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Carbon trading, carbon budgeting and carbon sequestration in relation to Agriculture

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Abstract

Agricultural systems are significant contributors to global greenhouse gas (GHG) emissions, primarily through methane (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂) fluxes associated with livestock production, fertilizer application and land-use change. This review critically synthesizes the concepts of carbon trading, carbon budgeting and carbon sequestration within the framework of climate-smart agriculture. Carbon trading mechanisms, including emissions trading systems, facilitate cost-effective mitigation through market-based allocation of emission allowances. Carbon budgeting provides a scientifically grounded approach linking cumulative CO₂ emissions to global temperature thresholds, thereby guiding mitigation targets aligned with international climate agreements. Carbon sequestration, particularly in terrestrial ecosystems, enhances soil organic carbon pools and contributes to long-term climate mitigation while improving soil health and ecosystem services. Agroforestry systems and sustainable land management practices are identified as key strategies for enhancing carbon storage. The integration of these approaches offers a comprehensive pathway toward achieving carbon neutrality, enhancing resilience and ensuring sustainable agricultural productivity under changing climatic conditions.

Keywords: Carbon trading, carbon budgeting, carbon sequestration, sustainable agriculture, greenhouse gas emissions

Introduction

Agriculture plays a vital role in ensuring global food security and sustaining livelihoods; however, it also represents a major source of climate change drivers. Greenhouse gas (GHG) emissions arising from agricultural systems particularly livestock production, crop cultivation and land-use and land-cover changes contribute an estimated 10-12% of total global anthropogenic GHG emissions. With the global population expected to approach 9 billion by 2050 and climate change intensifying environmental stresses such as droughts, floods and heatwaves, there is a pressing need to reorient agricultural systems toward practices that reduce greenhouse gas emissions while strengthening climate resilience ^[19].

Origins and Key Drivers of Greenhouse Gas Emissions in Agriculture

Agricultural practices contribute to greenhouse gas emissions mainly through the release of methane (CH₄) and nitrous oxide (N₂O), both of which have high global warming potential. Livestock production, especially involving ruminant animals such as cattle, sheep and goats, represents a major source of methane due to enteric fermentation during digestion. In addition, manure management practices including storage, treatment and soil application can generate methane emissions when manure is decomposed under anaerobic conditions. In contrast, nitrous oxide emissions are largely linked to the use of synthetic nitrogen fertilizers, biological nitrogen fixation by leguminous crops and the microbial decomposition of organic matter in agricultural soils ^[19]. Land-use change, deforestation and the expansion of agriculture into natural ecosystems lead to the release of carbon dioxide (CO₂) into the atmosphere, thereby intensifying the greenhouse effect. Beyond methane and nitrous oxide, CO₂ emissions arising from land-use change and agricultural operations make a substantial contribution to the overall greenhouse gas footprint of the agricultural sector. Deforestation, driven largely by the conversion of forested land to agricultural use, releases vast amounts of carbon previously stored in biomass and soils,

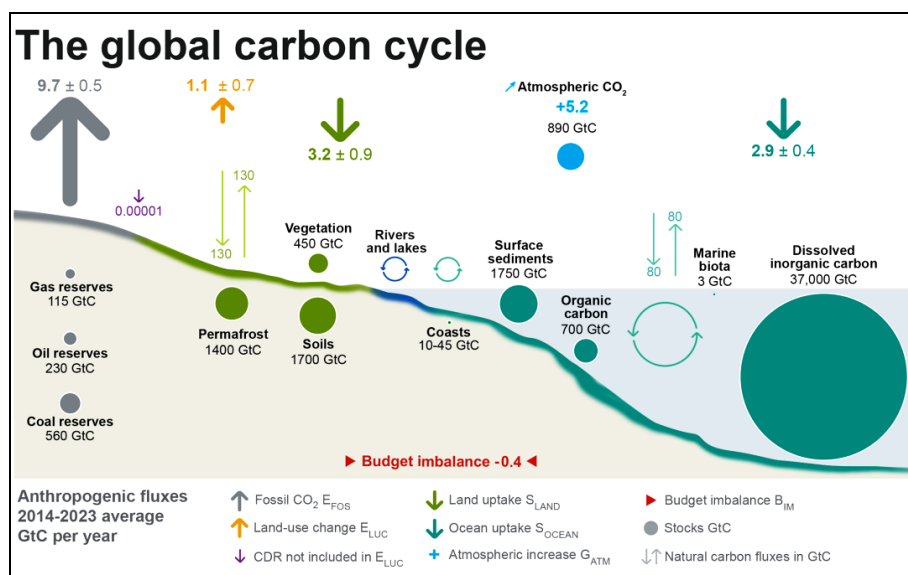
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representing a significant share of global CO₂ emissions. Furthermore, land degradation, soil erosion and peatland drainage associated with agricultural activities can amplify CO₂ emissions by diminishing the carbon sequestration potential of soils and ecosystems [9].

