Sequestering Carbon in Agriculture: Innovations for Climate Mitigation

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Abstract— *Carbon sequestration plays a crucial role in addressing climate change by lowering the concentration of carbon dioxide (CO_2) in the atmosphere. With the rapid increase in greenhouse gas (GHG) emissions, the Earth's climate is undergoing significant transformations, making it essential to adopt strategies that counteract these emissions. Among various solutions, soil carbon sequestration stands out as an effective method, particularly because degraded and agricultural soils hold substantial capacity for storing additional carbon. Globally, soils are capable of storing nearly twice as much carbon as the atmosphere and terrestrial vegetation combined. The amount of carbon held in soil is influenced by both climatic conditions and soil characteristics. Agricultural practices—including land-use changes, crop residue handling and soil management—play a major role in determining soil carbon levels. Improving these practices not only enhances soil carbon stocks but also supports food security and promotes sustainable farming systems. The development of carbon sequestration technologies is increasingly important. Abiotic approaches such as CO_2 injection into oceans, geological formations, and mineral carbonation offer long-term storage solutions, while biotic approaches rely on natural processes and tend to be more affordable and faster to implement. Together, these methods complement each other and contribute to reducing the risks associated with climate change. Human activities, especially the burning of fossil fuels, have significantly increased atmospheric CO_2 concentrations, resulting in global warming and a range of environmental challenges. Therefore, it is essential to adopt strategies that both limit emissions and actively remove CO_2 from the atmosphere. This chapter provides an in-depth examination of carbon sequestration—its definition, processes, benefits, and challenges—along with its importance in mitigating climate change and enhancing our understanding of its overall potential.*

Keywords— Carbon sequestration, climate change mitigation, greenhouse gas emissions, soil carbon sequestration, geological sequestration, terrestrial sequestration, and oceanic sequestration.

I. INTRODUCTION

Carbon is an essential component for maintaining soil biological processes, ecosystem productivity, soil biodiversity, and overall environmental quality (Gaikwad, 2021). Atmospheric carbon enters land-based ecosystems primarily through photosynthesis, while it returns to the atmosphere through various respiration processes (Gaikwad, 2021). Even slight imbalances between the amount of carbon captured from the atmosphere and the amount released back can produce noticeable shifts in climate patterns over decades. In recent years, the excessive emission of carbon has negatively affected air, water, soil, and human well-being (Gaikwad, 2021).

Since the late 19th century, global surface temperatures have increased by approximately 0.88°C, with 11 of the 12 warmest years occurring after 1995 (IPCC, 2007). Projections indicate that Earth's average temperature could rise by 1.5–5.8°C by the end of the 21st century (IPCC, 2001). The warming trend has accelerated since 1975, with an estimated increase of 0.158°C per decade. These temperature shifts have also contributed to major ecological changes (Greene & Pershing, 2007) and a rise in both the frequency and severity of wildfires (Running, 2006; Westerling et al., 2006). Much of this climate change is attributed to greenhouse gas (GHG) emissions produced by human activities—including land-use conversion, deforestation, biomass burning, drainage of wetlands, soil disturbance, and the combustion of fossil fuels.

Since the Industrial Revolution around 1850, concentrations of GHGs and their radiative forcing have steadily increased alongside human population growth. Carbon dioxide (CO_2) levels, for example, climbed from 280 ppmv in 1850 to 380 ppmv in 2005, and continue rising by roughly 1.7 ppmv (or 0.46%) each year (WMO, 2006; IPCC, 2007). Methane (CH_4) and nitrous oxide (N_2O) show similar long-term upward trends (IPCC, 2001, 2007; Prather et al., 2001; WMO, 2006). Altogether, the total radiative forcing resulting from all greenhouse gases since 1850 is estimated at 2.43 W m^{-2} (IPCC, 2001, 2007).

To mitigate climate change and reduce CO_2 emissions, several strategies have been proposed (Schrag,2007):

1) Lowering global energy demand,
2) Developing energy sources that are low-carbon or carbon-neutral, and
3) Utilizing both natural and technological methods to capture and store CO_2 from emission sources or directly from the atmosphere.

Between 1850 and 1998, fossil fuel use emitted an estimated 270 ± 30 Pg of carbon, while land-use change, deforestation, and soil cultivation released an additional 136 ± 30 Pg (IPCC, 2001). At present, fossil fuel combustion contributes about 7 Pg C per year (Pacala & Socolow, 2004), and land-use change contributes another 1.6 Pg C annually. Of the total anthropogenic emissions of roughly 8.6 Pg C each year, about 3.5 Pg accumulates in the atmosphere, 2.3 Pg is absorbed by the oceans, and the remainder goes into an unidentified terrestrial sink—likely situated in the Northern Hemisphere (Tans et al., 1990; Fan et al., 1998).

