



A review on exploring carbon dynamics and sequestration in agroecosystems: Pathways to climate resilience and sustainable agriculture

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Abstract

Carbon are critical components of the global cycle and have significant implications for climate change mitigation and agricultural sustainability. Carbon enters the soil through various sources such as photosynthesis, plant debris, soil organic matter, root exudates, sediment accumulation, and rocks weathering. Soil organic carbons (SOC) consists of different fractions such as active, slow, and passive carbons. SOC plays a significant role in enhancing the soil quality, and sustaining and increasing food production in different ecosystems. Sequestered carbon is also lost in various forms, which results in the rise of greenhouse gases that influence global climate change across various ecosystems. India has distinct ecosystems *viz.*, forests, wetlands, mangroves and dryland ecosystems. The annual rainfall, soil type, period of crop, and available water holding capacity of vegetation have pronounced effects on carbon cycling and its dynamics which vary with each system. Efforts to enhance carbon stocks in agroecosystems involve implementing sustainable agricultural practices that promote carbon sequestration and reduce carbon emission. The objective of this review is to illustrate carbon dynamics and its sequestration in various ecosystem.

Keywords: Carbon cycle, carbon losses, carbon stock, carbon sequestration, terrestrial ecosystem

Introduction

Carbon is a fundamental component of life, understanding its dynamics is crucial for assessing ecosystem soil health, climate change impacts, and ecosystem soil management. India has various ecosystems such as forests, drylands, wetlands, and oceans, exhibits unique carbon dynamics based on environmental conditions, vegetation types, human influences, and agricultural management. The mechanism that influences the movement and modification of carbon within the soil ecosystem is referred to as the soil carbon dynamics. Plant residues and root exudates from living plants are the major carbon inputs into the soil (Feng, 2022)^[13]. Plants intake carbon dioxide from the atmosphere and convert it into organic compounds through photosynthesis. When plants die or shed leaves, these residues become inputs of carbon to the soil. Organic compounds released by living roots in soil are commonly known as root exudates. These organic compounds contain carbohydrates and soluble carbon. These inputs are decomposed by microorganisms in soil such as Bacteria and Fungi, Actinomycetes, a complex organic compound that is broken down into simpler forms (Vives-Peris *et al.*, 2020)^[44]. After the complete decomposition of complex organic compounds some compounds are left undecomposed which is termed Humus. (Senesi & Loffredo, 2018)^[37].

Soil organic carbon acts as a potential indicator of soil quality and plays a dynamic and critical role in maintaining global climate change through C emissions and sequestration. Soil organic carbon constitutes mainly composed of Dissolved organic carbon (DOC) and Particulate organic carbon (POC). Dissolved organic carbon (DOC) is the form of organic carbon in the soil solution that is directly involved in the soil biochemical processes (Shen *et al.*, 2021)^[40]. Living plant roots release substances known as root exudates into the soil, which include glucose and other forms of dissolved carbon. Microbes consume these compounds in the soil and produce a substance called

Particulate Organic Carbon (POC). POC is also formed by the physical fragmentation of structural residues and can be influenced by external environmental factors. Heavy-POC is formed when POCs from broken-down wastes and microbial by-products bond to silt and clay-sized soil minerals (Microaggregates production).

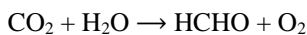
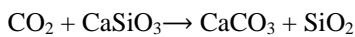
SOC contains several pools, namely active, slow and passive. The active pool of soil carbon (SOC) also known as the labile form of C consists mainly of recently decomposed plant and animal remains that break down quickly within a span of weeks, to a few years. Labile organic carbon is directly available for microbial activity and is easily mineralized. The nonlabile form of carbon or the passive SOC pool, is a stable and long-term source of carbon storage inside the soil matrix. This is also referred to as humus. These pools are vital for the carbon cycle and for understanding soil carbon dynamics, nutrient cycling, and long-term carbon sequestration. Humus and mineral associated organic carbon (organic carbon bound to mineral particles in the soil). This association protects the carbon from microbial decomposition by passive carbon pools in soil (Chen *et al.*, 2023)^[9]. In the study of carbon dynamics, the important terms are carbon sequestration and other is carbon stock.

The quantity of carbon stored in an ecosystem is referred to as "carbon stock." Typically, this measurement is stated in terms of carbon dioxide (CO₂), or carbon (C) (Hendriks *et al.*, 2020)^[18]. It plays a significant role in understanding forms, such as living organisms like plants and animals, soil and organic matter. To assess the impacts of changes in land use, deforestation, and other human activities on the equilibrium of carbon levels in Earth's atmosphere, the concept of carbon stock was crucial C outputs, such as mineralization, soil erosion, and losses, and C inputs, such as plant residues, secretions, and exudates of plants, animals, and microorganisms, often regulate the SOC

stocks. Soils store the majority of Earth's organic carbon. The SOC is influenced by time, temperature, vegetation, soil texture, and other factors. The dynamics of the SOC will also change in response to changes in the climate.