Possible Effects of Climate Change on Agricultural Productivity

Climate change presents substantial risks to agricultural productivity and global food security by influencing crop performance, livestock health and water availability. Increasing temperatures, altered precipitation regimes and a higher frequency and intensity of extreme weather events - including droughts and floods can disrupt agricultural production systems and intensify existing structural vulnerabilities. Changing climatic conditions may also modify the spatial and temporal distribution of pests and pathogens, resulting in increased crop damage and yield reductions. Smallholder farming systems, particularly in low-income regions, are especially vulnerable due to limited adaptive capacity, technological access and financial

resources to withstand climatic shocks. Furthermore, variability in rainfall patterns and freshwater availability can significantly affect crop water requirements, irrigation efficiency, and sustainable water resource management, thereby constraining overall agricultural productivity [17, 22]. Droughts, floods and highly variable rainfall patterns can disrupt cropping calendars, reduce crop productivity and constrain water availability for irrigation, particularly in rainfed farming systems. In arid and semi-arid regions, where water scarcity is already severe, climate change intensifies competition for limited water resources among agriculture, industry and domestic sectors. Moreover, changes in the frequency and magnitude of extreme climatic events - such as hurricanes, cyclones and typhoons - can result in substantial crop losses, damage to agricultural infrastructure and accelerated soil erosion, thereby weakening agricultural resilience and rural livelihoods, especially in vulnerable communities. Additionally, climate change can influence the distribution, abundance and dynamics of pests, diseases and invasive species, creating further constraints on agricultural productivity and food security [10, 20].



Source: Global Carbon Budget 2024

Fig 1: The Global Carbon Cycle

Carbon trading

Carbon trading constitutes a sophisticated market-oriented policy instrument for climate change mitigation, facilitating the regulated exchange of emission rights associated with six principal greenhouse gases - carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆). At present, multiple emissions trading schemes (ETSs) are in operation across various regions worldwide. Eg; The European Union Emissions Trading System (EU ETS), the Regional Greenhouse Gas Initiative (USA), New Zealand Emissions Trading Scheme, Tokyo metropolitan trading scheme, the New South Wales Greenhouse Gas Abatement Scheme (Australia) [16]. According to the Intergovernmental Panel on Climate Change (IPCC), achieving carbon neutrality in global energy systems by approximately 2050 is essential to restrain global temperature rise to within 1.5 °C. The decarbonization of energy systems particularly the fossil fuel dominated power sector, which contributes nearly 40% of global carbon emissions is therefore central to climate change mitigation. To curb global warming through emission reductions, a range of strategies and

policy instruments are being implemented to enable a low-carbon transformation of the energy system, encompassing interventions on both the supply and demand sides. On the energy supply side, the expanding integration of renewable energy sources particularly solar photovoltaic (PV) and wind power, alongside carbon capture, utilization and storage (CCUS) technologies has been widely recognized as an effective pathway for reducing carbon emissions within energy systems. In alignment with this transition, the United Nations Sustainable Development Goal 7 advocates for access to affordable and clean energy, with a specific objective of significantly increasing the share of renewables by 2030. Accordingly, numerous countries and subnational regions, including Hawaii, California and several developing economies, have committed to achieving 100% renewable electricity generation by the middle of the century. On the demand side of the energy system, distributed generators (DGs), energy storage systems (ESSs) such as lithium-ion batteries and flexible, controllable loads, including electric vehicles and heat pumps, significantly enhance system flexibility and enable consumers to act as prosumers by both consuming and supplying electricity. In parallel, peer-to-peer

(P2P) electricity trading platforms, such as Piclo in the United Kingdom, Vandebron in the Netherlands, and the Sonnen Community in Germany, illustrate how distributed energy resources (DERs) can be efficiently and economically integrated into modern energy systems ^[11].