The purpose of this chapter is to examine the processes and technological pathways for long-term CO_2–C sequestration in major global carbon reservoirs. While presenting a broad overview of CO_2 sequestration, particular attention is directed toward soil-based (terrestrial) carbon sequestration and its role in reducing the rate of atmospheric CO_2 accumulation.

II. WHAT IS CARBON SEQUESTRATION?

Carbon sequestration is the process of capturing carbon dioxide (CO_2) from the atmosphere and storing it in forms that prevent its return to the air. This storage can take place through natural ecological pathways or through human-developed technologies. The concept includes both naturally occurring mechanisms and deliberate interventions that remove CO_2 from the atmosphere or prevent it from being emitted in the first place. These approaches store carbon in different reservoirs, such as oceans, terrestrial ecosystems (including soils, vegetation, and sediments), and deep geological formations.

Before human activities began significantly increasing CO_2 emissions, the global carbon cycle (Figure 1) maintained a stable balance between the absorption and release of carbon. Today, however, the natural carbon sinks responsible for CO_2 uptake cannot keep pace with the rapid and continuous emissions generated by human actions. As a result, the planet's natural systems are no longer able to offset the accelerated rise in atmospheric CO_2.

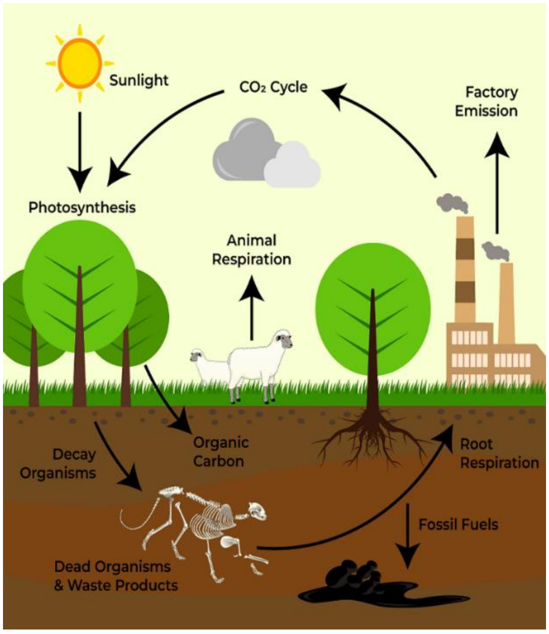
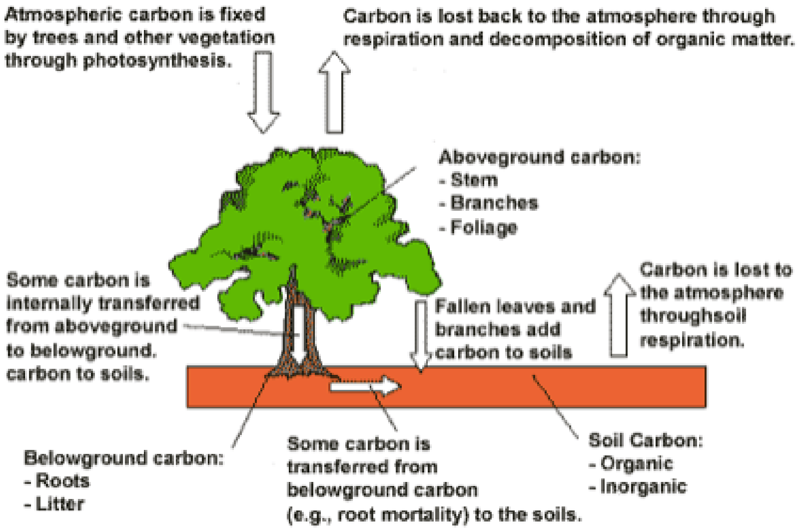


FIGURE 1: The global carbon cycle

III. CARBON SEQUESTRATION APPROACHES

3.1 Terrestrial Sequestration:

Terrestrial carbon sequestration refers to the uptake of atmospheric carbon dioxide (CO_2) by vegetation—such as trees, crops, and other plants—through the process of photosynthesis. The absorbed carbon is then stored in plant biomass, including trunks, branches, leaves, roots, as well as in soil organic matter. Forests, agricultural lands, and grazing areas are often described as "carbon sinks" because of their capacity to capture and retain carbon. However, these same systems can also emit CO_2 through various agricultural and forestry operations. A landscape functions as a carbon sink only when the amount of carbon it captures exceeds the amount it releases over a specific period.



