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Carbon Sequestration: A Key Strategy for Climate Change Mitigation towards a Sustainable Future

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ABSTRACT

Carbon sequestration plays a vital role in mitigating climate change by capturing and storing carbon dioxide (CO_2) from the atmosphere, thereby reducing greenhouse gas emissions. This abstract provides a comprehensive overview of carbon sequestration, highlighting its significance, strategies, and potential environmental benefits. Firstly, the abstract outlines the importance of carbon sequestration as a solution to the growing challenge of global warming. It emphasizes the urgent need to address rising CO_2 levels and the detrimental impacts of climate change on ecosystems, human health, and the economy. Next, the abstract explores various carbon sequestration strategies employed across different sectors. It discusses natural carbon sinks such as forests, wetlands, and agricultural lands, which effectively absorb CO_2 through photosynthesis and store it in vegetation and soils. Additionally, it covers the emerging field of technological carbon capture and storage (CCS), which involves capturing CO_2 emissions from industrial sources and storing them underground in geological formations. Furthermore, the abstract highlights the potential environmental benefits associated with carbon sequestration efforts. It emphasizes the restoration and preservation of ecosystems, including reforestation and afforestation initiatives, as effective means to enhance carbon sinks. The abstract also acknowledges the co-benefits of these initiatives, such as biodiversity conservation, improved soil health, and enhanced water quality. Lastly, the abstract touches upon the challenges and considerations related to carbon sequestration. It discusses the need for sustainable land management practices, policy support, and international cooperation to facilitate large-scale implementation. The abstract also addresses concerns regarding the permanence and monitoring of carbon storage, as well as the costs and scalability of technological solutions.

Keywords: *Carbon sequestration, forests, wetlands, and agricultural lands*

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INTRODUCTION

Since the late nineteenth century, the Earth's global surface temperatures have risen by approximately 0.88 ºC. It's worth noting that 11 out of the 12 warmest years ever recorded occurred after 1995, as reported by the IPCC in 2007. Looking ahead, projections indicate that the average global temperature could increase by 1.5–5.88 ºC during the twenty-first century, according to the IPCC's 2001 assessment. The rate of temperature increase on a global scale has been approximately 0.158 ºC per decade since 1975. In addition to this warming trend, there have been noticeable impacts on ecosystems and an increase in the frequency and intensity of wildfires. Over the twentieth century, sea levels rose by approximately 15–23 cm, as outlined in the IPCC's 2007 report. Carbon, an essential chemical element, plays a fundamental role in supporting life. It serves as a building block for biomolecules and can exist in various forms, including solid (graphite and diamond) and gaseous (carbon dioxide or CO_2) states. Carbon dioxide, a greenhouse gas, has the ability to trap heat in the atmosphere and contributes to global warming. This gas is produced naturally as well as through human activities. Human activities, particularly the burning of fossil fuels such as coal, natural gas, and oil for energy production and transportation, are significant contributors to carbon dioxide emissions. Land use changes, oceanic biological processes, organic matter decomposition, and forest fires also release carbon dioxide into the atmosphere. The accumulation of carbon dioxide and other greenhouse gases exacerbates climate change by trapping heat. Scientists view the capture and storage of carbon dioxide as a crucial approach to mitigating the effects of atmospheric warming. This method is now widely recognized within the scientific community as an essential component of addressing climate change.

Carbon sequestration, the process of capturing and storing carbon dioxide (CO_2) from the atmosphere, has become a crucial strategy in addressing climate change and mitigating the impacts of greenhouse gas emissions (Roy et al., 2023). Prospects of carbon capture, utilization and storage for mitigating climate change. The concentration of CO_2 in the atmosphere continues to rise primarily due to human activities such as burning fossil fuels and deforestation, making it more urgent than ever to reduce carbon emissions and enhance carbon sinks. Carbon sequestration encompasses a range of approaches, including both natural and technological methods, which aim to remove CO_2 from the atmosphere and store it in various reservoirs such as forests, soils, oceans, and geological formations (McLaughlin et al., 2023). Natural carbon sinks, such as forests, wetlands, and agricultural lands, play a vital role in absorbing CO_2 through photosynthesis and storing it in vegetation and soils. On the other hand, technological solutions like carbon capture and storage (CCS) involve capturing CO_2 emissions from industrial sources and storing them underground in geological formations. The potential environmental benefits of carbon sequestration are significant. By removing CO_2 from the atmosphere, it helps reduce greenhouse gas concentrations, mitigating the warming effect and contributing to climate stabilization. Carbon sequestration also offers co-benefits, such as improving air quality, conserving biodiversity, enhancing soil health, and supporting sustainable land management practices (Nguyen et al., 2023). However, implementing effective carbon sequestration initiatives is not without challenges. Ensuring the permanence and integrity of carbon storage, addressing potential leakage risks, minimizing adverse environmental impacts, and ensuring cost-effectiveness are among the key considerations. Additionally, scaling up carbon sequestration efforts to make a significant impact on a global scale requires policy support, international cooperation, and the development of appropriate regulatory frameworks.

