Raza et al., 2021).

Soil carbon reserves are a practical way to both mitigate and adjust the effects of climate change, assuming that good soil and agricultural practices may increase the soil's capacity to store carbon (Lal, Monger, et al., 2021). This can be accomplished by increasing the levels of Soil Organic Carbon (SOC), stabilizing SOC, and improving its vertical distribution. Carbon can be stabilized by transforming it into recalcitrant carbon with a longer turnover time or by integrating it into stable clay-humic complexes, which protect it from microbial degradation (Lal, 2004b). Improved quality of soil and agricultural ecosystem functioning as a consequence may support several interconnected sustainable development objectives, including Agenda 2030 of the United Nations (Lal, Bouma, et al., 2021).

Storing carbon in the soil can be accomplished by enhancing the total movement of carbon from the surroundings to the terrestrial ecosystem. This can be done by raising the global carbon influx into soils through elevated primary production rates, maintaining a higher proportion of carbon at current productivity levels, or slowing the decomposition process to reduce soil carbon losses (Pete Smith, 2008). Solutions for carbon capture and storage cannot be implemented until new technologies are developed and the soil's health is improved. Additionally, by improving the structural properties of soil, these actions help adjust ecological services and soil changes while also strengthening the soil's resistance to changes in the climate (Lal,

Follett, Stewart, & Kimble, 2007), (Powlson et al., 2014).

The increased soil organic carbon must be in resistant forms in order to offer a long-term mitigation of climate change (Powlson et al., 2014). Converting profitable agricultural areas back to their natural conditions produces the highest levels of soil organic carbon storage (Pete Smith, 2012), but this land use transition is challenging due to the unstable condition of the soil and the slow rates of conversion. It also clashes with the requirement to feed people (Powlson et al., 2014). The increasing effects of global warming emphasize how urgently effective mitigation measures are needed. By implementing practices that increase SOC, the soil may both decrease the of GHGs emissions and increase the adaptability of these areas.

Ecosystem Services and Environmental Benefits:

The majority of carbon (about 90%) that is taken up by photosynthesis in natural environment is sent into the soil, in which it quickly decomposes and ultimately leaves behind permanent leftovers that make up a significant amount of SOC (Janzen, van Groenigen, Powlson, Schwinghamer, & van Groenigen, 2022). Plant and microbial development is supported by this organic matter, which also has a substantial influence on the characteristics of the soil. Soil organic carbon regulates the health of the soil in addition to giving plants and soil microorganisms carbon and nutrients. It does this by enhancing soil structure, retaining more water and nutrients, lowering soil erosion, and lowering greenhouse gas emissions. These actions enhance the ground and surface water quality, boost yields of crops, and support food security (Ontl & Schulte, 2012), (Thangarajan, Bolan, Tian, Naidu, & Kunhikrishnan, 2013), (Durán-Zuazo & García-Tejero, 2022) (**Figure 2**).

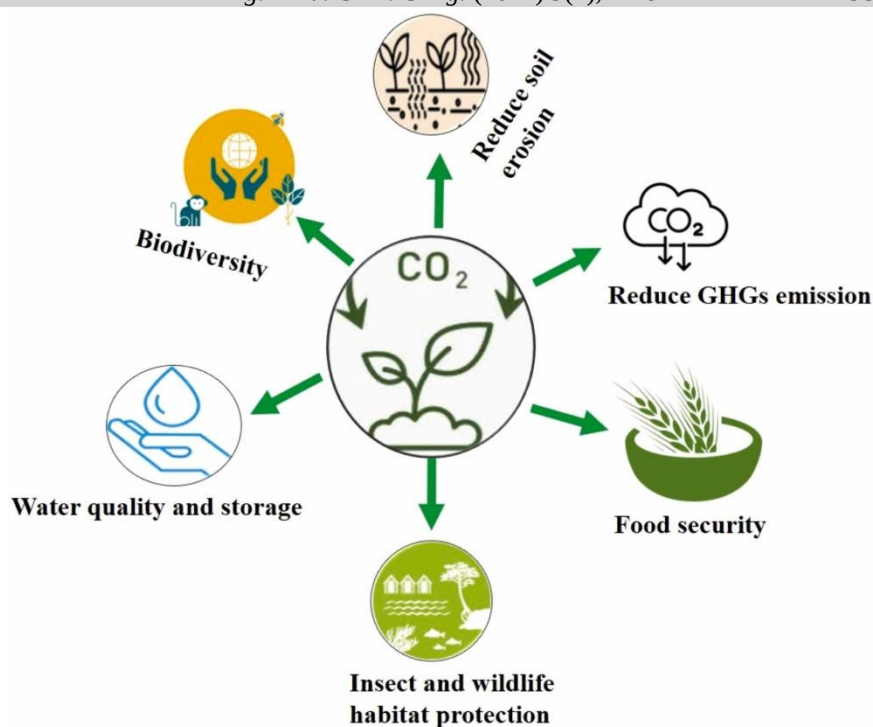


Figure 2 Additional Advantages of Soil Carbon Sequestration from the paper (Siddique, Bolan, Rehman, & Farooq, 2024)

Numerous co-benefits might result from soil carbon storage. Specifically, it is impossible to isolate soil carbon storage from other ecosystem benefits (Stockmann et al., 2013). Controlling the loss of soil, durability against drought, habitat for animals, the quality of water, and aesthetic value are additional co-benefits. For instance, a reasonable quantity of soil organic carbon increases the soil's ability to filter water (Pattanayak et al., 2005), (Greenhalgh & Sauer, 2003). Elevated soil carbon sequestration lowers nitrogen and phosphorus pollution, improves habitat for animals, and dramatically lowers the erosion of soil (Plantinga & Wu, 2003), (McCarl & Schneider, 2001). Biodiversity benefits from storing carbon via afforestation, while regional differences may exist (Wiesmeier et al., 2019). Apart from their noteworthy capacity to sequester carbon, forests have a high carbon density above as well as below ground, a wide variety of tree species, and a considerable share of vital habitat for endangered or threatened species of vertebrates (Buotte, Law, Ripple, & Berner, 2020). A deep knowledge of the environment, the roots biology, and the variables influencing soil organic

carbon storage is necessary for soil C restoration.