Source: https://www.projectguru.in/carbon-sequestration-to-prevent-global-warming/

3.1.1 Terrestrial Activities for CO_2 Sequestration:

Carbon sequestration in terrestrial ecosystems can be increased through strategic land-use practices and management decisions that enhance carbon storage in soils, croplands, and forests. Practices such as diversified crop rotations, no-till farming, reducing summer fallow periods, planting cover crops (e.g., wheat, rye) or high-residue crops (e.g., corn, grain sorghum), and establishing vegetative buffer zones all contribute to carbon accumulation in cropland soils.

Additional measures include converting underutilized or marginal agricultural lands into grasslands or forests, selecting crop varieties with higher carbon storage potential, and adopting land management techniques that limit soil disturbance, erosion, and the removal of organic carbon from the land. These approaches collectively strengthen the role of terrestrial ecosystems as effective carbon sinks.

3.2 Geologic Sequestration

Geologic sequestration of CO_2 involves three main stages: capturing the CO_2, transporting it, and storing it in deep underground formations.

3.2.1 Capture:

CO_2 produced by power plants is captured using several techniques, including flue-gas separation, oxy-fuel combustion, and pre-combustion methods:

- **Flue-gas separation**: CO_2 is removed from exhaust gases using solvents. The CO_2 is then released from the solvent using steam, producing a concentrated CO_2 stream that can be commercially utilized.
- **Oxy-fuel combustion**: Fuel is burned in pure or oxygen-enriched air, producing flue gas that primarily contains CO_2 and water vapor.
- **Pre-combustion capture**: CO_2 is removed before fuel combustion, often as part of a gasification process.

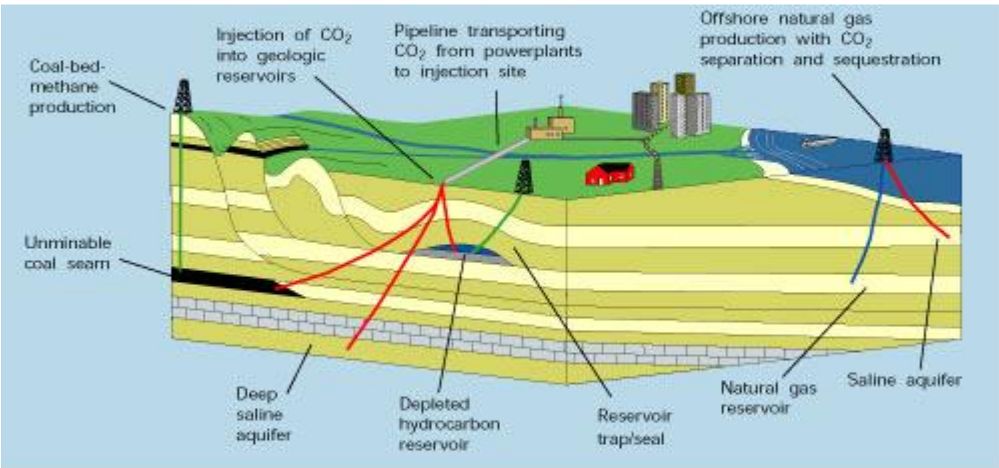
3.2.2 Transportation:

Once captured, the CO_2 is transported—typically via pipelines—to a designated storage site. Selection of the site involves input from geologists, engineers, project managers, and other specialists.

3.2.3 Storage:

The CO_2 is injected into deep underground rock formations with high porosity and permeability. Porosity refers to the volume of pore spaces in the rock where CO_2 can reside, while permeability describes how well these pores are interconnected, allowing the CO_2 to flow efficiently during injection.

