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# 5. Different Approaches of Carbon Sequestration

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***Abstract:***

*The chapter "Different Approaches of Carbon Sequestration" delves into the various methodologies employed to mitigate atmospheric carbon dioxide levels through sequestration practices. It provides an in-depth analysis of both natural and engineered techniques, including afforestation, reforestation, soil carbon enhancement, biochar application, and carbon capture and storage (CCS). Emphasizing the ecological and technological perspectives, the chapter evaluates the efficacy, scalability, and potential environmental impacts of each approach. Case studies and empirical data illustrate successful implementations and the challenges faced in diverse geographical contexts. By integrating interdisciplinary research and innovative strategies, this chapter offers a comprehensive overview of carbon sequestration as a critical tool in combating climate change and achieving long-term sustainability goals.*

***Keywords:***

*Carbon Sequestration, Afforestation, Reforestation, Soil Carbon, Biochar, Carbon Capture and Storage, Climate Change Mitigation, Sustainability, Environmental Impact and Policy Frameworks.*

## 5.1 Introduction:

Carbon sequestration refers to the process of capturing, removal, and long-term storing of atmospheric carbon dioxide and preventing its release to mitigate the contribution to global warming and climate change. It is the key method for removing of carbon from the atmosphere. Carbon can be stored in various natural reservoirs such as plant, soils, geologic formation, and the oceans (Selin, 2023).

Global warming and climate change impact most of the ecosystems of the Earth. According to the NOAA Climate.gov report, global average surface temperature is increased by $1.18^0$ C from 1880 to 2023. The melting of polar ice and glaciers has caused global sea-levels to increase by around 20 cm over the previous 170 years. Since the early 21st century, the pace of sea-level rise has been approximately 0.8 mm per year, increasing with each decade.

In response to growing interest about climate change resulted by rising carbon dioxide concentrations in the atmosphere, considerable interest has been shown in the possibility of speeding up carbon sequestration through different approaches discussed below.

## 5.2 Carbon Sequestration and Climate Change Mitigation:

The Kyoto Protocol, an approach under the United Nations Framework Convention on Climate Change, authorizes countries to receive carbon credits for carbon-sequestration activities in the areas of land use, land-use change, and forestry as part of their responsibilities under the protocol (Britannica, 2024). Afforestation, reforestation, improved forestry or agricultural practices, and revegetation are the common activities for carbon sequestration. According to the Intergovernmental Panel on Climate Change (IPCC), forest-related mitigation activities and improved agricultural practices can make a significant contribution to the removal of carbon dioxide from the atmosphere at relatively low cost. This includes some sustainable activities like improved crop and grazing land management, increasing fertilizer use efficiency, conservation tillage practices, degraded land restoration, and existing forest preservation, which helps in the sequestration of carbon in those key terrestrial sinks.

### 5.2.1 Sequestration Approaches:

Carbon sequestration encompasses a range of approaches aimed at removing carbon dioxide ($CO_2$) from the atmosphere and securely storing it to mitigate climate change. These approaches include biological methods like afforestation, sustainable agriculture practices, and ocean fertilization that enhance natural carbon sinks; geological techniques like carbon capture and storage (CCS) from industrial sources and direct air capture (DAC) followed by underground storage; chemical processes that convert $CO_2$ into stable minerals or useful products; and ocean storage by injecting $CO_2$ into deep waters. Moreover, climate-smart agriculture (such as biochar amendments, cover crops, and conservation tillage) have shown to be successful in raising soil organic carbon sequestration and lowering greenhouse gas emissions. Each method has its own merits, challenges, and potential impacts, with ongoing research efforts focused on improving their efficiency, cost-effectiveness, and scalability to contribute to global efforts in reducing greenhouse gas emissions and combating climate change.