Carbon sequestration is the process of capturing carbon dioxide (CO_2) from the atmosphere and storing it long-term, thereby reducing its contribution to global warming (Yadav et al., 2023). Its aim is to mitigate climate change by decreasing greenhouse gas concentrations. There are natural methods, including photosynthesis by forests, plants, and vegetation that absorbs CO_2 and store carbon in soils, wetlands, and oceans, known as natural carbon sinks. Artificial methods involve capturing CO_2 emissions from industries or directly from the air and storing them in underground geological formations like depleted oil and gas reservoirs, deep saline aquifers, or coal seams (Amirthan & Perera, 2023). This process is called carbon capture and storage (CCS) or carbon capture, utilization, and storage (CCUS). Another emerging technology is direct air capture (DAC), which directly captures CO_2 from the atmosphere. Soil carbon sequestration occurs when CO_2 is removed from the atmosphere and stored in the soil carbon pool. This is primarily achieved through photosynthesis by plants, with carbon stored as soil organic carbon (SOC). In arid and semi-arid regions, soil carbon sequestration can also occur through the conversion of soil air CO_2 into inorganic forms like secondary carbonates, although the rate of inorganic carbon formation is relatively low. Since the industrial revolution, converting natural ecosystems to agriculture has depleted SOC levels, releasing 50 to 100 GT of carbon from the soil into the atmosphere. This depletion is due to reduced return of plant roots and residues to the soil, increased decomposition from soil tillage, and amplified soil erosion. This has resulted in a soil carbon deficit, creating an opportunity to store carbon through various land management approaches. However, future soil carbon change depends on factors such as climatic controls, historical land use patterns, current land management strategies, and topographic variations.

Increasing atmospheric CO_2 and global temperatures can affect soil carbon inputs through their influence on photosynthetic rates, as well as carbon losses through respiration and decomposition. Higher CO_2 concentrations have been shown to enhance carbon fixation through photosynthesis, leading to increased biomass. However, there can also be increased carbon loss due to greater plant respiration from increased root biomass or accelerated decomposition of soil organic matter (SOM) caused by heightened microbial activity. Elevated temperatures can limit water availability, reducing photosynthesis rates, but under non-limiting water conditions, they may enhance plant productivity, thereby impacting the carbon balance. Higher temperatures can also accelerate SOM decomposition, releasing more CO_2 and contributing to positive feedback on climate change (Liáng et al., 2023). At a smaller scale, the carbon sequestration capacity of soil within a watershed or crop field is influenced by local ecosystem processes. Factors like rainfall infiltration, soil erosion, sediment deposition, and soil temperature vary due to landscape heterogeneity, affecting carbon input and loss rates. These variations result in differences in SOC contents along topographic gradients. For instance, slope position impacts soil moisture, nutrient levels, and root growth, all of which can influence soil carbon. The combined effects of changes in carbon inputs and losses from land use, management practices, and landscape-level factors lead to variations in the capacity for carbon sequestration across landscapes (Marland et al., 2004). There are several potential management practices to increase SOC levels, including reducing carbon losses and increasing carbon inputs in agricultural systems.

The potential for carbon sequestration depends on understanding the historic SOC stocks under natural vegetation before land conversion and the impacts of land use on carbon loss. Land uses and management practices that decrease carbon inputs or increase losses compared to natural vegetation result in SOC reductions over time, leading to a soil carbon deficit relative to previous levels. However, such deficits offer opportunities to store carbon by implementing land use changes that increase inputs or decrease losses of carbon. For example, reforestation or restoring grasslands on former crop fields can reduce the carbon deficit caused by years of agricultural production and sequester carbon through higher root productivity. Wetland and pond creation can also sequester substantial amounts of carbon since waterlogged soils reduce decomposition. Other practices like irrigating pastures or rangelands may increase carbon levels beyond historic SOC stocks if carbon inputs under new management exceed natural conditions. Assessing changes in SOC stocks due to land management takes time and presents measurement challenges, as these changes typically occur over several decades.

3.1 TYPES OF CARBON SEQUESTRATION

3.1.1. Biological Carbon Sequestration

Biological carbon sequestration is the storage of carbon dioxide in vegetation such as grasslands or forests, as well as in soils and oceans.

