BioThink E – Magazine, Vol. -2, Issue -4, October 2025
ISSN No. – 3048- 7943
www.biothink.in

Soil Carbon Sequestration to Mitigate Climate Change and Enhance Food Security

[1]**Varun Parmar**✉, [1]Rushali Katoch, [2]NK Sankhyan

Department of Soil Science, CSK HPKV, Palampur

[2]Principal Scientist, Soil Science and Registrar, Central University of Himachal Pradesh

✉ v.parmar21505@gmail.com DOI : 10.5281/zenodo.17332319

Abstract

Climate change, driven largely by greenhouse gases (GHGs), poses severe risks to agriculture and food security. Carbon dioxide (CO_2) alone contributes over 80% of global warming, with impacts including glacier retreat, sea-level rise, extreme weather and soil degradation. Soils are the largest terrestrial carbon reservoir, storing ~2,500 Gt of carbon, yet unsustainable land use has depleted it over 50 Gt historically thereby, affecting soil health and productivity. Soil carbon sequestration (SCS), which involve the capture of atmospheric CO_2 through plants and its storage in soils, offers a cost-effective strategy to mitigate climate change while enhancing soil fertility and crop productivity. Agricultural soils can potentially offset 0.4–1.2 Gt C annually. Practices such as residue retention, reduced tillage, crop diversification, biochar application, agroforestry, and balanced nutrient management are most effective when performed in an integrated manner. Embedded in climate-smart agriculture, SCS can simultaneously mitigate GHGs, improve resilience, and ensure food security.

Keywords: carbon sequestration, soil organic carbon, climate change, food security, sustainable agriculture and agro-ecosystem management

Introduction

The 21st century will be remembered as the era when the realities of climate change became impossible to ignore. Each day brings reports of extreme weather events somewhere on the planet be it wildfires in Australia, hurricanes in the United States or prolonged droughts in sub-Saharan Africa. Scientists now describe this period as the Anthropocene Epoch, a geological era defined by the profound impact of human activity on Earth's climate and ecosystems. This epoch is marked not only by rising global temperatures but also by the increasing frequency and severity of climate extremes.

From a broader perspective, the drivers of this crisis are greenhouse gases (GHGs), particularly CO_2, CH_4, and N_2O with CO_2 alone contributing nearly 82% (Figure 1) of global warming (Montzka et al., 2011). Current atmospheric CO_2 levels, now exceeding 412 ppm compared to pre-industrial of around 280 ppm (IPCC, 2013), underscore the scale of the challenge. Consequences such as glacier retreat, extreme weather phenomenon, seal level rise and agricultural disruptions are already evident, with profound implications for food security in vulnerable regions like South Asia (Bhattacharya, 2019).

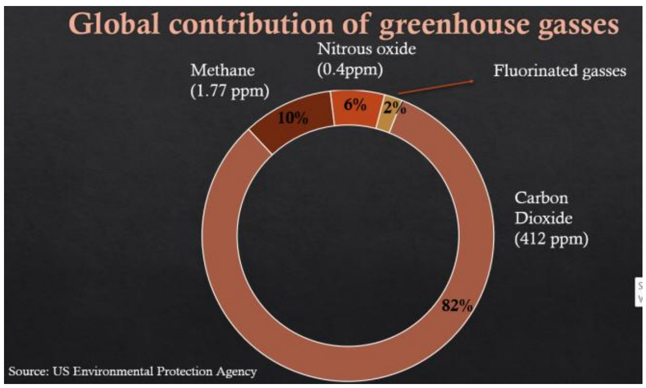

Figure 1. Relative contributions of greenhouse gases to global warming

Ensuring food security for a global population which is projected to reach 9 billion, including 1.7 billion in India by 2050 (United Nations, 2017), will require agriculture that is both productive and climate-resilient. This challenge is compounded by projections of a 70–100% increase in food demand alongside intensifying competition for land, water and energy.

Against this backdrop, soil carbon sequestration (SCS) emerges as a pivotal strategy. Through improved agricultural management, soils can act as a carbon sink, simultaneously mitigating greenhouse gas concentrations and enhancing soil fertility, productivity and resilience (Lal, 2004 2008). This article evaluates the potential of SCS practices in strengthening both climate mitigation and food security.

