Sustainability and Biodiversity Conservation

Carbon sequestration by terrestrial and marine biodiversity- a tool for combating climate change

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Abstract

Carbon sequestration by terrestrial and marine biodiversity is a critical mechanism for mitigating climate change. This paper explores the significant role of diverse ecosystems, including forests, grasslands, wetlands, seagrasses, mangroves, and salt marshes, in capturing and storing carbon. Terrestrial ecosystems act as substantial carbon sinks through processes such as photosynthesis, organic matter decomposition, and soil carbon storage, with grasslands being particularly noteworthy. Coastal blue carbon ecosystems, including seagrasses, mangroves, and salt marshes, efficiently trap and store carbon in marine environments. Marine biodiversity, encompassing coral reefs and plankton, also contributes to carbon sequestration through various mechanisms. Despite their importance, these ecosystems face threats from climate change and human activities. Preserving and restoring biodiversity in both terrestrial and marine environments is crucial for maintaining their capacity to sequester carbon and, consequently, for global climate change mitigation. This review underscores the urgent need to prioritize conservation efforts aimed at safeguarding these invaluable ecosystems for the benefit of the planet's climate and biodiversity.

Keywords: carbon, sequestration, trees, soil, flora, marine, planktons, carbonate.

Introduction

Carbon sequestration, a paramount concept in the realm of climate change mitigation, refers to the process by which carbon dioxide is captured and stored, preventing its release into the atmosphere. As human activities, particularly the burning of fossil fuels and deforestation, contribute to the escalating levels of greenhouse gases, carbon sequestration has emerged as a pivotal strategy to counteract the adverse impacts of climate change. By harnessing the natural capacity of various ecosystems, such as forests, oceans, and wetlands, to absorb and store carbon, scientists and policymakers seek to curtail the concentration of atmospheric carbon dioxide. This multifaceted approach not only addresses the urgent need to reduce emissions but also underscores the importance of preserving and restoring ecosystems that serve as formidable carbon sinks. The pursuit of effective carbon sequestration techniques stands at the forefront of global efforts to achieve a more sustainable and resilient future in the face of climate challenges.

Carbon Sequestration by Terrestrial Biodiversity

The role of terrestrial biodiversity in carbon sequestration has garnered increasing attention as a pivotal component of sustainable ecological systems and climate change mitigation. Terrestrial ecosystems, encompassing diverse habitats such as forests, grasslands, and wetlands, actively participate in sequestering atmospheric carbon dioxide through a complex interplay of biological processes. In these ecosystems, a myriad of plant and microbial species contribute to the fixation and storage of carbon, influencing both aboveground and belowground carbon pools. The relationship between terrestrial biodiversity and carbon sequestration emphasizes the ecological mechanisms that underpin the ability of diverse ecosystems to serve as vital carbon sinks. As anthropogenic pressures continue to threaten biodiversity, understanding and harnessing the potential of terrestrial ecosystems for carbon sequestration becomes imperative for sustaining global climate resilience and ecological balance. Terrestrial ecosystems can take up carbon from the atmosphere, which can mitigate the increase in the atmospheric CO2 concentration. A general representation of carbon sequestration by terrestrial biodiversity is given in Figure 1.

Vegetation and Forest

Photosynthesis is a fundamental process in which green plants, including trees, utilize sunlight to convert carbon dioxide (CO2) from the atmosphere and water into glucose and oxygen. This phenomenon takes place within the chloroplasts of plant cells and is represented by the following simplified equation:

$6CO_2+6H_2O+\text{light energy}\rightarrow C_6H_{12}O_6+6O_2$

The organic carbon generated through the process of photosynthesis is stored in various components of the plant, including leaves, stems, branches, and roots. In forests, trees play a significant role in storing carbon within living plant tissues, commonly referred to as "above-ground biomass." This carbon storage encompasses the roots, stems, branches, and leaves of trees. Throughout their life cycle, trees continue to sequester carbon, serving as enduring repositories for atmospheric CO2 (Sedjo & Sohngen, 2012).