Socioeconomic Implications of SOC Sequestration:

The economic and social advantages and compromises of soil organic carbon storage need to be evaluated in the framework of sustainable growth and the fight against poverty, especially in impoverished countries where agriculture frequently encounters difficult social and financial circumstances (Graff-Zivin & Lipper, 2008). Restoring ecosystems is essential for stopping land degradation and storing carbon in the atmosphere. Removing land for agriculture from production has the potential to act as a large carbon sink, assisting in the removal of surplus CO₂ from the environment. However, there are a variety of cheap, minimum management techniques as well as more costly, active restoration ways for restoring land. To speed up carbon recovery and restore diverse ecosystem processes, active restoration entails sowing seeds on formerly farmed land. On the other hand, recent worldwide research indicates that spontaneous regeneration—letting abandoned farmland regenerate on its

own—might accelerate the recovery of primary output in tropical forests compared to intensive restoration (He, Jiang, Lei, Cai, & Zhang, 2022). This research suggests that significant financial outlays for vigorous restoration could not necessarily result in higher carbon sequestration than inexpensive spontaneous regeneration (Osborne et al., 2021).

Due to different treatments and shifting ecological factors in research, maximizing the possible return on investment for the restoration of ecosystems is still unclear. To maximize the carbon storage in the soil, agreement on resource distribution is hampered by this uncertainty. One of China's largest ecological rehabilitation projects, 'Grain for Green,' intends to turn croplands into grasslands, woods, or shrubby areas. It enables straightforward comparisons between active restoration and spontaneous regeneration at various locations. Researchers evaluated parameters such as depth of soil, weather, environment type, restoration period, and soil organic carbon using data from 617 observations. The circumstances under which each restoration technique maximizes the storage of soil carbon were determined by this research (Nazir et al., 2024).

Economic and Social Barriers to Soil Carbon Sequestration

Economic Barriers:

A substantial cost barrier exists for farmers looking to use net SCS techniques. High upfront expenses are common, particularly for activities like agroforestry or water management that need expensive equipment. Establishment costs apply to even low-investment strategies like planting cover crops. Farmers' finances are further strained by maintenance expenses and possible income losses from missed produce or residue sales. Still, the situation isn't totally hopeless. Certain "win-win" techniques, such as decreased tillage, enhanced fertilization, and legume cover crops, may actually increase farm income over time (Wreford, Ignaciuk, & Gruère, 2017), (Sykes et al., 2020).

The issue is that these procedures may be expensive up front, making them unaffordable for farmers with little funds or credit availability. The problem is made more difficult by the delay between investment and return on investment. Furthermore, there are significant variations in the mitigation capacity of various activities based on the price of carbon. Restoring organic soils, for instance, may significantly reduce emissions, but it won't be financially viable until carbon prices rise (Pete Smith et al., 2014). In general, financial factors are a significant factor in the adoption of net SCS, and methods to overcome these obstacles are essential for broad deployment.

Opportunity Costs:

When SCS policies force farmers to give up income from other sources, they may result in opportunity costs in addition to direct financial losses. For instance, reclaiming farmed organic soils may require stopping farming on particular areas, which would result in revenue losses. On the other hand, holding onto agricultural leftovers might mean losing out on money from selling it or from using it as bedding or feed for animals (Henderson et al., 2022).

Technical Barriers:

The technological obstacles related to SCS are similarly intimidating. For instance, it is difficult and expensive to measure and validate soil carbon levels correctly. Due to the intrinsic temporal and geographical variability of soil carbon increases, it is difficult and costly to monitor and comply with SCS procedures. This unpredictability increases the transaction costs associated with establishing accurate baselines, tracking contract compliance across wide and diverse geographic regions, and quantifying sequestration results (Frelih-Larsen et al., 2020).

Non-Permanence:

The non-permanence problem is one particular difficulty for SCS. The advantages of SCS may be readily undone by changes in land management techniques or natural disasters like droughts or floods, which increase the

danger of carbon stocks being released back into the atmosphere. To guarantee that buried carbon remains permanently, this uncertainty necessitates continuing monitoring and sometimes expensive enforcement actions (P Smith, 2005).

Transaction Costs and MRV:

From the creation of policies to their implementation, transaction costs arise at every step of the policy cycle. These expenditures consist of standard transaction charges for finance, such legal and broker fees, as well as costs related to purchasing carbon offsets, like measurement, reporting, and verification (MRV) and contract compliance (Mooney, Antle, Capalbo, & Paustian, 2004). The broad adoption of SCS policy is still significantly hampered by the lack of reliable, affordable, and adaptable instruments for measuring soil carbon (Olesen et al., 2020).

Policy Design Challenges in Soil Carbon Sequestration

Additionality:

A key idea in SCS policy is additionality, which is the need that SCS activities produce carbon sequestration that would not have happened in the absence of the policy intervention. Since assessing additionality entails figuring out what would have occurred if the policy hadn't been in place, the process is inherently complicated (Glenk & Colombo, 2011). Due of its intricacy, policymakers may support projects that do not really produce in more carbon sequestration, overstating the benefit of emissions reductions and perhaps overpaying for SCS. This is known as the risk of non-additionality (Henderson et al., 2022).

Permanence:

Another major problem is ensuring the durability of sequestered carbon over the long term. In order to prevent the sequestered carbon from being released back into the atmosphere, SCS techniques must be maintained over lengthy periods of time. The complexity and long-term expenses of SCS projects are increased by this necessity. Furthermore, a number of variables, like as changes in land use, environmental disturbances, and management techniques,

have the potential to jeopardize the stability of sequestered carbon, making it an essential topic for policy attention and development (Henderson et al., 2022).

Measurement, Reporting, and Verification (MRV):

Successful MRV systems are necessary for SCS policies to be successful. But creating and putting these systems into place may be expensive and difficult technically. The geographical and temporal variability of soil carbon complicates the monitoring process, and accurate detection of changes in soil carbon needs sophisticated techniques and procedures. To guarantee compliance and enforce contracts, these systems must also be sufficiently strong, which raises the total transaction costs of SCS projects (Cacho, Lipper, & Moss, 2013), (Olesen et al.).

Future perspectives:

Careful handling of resources and the adoption of farming techniques that improve soil carbon storage will be crucial to reducing the negative effects of global warming on the farming industry, a sector that is very vulnerable to shifting climatic conditions. A win-win approach that addresses climate adaptation and mitigation is closely linked to soil carbon sequestration. By absorbing ambient CO₂ into the soil, this technique protects soil-based carbon stores against microbial populations in the soil that can send carbon into the surrounding environment. Restoring soil and storing carbon in the atmosphere can be effectively accomplished by converting marginal or degraded regions to permanent land use and by converting from conventional tillage to no-till farming techniques. No-till farming boosts soil health, preserves ecosystems, uses water and nutrients more efficiently, and sequesters significant amounts of CO₂ from the atmosphere. Retaining crop residue on the field in combination with little or no tillage is necessary to attain these benefits. Crop rotation is another intriguing method that, particularly in conservation agriculture systems, enhances the soil's fertility and biodiversity while accelerating the

pace at which SOC accumulates at various soil depths.