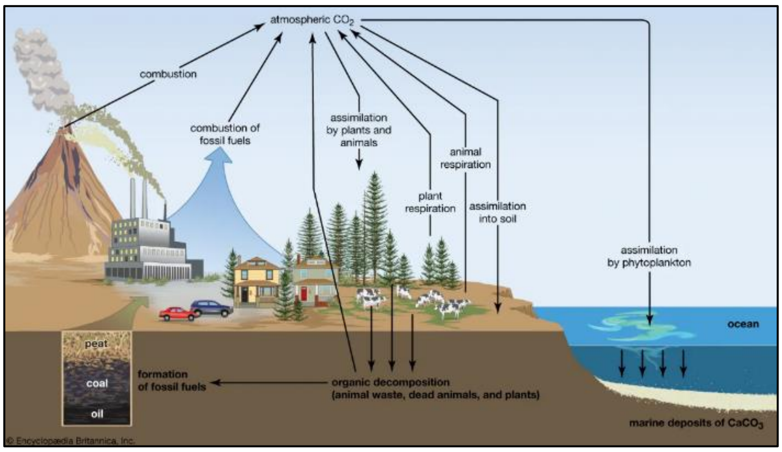


**Figure 5.1: Carbon Sequestration (Image source: carbon sequestration, Encyclopedia Britannica, 2024.**

### 5.2.2 Terrestrial Sequestration:

Terrestrial sequestration is a process that captures and stores carbon dioxide ($CO_2$) in vegetation and soil within a few feet of the Earth's surface, providing them with the components they need to live and grow and reducing $CO_2$ in the atmosphere. During photosynthesis, carbon from atmospheric carbon dioxide is transformed into components necessary for plants to live and grow. As part of this process, the carbon present in the atmosphere as carbon dioxide becomes part of the plant in a leaf, stem, or roots, and the carbon is sequestered for a long period of time. Once the plant dies, or as limbs, leaves, seeds, or blossoms drop from the plant, the plant material decomposes and the carbon is released. Trees are valuable as greater amounts of carbon are tied up for longer time periods.

Terrestrial ecosystems, comprising vegetation and soil in uplands and wetlands, significantly impact the global carbon (C) cycle and, under natural conditions, are a sink of atmospheric carbon dioxide ($CO_2$) and methane ($CH_4$). However, conversion of natural to managed ecosystems (i.e., agroecosystems, urban lands, and mined lands) depletes ecosystem C stocks, aggravates gaseous emissions, and exacerbates radiative forcing.

Therefore, these sinks most likely became sources of greenhouse gases (GHGs) (Ruddiman, 2003), primarily $CO_2$, $CH_4$, and $N_2O$, when agriculture began to spread approximately 8000 BC, depleting the terrestrial (soil, vegetation, and peatlands) carbon stocks. A voluntary "4 Per Thousand" (4PT) strategy to trap carbon in global soils at a rate of 0.4% annually to 0.4 m (1.3 ft) depth was proposed by the Paris Climate Agreement (UNFCC, 2015). Since then, there has been a rise in national, regional, and worldwide interest in low-carbon agriculture (Nayak et al., 2022)

## 5.3 Conventional Approach to Sequester Carbon in Soil:

Conventional methods of storing carbon in soil mostly consist of improved land management and agricultural approaches meant to raise the content of organic matter and boost carbon storage in soils.

### 5.3.1 Conservation Tillage:

Tillage is generally used for crop residue management and better seed bed preparation for crops. It is the main source of soil disturbance in annual crop fields. It loosens the soil, increasing the exposure of soil organic matter and induce oxidization. The organic matter content of soil is reduced with the release of $CO_2$ into the atmosphere. Farmers in recent decades use advanced tillage technologies and agronomic practices to reduce tillage frequency and intensity. Sometimes they also practice no-till cropping (Paustian *et al*. 2019). Tillage is responsible for breakdown of stable soil aggregates that can protect organic matter from decomposition (Six *et al*., 2002). The aggregation and aggregate stability of soil are significantly enhanced by no tillage practices. Aggregation of soil with organic carbon is believed to be the main factor responsible for increased carbon storage under no-tillage practices (Six and Paustian, 2014). Research conducted by Alhassan and his coworkers, represented that conservation tillage practices especially no-tillage along with straw mulch application improved soil water content as well as reduced soil temperature.