Concerning carbon preservation in forested areas, it is more advantageous to prevent deforestation than to cut down trees and subsequently engage in reforestation efforts. Deforestation entails irreversible consequences, such as biodiversity loss and soil degradation (Moomaw et al., 2019). Furthermore, the impacts of afforestation or reforestation are delayed compared to the immediate benefits of maintaining existing forests intact (Nabuurs et al., 2013). The restoration of carbon sequestration levels in reforested areas takes an extended period, spanning several decades, to match those found in mature tropical forests (Baccini et al., 2017). Reforestation and the reduction of deforestation contribute to increased carbon sequestration through four primary mechanisms. Firstly, by increasing the size of the current forests. Secondly, by enhancing the carbon current forest density at both stand and landscape scales (Spawn et al., 2020. Thirdly, by broadening the utilization of forest products that have the potential to substitute for fossil fuel emissions sustainably. Lastly, by decreasing carbon emissions arising from the processes of degradation and deforestation (IPCC, 2007). Cultivating trees in areas with marginal crop and pasture lands is an effective strategy for incorporating carbon from the atmosphere, CO2, into biomass (Montaigne, 2019). However, for this process of carbon sequestration to be successful, measures must be taken to prevent the released carbon from returning to the environment through biomass burning or decomposition that occurs after the trees reach the end of their lifespan (Hunt, 2009). Ensuring the allocated land for trees remains untouched and managing disturbances to evade extreme events are crucial considerations. On the other hand, the timber from these trees must undergo sequestration itself, using methods such as bio-energy with carbon storage (BECS), biochar, landfill, or integration into construction. Reforestation efforts employing long-lived trees (with a lifespan exceeding 100 years) are particularly effective in sequestering carbon for extended periods, gradually releasing it, and minimizing its climate impact throughout the 21st century. The global capacity to plant an extra 1.2 trillion trees exists (Thomas& Jump, 2023), and preserving these trees could offset approximately ten years of CO2 emissions, sequestering a substantial 205 billion tons of carbon (Canadell & Raupach, 2008). This approach aligns with the Trillion Tree Campaign and has the potential to capture around 2/3 of all carbon emissions by restoring degraded forests worldwide (McDermott, 2008; Lefebvre et al., 2021). Over a three-decade span leading up to 2050, if 90% of global construction utilizes wood products, especially through mass timber adoption in low-rise construction, it could sequester an impressive 700 million net tons of carbon per year (Gorte, 2009; Crowther et al., 2015). This would offset around 2% of annual carbon releases recorded in 2019 (Bastin et al., 2019). Additionally, such a shift would eliminate carbon emissions associated with displaced construction materials like steel or concrete, known for their carbon-intensive production processes. The current woods are essential to the annual absorption of about 2 gigatonnes of carbon, contributing significantly to the terrestrial carbon sink. The forests hold about 45% of the land's organic carbon in biomass and soils (Bonan, 2008; Pugh et al., 2019). An extra 0.9 billion hectares of tree planting are predicted to be planted, which could result in the capture of 205 gigatonnes of carbon, or about one-third of all anthropogenic emissions to date. But it would take more than a century to do this (Bastin et al., 2019; Bonan, 2008). However, these estimates may overstate the possibility of forests capturing carbon and the availability of adequate land and water for reforestation, as indicated by research by Lewis et al. (2019) and Veldman et al. (2019). According to more meticulous estimates, once forests reach maturity, massive afforestation and replanting efforts could remove between 40 and 100 gigatonnes of carbon from the atmosphere, which is only about equivalent to ten years' worth of current anthropogenic emissions (Lewis et al., 2019; Veldman et al., 2019).

Prolonged Carbon Storage in Trees

Efficient and sustainable long-term management of carbon within trees is a critical determinant of the carbon capture potential in both natural and planted forests. Hemingway et al. (2019) state that some carbon stored in tree biomass will eventually be absorbed into the soil through rhizodeposition and litterfall, where it may stay for decades to millennia. Since soils hold more carbon than the atmosphere and terrestrial plants put together, even little variations in this pool's size will significantly affect the capacity of the forest to store carbon. At decadal timescales, afforestation and reforestation often have a positive impact on soil carbon storage (Nave et al., 2018; Paul et al., 2002); however, planting trees can occasionally cause carbon loss, especially on rich carbon soils like peatlands and many grasslands (Chen et al., 2016; Berthrong et al., 2009; Richards et al., 2017). Current research challenges previous assumptions about the extended retention of carbon in forests. Formerly, it was thought that the longevity of added substrates was determined by their chemical composition. Present research indicates that some biomolecules, such as lignin, are lost during the process of producing soil organic matter (Schmidt et al., 2011). Instead, the fate of plant-derived carbon in soils is determined by the physiology of decomposer microorganisms and their interactions with soil minerals (Dungait et al., 2012; Cotrufo et al., 2013). This emphasizes how crucial it is to understand soil characteristics in order to maximize carbon storage (Hemingway et al., 2019). The turnover of soil carbon is greatly influenced by forest management methods; nutrient inputs, in particular, are critical, particularly in light-textured sandy soils and old tropical soils (Adams and Pfautsch, 2018). Fertiliser application may have an impact on soil organic matter cycling and stabilization (Averill and Waring, 2018). Plantation timber that has been harvested has important implications. The building industry contributes around one-fifth of worldwide emissions of greenhouse gases; replacing carbon-intensive materials like steel and cement with wood products could mitigate these effects (Waring et al., 2020). By replacing steel, stone, and concrete with wood, carbon emissions are reduced, allowing buildings and infrastructure to act as an urban carbon sink (Churkina et al., 2020). However, these advantages must be carefully considered because improperly planned land use changes or a lack of focus on long-term management might negate them. For example, biofuel-established tree plantations may be managed in a way that is incompatible with biodiversity protection and needs a lot of land; bioenergy production from wood residues, on the other hand, may provide a more environmentally friendly option (Groom et al., 2008). Subsequently, initiatives aiming to prolong the longevity of wood products can gain from the rigorous application of well-established knowledge about forest growth and structure. Practices like thinning, for instance, offer opportunities to distribute net primary production among fewer but larger trees, leading to a broader range of wood products, particularly those with extended lifespans (Braun et al., 2016). A sustainable provision of wood products has the potential to generate income for local, frequently rural communities, and this income can be reinvested to further expand forest areas.