Global Carbon cycle

Carbon is constantly cycling between different global carbon pools as it changes molecular forms. Photosynthesis and the subsequent use of its by-products by other organisms, cycles carbon between the atmosphere into forests, soils and oceans (Figure 2). While human energy consumption cycles carbon from fossil fuel pools to the atmosphere. As carbon flows between them, each of these different pools has the capacity to be either a source or a sink. Carbon sinks are pools that accumulate more carbon than they release, while carbon sources release more carbon than they accumulate. Currently the atmosphere and ocean have too much carbon while soils have lost carbon at an alarming rate due to development, conversion of native grasslands and forests to cropland and agricultural practices that decrease soil organic matter. Oceans and aquatic systems are by far the largest sink to atmospheric carbon at an estimated capacity of 38,000 gigatons (Gt) and vegetation is the smallest of the pools at an estimated 650 Gt. Soil is about four times the size of the vegetation pool at an estimated 2500 Gt, making it the largest terrestrial pool of carbon (Batjes 1996). The global soil carbon pool of 2500 gigatons (Gt) includes about 1550 Gt of soil organic carbon (SOC) and 950 Gt of soil inorganic carbon (SIC). The soil C pool is 3.3 times the size of the atmospheric pool (760 Gt) and 4.5 times the size of the biotic pool (560 Gt). Severe depletion of the SOC pool degrades soil quality, reduces biomass productivity, and adversely impacts water quality, and the depletion may be exacerbated by projected global warming.

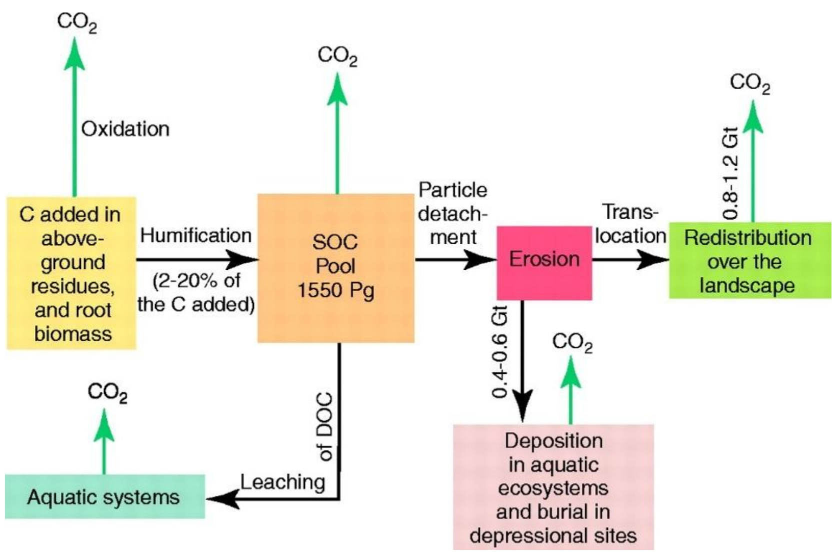

Figure 2. Schematic representation of soil organic carbon (SOC) cycle through various pathways

Impact of Climate change on agriculture

The agriculture sector both contributes to climate change, as well as is greatly affected by it. Agriculture and the changes in land-use that are associated with it, are one of the principal contributors to climate change, accounting for one-third of global greenhouse gas emissions. The impact and consequences of climate change for agriculture tend to be more severe for countries with higher initial temperatures, areas with marginal or already degraded lands and lower levels of development with little adaptation capacity.

Climate change could influence agricultural production adversely due to resulting:

- Geographical shifts and yield changes in agriculture,
- Reduction in the quantity of water available for irrigation and
- Loss of land through sea level rise and associated salinization.

The yields of different crops may be altered by changes in soil moisture, temperature, precipitation, cloud cover as well as increases in CO_2 concentrations. Low rainfall and high temperature could reduce soil moisture in many areas, particularly in some tropical regions, reducing the available water for irrigation and impairing crop growth in dryland areas. The changes in soil properties such as the loss of soil organic matter, leaching of soil nutrients, salinization and erosion are a likely consequence of climate change for some soils in some climatic zones. The summer monsoon is predicted to become stronger and move north-westward. However, this increased rain could be beneficial to some areas. The risk of losses due to weeds, insects and diseases is likely to increase. The range of many insects will change or expand and new combinations of diseases and pests may emerge as natural ecosystems respond to shifts in temperature and precipitation profiles. Winter mortality of adults of *Nezara viridula* and *Halyomorpha halys* is predicted to be reduced by 15% by each rise of 1°C temperature. In *Chilo suppressalis* two generation per year after 2°C warming has been observed (Kiritani 2006). The effect of climate on pests may add to the effect of other factors such as the overuse of pesticides and the loss of biodiversity, which already contribute to plant pest and disease outbreaks. Agriculture in low-lying coastal areas or adjacent to river deltas may be affected by a rise in sea level. Flooding will probably become a significant problem in some already flood-prone regions of South-East Asia. According to IPCC, a 1 m rise in sea level has been predicted by the end of century. By 2050 36 million Indian could lose their home by flooding due to rise in sea level and the impact will be concentrated on areas of coastal Gujarat, Mumbai, coastal areas of Karnataka and Kerela, Chennai, Kochi, Kolkata entire Oddisha coast. Decrease in productivity is most likely prevalent in those regions, which are already flood-insecure. In addition, extreme climatic events such as changes in rainfall and temperature could be damaging and prove to be costly to agriculture.