Global cycle of carbon

The constant movement of carbon between the Earth's atmosphere, biosphere, hydrosphere, pedosphere, and geosphere is known as the "Global carbon cycle." There are two types of cycles related to carbon the long-term and the short-term. Specifically, the long-term carbon cycle is the movement of carbon from rocks to the Earth's surface, which include the soil, ocean, atmosphere, and biosphere. Rainfall initiates the movement of carbon from the atmosphere to soil. Carbonic acid (a weak acid) is produced when water and atmospheric carbon interact. Chemical weathering is a process by which rocks dissolve in acids. Through this process calcium, magnesium, potassium, sodium ions are released and transported to the ocean via rivers. Calcium carbonate accumulates in the ocean when calcium and bicarbonate ions interact with each other. Calcium carbonates are produced by calcifying organisms, such as corals and plankton (including coccolithophores and foraminifera). Atmospheric CO₂ concentration over long periods of time (>100,000 years) is predominantly controlled by the carbon cycle. The major gases originating from atmospheric carbon sources are carbon-dioxide (CO₂), methane (CH₄), Carbon monoxide (CO), and non-methane hydrocarbons. This cycle is represented by simplified equations making it a crucial concept in understanding the dynamics of CO₂ in the atmosphere.



These carbonates can remain stored for millions to billions of years as they lithify into rock. However, the carbonates may undergo diagenesis and metamorphism at different pressures and temperatures during deep ocean burial, releasing some carbon dioxide back into the atmosphere and ocean. Carbonate-C in sediments is moved down into the mantle by the movement of the Earth's crust tectonic plates, and it is released into the atmosphere as CO₂ through volcanic eruptions or underwater vents.

Along with this process, atmospheric CO₂ is also taken by plants through photosynthesis, with a net flux of 0.4 Pg C in pre-industrial times. Some of this carbon is stored underground in the form of organic matter in sediment layers. These sediments, which containing approximately 150 Pg C, can also be transported into the mantle through subduction, releasing even more CO₂ into the air through volcanic activity. Alternatively, buried organic matter can undergo transformation into substances such as kerogen, oil, gas, and coal through diagenesis and metamorphism. Deposits of lignite and hard coal, with ages ranging from 10³ to 10⁹ years, have the capacity to store C for a very long period. In the meantime, 3,700 Pg C were found in a pre-industrial fossil fuel reservoir. Carbon is also released into the atmosphere through volcanic activity and undersea

vents; however, it also occurs naturally through the oxidative weathering of organic matter on land due to erosion. As the short-term carbon cycle continuously moves large quantities of C between the ocean, biosphere, and atmosphere, it is important to regulate the atmospheric CO₂ and methane (CH₄). Plants fix atmospheric CO₂ during photosynthesis and under aerobic conditions CO₂ is released into the atmosphere and CH₄ in anaerobic.

Sequestering carbon in soil to mitigate climate changes

Soil organic carbon sequestration includes humification, aggregation and deep incorporation of carbon in the subsoil and calcification. The applications of ecological concepts to management of natural resources (e.g., nutrient cycling, energy budget, soil engineering by macroinvertebrates, and enhanced soil biodiversity) may be important factors leading to improvements in soil quality and SOC sequestration. The are specific practices to improve SOC such as Mulching and conservation tillage

SOC in agricultural soils is depleted due to mechanical tillage and accelerated soil erosion. The presence of residues and on soil surface is the integral part of conservation tillage. This tillage increases SOC concentration by reducing soil disturbance, soil erosion, increasing filtration and maintains soil moisture and increase soil biodiversity. Tropical dryland of Uttar Pradesh in India results in 2.3 g/kg SOC gain by adapting conservation tillage. At Brazil in sandy clay loam soil have sequestered 44 Mg C/ha over 9 years.

Cover crops

Growing leguminous cover crops enhances biodiversity and quality of residue input. Thus, the high biodiversity sequesters more C than low biodiversity.

Nutrient management

Judicious nutrient management is important for humification process to sequester C in the soil. For sequestering 10000 kg of C in humus, 833 of kg N, 200 kg of P and 143 kg of s are required. Soil humus has low C: N, C:P and C:S than those in crop residues. Humification efficiency depends on availability of N, P, and S. Soil carbon has the ability to maintain soil structure due to its biochemical resistance, particularly through compounds such as lignin and melanin synthesized soil micro-organisms. The resistance rate was influenced by both soil moisture and soil temperature. Microbial activity rises with temperature, with each 10°C rise in temperature resulting in a doubling of this activity. In waterlogged condition decomposition rate slows down and becomes incomplete due to the absence of O₂ (Hartmann, 2023) ^[17]. When labile carbons are mixed into soil aggregates, they remain protected from breakdown. These aggregates are disrupted by either natural process (wet-dry) or human action (tillage) which promotes organic C decomposition which was present within the soil aggregates (Lei Wu, 2023). Soil structure protects soil carbon from decomposition. Structural stability is affected in cultivated soil and decreases amount of soil carbon which limits the proportion of soil macroaggregates.