a) Oceanic Carbon Sequestration: The marine biological pump is a natural process in which the ocean plays a crucial role in removing carbon from the atmosphere and land runoff, transporting it to the deep ocean and seafloor sediments (Lønborg et al., 2020). This pump is responsible for transferring around eleven billion tons of carbon annually into the ocean's depths. The majority of this carbon becomes part of organic and inorganic biological matter on the ocean floor, initiating its descent towards the seafloor. The deep ocean acquires most of its nutrients from the upper water column as they sink down in the form of marine snow. The organic pump converts dissolved inorganic carbon (DIC) into organic biomass and transports it, either in dissolved or particulate form, to the deep ocean. During the process of photosynthesis, phytoplankton utilizes inorganic nutrients and carbon dioxide, releasing dissolved organic matter (DOM) into the water. This DOM, along with aggregates, is then exported to the deep water, where it is consumed and respired. As a result, organic carbon is returned to the vast reservoir of dissolved inorganic carbon in the deep ocean. These combined processes effectively remove carbon in organic form from the surface and redistribute it as dissolved inorganic carbon at greater depths, creating a gradient of DIC from the ocean's surface to its deep regions. Colder and nutrient-rich areas of the ocean have a higher capacity to absorb carbon dioxide compared to warmer regions. Consequently, Polar Regions often act as significant carbon sinks. By the year 2100, it is projected that a substantial portion of the global ocean will serve as a significant sink for carbon dioxide. However, this could lead to changes in ocean chemistry, a decrease in water pH, and increased acidity, impacting marine ecosystems.

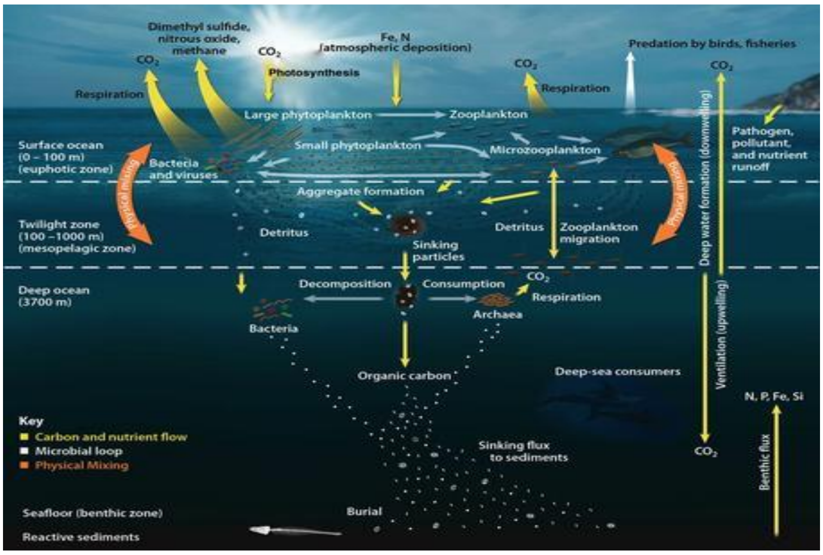

Fig.1. The Ocean Carbon Cycle

b) *Terrestrial Carbon Sequestration*

Soil: Plants play a critical role in sequestering carbon in the soil through photosynthesis, which leads to the formation of soil organic carbon (SOC). However, SOC levels can be depleted in agricultural ecosystems (Zhang et al., 2023). Nonetheless, this carbon deficit presents an opportunity to store carbon by adopting new land management practices. Besides organic carbon, soil can also store carbon in the form of carbonates. Over thousands of years, carbon dioxide dissolves in water and infiltrates the soil, where it combines with calcium and magnesium minerals, resulting in the formation of "caliche" in arid and desert soils. Carbonates are inorganic compounds capable of long-term carbon storage, with a lifespan exceeding 70,000 years, while soil organic matter typically retains carbon for several decades. Researchers are actively investigating methods to expedite the process of carbonate formation by incorporating finely crushed silicates into the soil. This approach aims to enhance the long-term storage of carbon in soils and improve carbon sequestration capabilities.

Forests: Large herbivores have the capacity to significantly influence both the aboveground and belowground components of an ecosystem through selective feeding, trampling, and waste deposition, all of which can impact plant production (Zhang et al., 2023). When herbivores selectively consume high-quality vegetation, it reduces the overall aboveground plant biomass. On the other hand, trampling by large herbivores leads to soil compaction, resulting in increased soil bulk density and reduced soil oxygen levels. Furthermore, the waste produced by these large herbivores contributes to an elevated release of carbon dioxide into the environment. The impact of large herbivores on the atmosphere underscores their importance in the carbon cycle. In the presence of natural disturbances, increased populations of herbivores can shift a carbon sink, an ecosystem that absorbs more carbon than it releases, into a carbon source, where more carbon is released than sequestered. This highlights the intricate relationship between large herbivores and the carbon dynamics within forest ecosystems.

Grasslands: In contrast to forests, which have faced challenges as carbon sinks in California due to rising temperatures, droughts, and wildfires, grasslands and rangelands have shown greater reliability in carbon storage, according to research from the University of California, Davis. These ecosystems have proven to be more resilient in the face of droughts and wildfires, which have less severe impacts compared to forests (Zhang et al., 2023). Unlike trees, grasslands primarily sequester carbon below ground. When grasslands burn, the carbon remains fixed in the roots and soil rather than being released through leaves and woody biomass. While forests have a greater capacity for carbon storage, the unstable conditions resulting from climate change have made grasslands a more resilient option. In the context of California's modern-day climate challenges, grasslands and rangelands have emerged as valuable carbon sinks due to their ability to withstand drought and fire disturbances while maintaining carbon storage in the soil and roots.