What is soil carbon ?

Although some soil carbon comes from mineral sources, the vast majority of it is derived from plants and animals. As theyt grow and die, they leave behind organic, carbon-based compounds in the soil of varying size and chemical composition. Under the right conditions, soil fauna metabolize these compounds, incorporating some of the carbon in them into new chemical compounds within their own biomass, while respiring the rest to the atmosphere as CO_2 or excreting it back into the soil. This continuous movement of carbon through the soil food web means that carbon is constantly changing forms in the soil as it is incorporated into new organisms or converted into different compounds. Soil scientists classify carbon into general categories or pools based on how long the carbon remains in the soil, a figure often referred to as "mean residence time." The most commonly used model of these pools includes three different groupings: the fast or labile pool, the slow pool, and the stable pool. The fast pool is soil carbon that turns over and returns to the atmosphere sometimes within a few days to a few years. Carbon in this pool is typically composed of recently incorporated plant residues and simple carbon compounds that are exuded by roots. This labile pool is the one most readily used by soil microbes, meaning it generates a great deal of CO2. The slow pool is composed of more processed plant residues, microbial by-products of the fast pool, and carbon molecules that are protected from microbes by physical or biochemical soil processes. Mean residence time of the slow pool is generally considered to be in the range of years to decades, but this range can be heavily influenced by soil texture, management, and climate. In contrast, the stable pool is most resistant to disturbances and is extremely slow to change, with mean residence times ranging from centuries to millennia. This pool is comprised of what is often called humus, a loose term for a group of carbon compounds that are extremely resistant to decomposition, and soil carbon that is very well protected from microbial decomposition (Six et al., 2002). The relative size of each of these pools can vary in different soils. But in general, the size of the stable pool remains relatively constant, while the sizes of the labile and slow pools are sensitive to management.

Soil carbon sequestration

Soil carbon sequestration is the process by which atmospheric carbon dioxide is taken up by plants through photosynthesis and stored as carbon in biomass and soils. It involves replenishing lost carbon and adding new carbon. Historically, agricultural soils have lost more than 50 Gt (1 Gt = 1 billion tons) of carbon. Some of this carbon, however, can be recaptured through sustainable land management practices. For instance, the use of crop residues as mulch, intercropping food crops with trees and integrated nutrient and water management also sequester carbon in the soil (Table 1). By adopting improved land management practices to increase soil carbon, farmers can increase crop yields, reduce rural poverty, limit GHG concentrations in the atmosphere and reduce the impact of climate change on agricultural ecosystems.

Conclusion

Climate change represents profound challenges for agriculture but it also offers opportunities to innovate management practices that safeguard both environment and food security. Among various mitigation strategies, SCS stand out as a practical and cost-effective approach. Agricultural soils have the capacity to offset large amount of C annually thereby, making them a significant sink for atmospheric CO_2. Beyond mitigation, enhanced SOC improves fertility, resilience and long-term productivity thereby directly contributing to food security. However, no single management practice can achieve substantial sequestration in isolation. Maximum benefit will arise from integrating various approaches. Critical challenges in terms of residue competition, limited organic resources violability, adoption barriers and the need for supportive policies. Addressing these requires a prolonged strategy, farmer awareness, economic incentives for carbon enriching practices and robust monitoring frameworks to verify SOC gains. All in all, SCS is not a stand-alone solution but a pivotal component of climate smart agriculture. When embedded in broader policies for sustainable land use, it can simultaneously mitigate climate change, enhance soil health and ensure food security.