Factors influencing SOC

Table 1: Factors influencing SOC in various ecosystem

Factors.	Influencing Mechanism	Wetland	Forest	Dryland	Mangrove	References
pH	OC negatively correlated	6.5 to 9.0	6 to 6.5	6.58 to 7.92	2.87-6.40	(von Lampe <i>et al.</i> , 2023);
Temperature	Negative correlation with temperature	24.4° C-1.1° C	10° C to 31° C	>70°C	13-23° C	(Breithaupt <i>et al.</i> , 2023; Grünzweig <i>et al.</i> , 2022; Inglett <i>et al.</i> , 2012; Li <i>et al.</i> , 2020) [6], [16]
Moisture	Positively correlated with SOC	23.72% (moist)	73.39%	16.01%	43- 88%	(Adeniran & Babatunde, 2010; Osman & Osman, 2018) [2], [32]
Decomposition rate	Negatively correlated to SOC	Low	High	High	low	(Adame <i>et al.</i> , 2023);
Erosion	Negatively correlated to SOC	Low	Low	High	Low	(SteinhoffKnopp <i>et al.</i> , 2021); (Ayoubi <i>et al.</i> , 2021)
Rainfall	Positively correlated to SOC	50-150 cm	7501500 m year ⁻¹	500 to 800 mm	>200 cm	(Singh <i>et al.</i> , 2024) [41]

In general, soils with pH values ranging from neutral to slightly acidic have high organic carbon. Organic matter breakdown in acidic (low pH) soils frequently results in increased carbon accumulation. In contrast, due to more microbial activity and quicker degradation, alkaline soils (high pH) contain low organic carbon. Soil carbon loss occurs rapidly when decomposition rates are higher which was brought about by the release of CO₂ into the atmosphere as a result of the breakdown of organic compounds. Soil carbon storage increases when breakdown rates are slower because more organic matter are formed as humus. SOC decomposition is accelerated by increasing soil temperature. Temperature-dependent activities carried out by microorganisms accelerate the release of carbon dioxide (CO₂) from the soil into the atmosphere. Appropriate rainfall enhances plant growth, increases litter inputs, and promotes microbial activity, all of which support the formation of SOC. When the soil moisture was below the optimum range soil microbial activity decreases which results in slower decomposition rate and increases SOC. water and wind erosion increase the amount of SOC decreased which was most common in dryland ecosystem.

Forest ecosystem

Forest soils are world's largest carbon sinks, because of their high organic matter content, and plays a vital part in the global carbon cycle. Terrestrial and subterranean living biomass, dead wood, litter, and soils are the main carbon stores in forests. Major input of carbon to forest ecosystem is through photosynthesis, autotrophic respiration. Autotrophs utilize CO₂ as their only source of carbon, producing the crucial biomass that sustains all other organisms. Gross primary production (GPP) is precisely defined as the total amount of CO₂ absorbed by autotrophic tissues and used for photosynthesis. Autotrophic respiration (R_a) plays a critical role in this carbon loss. The remaining C is used for other processes, such as the growth of plant biomass. The *Net Primary Production (NPP)* is a measure of the imbalance between gross primary production (GPP) and R_a

$$GPP = NPP + R_a$$

An estimated 75 Pg C of carbon is exchanged annually between forests and the atmosphere (GPP). Approximately half of the annual terrestrial NPP is found in wooded areas, accounting for 63 Pg C worldwide (Grace, 2016) [15].

Carbon Dynamics Dynamics of Carbon in Trees

Carbon was fixed through photosynthesis and then transported and partitioned throughout the different parts of trees. As part of photosynthesis or GPP, partitioned is defined as the flux of C to a certain component. Certain parts of trees, including the young leaves, stems, branches, reproductive organs, and roots, function as vital carbon sinks. An abundant source of carbon can be found in the stems of trees, with the highest concentration of this carbon found in wood, specifically in lignin. Interestingly, a portion of the carbon generated through photosynthesis is also transferred to mycorrhiza and microorganisms in soil, completing the cycle.

Carbon sinks within Plants

Table 2: Carbon storage forms within plant parts

Tree component	Carbon sink
Chloroplast	Wax, cutin, tannin, pectin, lignin, cellulose, hemicellulose, starch, and foliage proteins
Stem	Cellulose, hemicellulose, pectin, tannin, suberin, starch, and lignin
Reproductive materials	Proteins, starch, fat, sporopollenin, pectin, tannin, sucrose, fructose, and glucose
Roots	suberin, and lignin carbohydrates

Source: Sequestration of carbon in Forest Ecosystems (Lorenz & Lal, 2009) Carbon dynamics in Soil

Fluxes of dissolved carbon

The precipitation on forest brings dissolved C with it. The rain that reaches the soil is enriched with DOC due to compounds leaching from plant surfaces, while the DIC level may be similar to that of the original rain. A major factor in the synthesis of DOC in throughfall is the breakdown of chemicals from plant surfaces as well as soil and plant matter deposited on plants. Their leaves release organic components such as carbohydrates, organic and amino acids, alkaloids, and phenolics. The amount of throughfall in forests can vary significantly, both within and between different forests. In a northern hardwood forest, the carbon (C) flow with throughfall was minimal, making up less than 2% of the C flow from litterfall. This can be attributed to the fact that younger leaves are less prone to leaching compared to older leaves, and conifers are more resistant than deciduous trees. However, tropical rainforest plants are not as easily leached.