Carbon budgeting

The concept relies on estimating the global carbon budget, which represents the total quantity of carbon dioxide (CO₂) emissions that can still be released into the atmosphere without surpassing a specified global temperature threshold. This estimation is directly linked to the Paris Agreement climate goals, which aim to restrict the increase in global average temperature to 2°C and ideally 1.5°C above pre-industrial levels (Zhai *et al.*, 2018). Carbon budgeting links climate science with policy decisions by translating temperature limits into allowable greenhouse gas emissions. The concept became prominent in climate research around 2009, when studies showed a direct relationship between cumulative carbon emissions and global temperature increase. Scientific studies demonstrated that global warming is approximately proportional to cumulative CO₂ emissions, meaning each additional tonne of CO₂ contributes to further warming. Carbon budgeting provides a scientific basis for achieving international climate targets, such as limiting warming to 1.5°C or 2°C above pre-industrial levels. The concept gained global recognition after being included in IPCC assessment reports, making it a central framework for climate mitigation strategies. Recent research shows that carbon budget estimates vary due to uncertainties in climate models, non-CO₂ emissions, and Earth system feedbacks. Overall, carbon budgeting provides a geophysical foundation for achieving net-zero emissions, emphasizing that global CO₂ emissions must eventually decline to zero to stop further warming ^[9]. Atmospheric carbon dioxide (CO₂) concentration has risen markedly since the onset of the industrial period. During the pre-industrial baseline year of 1750, the global atmospheric CO₂ level was approximately 278 parts per million (ppm). Continuous anthropogenic emissions from industrialization, fossil-fuel combustion and land-use change have substantially elevated atmospheric CO₂ levels. By 2023, the mean global atmospheric CO₂ concentration had increased to 419.3 ± 0.1 ppm, indicating a significant accumulation of greenhouse gases in the atmosphere. This increase represents a major shift from the pre-industrial equilibrium state of the global carbon cycle, reflecting intensified anthropogenic carbon fluxes to the atmosphere. Global fossil fuel-derived CO₂ emissions, including those from cement production and carbonation, increased by 0.14 Gt C yr⁻¹ (0.5 Gt CO₂ yr⁻¹) in 2023 compared to 2022, reaching about 10.1 ± 0.5 Gt C yr⁻¹ (36.8 ± 1.8 Gt CO₂ yr⁻¹). Preliminary estimates indicate a further 0.8% rise in 2024, with emissions projected to reach approximately 10.2 Gt C yr⁻¹ (37.4 Gt CO₂ yr⁻¹), reflecting the continued growth of global fossil CO₂ emissions ^[3].

Carbon sequestration

Carbon sequestration refers to the long-term capture and storage of carbon dioxide or other carbon forms in reservoirs such as oceans, soils, vegetation (particularly forests) and geological formations. This process helps reduce or delay global warming by limiting the buildup of greenhouse gases released from human activities. Soil carbon sequestration is the process of

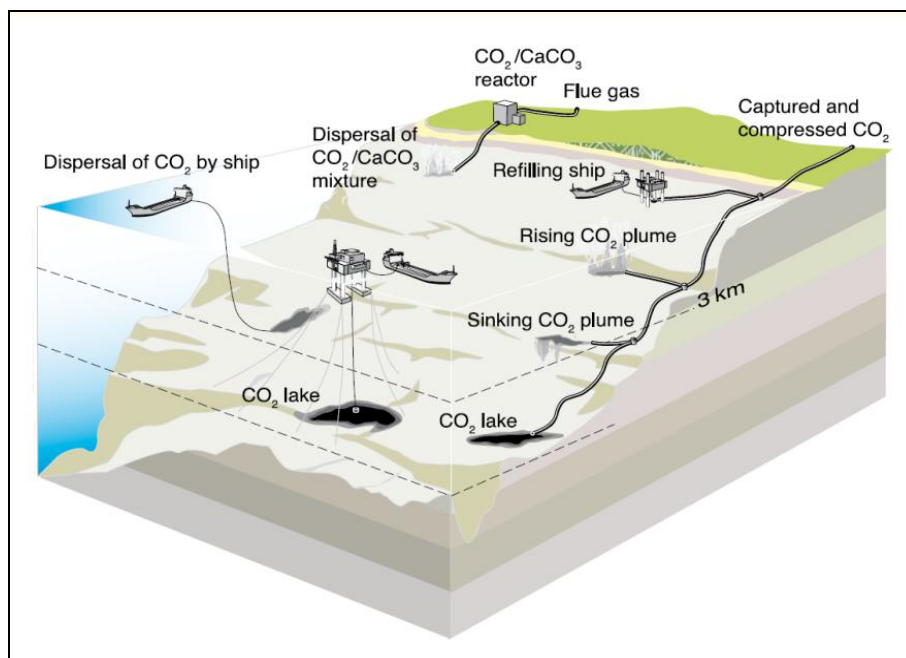
capturing atmospheric carbon dioxide and storing it in the soil through crop residues and other organic materials, in forms that remain stable and are not quickly released back into the atmosphere ^[14]. Terrestrial carbon sequestration provides many advantages, such as offsetting human-induced carbon emissions and slowing the rise of atmospheric CO₂ levels. It also improves soil and water quality, enhances ecosystem functions and services, reduces nutrient losses from ecosystems, lowers the risk of soil erosion, supports better habitats for organisms, increases soil water-holding capacity, helps restore degraded soils and promotes more efficient land use ^[18].