Table 1: Carbon sequestration practices in croplands

Practice	Description	References	Critical Insight
Nutrient Management	Integration of organic manures (e.g., FYM) with inorganic fertilizers enriches SOC and sustains yields.	Brar et al. (2015): SOC rose from 7.3 Mg/ha (control) to 11.6 Mg/ha with 100% NPK + FYM in 36-year maize–wheat.	INM is most reliable for SOC buildup, but adoption is limited by scarcity of organic resources.
Mulch & Residue Management	Retaining crop residues and mulching improve soil cover, microbial activity, and aggregate stability, boosting SOC.	Zhu et al. (2014): Straw return increased SOC and labile C fractions in rice–wheat. Zhao et al. (2018): 12.3% SOC increase after 7 years of straw incorporation in maize–wheat.	Proven SOC enhancer, but residues in South Asia often diverted for fodder/fuel, limiting adoption.
Reduced Tillage	Conservation tillage reduces disturbance and slows decomposition, improving SOC stabilization in surface layers.	Campbell et al. (2005): Reduced tillage sequestered ~0.25 Mg C/ha/yr in Great Plains. Sainju et al. (2006): Higher SOC under mulch tillage vs. conventional after 10 years.	Effective for surface SOC, but deeper soil benefits inconsistent, especially in coarse soils.
Crop Rotation	Diverse rotations with legumes/high-residue crops increase SOC via higher biomass inputs and microbial diversity.	Parmar & Thakur (2017): Organic cauliflower–pea system had max SOC stock (18.9 t/ha/yr).	Enhances SOC and yields, but monocultures driven by markets reduce rotation diversity.
Biochar	Stable carbon-rich product from biomass pyrolysis; resists decomposition, enhances SOC, reduces CH_4 and N_2O.	Feng et al. (2011): Biochar reduced methane emissions from paddy fields.	Strong potential for climate-smart agriculture, but high costs and site-specific responses limit adoption.

References

Batjes N.H. 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*. 47: 151–163

Bhattacharya A. 2019. NE glaciers may vanish by 2100 if warming unchanged-a study. *Times of India.* 11 February

Brar BS, Singh J, Singh G and Kaur G. 2015. Effects of Long-Term Application of Inorganic and Organic Fertilizers on Soil Organic Carbon and Physical Properties in Maize–Wheat Rotation. *Agronomy*. 5, 220-238

Campbell CA, Janzen HH, Paustian K, Gregorich EG, Sherrod L, Liang BC and Zentner RP. 2005. Carbon-Storage in Soils of the North American Great Plains:Effect of Cropping Frequency. *Agronomy*. 97: 349–363

Feng Y, Xu Y, Yu Y, Xie Z, and Lin X. 2011. Mechanisms of biochar decreasing methane emissions from Chinese paddy soils. *Soil Biology and Biochemistry*. 46: 80-88

Gupta N, Kukal S, Bawa SS and Dhaliwal. 2009. Soil organic carbon and aggregation under poplar-based agroforestry systems in relation to tree age and soil type. Agroforestry Systems. 76: 27-35

IPCC. 2013. Climate Change 2013-The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers. WMO-UNEP. Geneva

Kiritani K. 2006. Predicting impacts of global warming on population dynamics and distribution of arthropods in Japan. *Population Ecology*. 48: 5–12

Lal R. 2008. Carbon Sequestration. *Philosophical Transactions of the Royal Society*. 363: 815-830

Montzka S A, Dlugokencky E J and Butler J H. 2011. Non-CO_2 greenhouse gases and climate change. *Nature.* 476*:* 43–50

Parmar DK and Thakur DR. 2017. Improvement in soil physical, chemical and microbiological properties during cropping cycles under different nutrient management in Western Himalayas. *International Journal of Current Microbiology and Applied Science*. 6 (6): 487-496

Sainju UM, Singh BP, Whitehead WF and Wang S. 2006. Carbon supply and storage in tilled and non-tilled soils as influenced by cover crops and nitrogen fertilization. *Journal of Environmental Quality.* 35: 1507–1517

Six J, Conant R, Paul E and Paustian K. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant and Soil 241(2): 155–176

United Nations, Department of Economic and Social Affairs, Population Division. 2017. World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP/248. New York. United Nations

Zhaoa H, Shara AG, Lia S, Chena Y, Shia J, Zhanga X and Tiana X. 2018. Effect of straw return mode on soil aggregation and aggregate carbon content in an annual maize-wheat double cropping system. *Soil & Tillage Research* 175: 178-186

Zhu L, Hu N, Yang M, Zhan X and Zhang Z. 2014. Effects of Different Tillage and Straw Return on Soil Organic Carbon in a Rice-Wheat Rotation System**.** *PLoS ONE*. 9(2): e88900