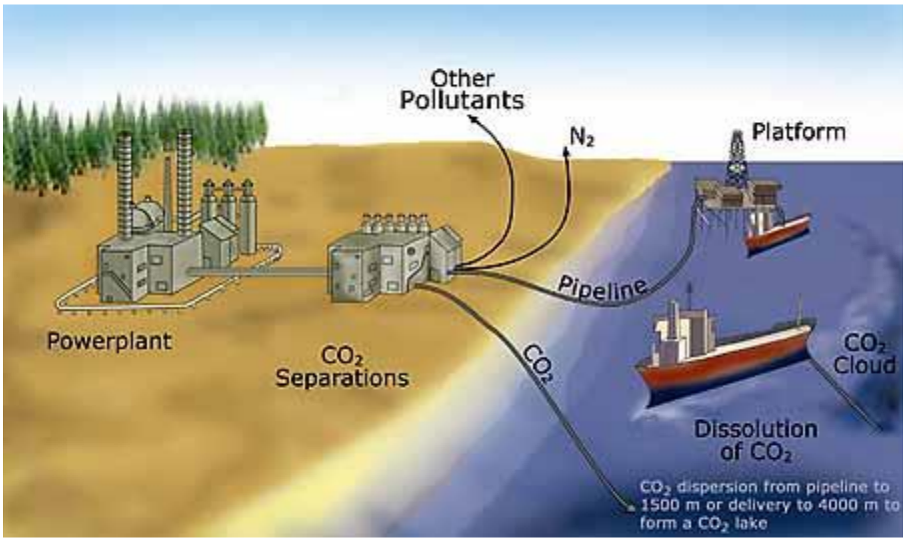
The storage formation, called the **reservoir**, must be capped by a low-permeability layer known as the **cap rock**, which prevents CO_2 from escaping. Suitable reservoirs include deep saline aquifers, depleted oil and gas fields, and unmineable coal seams. After injection, wells are sealed properly, and the site is monitored over the long term to ensure that no CO_2 leaks occur.



Source: https://pubs.usgs.gov/fs/fs026-03/fs026-03.html

3.3 Carbon Sequestration in the Oceans:

Enhancing the removal of carbon from the atmosphere by oceans can be achieved through methods such as fertilizing phytoplankton with nutrients or injecting CO_2 into ocean depths exceeding 1,000 meters. These processes, along with terrestrial and geologic approaches, are commonly referred to as carbon "sinks."



Source: https://www2.lbl.gov/Science-Articles/Archive/sea-carb-bish.html

Farmers who demonstrate that their practices have sequestered more carbon in soils than they emitted through machinery and other activities can earn **carbon credits**. The carbon stored in soils can then be used to offset emissions from activities such as fossil fuel combustion, cement production, and other industrial processes. In addition to reducing atmospheric CO_2, these practices enhance soil health and promote long-term agricultural productivity. It is estimated that globally, farmlands have the potential to offset up to 30% of annual CO_2 emissions from fossil fuels.

Establishing soil carbon offset credits for the market requires clear governance, including determining ownership of the carbon (e.g., landowners, operators, or government), identifying buyers of carbon offsets, defining contract durations, establishing verification procedures, and setting penalties for fraud or breaches.

Monitoring, verification, and accounting (MVA) are critical components of carbon sequestration. MVA ensures the permanence and safety of stored CO_2 by measuring the amount of carbon stored at specific sites, tracking its underground location, detecting potential leaks, and verifying that storage methods are secure and environmentally safe. Mitigation strategies are also essential, enabling a response to risks such as CO_2 leakage or environmental harm in the unlikely event of a storage failure.

IV. PRINCIPLES AND MECHANISMS OF CARBON SEQUESTRATION:

Several technological approaches exist for capturing atmospheric CO_2 and storing it in various global reservoirs. Choosing the appropriate methods is essential for designing energy policies that support sustainable economic growth and development at both national and international levels. These approaches are generally grouped into two main categories: **abiotic** and **biotic** carbon sequestration (Lal, 2008).

4.1 Abiotic carbon sequestration: Non-biological carbon capture

Abiotic sequestration refers to the capture and storage of carbon using physical, chemical, and engineering methods, without relying on living organisms such as plants or microbes. The concept of storing carbon in oceanic and geological formations has received considerable attention (Freund and Ormerod, 1997) because of its potential to hold larger amounts of CO_2 compared to biological methods. Significant progress is being made in developing and testing technologies for capturing, transporting, and injecting CO_2 into these reservoirs (Kerr, 2001).

4.1.1 Deep sea carbon injection or oceanic injection:

The injection of pure CO_2 into the deep ocean has been explored by engineers for nearly three decades, with gradual advancements in techniques and understanding. For long-term stability and to prevent CO_2 from returning to the atmosphere, injections must be carried out at substantial ocean depths. Several methods have been proposed for oceanic CO_2 sequestration (Lal, 2008):

1. **Injection below 1,000 meters from an ocean floor manifold**: Liquefied CO_2, being less dense than seawater, rises to around 1,000 meters, forming a plume of droplets.
2. **Injection of a CO_2-seawater mixture at depths of 500–1,000 meters**: The denser mixture sinks into deeper ocean layers.
3. **Discharge from a large pipe towed behind a vessel**: CO_2 is released directly into the water column.
4. **Pumping CO_2 into depressions on the seafloor**: This forms a localized “CO_2 lake” on the ocean bottom.