Using agricultural management strategies that promote carbon sequestration has numerous other benefits. These methods improve the soil's water-retention capacity and decrease runoff by fortifying the stability of the soil aggregate. An increase in soil fertility and structure is associated with increased agricultural production and food security. These benefits show how important it is to incorporate soil carbon sequestration into more all-encompassing plans for global warming adaptation and mitigation. The dynamics and long-term stability of soil carbon in different parts of the world remain little unknown, despite the great potential for carbon sequestration through agricultural systems. One of the primary barriers to promoting the widespread adoption of agricultural systems that store carbon dioxide is the variety of methods for managing land. It is difficult to create solutions that work for every situation because different regions have varying soil types, temperatures, and farming practices. Furthermore, societal and economic factors play a role in farmers' decisions to adopt new techniques. Overcoming these challenges requires tailored strategies that consider local conditions and involve farmers in the process of making decisions.

Despite these uncertainties, it is critical that we keep learning more about the dynamics of soil carbon. The primary objectives of research should be the development of accurate and dependable technologies for measuring soil carbon and the identification of optimum practices for different geographical areas. AI-powered prediction models, remote sensing, and soil health monitoring techniques have the potential to fundamentally alter how we track and assess soil carbon sequestration. Since conservation tillage methods are more effective than other atmospheric drawdown tactics, they might soon be improved and changed. Conservation tillage reduces soil disturbance, preserves higher SOC levels, and promotes sustainable land use. Cover crops

can help increase carbon sequestration when they are incorporated into conservation tillage systems. The addition of organic matter, improved soil structure, and continuous ground cover provided by cover crops all contribute to higher SOC levels. The adoption of sustainable farming practices requires financial incentives and supportive regulatory frameworks. Governments and international organizations should develop policies that encourage the adoption of carbon-sequestering methods. Financial incentives, technical assistance, and educational programs must be a part of these strategies. To provide the framework for sustainable land use, scientists, policymakers, and farmers must work together. It is critical that decision-makers understand the social and economic barriers to adoption and take targeted action to remove them. Soil carbon sequestration presents a significant opportunity for mitigating and adapting to the effects of global warming. Crop rotation, cover crops, and no-till farming are a few methods that we can employ to strengthen soil structure, take up CO₂ from the atmosphere, and boost agricultural sustainability. Soil carbon sequestration has significant possible advantages that surpass the challenges and risks involved, rendering it a crucial component of climate policies. More investigation, cutting-edge technology, and supportive legislation are required to properly use soil carbon sequestration and guarantee a strong and sustainable agricultural future.

CONCLUSION

Soil carbon sequestration (SCS) is a vital strategy for mitigating climate change and enhancing agricultural sustainability, offering benefits such as reduced atmospheric CO₂ levels, improved soil health, water retention, and increased agricultural productivity. Crop rotation, no-till farming, and crop residue retention are examples of effective agricultural techniques that increase soil organic carbon (SOC), stabilizing soil structure and increasing crop yields. Although it has great potential, mainstream adoption is hampered by a number of key obstacles, such as expensive starting

expenditures, technical difficulty with SOC monitoring, and ongoing maintenance. It is critical to address social and economic constraints, climate and soil variability among regions, and establish supporting policies and precise monitoring technology. We can fully exploit SCS's potential for a resilient and sustainable agricultural system by incorporating it into larger climate plans and involve farmers in the decision-making process.

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Author Contribution

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REFERENCES

- (IUCN)., & I. U. f. t. C. o. N. (2018). Retrieved from <<http://www.bonnchallenge.org/>> . 4 April 2023.
- Aakko-Saksa, P. T., Lehtoranta, K., Kuittinen, N., Järvinen, A., Jalkanen, J. P., Johnson, K., & Takahashi, C. (2023). Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options. *Progress in Energy and Combustion Science*, 94, 101055.
- Abebe, Minale, S., Teketay, A. S., Durai Long, D. J., & Thang, T. (2021). Biomass, carbon stock and sequestration potential of *Oxytenanthera abyssinica* forests in Lower Beles River Basin, Northwestern Ethiopia. *Carbon Balance and Management*, 16(1), 29.
- Ahkami, Amir, H., White, III, Handakumbura, R. A., Pubudu, P., & Jansson, C. (2017). Rhizosphere engineering: enhancing sustainable plant ecosystem productivity. *Rhizosphere*, 3, 233-243.
- Albaladejo, J., Ortiz, R., Garcia-Franco, N., Navarro, A. R., Almagro, M., Pintado, J. G., & Martínez-Mena, M. (2013). Land use and climate change impacts on soil organic carbon stocks in semi-arid Spain. *Journal of Soils and Sediments*, 13, 265-277.
- Albrecht, A., & Kandji, S. T. (2003). Carbon sequestration in tropical agroforestry systems. *Agriculture, ecosystems & environment*, 99(1-3), 15-27.
- Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., & Leifeld, J. (2020). Towards a global-scale soil climate mitigation strategy. *Nature communications*, 11(1), 5427.
- Angst, G., Mueller, K. E., Kögel-Knabner, I., Freeman, K. H., & Mueller, C. W. (2017). Aggregation controls the stability of lignin and lipids in clay-sized particulate and mineral associated organic matter. *Biogeochemistry*, 132, 307-324.
- Bai, Y., & Cotrufo, M. F. (2022). Grassland soil carbon sequestration: Current understanding, challenges, and solutions. *science*, 377(6606), 603-608.
- Barber, S. A. (1995). *Soil nutrient bioavailability: a mechanistic approach*: John Wiley & Sons.
- Batjes, N. H. (2014). Total carbon and nitrogen in the soils of the world. *European journal of soil science*, 65(1), 10-21.
- Bhattacharyya, S. S., Ros, G. H., Furtak, K., Iqbal, H. M., & Parra-Saldívar, R. (2022). Soil carbon sequestration—An interplay between soil microbial community and soil organic matter dynamics. *Science of The Total Environment*, 815, 152928.
- Bibi, F., & Rahman, A. (2023). An overview of climate change impacts on agriculture and their mitigation strategies. *Agriculture*, 13(8), 1508.