Organic Carbon of Soil (SOC)

Soil Organic Carbon is a vital component of terrestrial ecosystems, particularly in environments rich in vegetation, such as forests. The accumulation of SOC is intricately linked to the continuous cycle of plant material decomposition and the activities of various soil organisms. As leaves, twigs, and other plant residues fall to the forest floor, a diverse community of microorganisms, including bacteria and fungi, engages in the process of decomposition. This natural breakdown of organic matter results in the formation of simpler compounds, contributing to the rich mosaic of life within the soil. Throughout this decomposition process, a significant proportion of the organic matter transforms into a dark, carbon-rich substance known as humus. Humus, characterized by its stability, becomes a long-term reservoir of carbon in the soil. It can persist for extended periods, providing a stable form of SOC. This stabilization occurs through intricate interactions between soil organisms, temperature, and moisture conditions. Soil Organic Carbon is not uniformly distributed within the soil; rather, it can be found in various soil layers, including the topsoil, where plant roots are most active. The presence of SOC in the topsoil is crucial for soil fertility, structure, and water retention. Additionally, the carbon stored in soils plays a vital role in mitigating climate change. Acting as a long-term reservoir for carbon, it helps reduce the concentration of carbon dioxide in the atmosphere. The intricate interplay of processes involving photosynthesis, above-ground biomass, and the decomposition of organic matter creates a dynamic carbon cycle in ecosystems, contributing significantly to the overall carbon sequestration capacity of forests and other vegetation-rich environments. Researchers predict that soils, particularly in agricultural areas, have the potential to sequester an additional billion tons of SOC annually. Grasslands are a promising resource for storing soil organic carbon; they can store up to 6.5 billion metric tonnes of carbon annually, which is equal to the annual emissions of more than 1,400 coal-fired power plants (Sha et al., 2022). Croplands have the ability to sequester between 0.90 and 1.85 billion metric tonnes of carbon annually, which accounts for 26–53% of the aim set by the "4p1000 Initiative: Soils for Food Security and Climate." According to Zomer et al. (2017), this project is a global approach that aims to use soil to mitigate climate change.

Agriculture

Agriculture plays a pivotal role in carbon sequestration, acting as both a source and sink for atmospheric carbon dioxide. Through various sustainable practices, farmers can enhance carbon capture and storage in agricultural soils. Practices such as cover cropping, diverse crop rotations, and conservation tillage contribute to increased levels of soil organic carbon. Cover crops protect the soil from erosion, provide organic matter, and support microbial activity. Diverse crop rotations maintain continuous root presence and contribute a variety of organic residues to the soil. Conservation tillage reduces soil disturbance, preserving soil structure and minimizing carbon loss. Additionally, agroforestry, which integrates trees into agricultural landscapes, provides an extra dimension to carbon sequestration. The adoption of these practices not only enhances soil health and fertility but also contributes to mitigating climate change by sequestering carbon in agricultural ecosystems. As agriculture continues to evolve, sustainable land management practices are becoming increasingly crucial for both food security and environmental sustainability. Modifying agricultural practices stands out as a recognized approach to carbon sequestration, as the soil functions effectively as a carbon sink, potentially offsetting up to 20% of annual carbon dioxide emissions recorded in 2010 (Biggers, 2015). The restoration of organic farming and the promotion of earthworm activity may have the capacity to completely neutralize the annual carbon excess of 4 gigatons, contributing to the removal of the remaining atmospheric surplus (Bates and Draper, 2019). Strategies for reducing carbon emissions in agriculture can be broadly classified into two groups: those that target the reduction or displacement of emissions and those dedicated to improving carbon elimination from the atmosphere. Certain methods for emission reduction involve enhancing the overall efficacy of farm actions, such as adopting more fuel-efficient machinery, while others require interventions in the natural carbon cycle. It's worth noting that certain effective techniques, like eliminating stubble burning, may have adverse effects on other environmental aspects, such as an increase in herbicide use to manage weeds not eradicated by burning.