Litter Input

A substantial quantity of the net primary productivity (NPP) in the soil arrives from the breakdown of above and belowground plant litter. When the latitude gradient rises from tropical to boreal woods, the amount of litterfall decreases. Another factor contributing to litter input in forests is fire, which is particularly prevalent in boreal forests and can consume up to one-third of global boreal forest NPP. Burning plant components that are above ground minimizes the quantity of litter input. In extreme cases, even the roots are burned to further reduce the amount of litter. Quantity of NPP deposited through root turnover that is lower than that of aboveground turnover. Only a portion of litter C is progressively held in the forest floor, among the coarse woody debris (CWD) and the mineral soil, as it is deposited by various processes.

Decomposition

In terrestrial ecosystem, a significant amount of photosynthetic carbon is eventually processed by decomposers. The decomposition process begins with dead organic materials. Through this process, various types of detritus, including Rhizodeposits, plant litter, microbial activity, and fauna are effectively broken down and contribute to SOC. The compounds, such as lignin, lipids, waxes, cutins, and suberin, play a significant role in resisting decomposition, particularly in the early stages. Rhizodeposits consist of organic acids, proteins, carbohydrates, and amino acids, which are generally considered to have a lower level of resistance. Dead standing trees and decomposing logs, or CWD, are the sites of another significant decomposition process in forest ecosystems. Numerous processes, including microbial decomposition, combustion, insect ingestion, and physical degradation, have an impact on CWD. Notably, recalcitrant SOM fractions may be more affected by CWD than by fine litter.

Carbon sequestration

Boreal forests store enormous amounts of carbon in their soils, while tropical forests sequester the majority of their carbon in their flora, or biomass. SOC is a vital component of the carbon pools in forest ecosystems due to upper layers with maximum root density. Soil, litter, and forest vegetation are the three main sources of carbon sequestration in the forest ecosystem (Hérault & Piponiot, 2018; Lafleur *et al.*, 2018; Lee *et al.*, 2014) ^{[19], [23]}. Studies from the subcontinent shows that mountain forest could store more carbon (45.6 to 73.26 tonnes ha⁻¹) which is higher than tropical dry forest (36.04 tonnes ha⁻¹). Labile SOC are mineralized and nutrients are removed under forest vegetation, which helps to maintain agricultural output for a few years. However, intensive farming practices including draining, weeding, adding lime, adding mineral fertilizers, and tilling accelerate up the decomposition of SOC and increase atmospheric carbon emissions. Erosion processes alone release 1.14 Pg of CO₂ into the atmosphere every year. Tropical forests alone contain a 389 Pg C in plant biomass, followed by temperate forests with 159 Pg C and boreal forests with 67 Pg C. This means that 81% of the world's plant carbon pool can be found within forest ecosystems. Interestingly, the C storage pattern in these vital forests varies as well. The largest SOC pool to a depth of 1m is found in boreal forests at 338 Pg C, with tropical forests

following closely behind at 214 Pg C and temperate forests at 153 Pg C. However, tropical forests have a higher concentration of SOC in the 1–3 m range compared to the 0–1 m range. Additionally, temperate forests and boreal also play an essential role in the storage of carbon below a depth of 1m. The typical ratio of carbon pools in soil to plants varies from approximately 2:1 in temperate forests to 5:1 in boreal forests and 1:1 in tropical forests. Different tree species have different levels of carbon sequestration effectiveness due to differences in growth, death and decomposition, and dependence on climate. For the boreal biome, the range of C intake is 0.49 to 0.7 Pg C year⁻¹. 0.37 Pg C year⁻¹, and 0.72 to 1.3 Pg C year⁻¹ for the tropical forest habitat.

Mangrove Ecosystem

Mangrove forests are well-known for their high productivity and efficient trapping of suspended particle from the water. Mangrove soils receive a significant amount of their organic carbon through underground root growth and the abundant litter from trees, including leaves, propagules, and twigs (Song *et al.*, 2023) ^[42]. It is estimated that litterfall accounts for about one third of the net primary output. Along with these inputs, there are other important sources of organic carbon, such as allochthonous (from outside) material from rivers or the sea, autochthonous (produced in the same place) micro or macroalgae, and nearby production by phytoplankton in the water column.

A recent study on mangrove wetlands in the Indo-Pacific region has revealed that they average storage of 1023 Mg C ha⁻¹ ± 88. By taking into account factors such as tree size, density, biomass from dead wood, soil depth, and soil carbon content mainly contributed in carbon sequestration. In tropical upland, temperate, and boreal forests, the average carbon stock typically ranges from 200 to 400 Mg C ha⁻¹. This is more than 2.5–5 times higher than that rate. Thus, mangrove wetlands are among the tropical forests with the highest carbon concentration. The storage of carbon in mangroves, found in a variety of environments ranging from deltas to estuaries and even oceanic islands, is greatly impacted by the biomass growth in these forests as well as the carbon stored in the soil. According to the Intergovernmental Panel on Climate Change, these complex ecosystems play a major role in the global exchange of CO₂. Deforestation and land use changes are responsible for 8–20% of the carbon dioxide emissions generated from human activity. This implies that the one third of mangrove areas was as lost by land use changes and degradation which had a substantial impact on global carbon levels. Previous studies have emphasized the need to protect and restore mangrove forests in order to mitigate climate change and reduce carbon emissions, considering their vital role in carbon sequestration.