Conservation tillage practices also improved soil organic carbon and total nitrogen content especially within the soil layer between 0–20 cm. This practices further reduced net $CO_2$ flux and increased $CH_4$ absorption but less influenced $N_2O$ emissions in the dryland ecosystem (Alhassan *et al*., 2021).

## 5.4 Improved Crop Rotations and Cover Cropping:

Farmers may adopt several cropping practices that helps in increasing different form of carbon into soils. Cover crops/green manure, continuous cropping (reducing fallow land habit), planting of high-residue bearing crops, perennial grasses are the common practices done by farmers (CAST, 2004). A global review of cover crops reported a mean annual sequestration rate of 0.32 t C/ha/year, with several studies reporting rates higher than 1 t C/ha/year (Poeplau and, Don, 2015). Intensifying and diversifying crop rotations can increase average annual carbon inputs, leading to higher soil carbon stocks than high fallow frequency systems. In moister environments, perennial hay/forage crops to row crop rotations for 2-3 years enhances carbon inputs and increases organic carbon stocks of soil (Dick *et al*., 1998). A six-year field experiment conducted in the Plain of North China, demonstrating the benefits of diversifying rotation of traditional cereal monoculture (wheat–maize) with cash crops (sweet potato) and legumes (peanut and soybean). The rotations increase up to 38% of equivalent yield, 39% reduction of $N_2O$ emission, and 88% improvement of the greenhouse gas balance of the system. Legumes in crop rotations enhanced soil microbial activities, increased 8% soil organic carbon stocks, and improved soil health by 45% (Yang *et al*., 2024).

## A. Organic Amendments:

Organic matter is one of the key components of soil that significantly affects its physical, chemical, and biological properties. Soil organic matter (SOM) helps in improvement of soil health through increased retention of water and nutrients for better productivity of plants. SOM also improves soil structure and reduces erosion, improves the quality of groundwater and surface waters. Organic matter such as compost and manures addition can increase soil carbon contents, both by adding carbon content in the amendment itself and through improving soil physical, chemical, and biological health and nutrient availability for better plant productivity and increasing residue carbon inputs. Organic matter is readily decomposable carbon sources for soil microorganisms, promoting the formation of stable organic matter fractions and long-term carbon storage. Scientist Brenzinger and his coworkers reported that the combination of compost with any nutrient rich organic amendment (sewage sludge, digestate) helps in maintaining crop yield and reducing GHG emissions. They also observed a strong increase in microbial communities involved in GHG consumption (Brenzinger *et al*., 2018).

## B. Agroforestry:

Agroforestry is a useful and sustainable approach of carbon storage in mitigation of climate change. Agroforestry is a sustainable land use management which combines the cultivation of trees (perennial) with crops (annual) and/or livestock. It has various environmental, social, and economic benefits.

The perennial trees in agroforestry helps in carbon sinks They absorb $CO_2$ through photosynthesis and store it in their biomass as well as in the soil. Agroforestry system contributes to carbon sequestration through adding of tree biomass to the soil, storing of below-ground carbon through deep root system, releasing of litter and mulch, and there all possible interactions even with livestock.

## C. Biochar:

Intensive agriculture has many negative effects on environment. It has negative impact on soil (soil compaction, reduced root penetration, demand for fertilizer increased, reduced nutrient uptake efficiency etc.), impact on water (reduced water and nutrient holding capacity) and also impact on biodiversity (reduced nutrient mineralization, reduced micro/macro faunal activity). About $2/3^{rd}$ of total residue (683 million tons) produced in India every year contributed by only cereals (Jain *et al*., 2018; Datta *et al*., 2020). Various sectors like industrial, domestic and as livestock fodder recycle around 500 million tons of residue. There is still an excess of 178 million tons of residue which is left without any single use (MoA and FW, 2019). Farmers face many management challenges with surplus crop residues due to increased operating cost for crop residues incorporation into the soil. There is a short time span between harvesting and sowing of succeeding crop.

