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REVIEW ARTICLE

Agricultural carbon credits: A pathway to environmental sustainability

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Abstract

Climate change and ensuring food security for a rapidly growing global population are two of the biggest challenges in agriculture. To meet the commitments made in the Paris Climate Agreement, it is important to use effective methods for managing soil that can help sequester and stabilise carbon. Conservation agriculture has a huge potential to sequester carbon in plants and soil, making it a viable option for carbon trading despite its significant contribution to global greenhouse gas emissions. Carbon sequestration can be achieved through sustainable practices such as adopting conservation agriculture, crop rotation, cover crop cultivation, crop residue incorporation or mulching, effective management of nutrient supply to crops, and transforming towards organic agriculture and agroforestry. These practices promote food security and environmental improvement and help mitigate global warming. Carbon pricing mechanisms are policies that impose a cost on carbon pollution, encouraging people and organisations to choose low-carbon options and reduce their emissions. Agricultural producers can benefit from carbon trading by earning extra revenue by selling their excess carbon credits to those who emit higher amounts of greenhouse gases. Carbon credit systems in agriculture are still in the early stages, so farmers may have more opportunities to participate in future carbon trading.

Keywords

conservation agriculture; carbon pricing; carbon sequestration; GHG emissions; organic carbon

Introduction

Global climate change has led to the exploration of innovative solutions to reduce greenhouse gas (GHG) emissions in all sectors. Atmospheric carbon dioxide (CO_2) levels have surged dramatically from about 277 ppm in 1750 to 419.3 ppm in 2023 which owes to a 51% increase (1). Historically, developed nations have been the primary contributors to GHG emissions, but the past two decades have witnessed a significant rise in emissions from rapidly developing countries like India, despite their lower per-capita emissions (2). This trend highlights the urgent need for effective climate action. Efforts are now being made to reduce carbon footprints in all areas, including agriculture and food production. The critical role of GHGs in climate change has led to international negotiations, elevating carbon to a tradable commodity and fostering the growth of the global carbon market (3). Agriculture and land use change are pivotal in achieving net-zero emissions, functioning both as sources and sinks of GHGs (4). However, current policy measures have been deemed inadequate, underscoring the need for stable, well-crafted policies to reduce emissions effectively.

Carbon credits have emerged as a promising voluntary market mechanism to address this challenge. They incentivise sustainable agricultural practices, commonly known as carbon farming, which enhance the soil's capacity to sequester carbon and reduce GHG emissions (5). Farmers adopting practices like reduced tillage or optimised fertiliser use can generate carbon credits and trade them in the market, providing a sustainable pathway to transform agricultural systems while preserving farmers' economic viability (6).

Moreover, carbon farming offers a framework for guiding the global economy towards net-zero emissions and advancing climate action in line with the '4 per 1000 Initiative,' particularly the UN Sustainable Development Goals (SDGs) (5). This article explores the potential of carbon credits within the agricultural sector as a strategy to mitigate climate change, highlighting agriculture's dual role in both contributing to and combating GHG emissions. In addition, it assesses carbon trading mechanisms, pricing strategies, and policy frameworks that support global emission reduction targets and promote agriculture practices resilient to climate change.

Carbon credit

A carbon credit denotes reducing or eliminating one ton of CO_2 or its equivalent and other greenhouse gases (GHG) from the atmosphere (7). Carbon credits are important in carbon trading because they serve as a means to mitigate the negative impacts of greenhouse gas emissions on the environment (6). Carbon credits are earned by entities that emit less than their allocated limit in cap-and-trade systems. These credits can be exchanged or sold to other agencies that exceed their emission limits, providing economic incentives for businesses and individuals to reduce their carbon footprint.

Carbon credits provide a mechanism for countries and businesses to work towards meeting emission reduction targets outlined in international agreements like the Kyoto Protocol and the Paris Agreement. The demand for carbon credit is rising, resulting in a shift towards renewable energy alternatives and a low-carbon economy. The maximum carbon credit limit is determined by the rate of carbon emissions, which stands at 50 Gt CO_2-e/year (8). Carbon credit transactions entail the acquisition of emission licenses from individuals or entities capable of reducing greenhouse gas emissions or storing additional carbon. The cost per carbon credit is determined by market forces as buyers and sellers engage in trading activities (6, 8).