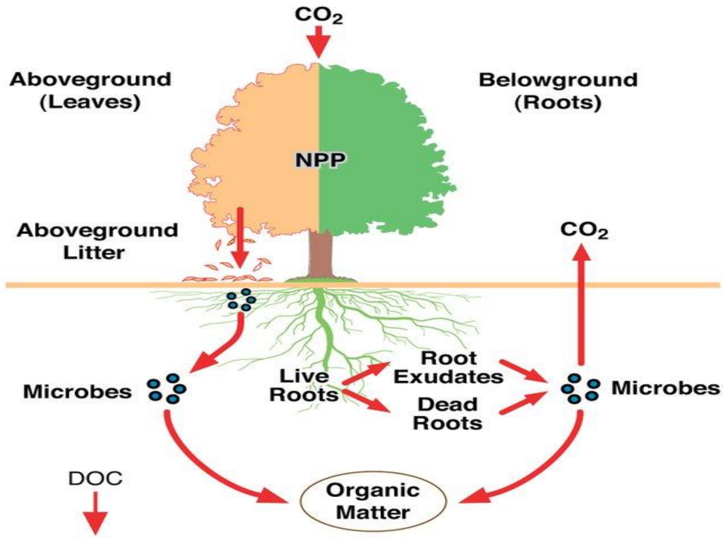

Figure2. Schematic diagram of terrestrial C sequestration (Oldenburg et al., 2008)

3.1.2 Geological Carbon Sequestration

Geological carbon sequestration involves the separation and capture of carbon dioxide (CO_2) at the point of emissions, followed by storage in deep underground geologic formations. This is also referred to as carbon (or CO_2) capture and storage (CCS).

a) Physical: Physical mechanisms for carbon capture and storage (CCS) typically involve the containment of CO2 within underground rock cavities (Zhang et al., 2023). These cavities can be either large man-made structures like caverns and mines or naturally occurring pore spaces within rock formations, such as depleted oil and gas reservoirs and aquifers. One application of CCS is enhanced oil recovery, where CO2 is injected into oil and gas reservoirs to help extract more resources and extend the production life of the site. The United States is a global leader in enhanced oil recovery technology, utilizing approximately 32 million tons of CO2 annually for this purpose. This demonstrates an economic advantage for CO2 capture and storage, particularly in the oil and gas industry. By employing physical mechanisms like underground storage in rock cavities and utilizing CO2 injection for enhanced oil recovery, CO2 capture and storage offer a potential solution for reducing greenhouse gas emissions while also providing economic benefits to certain industries.

b) *Chemical:* Chemical mechanisms of trapping CO_2 involve transforming the CO_2 or binding it chemically to another substance in the ground. This can be done in the following ways:

1. Dissolving CO_2 in underground water or reservoir oil
2. Decomposing CO_2into its ionic components
3. Locking CO_2into a stable mineral precipitate
4. Adsorption trapping

The fundamental mechanisms for CO_2 storage in underground geological media basically translate into the following trapping means:

1. CO_2 is dissolved into fluids, such as formation water and reservoir oil, that saturate the pore space within rock formations
2. Gaseous CO_2 is adsorbed onto a coal matrix underground because CO_2 has a higher affinity to coal than does the methane that is usually found in coal beds

3.1.3 Technological Carbon Sequestration

Technological advancements in carbon sequestration are being explored to remove and store carbon from the atmosphere. Researchers are not only focusing on carbon dioxide removal but also considering how it can be utilized as a resource (Zhang et al., 2023). Through innovations such as graphene production, direct air capture, and engineered molecules, researchers are striving to develop more efficient and cost-effective technologies for carbon sequestration. These advancements have the potential to not only reduce atmospheric carbon dioxide levels but also utilize it in beneficial ways.

a) Graphene Production (GP): Carbon dioxide is utilized as a raw material to produce graphene, a technologically advanced material used in the production of screens for smartphones and other electronic devices. While graphene production is currently limited to specific industries, it demonstrates how carbon dioxide can be harnessed as both a resource and a solution for reducing atmospheric emissions.

b) Direct Air Capture (DAC): This method involves capturing carbon directly from the air using advanced technology plants. However, the process is energy-intensive and expensive, costing between $500 and $800 per ton of carbon removed. While techniques like direct air capture can be effective, their current cost prevents widespread implementation.

c) Engineered Molecules (EM): Scientists are engineering molecules that can selectively capture carbon dioxide from the air by designing new compounds capable of targeting and attracting the element. These engineered molecules act as filters, specifically attracting the carbon dioxide they were engineered to seek.