As a result, farmers in India mostly adopting the practice of burning leftovers as it is cheapest and traditional practice. An amount of 87 million tons leftovers is burned out of 178 million tons every year (Datta *et al*., 2020). This procedure results in the release of greenhouse gases, and the heat generated by burning raises the temperature of the soil, killing out beneficial microbes. In addition, it emits hazardous particles that have a negative impact on human health. Production of biochar from excess crop biomass is one of the best ways to deal with those issues in a sustainable manner and reduce greenhouse gas emission from atmosphere. Biochar has the potential to be a sustainable method that enhances plant growth and soil quality. Biochar application has the capacity to overcome nutrient deficiency of the soil (Sameera *et al*.,2021).

Biochar is a fine-grained, carbon-rich, porous product. Biochar is produced when plant biomass is exposed to a thermochemical conversion process (pyrolysis) at temperatures ≈ 350-600°C in an oxygen-poor or oxygen-free atmosphere (Amonette and Joseph, 2009). It retains around 50% of the initial carbon whereas only about 3% and 10-20% carbon retains by burning or decomposition respectively (El- Naggar *et al*., 2018b). Thus, biochar performs both as source and sink of carbon in the soil. Recent studies showed that the use of biochar in paddy soil has the capability to minimize the $CH_4$ emission, but its essential mechanism has yet to be clarified. The ratios of Gram-positive/Gram-negative bacteria in the soil was enhanced by biochar application. These bacteria help in increasing $CO_2$ fluxes from soil organic carbon decomposition (Mitchell *et al*.,2015). Higher $CH_4$ consumption was seen after additions of biochar to the agriculture soil as it improves soil aeration and porosity and also enhances the performance of methanotrophs (Singh *et al*.,2017). There is a growing interest to increase the efficiency of biochar by altering production strategies and its modification. Different factors like type of activator, soaking time, activation time, activation temperature etc. affect the properties of biochar significantly. Some research resulted that addition of $H_3PO_4$ to rice straw biochar significantly enhanced surface area which can accumulate more soil organic carbon (Chen *et al*., 2018).

The reaction of $HNO_3$ with wheat straw biochar improved the presence of surface $COO^-$ group which would increase the negative surface charge of soil particles (Jin *et al*., 2018).

Longer term biochar field experiments are needed to monitor the effect of biochar on soil $CH_4$ emissions/consumptions after rainfall or N fertilization events and estimate its climate mitigation potential with taking measurements from the day of biochar application. Future studies should investigate whether biochar applications can affect the N use efficiency of paddy agriculture and population dynamics of methanogens/methanotrophs. The ability of biochar for increasing soil organic carbon is limited to small scale green house and laboratory conditions. In a time period of up-to 10 years biochar exhibits lower responses on field scale (Gross *et al*., 2021). Currently, it is difficult to evaluate the mitigation capacity of biochar and uncertain whether it is economically feasible to apply biochar on a large scale that affect carbon sequestration in biochar amendment.

## D. Afforestation:

In order to meet the goal of Paris Agreement to limit global warming to 1.5°C over pre-industrial levels, it will be necessary to quickly adopt negative emissions technology, especially expanding forest carbon sinks (Masson-Delmotte, V. *et al.*,2019). Currently, the world's forests stores almost a trillion tons of carbon dioxide ($CO_2$). It appears that trees are sequestering an extra 4 billion tons of $CO_2$ annually (Mendelsohn *et al*., 2012).