- Biswal, D. (2023). Soil nematodes as the silent sufferers of climate-induced toxicity: analysing the outcomes of their interactions with climatic stress factors on land cover and agricultural production. *Applied biochemistry and biotechnology*, 195(4), 2519-2586.
- Blankinship, J. C., Berhe, A. A., Crow, S. E., Druhan, J. L., Heckman, K. A., Keiluweit, M., & Rasmussen, C. (2018). Improving understanding of soil organic matter dynamics by triangulating theories, measurements, and models. *Biogeochemistry*, 140, 1-13.
- Blevins, R., Smith, M., Thomas, G., & Frye, W. (1983). Influence of conservation tillage on soil properties. *Journal of soil and water conservation*, 38(3), 301-305.
- Buotte, P. C., Law, B. E., Ripple, W. J., & Berner, L. T. (2020). Carbon sequestration and biodiversity co-benefits of preserving forests in the western United States. *Ecological applications*, 30(2), e02039.
- Cacho, O. J., Lipper, L., & Moss, J. (2013). Transaction costs of carbon offset projects: A comparative study. *Ecological Economics*, 88, 232-243.
- Cade, B. S., & Noon, B. R. (2003). A gentle introduction to quantile regression for ecologists. *Frontiers in Ecology and the Environment*, 1(8), 412-420.
- Canellas, L. P., & Olivares, F. L. (2014). Physiological responses to humic substances as plant growth promoter. *Chemical and Biological Technologies in Agriculture*, 1, 1-11.
- Canellas, L. P., Olivares, F. L., Aguiar, N. O., Jones, D. L., Nebbioso, A., Mazzei, P., & Piccolo, A. (2015). Humic and fulvic acids as biostimulants in horticulture. *Scientia horticultrae*, 196, 15-27.
- Chivenge, P., Murwira, H., Giller, K., Mapfumo, P., & Six, J. (2007). Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. *Soil and tillage research*, 94(2), 328-337.
- Christensen, B. T. (2001). Physical fractionation of soil and structural and functional complexity in organic matter turnover. *European journal of soil science*, 52(3), 345-353.
- Cotrufo, M. F., & Lavalley, J. M. (2022). Soil organic matter formation, persistence, and functioning: A synthesis of current understanding to inform its conservation and regeneration. *Advances in agronomy*, 172, 1-66.
- Cotrufo, M. F., Ranalli, M. G., Haddix, M. L., Six, J., & Lugato, E. (2019). Soil carbon storage informed by particulate and mineral-associated organic matter. *Nature Geoscience*, 12(12), 989-994.
- Cotrufo, M. F., Soong, J. L., Horton, A. J., Campbell, E. E., Haddix, M. L., Wall, D. H., & Parton, W. J. (2015). Formation of soil organic matter via biochemical and physical pathways of litter mass loss. *Nature Geoscience*, 8(10), 776-779.
- Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K., & Paul, E. (2013). The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? *Global Change Biology*, 19(4), 988-995.
- Daly, A. B., Jilling, A., Bowles, T. M., Buchkowski, R. W., Frey, S. D., Kallenbach, C. M., & Grandy, A. S. (2021). A holistic framework integrating plant-microbe-mineral regulation of soil bioavailable nitrogen. *Biogeochemistry*, 154(2), 211-229.
- Davidson, E. A., & Ackerman, I. L. (1993). Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry*, 20, 161-193.

- de Alcantara, I. R., Vieira Filho, J. E. R., & Gasques, J. G. (2021). Farming production in Brazil: innovation and land-sparing effect. *International Journal of Agricultural and Biosystems Engineering*, 15(10), 124-131.
- De Oliveira, D. C., Maia, S. M. F., Freitas, R. d. C. A., & Cerri, C. E. P. (2022). Changes in soil carbon and soil carbon sequestration potential under different types of pasture management in Brazil. *Regional Environmental Change*, 22(3), 87.
- Durán-Zuazo, V., & García-Tejero, I. (2022). Conservation Agriculture as a Sustainable System for Soil Health: A Review. *Soil Systems*, 6(4).
- Dybala, K. E., Matzek, V., Gardali, T., & Seavy, N. E. (2019). Carbon sequestration in riparian forests: A global synthesis and meta-analysis. *Global Change Biology*, 25(1), 57-67.
- Eftekhari, M. S. (2022). Impacts of climate change on agriculture and horticulture. In *Climate change: The social and scientific construct* (pp. 117-131): Springer.
- Faucon, M. P., Houben, D., & Lambers, H. (2017). Plant functional traits: soil and ecosystem services. *Trends in plant science*, 22(5), 385-394.
- Franzluebbers, A., Stuedemann, J., & Wilkinson, S. (2001). Bermudagrass management in the Southern Piedmont USA: I. Soil and surface residue carbon and sulfur. *Soil Science Society of America Journal*, 65(3), 834-841.
- Freluh-Larsen, A., Ittner, S., Tarpey, J., Olesen, J., Graversgaard, M., Esmøke Madari, B., & Swanepoel, C. (2020). European Union's Horizon 2020 research and innovation programme grant agreement No 774378-Coordination of *International Research Cooperation on soil CARbon Sequestration in Agriculture*. In.
- Friedlingstein, P., O'sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C., Hauck, J., & Peters, G. P. (2023). Global carbon budget 2023. *Earth System Science Data*, 15(12), 5301-5369.
- Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Khanna, T. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental research letters*, 13(6), 063002.
- Ganeshamurthy, A. (2009). Soil changes following long-term cultivation of pulses. *The Journal of Agricultural Science*, 147(6), 699-706.
- Garrity, D. P. (2004). Agroforestry and the achievement of the Millennium Development Goals. *Agroforestry systems*, 61, 5-17.
- Gerke, J. (2021). The effect of humic substances on phosphate and iron acquisition by higher plants: Qualitative and quantitative aspects. *Journal of Plant Nutrition and Soil Science*, 184(3), 329-338.
- Gerke, J. (2022). The central role of soil organic matter in soil fertility and carbon storage. *Soil Systems*, 6(2), 33.
- Gilley, J. E., & Risse, L. M. (2000). Runoff and soil loss as affected by the application of manure. *Transactions of the ASAE*, 43(6), 1583-1588.
- Glenk, K., & Colombo, S. (2011). Designing policies to mitigate the agricultural contribution to climate change: an assessment of soil based carbon sequestration and its ancillary effects. *Climatic Change*, 105(1), 43-66.
- Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., & Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. *science*, 327(5967), 812-818.
- Gonzalez-Sanchez, E. J., Veroz-Gonzalez, O., Conway, G., Moreno-Garcia, M., Kassam, A., Mkomwa, S., & Carbonell-Bojollo, R. (2019). Meta-analysis on carbon sequestration through Conservation Agriculture in