Agroforestry and Carbon Sequestration

Because soils hold the majority of carbon found on land, their degradation can have a substantial effect on the global carbon balance. The soil carbon pool can store both organic and inorganic carbon. Directly, that is, by inorganic chemical alteration process CO₂ into inorganic carbon molecules found in soil, like carbonates of calcium and magnesium. Indirect C fixation *via* photosynthesis is another possibility. The amount of carbon that different agroforestry methods can store varies depending on the types of plants used and different ecological and environmental factors. When looking at different elevations, lower elevations tend to have more stored carbon than higher elevations. This is because the soil is typically deeper, there's less soil erosion and there are more trees packed together on the lower slopes ^[1]. The amount of carbon dioxide in the atmosphere has increased from about 280 ppm by volume during the Industrial Revolution to about 405 ppm today. It's been suggested that planting trees is a good way to pull carbon dioxide out of the air and store it in their trunks, branches (Above-ground Biomass Carbon or ABC), and roots ^[4]. Growing woody perennials with agricultural crops is known as agroforestry, and it is regarded as a significant option for sequestering carbon ^[2]. The vast amount of carbon stored in soils makes them the largest terrestrial carbon sink, meaning that losses from this pool can substantially alter the global carbon budget. Carbon predominantly enters terrestrial ecosystems *via* photosynthesis and is initially stored in aboveground biomass. Yet, more than 50% of this carbon is transferred to the soil through the breakdown of dead plant matter, the growth and turnover of roots and root exudates ^[1]. In contrast to uncultivated soils, rice-wheat soils and maize-wheat soils, agroforestry and sugarcane systems were shown to have extremely labile carbon ^[2]. In silvo-pasture systems over time build up more soil carbon than intensive maize farming, mainly by increasing easily decomposable carbon compounds. This buildup of readily available carbon contributes to better soil health, as previously discussed. Agroforestry plots located 0.5 meters apart from almond rows had the highest carbon stocks^[21]. These carbon stocks were nearly twice as high as those observed in clover, wheat and barley monocropping systems. The agroforestry systems closest to the trees had the highest SOC (1.82%) rates ^[12].

Marine Carbon Sequestration

The ocean holds roughly 38,000 Pg of carbon, about 60 times more than the atmosphere. The oceanic carbon cycle therefore plays a vital role in regulating atmospheric CO₂ levels ^[15].



Source: Chow *et al.*, 2014

Fig 2: Ocean storage strategies

Conclusion

Agriculture plays a dual role as both a contributor to and a solution for climate change. This review highlights that integrating carbon trading, carbon budgeting, and carbon sequestration provides a comprehensive framework for achieving sustainable and climate-resilient agricultural systems. Carbon trading offers economic incentives for reducing greenhouse gas emissions, while carbon budgeting establishes scientifically defined limits to guide global mitigation efforts. Carbon sequestration, particularly through soil management and agroforestry practices, enhances carbon storage and improves soil health, productivity, and ecosystem services. The adoption of climate-smart agricultural practices is essential to balance food security with environmental sustainability. Furthermore, strengthening policy support, technological innovation, and farmer awareness will be crucial in scaling these approaches. Overall, a synergistic implementation of these strategies can significantly contribute to carbon neutrality, mitigate climate risks, and ensure long-term agricultural sustainability in the face of global climate change.

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