Studies suggest that liquefied CO_2 injected at depths near 3,000 meters can remain stable over long periods (O’Connor et al., 2001). The ocean has a tremendous capacity to store carbon, estimated at 5,000–10,000 Pg C, which exceeds the total carbon content of known fossil fuel reserves (Herzog et al., 2002).

However, potential impacts on deep-sea organisms must be considered (Seibel & Walsh, 2001). The long-term stability of CO_2 injections also depends on ocean stratification and natural circulation processes. Beyond ecological concerns, economic factors and technical feasibility play a critical role in evaluating the practicality and sustainability of oceanic CO_2 sequestration.

4.1.2 Subsurface carbon storage or geological injection:

Geological carbon storage, also called subsurface carbon storage or geological injection, involves capturing CO_2 from industrial sources, converting it to a liquid state, transporting it, and injecting it into deep underground formations. Suitable formations include depleted coal seams, abandoned oil and gas fields, stable rock layers, or saline aquifers (Tsang et al., 2002; Klara et al., 2003; Baines & Worden, 2004; Gale, 2004).

Saline aquifers are porous sedimentary layers filled with brackish water located beneath freshwater reservoirs and separated from them by impermeable strata. Injected CO_2 is stored in these aquifers through a combination of physical trapping and chemical reactions that can form stable carbonates. Additionally, injecting CO_2 into underground reservoirs can be used as a cost-effective approach for **enhanced oil recovery (EOR)**, where it displaces remaining oil or gas and boosts production from mature or declining fields (Klusman, 2003).

4.1.3 Chemical scrubbing and carbon mineralization:

Mineral carbonation is a process that mimics natural reactions in which CO_2 is transformed into stable mineral forms, such as calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$). The process typically involves two main steps: **scrubbing** and **mineral carbonation**. Scrubbing captures CO_2 chemically using solvents like amines or carbonates, a widely used technique in carbon capture. The purified CO_2 is then converted into solid carbonates through mineral carbonation, permanently storing the carbon.

Ultramafic minerals are considered ideal feedstocks for mineral carbonation, providing long-term potential for industrial CO_2 emissions management (Goff et al., 1997, 2000). However, these geological reactions naturally occur at a slow pace. Methods to accelerate the reaction include reducing particle size, increasing temperature and pressure, and employing catalysts. These enhancements, however, require additional energy and can be costly (Fan & Park, 2004).

4.2 Biotic carbon sequestration: biological carbon capture-

Biotic carbon sequestration involves the active management of plants and microorganisms to capture CO_2 from the atmosphere. This approach emphasizes strategies that extend beyond simply reducing emissions or offsetting them. Improving the efficiency of resources such as water and energy also plays a role in managing carbon storage within terrestrial ecosystems. Some of the key methods for biotic carbon sequestration are briefly discussed below (Lal, 2008):

4.2.1 Marine carbon storage: Oceanic carbon sequestration-

Biological processes play a crucial role in oceanic carbon sequestration through photosynthesis. Phytoplankton, in particular, are responsible for capturing an estimated 45 Pg C per year (Falkowski et al., 2000). Some of the organic matter produced by these microscopic organisms sinks to the ocean floor, effectively storing carbon for long periods (Raven & Falkowski, 1999).

The growth of phytoplankton is often limited by the availability of iron (Fe), which has led to studies on the effects of iron fertilization on enhancing biotic CO_2 sequestration in marine environments (Martin et al., 2002; Boyd et al., 2004). However, the ecological consequences of ocean fertilization remain uncertain, and its potential impacts on marine ecosystems are still widely debated (Chisholm et al., 2001). Additionally, there is ongoing discussion about the possibility of trading the extra carbon sequestered through ocean fertilization as carbon credits in global markets. Despite these considerations, ocean fertilization remains a controversial approach due to limited scientific understanding and unresolved environmental risks (Johnson et al., 2002).

4.2.2 Terrestrial carbon capture: Soil, forest and wetlands carbon sequestration-

Terrestrial carbon sequestration is the process of capturing atmospheric CO_2 and storing it in organic matter and soil carbon pools within land-based ecosystems. Of the 8.6 Pg C released annually into the atmosphere, about 3.5 Pg C, or roughly 40% of anthropogenic CO_2, is absorbed by terrestrial carbon sinks, which are not fully specified but play a vital role in regulating the global carbon cycle.

Terrestrial ecosystems act as major carbon sinks by using photosynthesis to capture CO_2 and store it in living biomass and decomposing organic matter. Beyond mitigating climate change, terrestrial carbon sequestration provides additional benefits, including improved soil fertility, enhanced water quality, restoration of degraded lands, and increased agricultural productivity. For these reasons, it is often described as a **win-win** or **no-regrets strategy** (Lal et al., 2003), offering multiple advantages even if climate change were not a concern.