Carbon sequestration process

The mangrove trees comprised of wide range of compounds including triterpenoids, fatty acids, carbohydrates, amino acids, tannins, and phenols produced by lignin. The majority of the organic carbon in mangrove wood 65.5% is built up of carbohydrates. Additionally, lignins contribute to the overall yield by producing eight basic phenols, which make up 0.5 to 1.5% of total organic carbon in leaves and 3.8 to 5.1% in wood material. In the shallow waters of aquatic environments, there are two main sources of carbon:

through photosynthesis by plants and trees and the input of allochthonous carbon from the surrounding land, sea, and sky.

Mangroves are responsible for the majority of carbon fixation from the atmosphere. Macroalgae is the largest contributor of carbon storage which is attached to the aboveground roots of the mangroves, followed by microalgae that cover the forest floor. Finally, there is the movement and deposit of materials from the nearby coastal zone and upstream. On average, these trees contribute 58% of the soil carbon, while the remaining balance comes from a combination of seawater inputs and runoff from upland areas. Each year, soil accretion rate is roughly 5 mm and the carbon sequestration rate is about 174 g C m⁻². Globally, mangroves bury a staggering 24 Tg C annually.

Although mangroves have long been seen as the primary source of organic carbon for these marine creatures, it is now recognized that they also rely on a variety of other food sources. These comprise macroalgae, external sources brought in by tidal currents, bacteria, fungus, benthic microalgae, epiphytic algae, and mangrove trash (Kathiresan, 2022) [21]. The actions of these consumers can significantly impact the organic carbon cycle within mangrove systems. Microbes form dense mats in mangrove sediments, contributing a significant amount of organic carbon (up to 90%). Furthermore, found that early phase of mangrove forest formation is characterized by a high proportion of algal material in the sedimentary organic carbon. Overall, mangrove sediments tend to have a relatively high content of OC, with a medium Particulate organic carbon of 2.2%.

As deposited mangrove litter began to decompose, an abundance amount of soluble organic substances is released through leaching. Submerged mangrove litter that has only recently fallen can lose 20-40% of its organic carbon within 10-14 days in seawater. This rapid leaching process is mainly attributed to non-lignocellulose components such as carbohydrates. Almost 97% of cyclitols, a type of carbohydrate, are quickly lost through the decay of mangrove leaves. Additionally, tannins and other phenolic compounds found in the litter, which have the ability to inhibit microbial growth, make up an essential portion, of the dissolved organic matter (DOM) in mangrove leachate up to 18%. The leached DOM in mangroves is a highly labile substance that can be efficiently degraded in oxic and nutrient-rich environments. In fact, up to 90% of the polysaccharide (specifically, cellulosic) components of lignocellulose can be converted into microbial biomass.

Carbon output

Aerobic microorganisms have the remarkable ability to fully oxidize organic carbon to CO₂ using their enzymes. In the absence of oxygen, fermenting prokaryotes break down large organic molecules into smaller components. These smaller molecules of carbon were then completely converted to CO₂ by a different kind of anaerobic organisms, utilizing different electron acceptors in a sequential manner for energy production. The electron acceptors (Mn⁴⁺, NO₃⁻, Fe³⁺, and SO₄²⁻) are depleted and there is an excess of electron donors, then fermentation processes lead to the production of CH₄ from simple compounds like acetate, the reduction of carbon-dioxide (CO₂) by substances such as alcohols. Therefore, sulfate reduction is crucial in preventing the accumulation of

sufficient levels of hydrogen and acetate to sustain the growth of methanogenic microorganisms. Mangrove sediments typically exhibit low and fluctuating rates of methane production. Although the activity of methanogenic organisms, the level of CH₄ present in surface sediment porewaters was generally minimal as it is simultaneously eliminated by anaerobic CH₄ oxidation. As a result, methane emissions from these deposits are almost negligible, typically ranging from 0 to 5 mmol/m²/d. In the dark, it is estimated that the average global emission of CO₂ from mangrove residues was around 27 mol/m²/year. However, this emission rate could increase significantly due to the presence of open crab burrows. These burrows efficiently transport CO₂ gas from deeper sediments and release it into the atmosphere.

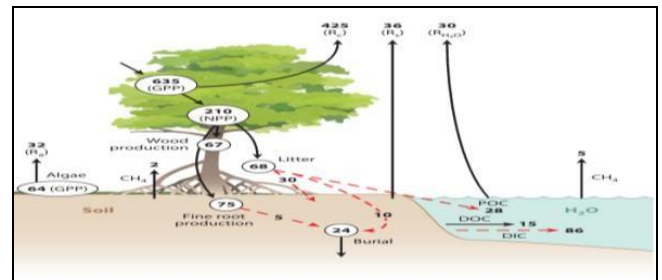


Fig. 1: Carbon flow through the world's mangrove ecosystems (All values are in Tg C y⁻¹)

Abbreviations: Particulate organic carbon (POC), gross primary production (GPP), net primary production (NPP), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC); Ra, respiration of algae; R_s is soil respiration; R_c is canopy respiration. Waterway respiration and RH₂O.