Emissions from agriculture

Intensive agricultural practices in developing countries significantly impact climate change due to the emission of greenhouse gases. Agriculture contributes 10–12% of global greenhouse gas emissions out of which, 19% are from India (2). The major activities that result in the emission of greenhouse gases are rice cultivation, the use of synthetic fertilisers, and the burning of crop residues. Specifically, in India, methane emissions from rice cultivation account for approximately 138.68 kilotons, while N_2O emissions result from the use of synthetic fertilisers, and the burning of crop residues emit around 405.77 kilotons and 3.59 kilotons, respectively (9). Furthermore, drained agricultural peatlands, which comprise only 1% of agricultural land, contribute to about 33% of global cropland greenhouse gas emissions (10). Emissions occur at every production stage, making non-resilient agricultural practices a key concern to climate change. Fig. 1 highlights the significant impact of different categories on greenhouse gas emissions. "Agrifood systems" contribute the most to the emissions, followed by "Emission on agricultural land" and "Farm gate". Other sources have relatively lower emissions. It suggests that to reduce overall emissions, efforts could be focused on areas like managing agrifood systems and emissions on agricultural land (9).

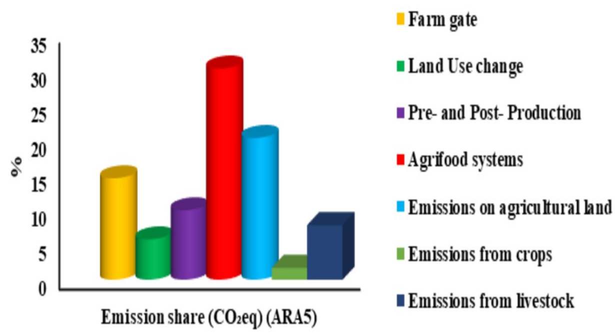

Fig. 1. Emission share of CO_2 equivalent of different categories [Data sourced from FAOSTAT for the year 2021] (9)

Chemical amendments

The increasing demand for food has resulted in a rise in the use of chemical fertilisers, which could harm ecosystems and contribute to greenhouse gas emissions. Nitrogen fertilisers are the major source of anthropogenic N_2O emissions, while their production alone accounts for nearly 1% of global GHG emissions (11). According to FAO predictions, the usage of synthetic N fertilisers is likely to rise globally by 50% from 2012 levels by 2050, which might threaten the climate aim outlined in the Paris Agreement. Phosphorus is essential for plant growth but is often lost to waterways, causing eutrophication (12). Potassium is an important nutrient for plant growth and its primary source is potassium chloride, which contributes to greenhouse gas emissions during production (13). Fig. 2 shows the major components of greenhouse gas emissions in the agrifood system worldwide. Emissions from livestock, synthetic fertilisers and fires in humid tropical forests have the highest impact. Managing livestock emissions and reducing synthetic fertiliser use can help reduce overall emissions (9).

Organic amendment

Organic farming has seen growth across countries, with approximately 70 million hectares of organic land managed by nearly 2.9 million farmers. Nonetheless, the

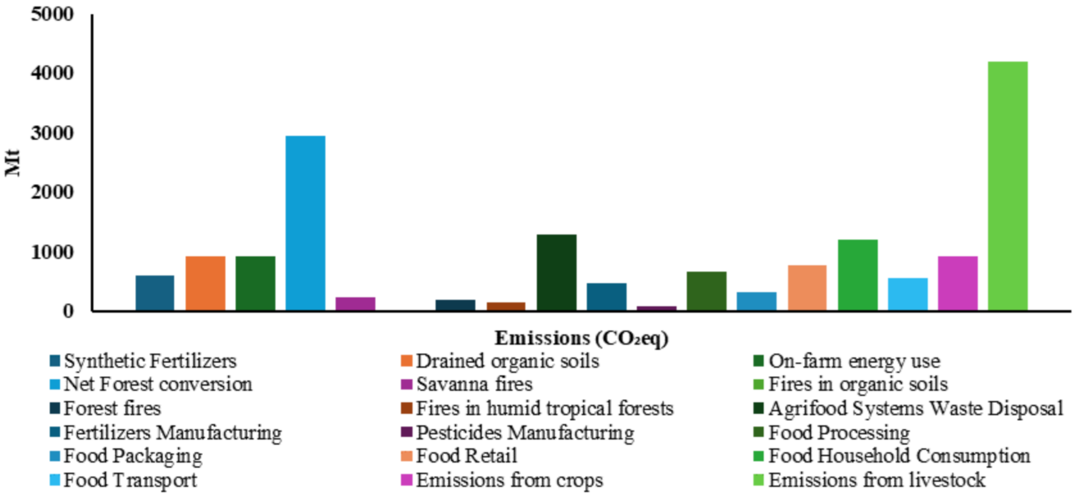

Fig. 2. Agrifood system emissions by component in India [Data sourced from FAOSTAT for the year 2021] (9)

application of amendments comes with drawbacks, including issues like nutrient eutrophication and the emission of greenhouse gases (3). Animal manure is widely used in agriculture, but it raises CO_2, CH_4 and N_2O emissions. Composting helps to transform organic waste into humus-like substances, but the process must be correctly handled to reduce GHG emissions (14).