The primary components of terrestrial carbon sequestration include:

1. **Soils**
2. **Forests**
3. **Wetlands**

4.2.3 Soil carbon sequestration:

Soil carbon sequestration involves enhancing the levels and storage of both **soil organic carbon (SOC)** and **soil inorganic carbon (SIC)**, including secondary carbonates, through various land management practices and land-use changes in agricultural, pastoral, and forest ecosystems. It also encompasses the rehabilitation of degraded or heavily disturbed soils. One approach includes the production of **charcoal** and the application of **biochar** as a soil amendment to improve fertility and store carbon (Fowles, 2007).

Unlike geological sequestration, which stores CO_2 deep underground at depths of 1–2 km, SOC sequestration focuses on carbon storage in the **topsoil**, typically within 0.5–1 m, through natural humification processes. In many managed ecosystems, SOC levels are lower than in natural ecosystems due to carbon depletion in cultivated soils. The most substantial SOC losses generally occur within the first 20–50 years following the conversion of natural ecosystems to agricultural lands in temperate regions, and within 5–10 years in tropical regions (Lal, 2001). On average, cultivated soils retain only 50–75% of their original SOC content. This depletion is mainly driven by processes such as **oxidation/mineralization, leaching, and soil erosion**.

4.2.4 Forest ecosystem: Carbon sinks-

Forest ecosystems serve as important carbon reservoirs due to the presence of lignin and other resistant polymeric compounds in vegetation. The current net carbon sequestration rate in forests, excluding areas affected by deforestation, is estimated at around 1.7 ± 0.5 Pg C per year (Fan et al., 1998). Carbon is stored not only in harvestable timber but also in woody debris, wood products, and woody plants encroaching into grasslands (Wofsy, 2001).

Rising atmospheric CO_2 levels have not yet saturated terrestrial **net primary productivity (NPP)** and may even enhance it through the **CO_2 fertilization effect** (Krishnamurthy & Machavaram, 2000). However, NPP saturation is predicted to occur at CO_2 concentrations of approximately 800–1,000 ppm (Falkowski et al., 2000), with the CO_2 fertilization effect on forest carbon uptake expected to peak around the mid-21st century. Nevertheless, further increases in CO_2 may be limited by nutrient constraints, including nitrogen, phosphorus, and water availability. Managing the interactions between carbon, nitrogen, phosphorus, and water cycles can help maximize terrestrial carbon sequestration.

Afforestation is recognized as an effective approach for sequestering carbon in terrestrial ecosystems (IPCC, 1999; Fang et al., 2001; Lamb et al., 2005). It is one of the 15 strategies proposed to stabilize atmospheric CO_2 at 550 ppm by 2050 (Pacala & Socolow, 2004). Modeling studies suggest that halting clear-cutting of primary tropical forests over the next 50 years could prevent approximately 0.5 Pg C emissions. Additionally, reforesting or afforesting around 250 million hectares in the tropics or 400 million hectares in temperate regions could sequester an additional 0.5 Pg C per year.

However, large-scale afforestation can have unintended consequences, such as reduced streamflow, soil salinization, and acidification (Jackson et al., 2005). The impacts on water availability must therefore be carefully evaluated when planning large-scale projects. Biodiversity loss is another concern, particularly when monoculture plantations are established, which can negatively affect ecosystem services (Bunker et al., 2005). Implementing regulatory frameworks, including carbon credit trading systems and permit processes, is essential. The overall costs of carbon sequestration, including opportunity costs, should also be considered in policy planning (McCarl & Schneider, 2001).

4.2.5 Wetlands: Carbon reservoirs-

Wetlands play a crucial role in carbon storage and sequestration, making them important ecosystems for mitigating greenhouse gas emissions and addressing climate change. Wetlands and their associated soils, often referred to as **histosols**, represent a major soil carbon pool, estimated at around 450 Pg C (Gorham, 1991; Warner et al., 1993). The carbon content in wetland soils can be up to 200 times higher than that of the aboveground vegetation (Milne & Brown, 1997; Garnett et al., 2001).

Since the post-glaciation period, wetlands and peat soils have sequestered carbon at an average rate of roughly 0.1 Pg C per year (Gorham, 1991; Kobak et al., 1998). However, human activities such as drainage and agricultural or forestry conversion have turned many peatlands into net sources of CO_2. Draining wetlands accelerates decomposition and soil subsidence, primarily due to oxidation, at rates of 1–2 cm per year (Rojstaczer & Deverel, 1995).