The average amount of CO₂ released globally from mangrove sediments at night is around 27 mol/ m²/year or 75 mmol/m²/d this ranges from 2 to 373 mmol m⁻² d⁻¹. However, recent measurements have demonstrated that open crab burrows and pneumatophores exposed to air significantly enhance CO₂ emissions to the atmosphere by effectively transferring CO₂ gas from deeper strata. So, according to Kristensen's research, 100 *Sonneratia alba* pneumatophores m⁻² and 100 *Avicennia marina* pneumatophores m⁻² each contribute roughly 170 mmol CO₂ d⁻¹ and 60 mmol CO₂ d⁻¹ respectively, to the basic rate measured for bare sediment.

Mangrove forests play a crucial part in the export of organic carbon. In addition to being emitted into the water column by tidal pumping of porewaters rich in DOC, suspended solids (POC) and floating debris also release DOC. The POC was disseminated at a rate of 3 mol C m⁻² year⁻¹ which was mainly attributed to leaf litter, as indicated by stable carbon isotope and lignin. In a particular mangrove forest, the export of POC and debris together amounts for 40% of the entire litter fall. Debris, POC, and DOC together account for 20 mol/C/m² of the total organic matter fractions exported every year. The molecular lignin profile of this DOM revealed that the primary source of DOC leaking out of the sediments is the breakdown products of mangrove detritus, primarily *Rhizophora mangle* (red mangrove) and *Avicennia germinans* (Black mangrove) litter. There, two major sources of DOM could be the stable carbon isotope composition of DOC closely followed the tidal cycle, and indicated inputs of ¹³C-enriched (seagrass) material into the

mangrove during flood tide, and ^{13}C depleted mangrove DOM leaving the system during ebb tide. A significant portion ($12 \text{ mol/C/m}^2/\text{year}$) of this organic matter was eventually carried through the shelf as DOC, most likely following widespread photo-chemical and microbial alteration.

Dryland ecosystem

Drylands had their distinctive combination of vegetation and exposed, parched earth. These areas are subjected to unpredictable rain patterns, resulting in drought-stricken plant life (Serrano-Ortiz *et al.*, 2010) [38]. Despite their resilience in the extreme weather, drylands were highly susceptible to disturbances like droughts, wildfires, and shifts in climate, which can ultimately lead to desertification which was referred to as land degradation occurs due to a combination of natural climate fluctuations and human activities. Drylands currently cover approximately 45.36% (or approximately 147 million km^2) of Earth's land area, are experiencing expansion due to the influence of climate change and human activities. Approximately 57% to 65% of the total 3.5 to 4.0 billion ha area is currently facing desertification or is at risk of facing it in the future (Plaza-Bonilla *et al.*, 2018) [33]. The Aridity Index (AI) quantifies the dryness of a region based on its precipitation and potential evapotranspiration (PET). It helps classify areas into different aridity levels, from hyper-arid to semi-arid. Aridity Index with $< 0.05 \text{ mm mm}^{-1}$ is arid regions and AI with $0.05\text{-}0.2 \text{ mm mm}^{-1}$ is semi-arid (Präválie, 2016) [34]. In arid regions, such as the Mediterranean, China, and Africa, carbonate rocks dominate the landscape. Interestingly, these rocks not only play a critical role in the transfer of carbon through photosynthesis and respiration, but also in other processes that either sequester or emit carbon into atmosphere. Deserts in Asia and Africa, known as hyperarid regions, have the potential to store approximately $0.04\text{-}0.40 \text{ kg}$ of carbon per square meter in plant bio-mass. Although drylands have low quality soils and lack consistent vegetation, they cover a significant portion of the earth's surface. This accounts for the estimated 400 Pg C stored in soil organic C (SOC), and their contribution of 20-30% to the terrestrial carbon pool.

Carbon cycle in dryland

The Carbon Cycle in Dryland, or CCD, shares key elements with the global carbon cycle (GCC), including the transfer of gases between the atmosphere, plant, soil, and ocean. Drylands have a significant impact on the global soil carbon stock, with a majority of it being inorganic carbon (SIC) rather than soil organic carbon (SOC) (Fig.8). The quantity of carbon stored in vegetation, above and below ground, is significantly lower (Blakemore, 2023) [4]. An estimated 95% of the SIC stock is found in drylands through the natural processes such as caliche and concrete formation. This carries the total SIC stock to $1237 \pm 15 \text{ Pg}$ for depths up to 2 meters. Drylands, on the other hand, have relatively low SOC densities, ranging from $1\text{-}3 \text{ kg Cm}^{-2}$ in Africa and North & Central America to $2 \text{ to } 7 \text{ kg C m}^{-2}$ in Asia (Serrano-Ortiz *et al.*, 2010) [38]. Approximately 11% of drylands are used for cultivation, with 30% dedicated to pastures. These agricultural areas have the capacity to store both Soil Organic Carbon and Soil Inorganic Carbon through implementing effective cultural practices. The potential C stock in hyper-arid and arid regions could be as high as 732-

Pg C . This is significantly higher than the global average estimate of $65\text{-}\text{Pg C}$ for dryland vegetation. In fact, in certain regions such as steppe grasslands and dry savanna, arise in carbon biomass stock can lead to surge in Soil Organic Carbon (SOC) and Soil Inorganic Carbon (SIC) stocks.