Afforestation has increased the area of planted forests by approximately $1.05 \times 10^8$ ha since the 1990s (FAO, 2016). However, the area and carbon sequestration potential of each afforestation will determine if mitigation goals can be met through afforestation. It was discovered that broad-leaved deciduous woods sequester more carbon than coniferous forests, and that moist cold temperatures sequester more carbon than moist warm climates. A forest's age less than 20 years significantly enhanced its SOC content in the top 0–20 cm of soil, whereas a forest's age more than 20 years boosted SOC content down to 100 cm of soil. (Deng *et al.*, 2017; Guo *et al*., 2021; Shi *et al*., 2016). However, little is known about how afforestation affects the dynamics of soil carbon. Based on variables like tree species, land-use history, stand age, climate, and soil type, it has been proposed that SOC stocks may rise, fall, or stay the same during afforestation (Shi *et al*., 2013; Don *et al*., 2011). Compared to crops or grassland, afforestation on barren land with low initial SOC stock has a higher potential to perform as a carbon sink. Instead, afforestation on land with a higher starting stock of soil organic carbon results in an initial loss of SOC because it disturbs the equilibrium of soil, making the soil organic carbon more prone to erosion and decomposition. Tree litter, a new source of SOC, has the potential to recharge the SOC pool and have priming effects. The priming effects get stronger in C-rich soils due to the overabundance of carbon availability, which enhances SOC loss (Guo *et al.*, 2021; Hong *et al*., 2020). large-scale afforestation initiatives must take into account a number of growth constraints on forests, not the least of which is the water supply necessary to sustain vegetation. According to estimates, 36% of the tropical land that is suitable for afforestation is located in regions where rainfall can only provide 40% of the water needed. In such areas, planting trees will just make the water shortage severe (Ricciardi *et al.*, 2022). Therefore, in order to increase carbon storage through reforestation, scientific designs and suitable management are needed.

## E. Restoration of Wetlands:

According to the Ramsar Convention of 1971, wetlands are defined as "areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salty, including areas of marine waters, the depth of which at low tide does not exceed six meters." Numerous beneficial ecosystem services are provided by wetlands, such as the protection of wildlife, the habitation of a wide variety of plants, animals, and microbes (biodiversity), a source of livelihood, fisheries and aquaculture, carbon sequestration, ecotourism, recreation, and aesthetics, improved water quality, groundwater recharge, flood mitigation, and protection of coastal lines etc. (Nag *et al*., 2021).

Wetlands have been drained and used for agriculture for millennia; rice fields and crop fields on river flood-plain soil are two major examples. According to Verhoeven and Setter (2010), agriculture, industry, or urbanization have caused the loss of about 50% of the world's wetlands. In addition to having a detrimental impact on biodiversity, the loss of a species-rich ecosystem like a wetland increases carbon dioxide emissions.

The wetlands and their corresponding soils make up a substantial carbon pool in pedology. One of the planet's most productive ecosystems, wetlands are a massive carbon sink. Therefore, appropriate management, restoration of already existing wetlands, and the development of new wetlands can somewhat mitigate climate change and lower carbon footprints.

One potential mitigation strategy is the restoration of wetlands through the cessation of land-use patterns and the recovery of SOC supplies (Badiou and colleagues, 2011; Cavallaro and colleagues, 2018; Hiraishi and colleagues, 2014). Wetland soils have a unique function in the global carbon cycle. Because of the high plant productivity and slow rates of decomposition in these habitats, carbon builds up in the soils of wetlands. When compared to other ecosystems, such as tropical forests, freshwater wetlands have a very high net primary productivity (NPP). These characteristics mean that in wetlands, production typically exceeds decomposition, leading to a net buildup of organic matter and carbon.

An essential part of carbon buildup in a wetland is played by aquatic plants. Plants require atmospheric $CO_2$ for photosynthesis. As plants die and decompose, organic matter is added to the marsh bottom. This has a significant impact on the sequestration of carbon in marsh soil. It has been found that rising $CO_2$ levels enhanced the carbon assimilation of numerous wetland plants, such as *Phragmites* sp. (Nag *et al*., 2021). Therefore, increasing the primary productivity of aquatic plants could improve carbon sequestration in wetland soil.