Grassland

Grasslands, comprising diverse ecosystems like prairies, savannas, and steppes, play a crucial role in carbon sequestration, with a primary focus on storing carbon in the soil. The extensive fibrous root systems of grasses, typical of these landscapes, effectively capture and store carbon in the form of organic compounds. Fine roots, constituting a substantial portion of grass biomass, actively contribute to nutrient and carbon uptake, enhancing the organic matter content in the soil. Grass roots release organic compounds, known as root exudates, fostering microbial activity that promotes the formation of stable soil aggregates and the sequestration of carbon in durable forms. The decomposition of grass residues in grasslands occurs at a relatively slow pace, particularly compared to some other plant types, leading to the accumulation of organic matter in the soil. Microbial communities in grassland soils play a pivotal role in decomposing this organic matter, interacting with plant roots to cycle carbon and form stable organic compounds. The partially decomposed organic matter further contributes to the formation of humus, a complex, stable organic material that enhances soil structure, water retention, and overall carbon storage. Carbon in grasslands is sequestered in various soil pools, including mineral-associated organic carbon (MOC), particulate organic carbon (POC), and dissolved organic carbon (DOC). Each of these pools has different turnover times, contributing to the long-term storage of carbon. The roots of grasses and their corresponding microbial communities also play a role in soil aggregation, forming structures that physically protect organic matter from rapid decomposition and help retain carbon in the soil for extended periods. Land management practices, such as sustainable grazing and controlled burns, influence carbon cycling in grasslands. Well-managed grazing systems, mimicking natural patterns, can enhance grass growth, root development, and the buildup of soil-based organic matter. Grasslands, despite often being overlooked compared to forests, store noteworthy amounts of carbon in their soils, participating substantially in worldwide carbon sequestration efforts. Their widespread distribution on every continent except Antarctica underscores their collective importance in the global context of carbon sequestration. The ability of grasslands to store carbon in the soil is a key subject of interest. According to Bay and Cotrufo (2022), by restoring biodiversity, managing grazing more effectively, and introducing planted legumes into pastures, worldwide grasslands can absorb between 2.3 and 7.3 billion tonnes of CO2 equivalents each year. To hasten the sequestration of soil organic carbon (SOC), grassland ecosystem restoration is also being investigated. Studies indicate that soils worldwide retain climatically crucial quantities of carbon in organic matter, more than 3.5 times the carbon in all living things and 2.3 times the carbon in atmospheric CO2 (Yang et al., 2019).

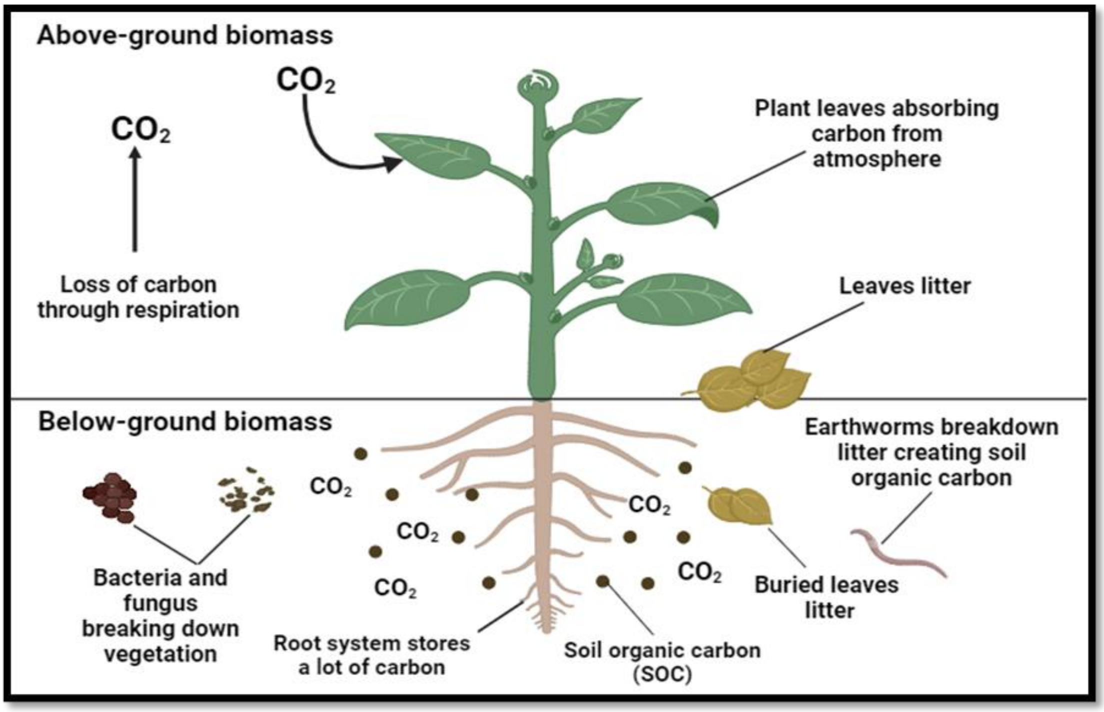

Figure 1. Terrestrial Carbon Sequestration (Plants and Soil)

Carbon Sequestration by Marine Biodiversity

Marine ecosystems, often referred to as blue carbon habitats, act as natural carbon sinks. These habitats include coastal wetlands, mangroves, seagrasses, and salt marshes, which cover a relatively small percentage of the Earth's surface but play a substantial role in carbon sequestration. The general representation of marine carbon sequestration is given in Figure 2. Carbon within oceans exists in diverse forms, locations, and quantities:

- Organic Carbon: This type of carbon resides in living marine organisms and plants, organic-rich litter, or carbon dissolved in organic matter.
- Inorganic Carbon: This form comprises atmospheric carbon dioxide that dissolves in seawater, resulting in the formation of carbonic acid, bicarbonate, and carbonate.
- Carbonate: Marine invertebrates excrete carbonate, and it is also integrated into their skeletons. Vertebrates, in turn, secrete carbonate.