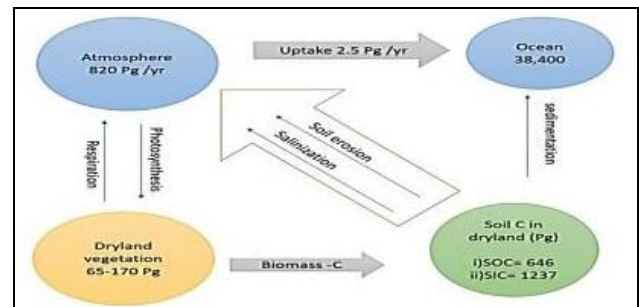


Fig 2: Carbon dynamics and stocks in Dryland ecosystem

Carbon sequestration

The amount of SIC stock found in drylands was made up of three main components: (i) primary carbonates that originate from calciferous rocks and other parent materials through weathering, (ii) secondary carbonates, also known as caliche or concrete, that form through soil processes and are impacted by land-use and soil management (Wang *et al.*, 2016) [46], and (iii) bicarbonates that have been leached into and reside in the ground water. Overall, the global SIC stock, encompassed of primary and secondary carbonates, is measured to be 1237 Pg in the first 2 meters of depth, with a supplementary 1404 Pg stored as bicarbonates in the ground water. It is estimated that drylands have the potential to sequester approximately $0.5 \text{ to } 1.4 \text{ Pg C/year}$ of soil carbon globally. To put this into perspective, during the last global maximum, the carbon stock in the atmosphere was around 360 Pg (Le Quéré *et al.*, 2018). During the preindustrial era, it reached 560 Pg and currently stands at 820 Pg , with an annual increase of approximately 4.7 Pg C . The total quantity of SOC in dryland areas was 241 Pg , accounting for 15.5% of the global's overall SOC of 1550 Pg at a depth of 1 meter. Unfortunately, desertification has led to a significant loss of 20 to 30 Pg of carbon.

In dryland ecosystems, secondary carbonates were formed as a way of sequestering SIC in addition to SOC. Carbonic acid was first formed by the dissolution of Carbon dioxide (CO_2) in the soil, which reacts with Ca^{+2} or Mg^{+2} , leads to the formation of carbonate which gets precipitated on the subsurface. (Cailleau *et al.*, 2004) found that fungi, lichens, and cyanobacteria were involved in the biomineralization processes responsible for calcite dissolution and precipitation. Breeman and Protz (Breeman & Protz, 1988) [5] reported that $6.8 \text{ g C/m}^2/\text{y}$ was the rate at which secondary carbonates formed when 5 Mg/ha/y of biomass was added. while an addition of 20 Mg/ha/y showed a rate of $13.9 \text{ g C/m}^2/\text{y}$. It was also enhanced the activity of soil fauna, particularly termites. These tiny creatures play a vital role in the creation of secondary carbonates. Interestingly, termites that feed on humus and those that produce CH_4 and CO_2 may contribute to the formation of biogenic carbonates through their activities. The elevated concentration of carbonates in the soil surrounding plant roots was attributed to the release of calcium ion (Ca^{+2}), HCO_3 , and acidic substances. The production of CaCO_3 occurs both inside and outside of the roots as a result of these rhizosphere

processes. Additionally, soil fertility improvement methods, such as the use of biosolids, can also promote the development of secondary carbonates. As soil fertility improves, there is a boost in the growth of root and shoot biomass, which, upon decomposition, results in a higher release of CO₂ into the soil air. Moreover, the introduction of Calcium ion (Ca²⁺) through fertilizers and other soil additives also contributes to the formation of secondary carbonates (Rattan, 2023) [35]. According to (Sahrawat, 2003), the SIC pool includes both primary inorganic carbonates and secondary inorganic carbonates, such as lithogenic and pedogenic carbonates. The addition of Ca²⁺ through silicate weathering or atmospheric deposition, along with a negative water balance, can lead to the formation of calcite and the sequestration of SIC. The influence of noncarbonate materials, such as caliche, to inorganic C formations ranges from 0.12 to 0.42 g C/m²/year. These formations were relatively stable, with turnover periods of over 1000 years resulting in the complexity and longevity of the SIC pool.

Carbon output

Carbon in dryland lost to atmosphere by means of desertification, soil erosion, soil salinity. Salinization reduces the amount of biomass-C that is incorporated into the soil and causes a loss of NPP, it increases SOC depletion. An average of 3.47 mg SOC/ha has been lost from saline soils, which cover over 397 M ha. According to (Lal, 2004) [24], desertification has caused a significant reduction of 9–14 Pg C in the ecosystem's carbon storage, with the biotic/vegetation pool alone experiencing a loss of 10–15 Pg C. According to a recent study was estimated that desertification has caused a 13–24 Pg loss of carbon in the world's grasslands and drylands. Accelerated soil erosion poses a threat to the estimated 50.5 Pg total SOC stock accelerated water erosion have already reduced SOC stocks by 25 Pg and 53.6 Pg, respectively (Darwish & Fadel, 2017) [10].