- Africa. *Soil and tillage research*, 190, 22-30.
- Graff-Zivin, J., & Lipper, L. (2008). Poverty, risk, and the supply of soil carbon sequestration. *Environment and Development Economics*, 13(3), 353-373.
- Greenhalgh, S., & Sauer, A. (2003). *Awakening the dead zone: an investment for agriculture, water quality, and climate change*.
- Gregorich, E., Drury, C., & Baldock, J. (2001). Changes in soil carbon under long-term maize in monoculture and legume-based rotation. *Canadian Journal of Soil Science*, 81(1), 21-31.
- Guo, L. B., & Gifford, R. M. (2002). Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, 8(4), 345-360.
- Hao, Y., Lal, R., Owens, L., Izaurrealde, R., Post, W., & Hothem, D. (2002). Effect of cropland management and slope position on soil organic carbon pool at the North Appalachian Experimental Watersheds. *Soil and tillage research*, 68(2), 133-142.
- Harden, J. W., Hugelius, G., Ahlström, A., Blankinship, J. C., Bond-Lamberty, B., Lawrence, C. R., & Ogle, S. (2018). Networking our science to characterize the state, vulnerabilities, and management opportunities of soil organic matter. *Global Change Biology*, 24(2), e705-e718.
- Hatfield, J. L., Antle, J., Garrett, K. A., Izaurrealde, R. C., Mader, T., Marshall, E., & Ziska, L. (2020). Indicators of climate change in agricultural systems. *Climatic Change*, 163, 1719-1732.
- He, J., Jiang, X., Lei, Y., Cai, W., & Zhang, J. (2022). Temporal and spatial variation and driving forces of soil erosion on the Loess Plateau before and after the implementation of the Grain-for-Green project: A case study in the Yanhe river basin, China. *International Journal of*
- Environmental Research and Public Health*, 19(14), 8446.
- Henderson, B., Lankoski, J., Flynn, E., Sykes, A., Payen, F. T., & MacLeod, M. (2022). Soil carbon sequestration by agriculture: Policy options.
- Hergart, C. (2022). Sustainable transportation. *Engines and Fuels for Future Transport*, 7-38.
- Hu, Y., Zhang, Q., Hu, S., Xiao, G., Chen, X., Wang, J., & Han, L. (2022). Research progress and prospects of ecosystem carbon sequestration under climate change (1992–2022). *Ecological Indicators*, 145, 109656.
- IPCC. (2019). *Special report: climate change and land*. Retrieved from
- Jansson, C., Wulschleger, S. D., Kalluri, U. C., & Tuskan, G. A. (2010). Phytosequestration: carbon biosequestration by plants and the prospects of genetic engineering. *Bioscience*, 60(9), 685-696.
- Janzen, H. H., van Groenigen, K. J., Powlson, D. S., Schwinghamer, T., & van Groenigen, J. W. (2022). Photosynthetic limits on carbon sequestration in croplands. *Geoderma*, 416, 115810.
- Jilling, A., Kane, D., Williams, A., Yannarell, A. C., Davis, A., Jordan, N. R., & Snapp, S. S. (2020). Rapid and distinct responses of particulate and mineral-associated organic nitrogen to conservation tillage and cover crops. *Geoderma*, 359, 114001.
- Jones, C., McConnell, C., Coleman, K., Cox, P., Falloon, P., Jenkinson, D., & Powlson, D. (2005). Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil. *Global Change Biology*, 11(1), 154-166.
- Jose, S., Gillespie, A., Seifert, J., & Biehle, D. (2000). Defining competition vectors in a temperate alley cropping system in the midwestern USA: 2.

- Competition for water. *Agroforestry systems*, 48, 41-59.
- Kallenbach, Grandy, C. M., Frey, A. S., Diefendorf, S. D., & A. F. (2015). Microbial physiology and necromass regulate agricultural soil carbon accumulation. *Soil Biology and Biochemistry*, 91, 279-290.
- Kallenbach, C. M., Frey, S. D., & Grandy, A. S. (2016). Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. *Nature communications*, 7(1), 13630.
- Kästner, M., & Miltner, A. (2018). SOM and microbes—What is left from microbial life. In *The future of soil carbon* (pp. 125-163): Elsevier.
- Keenan, T., & Williams, C. (2018). The terrestrial carbon sink. *Annual Review of Environment and Resources*, 43(1), 219-243.
- Kimble, J. M., Follett, R. F., & Cole, C. V. (1998). *The potential of US cropland to sequester carbon and mitigate the greenhouse effect*: CRC press.
- King, A. E., & Blesh, J. (2018). Crop rotations for increased soil carbon: perenniality as a guiding principle. *Ecological applications*, 28(1), 249-261.
- Kopittke, Peter M Menzies, Neal W Wang, McKenna, P., Brigid A Lombi, & Enzo. (2019). Soil and the intensification of agriculture for global food security. *Environment international*, 132, 105078.
- Kramer, M. G., & Chadwick, O. A. (2018). Climate-driven thresholds in reactive mineral retention of soil carbon at the global scale. *Nature Climate Change*, 8(12), 1104-1108.
- Kravchenko, A. N., & Guber, A. K. (2017). Soil pores and their contributions to soil carbon processes. *Geoderma*, 287, 31-39.
- Kyker-Snowman, E., Wieder, W. R., Frey, S. D., & Grandy, A. S. (2020). Stoichiometrically coupled carbon and nitrogen cycling in the MIneral-
- MIneral Carbon Stabilization model version 1.0 (MIMICS-CN v1. 0). *Geoscientific Model Development*, 13(9), 4413-4434.
- Lai, R. (1989). Conservation tillage for sustainable agriculture: tropics versus temperate environments. *Advances in agronomy*, 42, 85-197.
- Lal, Rattan, Negassa, Wakene, Lorenz, & Klaus. (2015). Carbon sequestration in soil. *Current Opinion in Environmental Sustainability*, 15, 79-86.
- Lal, R. (1997). Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO₂-enrichment. *Soil and tillage research*, 43(1-2), 81-107.
- Lal, R. (2004a). Soil carbon sequestration impacts on global climate change and food security. *science*, 304(5677), 1623-1627.
- Lal, R. (2004b). Soil carbon sequestration to mitigate climate change. *Geoderma*, 123(1-2), 1-22.
- Lal, R. (2008). Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492), 815-830.
- Lal, R. (2011). Sequestering carbon in soils of agro-ecosystems. *Food policy*, 36, S33-S39.
- Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, 7(5), 5875-5895.
- Lal, R., Bouma, J., Brevik, E., Dawson, L., Field, D. J., Glaser, B., & Lascelles, B. (2021). Soils and sustainable development goals of the United Nations: An International Union of Soil Sciences perspective. *Geoderma Regional*, 25, e00398.
- Lal, R., Follett, R. F., Stewart, B. A., & Kimble, J. M. (2007). Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science*, 172(12), 943-956.
- Lal, R., Monger, C., Nave, L., & Smith, P. (2021). The role of soil in regulation