4. PROMISING AGRICULTURE TECHNOLOGIES FOR CARBON SEQUESTRATION

Land managers have the potential to enhance soil carbon sequestration through various strategies. These strategies involve increasing the rates of organic matter input, directing carbon towards longer-lasting carbon pools, and extending the lifespan of all or specific carbon pools (Zhang et al., 2023). By employing different agricultural management approaches, it becomes possible to reverse the processes that have historically led to the depletion of soil carbon stocks previously accumulated under native perennial vegetation. Intensive studies on soil management practices have provided valuable information regarding the processes involved in augmenting soil carbon content (Post et al., 2004).

4.1 Cropping intensification: Eliminating fallow periods, using high-yielding crop varieties, and applying fertilizers and soil amendments significantly increase organic matter production and input into the soil. Precision agriculture also enhances soil carbon inputs. However, a portion of increased crop residue easily decomposes and doesn't contribute to long-term soil carbon accumulation. Nevertheless, some residue converts to humus, promoting long-term soil organic carbon buildup. While cropping intensification alone has limited impacts on soil carbon, greater enhancements can be achieved by using manures or biologically altered inputs. These amendments increase organic carbon input and contain materials more resistant to decomposition. Utilizing manures as soil amendments boosts organic carbon levels and contributes to enduring carbon accumulation.

4.2 Conservation tillage: When native vegetation is cleared for row crops, a decline in soil organic carbon (SOC) occurs due to mechanical soil disturbance. The soil structure plays a critical role in protecting soil organic matter (SOM) by regulating microbial access, turnover processes, and interactions within the decomposer food web. Incorporation of organic material into soil aggregates or micro-pores shields labile organic matter from decomposition. Macro aggregates (diameter ≥ 0.25 mm) are highly susceptible to disturbance, while micro aggregates (diameter < 0.25 mm) are more stable, exhibit slower turnover rates, and are more resistant to disturbance. The increase in SOC is closely linked to the interplay between macro aggregate turnover, micro aggregate formation, and carbon stabilization within micro aggregates. Recent research utilizing soil fractionation techniques and stable carbon isotopes has revealed that micro aggregates facilitate the creation of chemically resistant organic-mineral associations with prolonged residence times. Plant inputs contribute up to 40% of the chemically resistant carbon in the mineral fractions of micro aggregates generated over a period of 62 years. In contrast, new carbon constitutes less than 30% in non-micro aggregated soil. By reducing tillage intensity, aggregation processes can be restored, thus rebuilding the physical protection mechanism. Studies show that management practices aimed at reducing disturbance, such as no-till cultivation or establishing perennial vegetation, promote fungal-dominated pathways in organic matter cycling. This shift prolongs the residence time of microbial residues and contributes to their accumulation in SOC. Additionally, decreased disturbance and changes in plant communities foster the growth of mycorrhizal fungal biomass, which is biochemically resistant and derived from plant photosynthesis. Conservation tillage also mitigates wind and water erosion, which disrupts soil aggregates and leads to the loss of particulate organic matter. These losses reduce soil water-holding capacity, hinder nutrient regeneration, and potentially decrease crop productivity. Erosion, both directly and indirectly, contributes to the loss of soil carbon, necessitating increased irrigation or fertilizer application to maintain or enhance SOC levels.

4.3 Liming, irrigation, and fertilizer management: Transformations involving the creation of melanin-like humic compounds play a vital role in increasing the resistance of organic matter to decomposition. Phenoloxidase enzymes and abiotic oxidants facilitate these transformations. Recent studies indicate that maintaining a neutral or higher soil pH enhances the stability and activity of these enzymes and oxidants. The chemical stability of humic compounds leads to accelerated formation and reduced mineralization, ultimately resulting in increased soil organic carbon levels. Optimal conditions for humic compound formation involve a partly oxidizing environment, balancing oxygen availability to prevent complete mineralization or insufficient oxidative polymerization. Cycles of wetting and drying promote the oxidative polymerization reaction that stabilizes carbon, preventing stagnation under oxidizing or reducing conditions. Maximizing the presence of minerals containing iron and manganese oxide can also stimulate the formation of humic materials. Slowing down mineralization can be achieved by forming chemical or physicochemical associations between decomposable compounds and soil mineral components. Sorption of organic compounds to clay surfaces via polyvalent cation bridges enhances protection against microbial and chemical degradation. Adding divalent liming agents, iron, and manganese fertilizers, while managing drainage conditions, can significantly enhance carbon sequestration rates in soils. Soil anions, such as sulfate and phosphate, can compete for sites of dissolved organic carbon (DOC) sorption, leading to DOC release into the pore water. In soils with limited lateral flow, this process can enhance organic carbon sequestration as the DOC has opportunities to reabsorb onto mineral particles deeper within the soil. Manipulating the geochemical environment to facilitate carbon movement from upper to lower soil layers through DOC desorption and adsorption represents a potential approach to enhance subsurface carbon sequestration. Managing fertilizer sources to drive organic carbon deeper into the soil profile and manipulating mineral components to favor carbon sorption are potential land management strategies for augmenting subsurface organic carbon sequestration.