Wetlands also acts as a largest natural source of GHGs especially methane ($CH_4$) due to methanogenesis occurring in the sediments. Additionally, wetlands may act as a source of $CO_2$ when the breakdown of organic matter exceeds the rate of production. Still, wetlands sequester carbon net cumulatively over time, even in spite of carbon release from $CO_2$ and $CH_4$ emissions. Therefore, in order to protect the planet from climate change and global warming, suitable management strategies should be implemented to preserve and improve the carbon reserve in wetlands.

## 5.5 Technological Carbon Sequestration Approach:

- **Direct Air Capture (DAC):**

We will probably need to find techniques to remove a considerable amount of carbon dioxide ($CO_2$) from the atmosphere since there is only a limited amount of $CO_2$ that can be released before global warming reaches 1.5–2°C target set by the Paris Agreement. In addition to conventional approaches, direct air capture and storage is emerging as synthetic carbon sequestration approach (Gambhir & Tavoni, 2019). Direct air carbon capture and storage (DACCS) and $CO_2$ utilization (DACCU) for fuels in the transportation sector, especially in the marine, aviation, and chemical industries, where sustainable solutions are not common, are two applications for which DAC is a supporting technology (Haegel *et al*., 2019; Fuss *et al*., 2018). DAC is mostly used for two purposes: carbon capture and utilization (CCU) and CDR (Carbon di-oxide removal) as CCS.

There are still a number of research questions in the relatively new field of DAC technology. Further research is required on sorbents with a high $CO_2$ capacity, favourable kinetics, ease of regeneration, and long lifespan. Furthermore, it is necessary to demonstrate how well DAC functions in various weather scenarios and how DAC may be integrated into systems that generate a lot of waste heat. There are still very few lifecycle assessment studies for DAC (Grubler *et al*., 2018; Socolow *et al*., 2011), which require more attention.

## 5.6 Conclusion:

It is imperative that negative emission techniques be implemented in order to reduce the amount of $CO_2$ that damaged coastal ecosystems contribute to global emissions. This can be achieved through conservation and restoration activities. Conservation agriculture, agroforestry, and biochar adoption rates have been steadily increasing, driven by their soil protection benefits. Although there has been much research done on the possibility of conservation agriculture and the application of biochar as a mitigation method, it is challenging to evaluate their impact on SOC stocks due to the numerous variables involved. Prior to large-scale adoption, soil and crop standardization is required. While agroforestry exhibits varied rates of SOC sequestration as well, all reports indicate that its effects are beneficial. Expanding the implementation to locations with major agricultural lands can both provide marketable environmental benefits and offset emissions.

Although the financial benefits of these services to farmers may not match those of monoculture, they are offset by advantages for sustainability. For a long time, reforestation has been essential to reducing climate change. Depending on the price of $CO_2$, it is predicted to give moderate to high rates of sequestration while also considerably increasing biomass carbon. However, extensive afforestation reduces food security by competing with agricultural land and raising food prices. Thus, careful planning is essential for sustainable forestry campaigns, which heavily rely on the carbon market. Soils in wetlands are rich in carbon. Carbon emissions have been made worse by the sharp decrease in wetland area, both terrestrial and marine, necessitating their conservation and restoration. However, a mitigating bottleneck exists because of the high expense of restoration and the absence of financial incentives for landowners.

Wetland restoration may be made more economically valuable and the means for restoration could be made available by introducing "blue carbon credits" into the carbon market. In a nutshell, many nations could move to implement negative emission strategies in the agricultural sector and simultaneously enhance the resilience and health of their soils by utilizing the scientific knowledge and infrastructure that already exists, along with modest investments to further advance the knowledge base while creating new technologies. Promoting world-scale activities to help restrict average global temperature increases to less than 2°C would be stimulated by these approaches.

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