Crops

Cereals are an important source of the human diet and account for a significant portion of global N fertiliser consumption. Rice is a major source of greenhouse gas emissions, contributing to around 30% of worldwide agricultural CH_4 emissions (15). According to FAOSTAT (9), rice has the highest N_2O emissions among all the crops in India's agricultural and food system. It contributes to 47.97% of the total emissions, followed by wheat with 27.98% (Fig. 3). This highlights the importance of reducing N_2O emissions from rice and wheat to mitigate the environmental impact of India's agrifood system. Maize output is increasing every year and nitrogen fertilisers are being largely used to increase production, which leads to an increase in emissions (16). Oil crops cultivated to extract oil emit around 2.8-19.7 kg CO_2 eq per kg of palm oil (17).

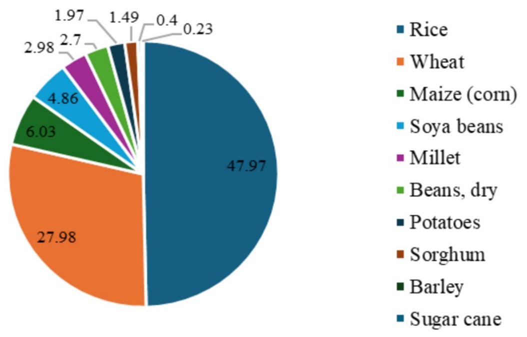

Fig. 3. Crop-wise emission of N_2O from India [Data sourced from FAOSTAT for the year 2021] (9)

Agricultural carbon sequestration

Carbon sequestration is a process that aims to minimise carbon emissions by stabilising photosynthesis and altering land use. It involves two main approaches: protecting and maintaining ecosystems and managing ecosystems to enhance carbon sequestration by increasing carbon content in soil and plant biomass (18). Soil can mitigate climate change by acting as the largest terrestrial carbon reservoir. Soil stores about 1526 Pg C of Soil Organic Carbon (SOC) and 940 Pg C of soil inorganic carbon. Soil and vegetation at a depth of one metre hold three times more carbon than the atmosphere, which currently stands at 880 Pg C (4). Approximately 10% of atmospheric CO_2 is cycled by the soil each year. The quantity of carbon in soil is determined by the equilibrium between the inputs of SOC and the rates at which it mineralises. Land use and soil management changes influence organic carbon sequestration rates in soil. It offers further benefits like food security, biodiversity, maintaining water quality and elemental recycling (5). Soil quality can be enhanced by improving the concentration of SOC by implementing sustainable agricultural practices (Table 1). Retention of soil carbon can be done through direct and indirect mechanisms. Direct mechanisms account for 50-80% of stable SOC and involve the synthesis and accumulation of plant-based carbon in microbial biomass. Indirect mechanisms enhance plant growth and increase biomass entering the soil. Carbon sequestration plays a role in the field of agriculture as it helps offset amounts of methane and nitrous oxide emissions caused by agricultural activities (19). Fig. 4 presents the estimated amount of carbon (Pg C yr^{-1}) that can be stored through soil organic carbon sequestration (7). Adopting Sustainable Soil Management (SSM) practices can mitigate between 0.14-0.56 Pg CO_2 eq yr^{-1} annually. This estimation is based on three scenarios: SSM1 with a 5% increase in carbon input, SSM2 with a 10% increase in carbon input and SSM3 with a 20% increase in carbon input.

Conservation agriculture and carbon sequestration

Intensive agricultural practices like tillage, over-fertilisation and excessive cultivation are used to fulfil the growing demand for food. Due to the degradation of soil characteristics and increased soil erosion caused by these activities, there is a global loss of 25-75% of SOC (20). Diversified cropping systems like intercropping, cover crops and crop rotation can mitigate this and facilitate SOC sequestration (21, 22). Legumes can fix atmospheric

Table 1. Overview of sustainable agricultural practices and its key benefits

Sustainable agricultural practices	Key benefits	Reference
• Conservation tillage • No-tillage • Cover crops • Crop residue • Organic farming • Crop rotation	Enhance SOC stock and improves SOC stabilization	(22, 61, 83, 84, 49, 87, 90, 91)
• Conservation tillage • No-tillage • Organic farming	Reduce GHG emission	(21, 72, 84)
• No-tillage • Crop residue • Crop rotation	Improve soil quality by improving soil aggregation and soil structure	(44, 84, 85,86,88)
• N fertilisers • Cover crops	Enhancing biomass production by increasing carbon and nitrogen inputs	(46, 89)
• Crop residue	Increase soil labile organic carbon fractions	(38)