Restoration of wetlands can reverse these effects and re-establish them as effective carbon sinks. Nevertheless, it can take considerable time after restoration for the ecosystem processes to return to levels comparable to those of natural wetlands.

4.2.6 Secondary carbonates:

Soil carbon sequestration can occur not only through soil organic carbon (SOC) but also via **secondary carbonates (SIC)** and the leaching of bicarbonates into groundwater. Secondary carbonates appear in a variety of forms, including films, threads, concretions, pedants, laminar caps, caliche, and calcrete (Gile, 1993). In gravel-rich soils, they may coat the lower surfaces of stones and pebbles.

There are four primary mechanisms for secondary carbonate formation (Monger, 2002; Mermut & Landi, 2006). Marion et al. (1985) proposed that carbonates form when CO_2 dissolves in the soil surface, followed by the downward movement and re-precipitation of $CaCO_3$ and $MgCO_3$ in the subsoil. Sobecki and Wilding (1983) suggested that capillary rise of $CaCO_3$ from shallow groundwater can lead to re-precipitation in the surface layer. Rabenhorst and Wilding (1986) described a mechanism involving in situ dissolution and re-precipitation, while Monger (2002) observed that some secondary carbonates are **biogenic**, produced through the activity of soil organisms such as termites.

Secondary carbonates typically form in soils with pH values between 7.3 and 8.5, provided there is sufficient $CaCO_3$ and $MgCO_3$. Precipitation is favored by decreasing soil water content, reduced CO_2 or HCO_3^- partial pressure in soil air, and increasing concentrations of $CaCO_3$ or HCO_3^- in the soil. Compared to SOC, the formation of secondary carbonates occurs at a slower rate. For example, in the deserts of southwestern USA, Pleistocene-era deposition rates ranged from 1.2 to 6 kg C/ha/yr (Marion et al., 1985; Schlesinger, 1985). Other studies in the same region reported rates of 1.2–4.2 kg C/ha/yr (Schlesinger, 1985) and 1–14 kg C/ha/yr (Monger & Gallegos, 2000). In Saskatchewan, Canada, secondary carbonate deposition rates were estimated at 9.9–13.4 kg C/ha/yr (Landi, 2002). Non-calcareous soils generally exhibited lower deposition rates of 1.7–6.1 kg C/ha/yr (Machette, 1985), indicating higher formation in calcareous soils.

Another pathway for SIC sequestration is the **leaching of bicarbonates (HCO_3^-) into groundwater**, particularly in irrigated soils using high-quality water (Nordt et al., 2000). In such soils, HCO_3^- leaching can reach 0.25–1.0 Mg C/ha/yr (Wilding, 1999). With approximately 250 million hectares of irrigated land worldwide, the potential global contribution of bicarbonate leaching to carbon sequestration is estimated at 62.5–250 Tg C/yr.

While technological options to accelerate secondary carbonate formation are limited, the use of **organic amendments**—such as crop residue mulch, manure, and biosolids—can enhance the activity of soil fauna, promoting biogenic carbonate formation. In irrigated soils, the application of high-quality irrigation water can also help increase HCO_3^- leaching, further contributing to long-term carbon storage.

4.2.7 Biofuels:

Producing ethanol from biomass-derived sugars and converting plant oils and fats into biodiesel is an effective approach to decrease dependence on fossil fuels and promote sustainable energy alternatives (Himmel et al., 2007; Stephanopoulos, 2007; Wald, 2007). In 2004, the global primary energy supply totaled 11.2 Pg of oil equivalent, with oil contributing 35.03%, coal 24.6%, natural gas 20.44%, nuclear energy 6.33%, and renewable sources 13.61% (Goldemberg, 2007). Within renewables, traditional biofuels such as crop residues, wood products, and animal dung accounted for 2.48%, while modern biofuels represented 1.91%. Other renewable sources, including hydro, solar, wind, and geothermal energy, collectively supplied only 3.22% of global primary energy.

Biofuels play a significant role in both scientific and policy discussions and are linked to carbon sequestration in two main ways. First, converting degraded or marginal agricultural soils into energy plantations helps restore soil organic carbon (SOC) pools, enhancing soil carbon storage. Second, biofuel production cycles atmospheric CO_2 back into biomass, contributing to carbon mitigation. By selecting suitable plant species and applying careful management practices, energy plantations with dedicated crops such as poplar, willow, switchgrass, miscanthus, karnalgrass, Andropogon, and Pennisetum can sequester carbon in soils, offset fossil fuel emissions, and slow the accumulation of atmospheric CO_2 and other greenhouse gases (GHGs).

Despite these advantages, concerns remain about potential competition for land and water resources required to establish energy plantations, highlighting the need for sustainable planning and management.