- of climate. *Philosophical Transactions of the Royal Society B*, 376(1834), 20210084.
- Lal, R., Negassa, W., & Lorenz, K. (2015). Carbon sequestration in soil. *Current Opinion in Environmental Sustainability*, 15, 79-86.
- Lal, R., Smith, P., Jungkunst, H. F., Mitsch, W. J., Lehmann, J., Nair, P. R., & Zinn, Y. L. (2018). The carbon sequestration potential of terrestrial ecosystems. *Journal of soil and water conservation*, 73(6), 145A-152A.
- Lavallee, J. M., Soong, J. L., & Cotrufo, M. F. (2020). Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology*, 26(1), 261-273.
- Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Peters, G. P., & Houghton, R. A. (2016). Global carbon budget 2016. *Earth System Science Data*, 8(2), 605-649.
- Lehmann, J., Hansel, C. M., Kaiser, C., Kleber, M., Maher, K., Manzoni, S., Torn, M. S. (2020). Persistence of soil organic carbon caused by functional complexity. *Nature Geoscience*, 13(8), 529-534.
- Liang, Lehmann, Y., Ballhausen, A., Max-Bernhard Muller, Rillig, L., & C. M. (2019). Increasing temperature and microplastic fibers jointly influence soil aggregation by saprobic fungi. *Frontiers in Microbiology*, 10, 2018.
- Mann, L. (1986). Changes in soil carbon storage after cultivation. *Soil Science*, 142(5), 279-288.
- McCarl, B. A., & Schneider, U. A. (2001). Greenhouse gas mitigation in US agriculture and forestry. In (Vol. 294, pp. 2481-2482): American Association for the Advancement of Science.
- McDaniel, M. D., Grandy, A. S., Tiemann, L. K., & Weintraub, M. N. (2014). Crop rotation complexity regulates the decomposition of high and low quality residues. *Soil Biology and Biochemistry*, 78, 243-254.
- Miltner, A., Bombach, P., Schmidt-Brücken, B., & Kästner, M. (2012). SOM genesis: microbial biomass as a significant source. *Biogeochemistry*, 111, 41-55.
- Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., & Das, B. S. (2017). Soil carbon 4 per mille. *Geoderma*, 292, 59-86.
- Mooney, S., Antle, J., Capalbo, S., & Paustian, K. (2004). Design and costs of a measurement protocol for trades in soil carbon credits. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, 52(3), 257-287.
- Moreno, J. L., Bastida, F., Díaz-López, M., Li, Y., Zhou, Y., López-Mondéjar, R., & García-Gil, J. C. (2022). Response of soil chemical properties, enzyme activities and microbial communities to biochar application and climate change in a Mediterranean agroecosystem. *Geoderma*, 407, 115536.
- Nardi, S., Ertani, A., & Francioso, O. (2017). Soil-root cross-talking: The role of humic substances. *Journal of Plant Nutrition and Soil Science*, 180(1), 5-13.
- Nayak, N., Mehrotra, R., & Mehrotra, S. (2022). Carbon biosequestration strategies: A review. *Carbon Capture Science & Technology*, 4, 100065.
- Nazir, M. J., Li, G., Nazir, M. M., Zulfiqar, F., Siddique, K. H., Iqbal, B., & Du, D. (2024). Harnessing soil carbon sequestration to address climate change challenges in agriculture. *Soil and tillage research*, 237, 105959.
- Nguyen, T. T., & Marschner, P. (2016). Soil respiration, microbial biomass and nutrient availability in soil after repeated addition of low and high C/N plant residues. *Biology and fertility of soils*, 52, 165-176.

- O'Rourke, S. M., Angers, D. A., Holden, N. M., & McBratney, A. B. (2015). Soil organic carbon across scales. *Global Change Biology*, 21(10), 3561-3574.
- Ogle, S. M., Breidt, F. J., & Paustian, K. (2005). Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry*, 72, 87-121.
- Olesen, J., Graversgaard, M., Freluh-Larsen, A., Ittner, S., Tarpey, J., Eموke Madari, B., & Swanepoel, C. European Union's Horizon 2020 research and innovation programme grant agreement No 774378-Coordination of *International Research Cooperation on soil Carbon Sequestration in Agriculture*. In.
- Olesen, J., Graversgaard, M., Freluh-Larsen, A., Ittner, S., Tarpey, J., Eموke Madari, B., & Swanepoel, C. (2020). European Union's Horizon 2020 research and innovation programme grant agreement No 774378-Coordination of *International Research Cooperation on soil Carbon Sequestration in Agriculture*. In.
- Ontl, T. A., & Schulte, L. A. (2012). Soil carbon storage. *Nature Education Knowledge*, 3(10).
- Osborne, T., Brock, S., Chazdon, R., Chomba, S., Garen, E., Gutierrez, V., & Sundberg, J. (2021). The political ecology playbook for ecosystem restoration: Principles for effective, equitable, and transformative landscapes. *Global Environmental Change*, 70, 102320.
- Pathak, H. (2023). Impact, adaptation, and mitigation of climate change in Indian agriculture. *Environmental Monitoring and Assessment*, 195(1), 52.
- Pattanayak, S. K., McCarl, B. A., Sommer, A. J., Murray, B. C., Bondelid, T., Gillig, D., & DeAngelo, B. (2005). Water quality co-effects of greenhouse gas mitigation in US agriculture. *Climatic Change*, 71, 341-372.
- Pattnaik, R., Sethi, K., & Das, D. (2020). Soil carbon sequestration through various agronomic practices: A way to mitigate climate change impacts. *Journal of Pharmacognosy and Phytochemistry*, 9(6), 755-761.
- Paul, E. A. (2014). Soil microbiology, ecology, and biochemistry: an exciting present and great future built on basic knowledge and unifying concepts. *Soil microbiology, ecology, and biochemistry*, 1-13.
- Paul, E. A. (2016). The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. *Soil Biology and Biochemistry*, 98, 109-126.
- Pausch, J., & Kuzyakov, Y. (2018). Carbon input by roots into the soil: quantification of rhizodeposition from root to ecosystem scale. *Global Change Biology*, 24(1), 1-12.
- Pellegrini, A. F., Harden, J., Georgiou, K., Hemes, K. S., Malhotra, A., Nolan, C. J., & Jackson, R. B. (2022). Fire effects on the persistence of soil organic matter and long-term carbon storage. *Nature Geoscience*, 15(1), 5-13.
- Pinton, R., Cesco, S., Iacoletti, G., Astolfi, S., & Varanini, Z. (1999). Modulation of NO₃-uptake by water-extractable humic substances: involvement of root plasma membrane H⁺ ATPase. *Plant and soil*, 215, 155-161.
- Plantinga, A. J., & Wu, J. (2003). Co-benefits from carbon sequestration in forests: evaluating reductions in agricultural externalities from an afforestation policy in Wisconsin. *Land Economics*, 79(1), 74-85.
- Pope, J. O., Brown, K., Fung, F., Hanlon, H. M., Neal, R., Palin, E. J., & Reid, A. (2022). Investigation of future climate change over the British Isles using weather patterns. *Climate Dynamics*, 58(9), 2405-2419.
- Post, W. M., Izaurralde, R. C., Jastrow, J. D., McCarl, B. A., Amonette, J. E.,