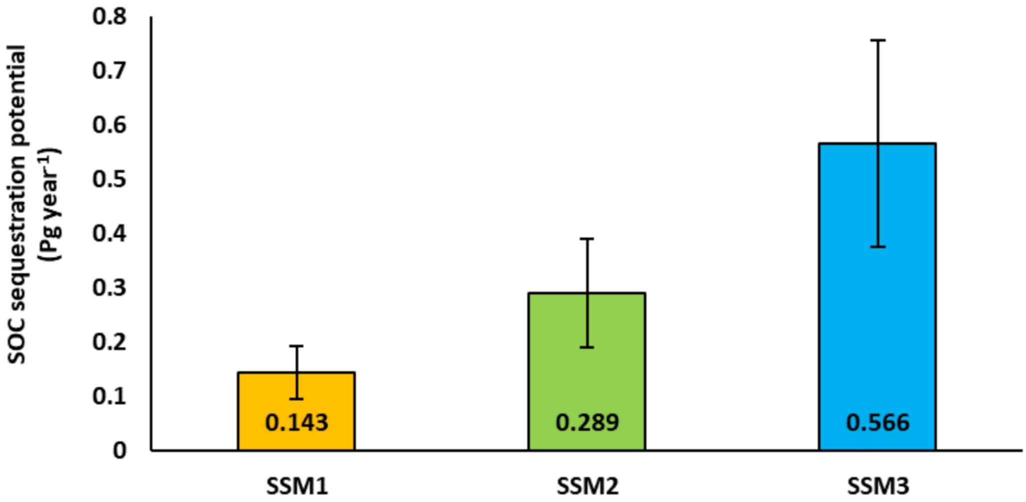

Fig. 4. Sequestration potential of various systems [Data sourced from FAO] (7)

nitrogen and increase nitrogen content when integrated into cropping systems (20).

Conservation Agriculture (CA) refers to a type of farming system involving minimal soil disturbance, permanent soil cover and diversification of crops. The FAO promotes CA as an effective approach to achieving sustainable land management, environmental protection and climate change adaptation and mitigation (23). Numerous global initiatives have identified CA as a significant contributor to the adaptation and mitigation of climate change in the field of agriculture (22). Conservation agriculture is an effective way to maintain soil health and increase SOC storage. It also provides other benefits that promote agricultural sustainability. Conservation agriculture can reduce CO_2 emissions by increasing carbon stored in soil and limiting vehicle use, lowering direct emissions (21). Conservation agriculture entails practically implementing three interrelated concepts and supplementary good agricultural practices, which play an important role in soil carbon sequestration. Further discussion on this topic can be found below.

Effects of tillage on carbon sequestration: Tillage practices significantly affect carbon sequestration and GHG production (24). Soil organic carbon and aggregate stability are interrelated and No-tillage (NT) methods can promote the development of soil aggregates, enhance their resilience and evenly distribute carbon among soil aggregates of various sizes (25). No-tillage increases top-layer carbon storage more than conventional tillage (26, 27) by enhancing soil organic carbon, microbial biomass carbon, dehydrogenase, alkaline phosphatase and β-glucosidase and notably reduces global warming potential (24, 28). According to a previous study, NT methods improved soil total organic carbon stock by 9.0% compared to CT in 0-40 cm soil depth. The carbon pool management index was also improved by 16.5% (29). NT effectively stores both labile and recalcitrant carbon, favouring diverse carbon conversion. NT reduces the alkyl

C to O-alkyl C conversion and lignin to polysaccharides ratio, indicating lower organic carbon decomposition (30).

No-tillage resulted in higher SOC stock in the topsoil (0-20 cm) than conventional tillage. After 23 years, SOC was 21% greater under NT in the topsoil, indicating an effective system to recover lost SOC (26). Conservation tillage practices increase SOC accumulation and tillage with straw mulch is more effective in promoting SOC accumulation than other tillage methods (28). Deep tillage increased SOC stock significantly by (7.36%) over conventional tillage. Subsoiling increased SOC (8.76%) than deep ploughing (5.85%). Subsoiling increased SOC in the top 40 cm layer, with the most significant improvement at the 0-10 cm layer (11.41%). Deep ploughing increased SOC stock in the 10-40 cm layer but had no effect on the SOC of the 0-10 cm layer (31). The application of straw to soil increases easily oxidisable and particulate organic carbon. When combined with NT, residue return leads to improved soil carbon sequestration (32).

Effects of crop residue on carbon sequestration: Crop residues play a significant role in increasing soil organic matter, which in turn affects nutrient availability and carbon storage (11). Which further promotes humus formation, improves soil quality and adds carbon and nutrients to the soil (32-34). Many studies conducted in developing regions have reported positive impacts of crop residue on soil quality, including increased organic matter, carbon stock, water holding capacity, nutrient recycling and reduced soil loss (32, 35, 36). Additionally, crop residue provides the necessary energy source for soil organisms, which contributes to the stability of soil aggregates, enhances the permeability of the soil and favours the movement of soil air, water and heat (37). Adding crop residues into the soil can affect both passive and labile soil carbon pools, leading to emissions, whereas the resistant proportion aids in carbon sequestration. The amount of carbon added depends on the method of residue management, as surface retention and incorporation can improve SOC at different depths (38).