4.4 Perennial vegetation: The establishment of perennial vegetation on previously plowed cropland leads to significant increases in soil carbon levels. Surprisingly, even without additional management, the rate of soil carbon increase following perennial vegetation establishment is comparable to, or even higher than, that observed when converting to no-till cropland. This increase is attributed to enhanced formation of soil aggregates, a shift towards fungal-dominated decomposition pathways, increased organic matter inputs (especially belowground through roots and mycorrhizal fungi), and reduced erosion, similar to the processes associated with conservation tillage. In addition to these factors, the accumulation of biomass from perennial vegetation also contributes to carbon sequestration. In forest ecosystems, carbon accumulation in biomass generally exceeds soil accumulation. However, it is essential to consider potential losses of biomass due to events like fires or insect outbreaks. When estimating the impact of biomass accumulation, the frequency of such events needs to be taken into account and the projected effects adjusted accordingly. One advantage of perennial vegetation grown as a biomass crop is that a portion of the biomass can be used to offset fossil fuel usage. Estimates show that the carbon emissions saved through biofuel use exceed the sequestration potential of the same land area. Moreover, while soil carbon accumulation may reach saturation over time, the offset provided by biofuel production has the potential to accumulate indefinitely.

4.5 Microbial manipulation: Soil microbes regulate and stabilize organic leftovers. To stabilize carbon, these communities must be managed. Nucleic acid-based methods are useful for studying natural microbial populations. Researchers used 16S and 18S ribosomal DNA probes and T-RFLP to profile soil microbial community structure in farmland, prairies restored in 1993 and 1979, and native prairie. Despite fungal biomass and activity, bacterial communities recovered faster during prairie reversion. Microarrays may improve nucleic acid-based methods. It organizes thousands of spot DNA samples on glass slides to identify known and unknown DNA using base-pairing criteria. This method may detect natural microorganism populations. DNA microarray technique can analyze gene expression in pure cultures, but it is still being tested in complicated environmental samples. Different soil sample microarrays have been tested. Developing and testing oligonucleotide microarrays using 50-mer probes for all genes involved in nitrogen cycle, carbon cycling, sulphate reduction, phosphorus utilization, organic pollutant degradation, and metal resistance. Oligonucleotide microarrays can analyze the composition, structure, function, and dynamics of microbial communities under different environmental situations. Once researchers and managers understand the specific microbial processes involved in carbon sequestration, they may be able to manipulate microbial populations directly (e.g., inoculation or biocide use) or indirectly (e.g., vegetation, soil pH, or substrate additions). This alteration might increase or reduce biochemically resistant compound synthesis and breakdown. Technology based on soil carbon processes may improve carbon sequestration in land management. Current and new technologies may manipulate biochemical recalcitrance, chemical protection, and physical protection to promote soil carbon sequestration.

Table 1: Possible management practices for increasing SOC levels through reduced carbon and increased carbon inputs in agricultural systems

Management Practice	Effect
Reduced tillage/ No tillage	Reduced C loss
Erosion control (Contour Plowing, terracing)	Reduced C loss
Addition of organic amendments (Compost, Manure, Crop residues)	Increased C input
Use of Cover Crops	Reduced C loss/ increased C input

5. ADVANTAGES OF CARBON CAPTURE AND STORAGE (CCS) OR CARBON SEQUESTRATION (CS)

5.1 CCS Can Reduce Emissions at the Source: Almost 50% of the greenhouse gas emissions in the United States come directly from energy production or industry.2 Perhaps the biggest advantage of CCS is its ability to capture CO_2 from these point sources and then permanently store it in geological formations. The International Energy Agency estimates that CCS could be responsible for removing as much as 20% of total CO_2 emissions from industrial and energy production facilities.

5.2 CO_2 Is Easier to Remove at Point Sources: One of the major disadvantages of removing CO_2 from the air—through technologies like direct air capture—is that the concentration of the gas in the atmosphere is relatively low. In one type of CCS, known as pre-combustion, fuel is treated to form a mixture of hydrogen and carbon monoxide. Known as syngas, the mixture reacts with water to form hydrogen and highly concentrated CO_2. In the CCS process of oxyfuel combustion, oxygen is used to combust the fuel, and the leftover exhaust gas also has a very high concentration of CO_2. This makes it much easier for the CO_2 to react with the sorbent in the CCS process and then be separated.

5.3 Other Pollutants can be removed at the Same Time: During oxyfuel combustion, high concentrations of oxygen used for combustion leads to a significant reduction of nitrogen oxide (NOx) and sulphur dioxide gases. One study conducted for the Argonne National Laboratory showed a 50% decrease in NOx gases in oxyfuel combustion compared with combustion using regular air.5 Particulates created by oxyfuel combustion CCS can be removed with an electrostatic precipitator.