Table 3: Comparative study on different ecosystem

Ecosystem	Carbon input source	Carbon output source	Amount of carbon sequestered	Reference
Wetland	Plant debris, Root exudates, sediments accumulation	Methanogenic bacteria, Anaerobic bacteria, Terrestrial Runoff	500 Pg of C	(Bridgham <i>et al.</i> , 2014; Were <i>et al.</i> , 2019)
Forest	Plant litters, Deadwood, Photosynthesis, organic matter, microbes	Respiration, Decomposition, Wild fires, Deforestation	Tropical forest-398 Pg of C, Temperate forest 159 Pg of C, Boreal forest -67 Pg of C	(Lal <i>et al.</i> , 2018; Lorenz & Lal, 2022) [26], [30]
Dryland	Formation of caliche, pedogenic carbonates, leaching of bicarbonates, photosynthesis, weathering of silicate minerals	Decomposition, Desertification, soil erosion, soil salinization, phytodegradation, wild fires	732 Pg of C	(Chappell <i>et al.</i> , 2019; Hoyle <i>et al.</i> , 2013; Lal, 2019; [8], [25] Schlesinger, 2017; Setia <i>et al.</i> , 2013; Sietz <i>et al.</i> , 2011) [20], [36]
Mangrove	Photosynthesis, macroalgae, microalgae, Deposition from upstream and adjacent coastal zones, plant litters	Pelagic metabolism Respiration, tidal export macrofauna (fish, crab)	2500 Pg of C	(Dittmar <i>et al.</i> , 2006; Feller <i>et al.</i> , 2010; Giri <i>et al.</i> , 2011; Kristensen, 2007; Mitsch <i>et al.</i> , 2015) [11], [12], [14], [22], [31]

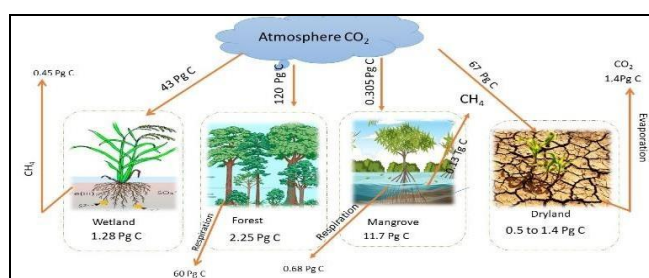


Fig :3 Carbon Sequestration and Losses in different ecosystem

Future challenges

Research conducted in agricultural ecosystem across the globe has revealed that increasing atmospheric CO₂ causes plants to assimilate more carbon. It also causes litter accumulation in natural systems and crop residues in agroecosystems, which increases soil carbon storage. The Studies revealed that mangrove ecosystem can sequester more SOC as compared to other ecosystem. Soil's potential to sequester carbon will depend on its primary productivity, which is restricted by the soil, climate, and management. The effects of climate change, particularly rising temperatures, pose a threat to the level of carbon stored in the soil. Many factors are responsible for carbon

sequestration and loss which may varies to each agro-ecosystem. Still there is a lack of information about the factors influencing carbon dynamics on soil. Despite the experimental research discussed in this work, modelling of Carbon dynamics has been done to examine how various agro-ecosystem soil C dynamics are affected by their combination properties and potential climate change. Such research is required to ascertain the function of soil in storing carbon and to develop management strategies that maximize soil carbon sequestration.

Conclusion

Soils are vital in regulating atmospheric CO₂ levels and have the capacity to store significantly more carbon than the atmosphere itself. Unfortunately, the effects of climate change, particularly rising temperatures, pose a threat to the level of carbon stored in the soil. Agricultural soils have been responsible for depleting approximately 42x10³ – 78x10³ Mg of carbon from the historical terrestrial carbon pool. There are several tactics that can be used to increase the quantity of carbon sequestered in the soil. These include reducing tillage, increasing inputs of crop residues and manure, managing nutrients, eliminating summer fallows, and restoring permanent forests and grasslands. An effective

and efficient method for enhancing carbon sequestration is by implementing No tillage practices when planting crops. The levels of temperature and precipitation in arid and semi-arid regions have a significant impact on the potential for soil carbon sequestration, as they directly affect biological processes both below and above the ground. This means that implementing agricultural practices to specific regions can play a crucial role in reducing carbon footprints. To enhance carbon storage in drylands implementation of less extreme forms of land use practices, such as minimum- or no-till methods in agriculture. By allowing crop residues to remain on the soil surface and falling the frequency of uncultivated croplands and impermanent grazing prohibitions in grassland areas, we can potentially see a 20% increase in soil organic carbon (SOC) levels with no-till management and a 45% increase with a decrease in grazing activity in grasslands. These strategies present feasible options for enhancing SOC sequestration in drylands. Therefore, variations in precipitation patterns are expected to significantly affect both the absorption of carbon by plants and carbon storage in the soil. Carbon dynamics on different ecosystem should be maintained separately. Among the diverse ecosystem, mangrove sequester larger amount of carbon (Table 2). In conclusion, soil carbon dynamics are pivotal for our understanding of future atmospheric CO₂ concentrations and climate change. Researchers continue to explore this complex field, aiming to unravel the intricate processes that govern soil carbon storage and fluxes.

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