Crop residues are the primary source of SOC, containing approximately 45% carbon and their management significantly impacts carbon dynamics (37). Globally, crop residues generate 2.4 Pg C annually, accounting for 25% of global carbon emissions from fossil fuels and cement production in 2021. China, the US, and India are the leading producers of crop residues. Cereal crops contribute the most at 1.62 Pg C year^{-1}, followed by oilseed/pulse crops at 0.45 Pg C year^{-1}. Maize has the highest potential for crop residue production at 0.58 Pg C year^{-1}, followed by rice at 0.49 Pg C year^{-1}. The European Union has a crop residue production potential of 0.18 Pg C, which is equivalent to 16% of its fossil carbon emissions for 2021 (39).

Effects of crop rotation on carbon sequestration: Crop rotation is a practice where different crops are grown sequentially on the same land. Recently, there's renewed interest in this practice for sustainable food production and minimal environmental impact (27, 40). Crop rotation benefits agriculture by improving soil structure, fertility, and nutrient use efficiency as well as controlling pests, weeds and diseases (27, 41, 42). Diverse crop rotation with cover crops and perennials can improve ecosystem services. In addition, crop residue can increase SOC and total carbon input, due to increased living soil cover.

Leguminous crops increase soil microbial activity, soil organic carbon, soil moisture and total porosity, enhancing the yield of subsequent crops (43, 44). Legume forage crops, used in rotations, provide nitrogen for subsequent non-legume crops and maintain soil nitrogen levels (41). Furthermore, leguminous crops also increase soil stability, porosity, available water, and the retention of soil carbon and nitrogen. Legume crop residue is a major carbon source in agricultural soils, favouring the accumulation of humus and the soil's carbon pool as legume residues decompose faster than non-legumes. Thus, Legume-based cropping is a key option for soil carbon sequestration, maintaining a favourable soil C/N ratio (43).

Grain legumes, with their deep and robust root system, contribute to SOC through leftover shoots and root biomass. The root of the pigeon pea crop, extending more than 1.5 m, is recognised for deep soil carbon sequestration. Carbon sequestration in deep soil is less prone to oxidation and has longer stability. Cultivating legumes in alternation with cereal crops can enhance the storage of carbon in soil by 9-45 Mg C ha^{-1}, while decreasing the release of greenhouse gases by 5-7 times when compared to non-leguminous plants (45). Biological nitrogen fixation indirectly reduces the use of chemical fertilisers, potentially reducing CO_2 emissions (43, 44).

Effect of cover crops on carbon sequestration: Cover crops are a type of crops that are planted between main crops to provide a range of benefits such as increasing soil organic carbon, improving soil structure, reducing erosion and nutrient leaching and promoting carbon sequestration and nitrogen retention (46, 47). Additionally, these crops help in mitigating climate change and reducing farming operations and fossil fuel consumption. Cover crops are also grown as green manure, which produce large biomass and help in enlarging the soil carbon sink (48). Cover crops have the potential to capture carbon in soils without affecting the yield of the primary crop (49). The presence of cover crops led to a 16% increase in SOC on a global scale when compared to not using them and resulted in a carbon sequestration rate of 167 kg C ha^{-1} yr^{-1}. Cover crop mixtures are more effective at promoting SOC buildup than single species (47). However, the carbon sequestration rate depends on the type of cover crop used, with non-legumes performing better than legumes due to their larger carbon -to-nitrogen ratios (50).

Effect of nutrient management on carbon sequestration

Fertilising with N, P, and K can affect soil carbon stocks by impacting plant productivity, litter composition and microbial metabolism. These nutrients boost plant growth, increase biomass and soil fertility, leading to a positive effect on SOC stocks (51). Organic amendments can help in carbon sequestration, improve soil fertility and combat climate change (52, 53). However, their effectiveness depends on local environmental conditions (54). Green manure can increase the carbon pool index (CPI) and reduce the carbon management index (CMI). Organic amendments can affect the rate of SOC decomposition, known as the priming effect (55, 56). It's crucial to consider carbon management indices, crop yield and GHG emissions when evaluating agricultural practices (57). Soil organic carbon stocks vary with the balance between carbon capture and decomposition (54). Manures combined with mineral fertiliser improved soil organic carbon storage and sequestration efficiency (58). This combination also enhances soil structure, fertility and microbial biomass, resulting in stable SOC in both macro and micro-aggregates (59, 60).