5.4 CCS Could Reduce the Social Cost of Carbon: The social cost of carbon is a dollar value of the estimated costs and benefits to society from climate change caused by one additional metric ton of CO_2 released into the atmosphere in a year. Examples of social costs of additional CO_2 emissions could be damage from hurricanes and adverse effects on human health. A benefit might be the increase in overall productivity in the agricultural sector. By removing CO_2 directly from the source, net damages to society could be decreased.

6. CHALLENGES OF CCS OR CARBON SEQUESTRATION

Even with the advantages of using CCS to help reduce the amount of CO_2 that is emitted into the atmosphere, there are several issues related to the implementation of the technology that still need to be worked out.

6.1 The Cost of CCS Is High: In order to equip existing industry and electric generation plants with CCS technology, the cost of the product being generated must increase if no subsidies are provided. One report from researchers at the University of Utah cites estimates of a 50% to 80% increase in the cost of electricity in order to pay for the implementation of CCS technology.6 There are currently no regulatory drivers in most places to incentivize or require the use of CCS, so the cost of equipment and materials to separate CO_2, build infrastructure to transport it, and then store it may be prohibitively high.

6.2 Using CCS for Oil Recovery Could Defeat Its Purpose: One current use of the CO_2 captured during the CCS process is enhanced oil recovery. In this process, oil companies purchase the captured CO_2 and inject it into depleted oil wells in order to free up otherwise unreachable oil. When that oil is eventually burned, it will release more CO_2 into the atmosphere. Unless the amount of CO_2 captured during CCS also accounts for the CO_2 released by the oil that was made available, CCS will simply be contributing to a larger amount of the greenhouse gas in the atmosphere.

6.3 Long-Term Storage Capacity for CO_2 Is Uncertain: The EPA estimates that not all countries will have enough CO_2 storage capacity to properly implement CCS.7 According to researchers at Khalifa University of Science and Technology, calculating the exact capacities of different storage sites is difficult.8 This means that the amount of CO_2 storage capacity throughout the world is not certain. Scientists at MIT have estimated that the storage capacity for CO_2 in the United States is adequate for at least the next 100 years, but uncertainty remains about any time frame beyond that.

6.4 CO_2 Transport and Storage Sites Could Be Dangerous: While accident rates during the transport of CO_2 are relatively low, the potential for a dangerous leak still exists. According to the Intergovernmental Panel on Climate Change, if CO_2 were to leak from a pipeline, a concentration between 7% and 10% in the ambient air could pose an immediate threat to human life. Leakage at the site of underground storage is also a possibility. If a sudden leak of CO_2 were to happen at an injection site, it could put the health of surrounding people and animals at risk. 10. A gradual leak from fractures in the rock layers or from injection wells has the potential to contaminate both the soil and groundwater in the area surrounding the storage site. And seismic events triggered by CO_2 injection could also disrupt the areas near the storage site.

6.5 Public Perception of Placing CO2 Near Them Is Negative: Storing carbon from CCS has several perceived risks that are not popular among the public. Large-scale implementation of CCS technology will require a place to store the CO_2. According to a study by scientists at the St. Petersburg Mining University in Russia, public awareness of CCS in most of the world is low.11 However, when people do know about CCS and what it entails, they often have a neutral or positive perception of it, until it comes to the carbon storage location. The negative NIMBY (Not in My Back Yard) effect is often stronger than the public's positive perception of CCS. People tend to reject large projects like CCS being built near them because of the perceived risks to health and lifestyle, or a feeling that it is not fair that the project is near them and not somewhere else.

7. IMPACTS OF CARBON SEQUESTRATION

The environmental benefits of carbon sequestration are multifaceted and involve various ecosystems and scientific advancements (Li et al., 2023; Cui et al., 2023, & Ma et al., 2023). Here are the details:

Forests, Farms, and Grasslands:

- Approximately 25% of carbon emissions have historically been captured by Earth's forests, farms, and grasslands.
- Scientists and land managers work together to promote vegetation growth and maintain soil hydration, enabling plants to absorb and store carbon.

Ocean Acidification:

- The upper layer of the ocean absorbs around 30% of carbon dioxide emissions from burning fossil fuels.
- However, this absorption increases water acidity, posing challenges for marine animals in building their shells.
- Scientists and the fishing industry are actively monitoring these changes and adapting fishing practices to mitigate the impact of ocean acidification.

Chemical Processes:

- Advanced technologies, such as electrocatalysis by a copper complex, have been developed to reduce carbon dioxide to oxalic acid.
- This process utilizes carbon dioxide as a feedstock to generate oxalic acid, contributing to carbon sequestration efforts.