Organic Carbon

Saltmarsh

Tidal salt marshes are examples of intertidal habitats where vascular plants predominate, although other primary producers such as phytoplankton, macroalgae, and cyanobacteria are also present. Plants in these wetlands take up CO_2 from the atmosphere rather than the ocean. Plant families and geographical areas differ in their ability to sequester carbon, both above and below ground. One characteristic that sets them apart is that, in contrast to terrestrial soils, the sediments that support seagrass beds, mangroves, and healthy saltmarsh plants do not become carbon-saturated when they accrete vertically with rising sea levels. Over time, the rate and amount of carbon sequestration can increase due to this special feature (Chmura et al., 2003).

Mangroves

Mangrove ecosystems are powerful carbon sequestration champions, playing a crucial role in mitigating climate change. The unique characteristics of mangroves, situated at the interface of land and sea, contribute to their exceptional carbon storage capabilities. The dense vegetation of mangrove forests, primarily composed of salt-tolerant trees and shrubs, captures substantial amounts of carbon in their aboveground biomass, including trunks, branches, leaves, and roots. The intricate root systems, such as prop roots and stilt roots, provide stability in waterlogged and unstable coastal soils, simultaneously acting as efficient carbon traps. Mangroves, through photosynthesis, fix carbon dioxide from the air, incorporating it into their plant tissues. These coastal ecosystems also exhibit belowground carbon storage, as their roots trap organic matter and sediments, leading to the burial of carbon-rich material in the soil. The waterlogged conditions prevalent in mangroves create anaerobic environments, limiting the complete breakdown of organic matter and facilitating the formation of peat, a carbon-dense material that contributes significantly to long-term carbon storage.

Mangroves are highly notable for being incredibly carbon-dense tropical forests, establishing themselves as vital repositories of carbon (Donato et al., 2011; Thompson et al., 2017). Although mangrove trees distribute carbon uniformly among their roots, leaves, and wood, the predominant carbon storage in mangrove habitats occurs not within the living biomass but predominantly in the soil and the decomposed, subterranean roots (Alongi, 2014; Thompson et al., 2017). The pace of carbon accumulation in mangrove ecosystems is notably ten times greater than in temperate forests and an impressive fifty times greater than in tropical forests per unit area (Bouillion et al., 2009; Thompson et al., 2017). Strikingly, mangroves store a higher amount of carbon per unit area (956 Mg C ha^{-1}) compared to salt marshes (593 Mg C ha^{-1}), seagrasses (142 Mg C ha^{-1}), peat swamps (408 Mg C ha^{-1}), and terrestrial rainforests

(241 Mg C ha−1). Despite covering only 1.9% of the tropical and subtropical coastline, mangroves make a substantial contribution, accounting for 5% of the net primary production of carbon and an impressive 30% of all carbon burial in coastal ecosystems (Alongi & Mukhopadhyay, 2015). The carbon sequestration services provided by mangroves extend beyond their aboveground and belowground biomass. They contribute to blue carbon ecosystems, emphasizing the importance of coastal and marine environments in global carbon cycling. Despite covering a relatively small percentage of the Earth's surface, mangroves store a disproportionately large amount of carbon, underscoring their significance in climate change mitigation.

Seagrasses

Seagrasses, submerged flowering plants uniquely adapted to coastal environments, play a crucial role in carbon sequestration, contributing to what is termed "blue carbon" ecosystems. These marine plants possess extensive root systems that serve not only to anchor them in the seabed but also to trap and stabilize organic matter. As seagrasses capture detritus and organic material in their root systems, a significant portion of this carbon-rich material becomes buried in the sediment, forming a robust carbon sink. The concept of "blue carbon" specifically refers to the carbon stored in coastal ecosystems, with seagrasses being prominent contributors to this phenomenon. The organic matter sequestered by seagrasses in their root systems and sediments has the potential for long-term storage, acting as a reservoir that mitigates the release of carbon dioxide into the atmosphere. Interestingly, seagrasses exhibit a unique carbon-export system, contributing to the cycling of carbon within coastal ecosystems. Approximately 24.3% of their net primary production is exported to various destinations. This includes providing sustenance for fauna that graze on the seagrasses, contributing to remineralization as dead plants or leaves fall to the seabed, and even reaching the deep sea (Thomas et al., 2017). Storm activities further enhance the export of seagrass carbon stocks, emphasizing the intermittent nature of this carbon-export system (Duarte and Jensen, 2017).

Macroalgae

Macroalgae, commonly known as 'seaweed,' are large marine plants that engage in photosynthesis. A substantial amount of the produce from these plants—43 %—is exported as dissolved or particulate organic carbon. This exportation happens when free-floating genera, such as Sargassum or detached fronds from coastal zones, add to the carbon supply that reaches the seafloor. This is usually a random phenomenon that intensifies following large-scale storms. In contrast to mangroves, seagrass beds, and salt marshes, the mechanisms behind macroalgae sequestration have not been thoroughly studied. It is imperative to closely monitor changes in carbon sequestration by macroalgae, especially considering factors like climate change and the harvesting of macroalgae for food consumption. The inclusion of these dynamics in blue carbon accounting initiatives is crucial (Krause-Jensen & Duarte, 2016).