Nitrogen input impacts soil organic carbon stocks due to changes in fresh particulate organic carbon and decomposed organic carbon output, increased soil lignin content and decreased CO_2 emissions (55, 61-63). Nitrogen bioavailability is critical for organic carbon cycling and sequestration (59). Increased nitrogen effectiveness promotes soil organic carbon sequestration by promoting plant growth and litter formation, reducing microbial activity and promoting aggregate formation (51, 62, 64, 65). It also enhances soil carbon stocks, including soil inorganic carbon, which store more carbon in deep soil than SOC and contribute to 30% of the world's total carbon in the top 1m of soil (66). This enhances soil carbon accumulation by stimulating plant growth and biomass production (67). However, nutrient addition can also accelerate organic matter decomposition, affecting carbon cycling and storage.

Effect of organic farming on carbon sequestration

Organic farming is a sustainable adaptation technique to overcome climate change. It is not just a specific agricultural production system but a systemic approach to sustainable livelihoods, considering physical, economic and socio-cultural factors (68). The Codex Alimentarius Commission has defined organic farming as a holistic food production management system that promotes agro-ecosystem health, biodiversity and soil biological activity while emphasising the use of management practices over off-farm inputs and synthetic materials. It assists in climate change adaptation and mitigation through nutrient management as it avoids using synthetic fertilisers, which play a key role in agricultural GHG emissions (69).

Compared to conventional farming, organic farming has greater potential in soil carbon sequestration (70, 71). This is accomplished by reducing N_2O emissions due to reduced nitrogen input, reduced CO_2 emissions from farming system inputs, and soil carbon sequestration, which is one of the potential mitigation strategies (72, 73). The soil carbon sequestration rate ranges from 200 kg to 2000 kg C ha^{-1} yr^{-1}, depending on the organic soil management practices that favour sequestering of carbon in the soil ecosystem (71).

Effect of agroforestry on carbon sequestration

Agroforestry is a sustainable land use system that combines agriculture and forestry to maximise benefits and resource efficiency (74). It is highly valued for its potential to support climate change adaptation and mitigation, with the greatest potential for carbon sequestration among all land uses, which can result in both environmental and economic benefits (11, 75). Agroforestry provides a multitude of advantages, including economic, socio-cultural and environmental benefits. These benefits include reduced erosion, enhanced soil fertility and water quality, improved aesthetics, greater biodiversity and carbon sequestration (76-78). Carbon sequestration in agroforestry occurs through the accumulation of aboveground and belowground biomass and soil, with trees playing a crucial role in adaptation and mitigation due to their significant aboveground biomass volume and deep, dense root systems.

Agroforestry is an essential component of developing countries nationally determined contributions, which could be a significant contributor in global climate goals (76). The IPCC has highlighted agroforestry as the most promising method for carbon sequestration by 2040. It estimates that agroforestry can mitigate between 1.1 to 2.2 Pg C through biomass production and soil organic carbon pool (74).

Agroforestry practices can intentionally increase the SOC pool (79). The integration of trees leads to enhanced CO_2 sequestration from the atmosphere through photosynthesis, resulting in enhanced carbon storage in tree components for long-term storage and its deposition in the soil as a stable organic matter pool (carbon storage) (80). In small-scale tropical agroforestry systems, the C sequestration rates range between 1.5-3.5 mg C ha^{-1} yr^{-1} (81). Between the ages of 10 and 20-30, trees have the highest capacity to sequester carbon. By the time forests reach the age of 30, they can sequester approximately 200-520 tonnes of CO_2 ha^{-1} (82).

Carbon trading

Carbon trading, also known as emissions trading, is a mechanism established under Kyoto Protocol (Article 17). It allows countries with unused emission units, i.e. emissions permitted but not utilised, to sell their excess unused units to other countries that have exceeded their emission targets (92). The carbon trading system significantly impacts the economy and society, affecting industries that emit high levels of carbon (93). The pressure to reduce emissions is increasing due to worsening climate conditions. Agricultural production must consider both ecological impact and direct emission reduction pressure during carbon trading. Carbon trading occurs in markets both within and outside the Kyoto Protocol. These markets are used to distribute and trade carbon credits (Fig. 5) through two types of transactions: allowance-based and project-based. In allowance-based transactions, buyers obtain emission allowances that are generated and allocated by regulators operating under cap-and-trade systems, including Assigned Amount Units (AAUs)