- Bailey, V. L., & Zhou, J. (2004). Enhancement of carbon sequestration in US soils. *Bioscience*, 54(10), 895-908.
- Post, W. M., & Kwon, K. C. (2000). Soil carbon sequestration and land-use change: processes and potential. *Global Change Biology*, 6(3), 317-327.
- Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A., & Cassman, K. G. (2014). Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change*, 4(8), 678-683.
- Pribyl, D. W. (2010). A critical review of the conventional SOC to SOM conversion factor. *Geoderma*, 156(3-4), 75-83.
- Qiu, J., Shen, Z., & Xie, H. (2023). Drought impacts on hydrology and water quality under climate change. *Science of The Total Environment*, 858, 159854.
- Ramesh, T., Bolan, N. S., Kirkham, M. B., Wijesekara, H., Kanchikerimath, M., Rao, C. S., & Choudhury, B. U. (2019). Soil organic carbon dynamics: Impact of land use changes and management practices: A review. *Advances in agronomy*, 156, 1-107.
- Raza, S., Zamanian, K., Ullah, S., Kuzyakov, Y., Virto, I., & Zhou, J. (2021). Inorganic carbon losses by soil acidification jeopardize global efforts on carbon sequestration and climate change mitigation. *Journal of Cleaner Production*, 315, 128036.
- Robertson, G. P., & Paul, E. A. (2000). Decomposition and soil organic matter dynamics. In *Methods in ecosystem science* (pp. 104-116): Springer.
- Rosenzweig, C., Major, D. C., Demong, K., Stanton, C., Horton, R., & Stults, M. (2007). Managing climate change risks in New York City's water system: assessment and adaptation planning. *Mitigation and Adaptation Strategies for Global Change*, 12, 1391-1409.
- Russel, J. (1929). 3. Organic Matter Problems Under Dryfarming Conditions 1. *Agronomy Journal*, 21(10), 960-969.
- Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the national academy of sciences*, 114(36), 9575-9580.
- Schimel, J. P., & Schaeffer, S. M. (2012). Microbial control over carbon cycling in soil. *Frontiers in Microbiology*, 3, 348.
- Schmidt, M. W., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., & Manning, D. A. (2011). Persistence of soil organic matter as an ecosystem property. *Nature*, 478(7367), 49-56.
- Schwertmann, U. (1991). Solubility and dissolution of iron oxides. *Plant and soil*, 130, 1-25.
- Shaver, T., Peterson, G., Ahuja, L., Westfall, D., Sherrod, L., & Dunn, G. (2002). Surface soil physical properties after twelve years of dryland no-till management. *Soil Science Society of America Journal*, 66(4), 1296-1303.
- Shi, L., Feng, W., Xu, J., & Kuzyakov, Y. (2018). Agroforestry systems: Meta-analysis of soil carbon stocks, sequestration processes, and future potentials. *Land Degradation & Development*, 29(11), 3886-3897.
- Shi, Z., Allison, S. D., He, Y., Levine, P. A., Hoyt, A. M., Beem-Miller, J., & Randerson, J. T. (2020). The age distribution of global soil carbon inferred from radiocarbon measurements. *Nature Geoscience*, 13(8), 555-559.
- Siddique, K. H., Bolan, N., Rehman, A., & Farooq, M. (2024). Enhancing crop productivity for recarbonizing soil. *Soil and tillage research*, 235, 105863.
- Singh, Mandeep, Sarkar, Binoy, Biswas, Bhabananda, & Jock, G. (2017). Relationship between soil clay mineralogy and carbon protection capacity as influenced by temperature