Microbial activity

Microbial activity is principally responsible for regulating carbon transport in the deep sea, with phytoplankton serving as the primary source of easily accessible dissolved organic matter (DOM). Through photosynthesis, phytoplankton convert nutrients and atmospheric CO_2 into sugar using solar energy. Recent technological advancements have facilitated interdisciplinary collaboration among scientists to understand the crucial role of microorganisms in the marine environment. DOM, composed of diverse organic compounds, plays a vital role in both terrestrial and marine cycles, serving as a carbon store comparable in quantity to atmospheric CO_2 (Thompson et al., 2017). The scientific community has not fully comprehended the intricate processes related to the mineralization and sequestration of organic materials that phytoplankton produce in the deep ocean. Future research aims to unravel the ocean's carbon cycle, precisely measure anthropogenic CO_2 sequestration, develop emission reduction methods, and find ways to mitigate climate change effects. It is not yet clear how factors like ocean acidification and rising sea temperatures may affect the microbial synthesis of DOM. Particulate organic carbon (POC) is integral to the Earth's carbon cycle, especially in the long-term storage of carbon. When POC reaches the ocean floor sediment, various fates await, such as ingestion by marine organisms or degradation by microbes. POC degradation contributes to the formation of vast gas hydrate reservoirs, serving as a long-term carbon sink that traps carbon for thousands of years. The storage of carbon in gas hydrates balances the release of inorganic carbon into the surrounding saltwater caused by the process. The sedimentation of carbon is closely linked to surface productivity, where the amount of carbon output in surface waters influences carbon sinking into the ocean floor's sediment. This, in turn, influences the amount of carbon buried or stored across geological timeframes. Only one percent of the overall organic carbon synthesis at sea level is sequestered by sediment, which means that very little of the carbon that falls to the ocean floor as part of POC is kept in long-term carbon storage (Nath, 2012; Suess, 1980).

Marine invertebrates

Marine organisms, encompassing invertebrates, vertebrates, and microbes, play integral roles in the ocean ecosystem by providing essential goods and services and participating in crucial biogeochemical processes. These processes involve the regulation of oxygen and carbon dioxide, and the cycling of elements like phosphorus, nitrogen, and sulfur (Beaumont et al., 2007). The Southern Ocean's Ross Sea stands out as a notable location for carbon sequestration, with rising sequestration attributed to rising sea temperatures and subsequent ice-sheet melt (Thompson et al., 2017). The expanded sea surface resulting from these changes provides more habitats for microscopic plants, phytoplankton, and algae that act as primary producers, absorbing atmospheric CO2 during photosynthesis in the sunlight zone. A key aspect of the carbon cycle involves the intricate interactions between phytoplankton, zooplankton, and benthos (invertebrates inhabiting marine sediments). Phytoplankton blooms, consumed by zooplankton, initiate a cycle where the zooplankton, in turn, are consumed by benthos. When benthic organisms perish, they sink to the ocean floor, where they securely store carbon for prolonged durations. The pelagic zone, positioned between the topmost photosynthetic layer and the seabed, is inhabited by various invertebrates such as pteropods, crustaceans, and mollusks. These organisms, including vertebrates, undertake diel vertical migrations, playing a significant role in carbon storage (St John et al., 2016). While the contributions of marine organisms to the carbon cycle are recognized, there remains a lack of comprehensive understanding, leading to ongoing research. Salps, for instance, gelatinous zooplankton found in the pelagic zone of nearly every ocean, have been understudied. Salps, which include 48 species ranging in size from 0.5 to 190 mm, are integral to the trophic food web and biogeochemical cycles. They produce heavy, carbon-rich fecal pellets, known as particulate organic carbon (POC), contributing to the transfer of carbon to the sea floor. Despite broad estimates of their carbon export capabilities, the full quantification of salps' carbon sequestration is yet to be realized. Benthic marine invertebrates, collectively known as 'benthic,' inhabit marine sediments and include macrofauna such as polychaetes, mollusks, and crustaceans. With an estimated 500,000 to 10,000,000 species, marine macrofauna play crucial roles in the ocean carbon cycle, nutrient cycling, and the metabolism of pollutants (Snelgrove, 1998).