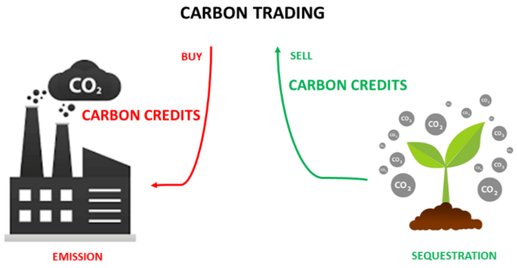

Fig. 5. Carbon trading

and European Union (EU) allowances (94). Countries that join the Kyoto Protocol and accept national limits are granted AAUs and assigned quotas to specific emitting activities or industrial units, such as power plants or paper manufacturers, to implement their emission targets. Allowance-based markets feature EU ETS, Australia's New South Wales Greenhouse Gas Abatement Scheme and the CCX, a voluntary but legally enforceable commitment (95). Regarding project-based transactions, the costumer buys emission credits from a project that demonstrates a reduction in GHG emissions over a period, compared to the emissions in the absence of that project. Many of these deals involve the forward sale of credits, which means that buyers are acquiring future reductions in emissions. The Clean Development Mechanism (CDM) and joint implementation plans of the Kyoto Protocol are the best-known instances of these transactions. Carbon credit mechanisms are in the development phase in 6 countries and have already been implemented in 17 countries. (Table 2) (96).

Carbon and its pricing

Carbon, in terms of Carbon credits is usually priced based on the demand and supply of carbon credits by various firms or countries. With the increase in demand, the price of carbon credits increases, and vice-versa.

According to a report (97), maintaining temperatures below 2°C (the upper limit agreed upon in the Paris Agreement) requires carbon prices to be set between USD 40/tons of CO_2 and USD 80/tons of CO_2 by 2020. Additionally, the report suggests that these prices should be further increased to between USD 50/tons of CO_2 and USD 100/tons of CO_2 by 2030.

The policy for greenhouse gas emissions affects the market conditions, which can also be impacted by changes in weather, energy prices and technical improvements. These factors are known to shift unpredictably, and the costs could vary significantly with the development of new technologies. The carbon credit market is a new and rising institution that may have more buyers or sellers at different times with varying prices. Soon, calculating the price of carbon credits will be challenging, even with models that reflect market features, due to the lack of understanding about the exact impact of supply and demand factors on pricing. As the carbon credit market evolves, more data on prices and quantities will incentivise greenhouse gas reductions (8).

Table 2. Global overview of carbon crediting mechanism initiatives

Country	Mechanism	Implementation status
Ecuador	Ecuador Crediting Mechanism	Under development
Egypt	Egypt Crediting Mechanism	Under development
India	India Crediting Mechanism	Under development
Indonesia	Indonesia Crediting Mechanism	Under development
Vietnam	Vietnam Crediting Mechanism	Under development
Mexico	Mexico Crediting Mechanism	Under development
United Kingdom	UK Woodland Carbon Code	Implemented in 2011
Spain	Spain FES-CO_2 Program	Implemented in 2011
Switzerland	Switzerland CO_2 Attestations Crediting Mechanism	Implemented in 2012
Japan	J-Credit Scheme	Implemented in 2013
Kazakhstan	Kazakhstan Crediting Mechanism	Implemented in 2013
Thailand	Thailand Voluntary Emission Reduction Program	Implemented in 2014
China	China GHG Voluntary Emission Reduction Program	Implemented in 2014
Korea	Republic of Korea Offset Credit Mechanism	Implemented in 2015
United Kingdom	Peatland Code	Implemented in 2015
Sri Lanka	Sri Lanka Carbon Crediting Mechanism	Implemented in 2016
Colombia	Colombia Crediting Mechanism	Implemented in 2017
South Africa	South Africa Crediting Mechanism	Implemented in 2019
Canada	Canada Federal GHG Offset System	Implemented in 2022
Australia	Australian Carbon Credit Unit Scheme	Implemented in 2024
Chile	Chile Crediting Mechanism	Implemented in 2024
Saudi Arabia	Greenhouse Gas Crediting and Offsetting Mechanism	Implemented in 2024
Portugal	Portuguese Voluntary Carbon Market	Implemented in 2024

Carbon credit systems allow farmers to earn additional income by selling their excess carbon credits to producers who emit higher levels of GHGs (7, 98). While these agricultural carbon credit systems are still in their early stages, the carbon credit market is expanding. This growth means that farmers may have additional opportunities to participate in the future. Additionally, farmers can be encouraged to participate in carbon-crediting mechanisms by stressing the benefits and accompanying economic incentives rather than focusing on the possible cash gain.

Policy framework

Agricultural carbon credits are actively traded within the Voluntary Carbon Markets (VCM), where companies either reduce emissions or acquire carbon credits to offset their environmental impact. In January 2024, India introduced the Carbon Credit Trading Scheme (CCTS) to promote sustainable agricultural practices that generate tradable carbon credits for farmers. India is already a major supplier of carbon offsets in the global voluntary market, but ensuring transparency within the ecosystem remains a critical challenge. Green washing, where entities falsely present themselves as environmentally friendly without making real environmental improvements, is a key concern. It can occur when carbon credits are misused by purchasing them without reducing emissions, providing misleading information, or relying on low-quality credits. To address green washing, stakeholders involved in agricultural carbon markets must prioritise high-quality, verified carbon credits, maintain transparent communication and comply with legal standards. Effective checking mechanisms include third-party verification, regulatory oversight and a comprehensive strategy that focuses on direct emission reductions alongside the responsible use of carbon credits.