- and moisture. *Soil Biology and Biochemistry*, 109, 95-106.
- Singh, Y., & Sidhu, H. (2014). Management of cereal crop residues for sustainable rice-wheat production system in the Indo-Gangetic plains of India. *Proceedings of the Indian National Science Academy*, 80(1), 95-114.
- Sissoko, A., & Kpombrekou-A, K. (2010). Carbon decomposition in broiler litter-amended soils. *Soil Biology and Biochemistry*, 42(4), 543-550.
- Smith, P. (2005). An overview of the permanence of soil organic carbon stocks: Influence of direct human-induced, indirect and natural effects. *European journal of soil science*, 56(5), 673-680.
- Smith, P. (2008). Land use change and soil organic carbon dynamics. *Nutrient Cycling in Agroecosystems*, 81, 169-178.
- Smith, P. (2012). Soils and climate change. *Current Opinion in Environmental Sustainability*, 4(5), 539-544.
- Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., & Jafari, M. (2014). Agriculture, forestry and other land use (AFOLU). In *Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 811-922): Cambridge University Press.
- Smith, P., Cotrufo, M., Rumpel, C., Paustian, K., Kuikman, P., Elliott, J., & Bustamante, M. (2015). Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. *Soil*, 1(2), 665-685.
- Smith, P., Powlson, D. S., Glendining, M. J., & Smith, J. U. (1998). Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming. *Global Change Biology*, 4(6), 679-685.
- Song, B., Almatrafi, E., Tan, X., Luo, S., Xiong, W., Zhou, C., & Zeng, G. (2022). Biochar-based agricultural soil management: An application-dependent strategy for contributing to carbon neutrality. *Renewable and sustainable energy reviews*, 164, 112529.
- Sovacool, B. K., Griffiths, S., Kim, J., & Bazilian, M. (2021). Climate change and industrial F-gases: A critical and systematic review of developments, sociotechnical systems and policy options for reducing synthetic greenhouse gas emissions. *Renewable and sustainable energy reviews*, 141, 110759.
- Stockmann, U., Adams, M. A., Crawford, J. W., Field, D. J., Henakaarchchi, N., Jenkins, M., & Singh, K. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, ecosystems & environment*, 164, 80-99.
- Sun, J., Peng, H., Chen, J., Wang, X., Wei, M., Li, W., & Mellouki, A. (2016). An estimation of CO₂ emission via agricultural crop residue open field burning in China from 1996 to 2013. *Journal of Cleaner Production*, 112, 2625-2631.
- Swamy, S., & Puri, S. (2005). Biomass production and C-sequestration of *Gmelina arborea* in plantation and agroforestry system in India. *Agroforestry systems*, 64, 181-195.
- Sykes, A. J., Macleod, M., Eory, V., Rees, R. M., Payen, F., Myrriotis, V., & Moran, D. (2020). Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. *Global Change Biology*, 26(3), 1085-1108.
- Thangarajan, R., Bolan, N. S., Tian, G., Naidu, R., & Kunhikrishnan, A. (2013). Role of organic amendment application on greenhouse gas emission from soil.

- Science of The Total Environment*, 465, 72-96.
- Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the national academy of sciences*, 108(50), 20260-20264.
- Tinker, P. B., & Nye, P. H. (2000). *Solute movement in the rhizosphere*: Oxford University Press.
- Trevisan, S., Pizzeghello, D., Ruperti, B., Francioso, O., Sassi, A., Palme, K., & Nardi, S. (2010). Humic substances induce lateral root formation and expression of the early auxin-responsive IAA19 gene and DR5 synthetic element in Arabidopsis. *Plant Biology*, 12(4), 604-614.
- Urrutia, O., Fuentes, M., Olaetxea, M., Garnica, M., Baigorri, R., Movila, M., & Garcia-Mina, J. (2020). The effect of soil organic matter on plant mineral nutrition. In *Achieving sustainable crop nutrition* (pp. 291-306): Burleigh Dodds Science Publishing.
- Valkama, E., Kunyapiyeva, G., Zhapayev, R., Karabayev, M., Zhusupbekov, E., Perego, A., & Grignani, C. (2020). Can conservation agriculture increase soil carbon sequestration? A modelling approach. *Geoderma*, 369, 114298.
- Venkatesh, M. S., Hazra, K. K., Ghosh, P. K., Praharaj, C. S., & Kumar, N. (2013). Long-term effect of pulses and nutrient management on soil carbon sequestration in Indo-Gangetic plains of India. *Canadian Journal of Soil Science*, 93(1), 127-136.
- Viscarra Rossel, R. A., Lee, J., Behrens, T., Luo, Z., Baldock, J., & Richards, A. (2019). Continental-scale soil carbon composition and vulnerability modulated by regional environmental controls. *Nature Geoscience*, 12(7), 547-552.
- Wang, Y., Tao, F., Chen, Y., & Yin, L. (2022). Interactive impacts of climate change and agricultural management on soil organic carbon sequestration potential of cropland in China over the coming decades. *Science of The Total Environment*, 817, 153018.
- Wiesmeier, M., Urbanski, L., Hobbey, E., Lang, B., von Lützow, M., Marin-Spiotta, E., & Garcia-Franco, N. (2019). Soil organic carbon storage as a key function of soils-A review of drivers and indicators at various scales. *Geoderma*, 333, 149-162.
- Wreford, A., Ignaciuk, A., & Gruère, G. (2017). Overcoming barriers to the adoption of climate-friendly practices in agriculture.
- Yadav, R., Purakayastha, T., Khan, M., & Kaushik, S. (2017). Long-term impact of manuring and fertilization on enrichment, stability and quality of organic carbon in Inceptisol under two potato-based cropping systems. *Science of The Total Environment*, 609, 1535-1543.
- Yu, K. L., Show, P. L., Ong, H. C., Ling, T. C., Chen, W. H., & Salleh, M. A. M. (2018). Biochar production from microalgae cultivation through pyrolysis as a sustainable carbon sequestration and biorefinery approach. *Clean Technologies and Environmental Policy*, 20, 2047-2055.
- Zandalinas, S. I., Balfagón, D., Gómez-Cadenas, A., & Mittler, R. (2022). Plant responses to climate change: metabolic changes under combined abiotic stresses. *Journal of Experimental Botany*, 73(11), 3339-3354.
- Zandonadi, D. B., Canellas, L. P., & Façanha, A. R. (2007). Indolacetic and humic acids induce lateral root development through a concerted plasmalemma and tonoplast H⁺ pumps activation. *Planta*, 225, 1583-1595.
- Zandonadi, D. B., Santos, M. P., Dobbss, L. B., Olivares, F. L., Canellas, L. P., Binzel, M. L., & Façanha, A. R. (2010). Nitric oxide mediates humic

Ahmad et al.	Emrg. Trnd. Clim. Chng. (2024) 3(1), 1-26	ISSN: 2583 – 4770
acids-induced root development and plasma membrane H⁺-ATPase activation. <i>Planta</i>, 231, 1025-1036. Zhang, Han, X., Xiaozeng, Y. U., Wang, W., Cheng, P., & Weixin. (2017). Priming effects on labile and stable soil organic carbon decomposition: Pulse dynamics over two years. <i>PloS one</i>, 12(9), e0184978.		Zhang, Y., Lavallee, J. M., Robertson, A. D., Even, R., Ogle, S. M., Paustian, K., & Cotrufo, M. F. (2021). Simulating measurable ecosystem carbon and nitrogen dynamics with the mechanistically defined MEMS 2.0 model. <i>Biogeosciences</i>, 18(10), 3147-3171.