Marine vertebrates

Marine vertebrates play a crucial role in the carbon cycle, contributing to the storage and export of marine carbon, as well as the secretion of carbonate (Pershing et al., 2010). Their significance lies in their ability to effectively mix nutrient-rich water throughout the water column, promoting phytoplankton's primary production and improving its ability to absorb excess CO2 from the atmosphere (Lutz et al., 2014). Large marine vertebrates, including cetaceans and tuna fish, actively engage in bio-mixing, facilitating vertical and horizontal nutrient transport in the water. This, in turn, leads to increased primary production, aiding in the fixation of atmospheric carbon. Whales and other marine vertebrates contribute substantially to the global oceanic biogeochemical cycle. In the Southern Ocean, for instance, a study suggests that approximately 12,000 sperm whales remove 2.4 x 105 tonnes of carbon annually, helping as a carbon sink (Lavery et al., 2010). Initially considered a source of CO_2 due to respiration, Southern Ocean sperm whales were later recognized as significant carbon removers. This is because they excrete iron-rich feces, stimulating primary production and the transfer of carbon to the deep sea. Organic carbon is accumulated by marine vertebrates throughout their lives, effectively removing it from the atmosphere during their lifespan. Larger animals, being more efficient at carbon storage, need a smaller amount of food relative to their body mass (Pershing, 2010). However, the function of large vertebrates in carbon cycling and sequestration in the marine ecosystem is still under investigation, posing a knowledge gap for scientists. The intricate process of moving carbon within different areas and through food webs remains poorly understood. Occupying the upper part of the food web, marine vertebrates play a vital role in maintaining ecosystem balance. Evidence points to the possibility that the elimination of organisms, specifically top predators, from one trophic level may possess cascading effects on other animals and plants at different trophic levels. For instance, grazing snail populations expanded as a result of the loss of predatory crabs, resulting in the depletion of saltmarsh habitat (Atwood et al., 2015). Considering the significance of salt marsh ecosystems in long-term carbon sequestration, disturbances to the food web can result in unexpected effects on the carbon cycle.

Inorganic carbon

Atmospheric carbon dioxide

Inorganic carbon, particularly atmospheric carbon dioxide, undergoes absorption by the oceans, but this process exhibits uneven distribution across different oceanic regions. The North Atlantic, for instance, stores a substantial 23% of anthropogenic CO_2, while the Southern Ocean retains a comparatively lower percentage at 9% (Sabine et al., 2004). According to Feely and coworkers (2001), the Pacific Ocean, being the largest, absorbs approximately 18% of anthropogenic CO_2. Surface waters exhibit a greater concentration of CO_2, and despite influences such as air temperature, ocean currents, and photosynthesis affecting the CO_2 flux between the atmosphere and the sea, around 50% of anthropogenic CO_2 is concentrated in waters shallower than 400 meters. Furthermore, the solubility of CO_2 is notably higher in cold polar waters, where it dissolves twice as readily compared to warmer equatorial waters (Feely et al., 2001).

Ocean acidification

The alterations in ocean chemistry attributed to the rise in atmospheric carbon dioxide resulting from fossil fuel combustion, particularly since the onset of industrialization around 1750, have been extensively documented. Ocean acidification, comprehensively examined in a report by the Plymouth Marine Laboratory, involves the dissolution of excess atmospheric CO2 into the ocean's surface layers (Turley et al., 2016). This process diminishes the pH of saltwater by elevating the hydrogen ions (H+) concentration. Since the pre-industrial period, there has been a 26% rise in H+, leading to a 0.1 decrease in seawater pH (Ciais et al., 2013). The equation representing the ocean acidification process is as follows:

CO^2 (aq.carbon dioxide) + H_2O (water) ↔ H_2CO_3 (carbonic acid) ↔ H^+ (hydrogen ion) + HCO_3^-(bicarbonate) ↔ $2H^+$(hydrogen ion) + CO_3^{2-} (carbonate)

This equation illustrates the dissolution of carbon dioxide in water to generate carbonic acid. The carbonic acid then dissociates to generate bicarbonate, carbonate, and hydrogen ions. Despite the presence of mitigating factors like the mixing of aged seawater, land weathering, and the carbonate buffer of the seafloor, the increased concentration of hydrogen ions gradually leads to a more acidic seawater environment over time (Honisch et al., 2012).

Carbonate

Plankton carbonate

According to a study by Cyronak and coworkers (2016), the impact of excess anthropogenic CO2 dissolving in the ocean on the concentration of carbonate ions has been widely recognized for its adverse effects on the creation of shells and skeletons by marine organisms. Traditionally, it has been believed, based on chemical equations, that in acidic seawater with reduced carbonate availability, marine organisms would face challenges in growing their shells and skeletons. However, Toyofuku and colleagues (2017) present a novel perspective, revealing that certain single-celled marine creatures, known as foraminiferans, demonstrate biochemical modulation of their local marine environment. These organisms can persistently form calcareous structures even in an acidic environment by actively expelling excess hydrogen ions. This regulatory mechanism allows them to maintain homeostasis and normal functioning in an acidic setting. The implications of this discovery extend to the broader ocean carbon cycle.The conventional understanding suggests that as surplus atmospheric CO2 dissolves into the ocean until it reaches saturation, any surplus CO2 beyond this point contributes to atmospheric retention, thereby contributing to global warming. The findings of Toyofuku et al. (2017) prompt consideration of whether other marine organisms might possess similar regulatory mechanisms, allowing them to continue forming shells and skeletons in an acidifying ocean. Further research is required to comprehensively understand how diverse marine organisms respond to ocean acidification concerning the vital processes of shell and skeleton formation.