Enhanced Natural and Managed Sinks:

- While natural terrestrial and oceanic sinks currently absorb approximately 60% of carbon emissions, their capacity is insufficient to fully offset projected anthropogenic CO_2 emissions.
- Managed ecosystems, including forests, soils, and wetlands, can be optimized as carbon sinks through strategic land use and the adoption of Resource Management Plans (RMPs) for forestry, agriculture, and pastures.
- Regulatory measures and policy incentives, along with a comprehensive systems approach, are crucial for the effectiveness of these management systems.

Coupled Cycles and Integrated Approach:

- The global carbon cycle is interconnected with the cycles of water (H2O) and other elements (e.g., N, P, and S).
- The effectiveness of biotic and terrestrial carbon sequestration depends on a scientific understanding of these coupled cycles.
- An integrated systems approach is necessary to effectively address the human impact on the carbon cycle and its interactions with other natural processes.

8. ENVIRONMENTAL BENEFITS OF CARBON SEQUESTRATION

Carbon sequestration provides significant environmental benefits that help mitigate climate change and protect ecosystems. Here are the details:

a) Decrease in Global Warming: Carbon sequestration plays a crucial role in reducing global warming. Approximately 45% of carbon dioxide is naturally sequestered by the ecosystem, while the remaining portion remains in the atmosphere. Increased atmospheric carbon dioxide leads to a greenhouse effect, trapping more heat and contributing to global warming. Global warming has detrimental effects, such as increased droughts, reduced rainfall, melting ice caps, rising sea levels, increased flooding, decreased agricultural productivity, and potential food scarcity.

b) Encouragement to Protect Forests and Grow Trees: Forests and other plants capture about 25% of carbon emissions, making them vital for carbon dioxide capture and storage. Recognizing the significance of carbon dioxide in climate change, efforts to protect existing forests and promote tree growth are likely to continue. By maintaining and expanding forest cover, carbon sequestration persists, leading to environmental preservation in the short and long term.

c) Reduction in Ocean Acidification: The upper layer of the ocean absorbs around 30% of carbon dioxide emitted during fuel combustion. This absorption increases the acidity of ocean waters, posing challenges for marine life survival and shell development. Carbon sequestration helps prevent disruptions to marine life, benefiting both the ecosystem and human populations that rely on seafood.

d) Decrease in Carbon Dioxide Emissions: Technological advancements continually improve carbon dioxide sequestration from coal-fired power plants and industrial smokestacks. Carbon dioxide can be safely stored deep underground or in the oceans, reducing its environmental impact.

9. FUTURE PROSPECTS

Future prospects of carbon sequestration are promising, with various avenues for further development and implementation (Hu et al., 2022; (Zhang et al., 2023). Here are the details:

a) Enhanced Natural Carbon Sinks: The preservation and restoration of natural carbon sinks, such as forests, wetlands, and oceans, offer significant potential for increased carbon sequestration. Efforts to protect and expand these ecosystems can contribute to enhanced natural carbon storage.

b) Advancements in Direct Air Capture (DAC) Technology: Direct Air Capture technologies, which remove carbon dioxide directly from the atmosphere, hold promise for scalable and efficient carbon sequestration. Ongoing research and development efforts aim to improve DAC systems and make them more cost-effective and accessible.

c) Continued Development of Carbon Capture, Utilization, and Storage (CCUS) Systems: CCUS systems, which involve capturing carbon emissions from industrial processes and storing them underground, continue to advance. Technological innovations, along with supportive policies and investment, can accelerate the deployment of CCUS at a larger scale.

d) Blue Carbon and Ocean Sequestration Opportunities: Blue carbon refers to carbon stored in coastal ecosystems such as mangroves, seagrasses, and salt marshes. Recognizing and harnessing the carbon sequestration potential of these habitats, as well as exploring other ocean-based approaches, can contribute to climate change mitigation efforts.

e) Advancements in Carbon Mineralization Techniques: Carbon mineralization involves converting carbon dioxide into stable carbonates, which can be stored long-term. Research and development in carbon mineralization techniques, including the use of mineral catalysts, offer potential solutions for carbon sequestration.

f) Supportive Policies and Financial Incentives: The implementation of supportive policies, such as carbon pricing and regulations, can incentivize carbon sequestration initiatives. Financial incentives, such as carbon offset markets and investment mechanisms, can encourage the adoption of carbon sequestration practices.

CONCLUSION

Carbon sequestration is vital in combating climate change, offering diverse natural and technological approaches with significant environmental benefits. However, implementing these strategies globally requires a collaborative and holistic approach. Abiotic sequestration, such as direct injection in oceanic and geological strata, and mineral carbonation into stable carbonates, show great potential but require further research for cost-effectiveness, risk reduction, and environmental safety. Addressing the human dimension and developing appropriate policies and regulations are crucial, including measurement, monitoring, residence time, and carbon credit trading. While carbon sequestration is important, the development of carbon-neutral technologies and alternatives to fossil fuels is also crucial, such as efficient energy production, usage measures, and biofuels.

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