V. ADVANTAGES AND DISADVANTAGES OF CARBON SEQUESTRATION

5.1 Biotic Carbon Sequestration:

- Involves the removal of atmospheric CO_2 through natural processes like photosynthesis.

- Woody plants and managed ecosystems are expected to sequester more CO_2 in the future due to the CO_2 fertilization effect.
- Can be enhanced through proper nutrient management (N, P, K, Ca, Mg, S, Zn, Cu, Mo) and efficient water management.
- Offers multiple co-benefits, including:
  - Improved soil and water quality
  - Reduced nutrient losses
  - Decreased soil erosion
  - Enhanced wildlife habitat
  - Increased water conservation
  - Restoration of degraded soils
  - Improved efficiency of agricultural inputs

5.1.1 Soil carbon sequestration includes both:

- Soil Organic Carbon (SOC)
- Secondary Inorganic Carbon (SIC)

5.1.2 Benefits of SOC sequestration:

- Enhanced soil structure and fertility
- Greater plant-available water
- Increased nutrient storage
- Detoxification of pollutants
- Climate moderation
- Higher agricultural productivity and food security
- Increased aesthetic and economic value of land

5.1.3 Recommended management practices (RMPs) for agricultural and forest soils exist for most ecoregions (IPCC, 1999).

5.1.4 Limitations:

- Total terrestrial capacity is relatively low (estimated 50–100 Pg C over 25–50 years) (Lal, 2004a,b).
- Carbon can be re-released due to soil management changes (e.g., ploughing) or land-use changes (e.g., deforestation).

5.2 Abiotic Carbon Sequestration:

- An engineered process involving technologies for CO_2 capture and storage.
- Includes deep injection of CO_2 into:
  - Oceans
  - Geological formations
  - Coal seams
  - Oil wells
- Current challenges:
  - High costs of implementation

- Risks of CO_2 leakage
- Need for careful monitoring and measurement
- Potential ecological impacts
- Regulatory and legal requirements

5.2.1 Advantages:

- Enormous storage capacity, potentially exceeding fossil fuel carbon reserves (thousands of Pg C).

5.2.2 Complementary to biotic sequestration:

- Biotic methods provide immediate, cost-effective mitigation
- Abiotic methods offer long-term, large-scale carbon storage potential
- Ecosystem-specific approaches may utilize both methods together.

5.3 Integration:

- Biotic sequestration is already accessible and can be implemented immediately.
- Abiotic sequestration, combined with carbon-neutral energy production, will become a viable alternative in the near future.
- Together, these strategies can reduce atmospheric CO_2 and mitigate climate change impacts effectively.

VI. CONCLUSION

Natural terrestrial and oceanic carbon sinks currently absorb roughly 60% of the 8.6 Pg C emitted annually. However, these sinks alone are insufficient to offset anticipated anthropogenic CO_2 emissions. Increasing the carbon storage capacity of managed ecosystems—such as forests, soils, and wetlands—requires careful land-use planning and the adoption of Resource Management Practices (RMPs). Effective biotic or terrestrial carbon sequestration depends on managing biological processes and understanding the interactions between carbon, water, and other nutrient cycles.

Abiotic sequestration techniques, including direct injection of CO_2 into oceans or geological formations and mineral carbonation to form stable carbonates, provide significant potential for long-term storage. While these engineering-based methods are under development and may become widely available by 2026, further research is needed to make them cost-efficient, minimize leakage risks, and reduce environmental impacts.

Human dimensions, such as policy frameworks, regulatory oversight, measurement, monitoring, carbon residence time, and carbon credit systems, are critical considerations for implementing both biotic and abiotic sequestration strategies. Alongside carbon sequestration, reducing emissions through carbon-neutral technologies is essential. This includes adopting energy-efficient production and consumption practices and exploring renewable fuels, such as bioethanol, biodiesel, methane from anaerobic digesters, and hydrogen derived from biomass.

Carbon sequestration offers multiple benefits: mitigating climate change, enhancing soil health to support plant growth, and improving food security. Environmental factors—such as temperature, precipitation, and elevated atmospheric CO_2—affect soil organic matter (SOM) decomposition, while soil texture significantly influences the accumulation of soil organic carbon (SOC). Agricultural practices impact SOC differently depending on soil characteristics, including physical and biological properties. Conservation tillage, combined with suitable crop rotations and the inclusion of legumes, can improve soil organic content and boost SOC storage.

Overall, carbon sequestration strategies contribute to sustainable agriculture by enhancing soil health, reducing pollutant loads, and lowering atmospheric CO_2 concentrations.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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