To further strengthen the policies, particularly in the agriculture sector where small and marginal farmers are predominant, it is crucial to focus on capacity building of farmers and investing in research to develop innovative techniques that improve soil health and enhance crop resilience to combat climate change. Incentives should be provided for adopting low emission technologies such as precision agriculture, organic farming and agroforestry. Government should focus on reducing GHG emissions, improve resource use efficiency, promote strategies to adapt climate change, and prioritise agricultural productivity. It requires the creation of credible databases or enhancing available databases (such as FAOSTAT and World Bank open knowledge repository) that contain reliable data and scientific research to improve policy decisions. Financial arrangements should be made for smooth implementation, while flexibility for convergence with other national/international activities, institutional arrangements and stakeholder knowledge should also be emphasised. The policies should prioritise sustainability and livelihood, resource inventory and all existing climate-smart practices while ensuring profitability for growers and emissions from farming activities.

Conclusion

The relationship between agriculture and carbon dynamics highlights the need for sustainable practices in the era of climate change. As the global community aims to reduce emissions, strategies like organic farming and conservation agriculture can promote soil health and carbon sequestration. Carbon trading systems offer a viable means of incentivising sustainable practices, with agriculture presenting significant potential for generating carbon credits despite its current limited contribution. Despite agriculture-related emissions mitigating projects accounting for just more than 1% of total carbon credits granted, it is crucial to recognise that land use, including forestry, is the most extensive source of carbon credits, awarding approximately half of its units issued to date (Fig. 6). This highlights the untapped potential of agriculture, which is another form of land use, in this industry. By concentrating on sustainable and carbon-sequestering agricultural practices, the agricultural sector has the potential to significantly increase its share of carbon credits issued. This benefits the environment and

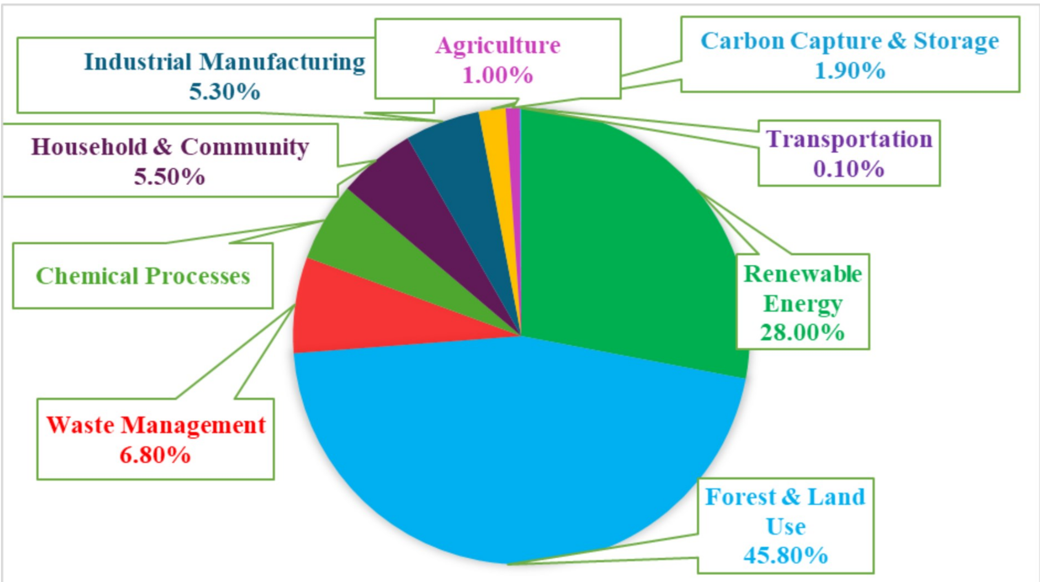

Fig. 6. Sector-Wise Share of Carbon credit issues [Data sourced from AgFunderNews] (99)

provides additional revenue streams for farmers and agricultural businesses. The future of agriculture in carbon trading is promising, with plenty of room for growth and innovation.

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Authors' contributions

KA conceptualized the study, performed the original draft preparation, and contributed to its review and editing. VM conceptualized and supervised the study and contributed to the review and editing of the manuscript. NS, DB and KPR contributed to the review and editing of the manuscript. VV contributed to the literature collection. All authors read and approved the final manuscript.

Compliance with ethical standards

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