Fish carbonate

Calcification plays a crucial role in the marine inorganic carbon cycle, with carbonate serving as a short-term carbon store. The formation of carbonate involves a process where calcium reacts with bicarbonate in seawater, resulting in the production of carbon dioxide, insoluble calcium carbonate, and water:

Ca^{2+}(Calcium) + HCO_3(bicarbonate) ↔ $CaCO_3$(calcium carbonate) + CO_2(carbon dioxide) + H_2O (water)

While the majority of calcification in the oceans is attributed to plankton, such as foraminifera and coccolithophores, a noteworthy 3-15% of oceanic carbonate is generated by fish. Fish use carbonate as a byproduct to maintain themselves in a state of equilibrium. The escalating concentrations of carbon dioxide in the ocean due to anthropogenic activities may amplify carbonate production by fish, underscoring the increasing significance of fish in marine inorganic carbon cycling (Wilson et al., 2009).

Coral carbonate

Corals, vital components of marine ecosystems, contribute to carbon sequestration through a unique process involving the formation of calcium carbonate structures. Coral reefs, built by colonies of tiny organisms known as polyps, play a dual role in carbon storage. Firstly, corals extract dissolved inorganic carbon from the water to build their calcium carbonate skeletons, forming intricate reef structures. These structures not only provide habitats for a myriad of marine life but also serve as a reservoir for stored carbon. Secondly, the organic carbon produced by symbiotic algae living within coral tissues during photosynthesis becomes integrated into the coral biomass. Coral reefs are estimated to sequester approximately 900 million tons of carbon annually (Shi et al., 2021). This process involves the accumulation and storage of carbon in the form of calcium carbonate (CaCO3), which constitutes the calcareous skeleton of coral reefs. The calcium carbonate skeletons of corals persist over long periods, contributing to the sequestration of carbon in the form of reef structures. However, coral reefs are facing significant threats, including climate change-induced coral bleaching and ocean acidification, which jeopardize their ability to continue sequestering carbon effectively.

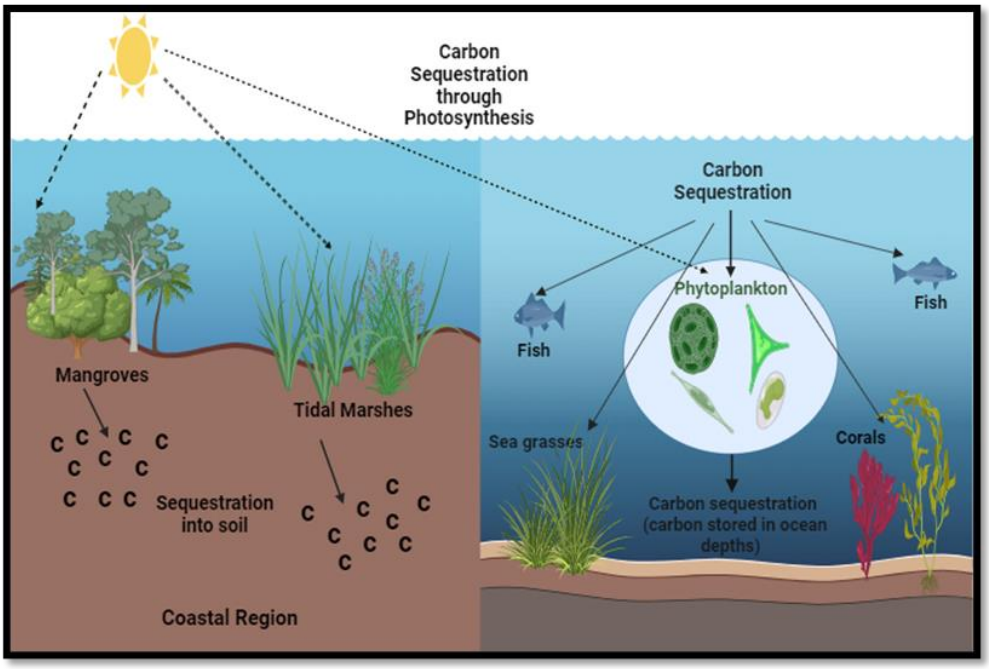

Figure 2: Carbon sequestration by coastal vegetation and marine biodiversity

Conclusion

In conclusion, the intricate web of life on Earth, spanning terrestrial, aquatic, and marine realms, plays a crucial role in carbon sequestration, offering a formidable defense against the escalating challenges of climate change. Terrestrial ecosystems, with their lush forests and expansive grasslands, serve as essential carbon sinks, capturing atmospheric carbon through photosynthesis and storing it in biomass and soils. Marine ecosystems, represented by seagrasses, mangroves, and salt marshes, exemplify the prowess of blue carbon, efficiently trapping and storing carbon in coastal environments. The ability of marine biodiversity to engage in photosynthesis, deposit calcium carbonate, and influence sediment dynamics all contribute to the overall carbon sequestration capacity of these ecosystems. As climate change intensifies, these ecosystems face unprecedented challenges, demanding urgent conservation and restoration efforts. Sustaining and enhancing the carbon sequestration potential of terrestrial, aquatic, and marine biodiversity is not merely an environmental imperative but a global responsibility, ensuring a resilient and balanced planet for future generations.

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