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Can Conservation Agriculture Save the Climate?

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Climate change poses significant threats to global food security, with agriculture both contributing to and suffering from its impacts. Conservation agriculture (CA), as a core component of carbon farming, offers a strategic pathway to mitigate greenhouse gas (GHG) emissions while enhancing climate resilience. This article examines the potential of CA practices such as minimal soil disturbance, permanent organic soil cover, and diversified crop rotations, to sequester atmospheric carbon and reduce emissions of CO_2, CH_4, and N_2O. Evidence suggests that CA not only improves soil organic carbon storage and biological activity but also enhances water retention, nutrient cycling, and crop productivity under climate stress. However, widespread adoption faces challenges such as limited farmer awareness, resource constraints, and context-specific outcomes based on soil and climate variability. Integrating CA into national climate strategies and sustainable agriculture agendas can make it a transformative tool for low-carbon development and ecological resilience.

Keywords: Conservation agriculture, climate change mitigation, soil carbon sequestration, greenhouse gas emissions, sustainable agriculture

Introduction

The escalating impacts of climate change like rising temperatures, shifting precipitation patterns, and increasing frequency of extreme weather events etc pose serious threats to global food security and environmental sustainability. Agriculture is a paradox in this context: it is both a significant contributor to climate change and a potential solution. However, if managed appropriately, agricultural systems can become powerful carbon sinks, aiding in climate mitigation efforts (Sarkar et al., 2022; Sarkar et al., 2023a, Sarkar et al., 2025). One emerging pathway to achieve this is carbon farming which is a set of land management practices that enhance carbon sequestration in soils and vegetation while reducing emissions. Among the various strategies, Conservation Agriculture (CA) is gaining global traction as a practical and scalable solution (Sarkar et al., 2023b). CA integrates three fundamental principles: minimal soil disturbance (no-tillage or reduced tillage), continuous soil cover (through crop residues or cover crops), and diversified crop rotations or intercropping (Sarkar et al., 2022; Sarkar et al., 2023b). These practices work synergistically to improve soil health, enhance biodiversity, and increase soil organic carbon (SOC) stocks. Scientific evidence increasingly supports the role of CA in mitigating climate change. By minimizing tillage and maintaining organic soil cover, CA reduces soil erosion and enhances SOC accumulation. Simultaneously, it fosters microbial and root activity that promotes stable carbon pools within soil aggregates. In addition to mitigation, CA offers co-benefits that improve climate resilience, such as better water retention, reduced production risk, and enhanced nutrient cycling. These multifaceted benefits position CA at the intersection of climate action and sustainable development, aligning with the goals of climate-smart agriculture (CSA) and multiple Sustainable Development Goals (SDGs). This article critically examines the potential of conservation agriculture as a tool for carbon farming, explores real-world case studies, assesses policy and market frameworks, and discusses the challenges and opportunities of scaling CA as a climate mitigation and adaptation strategy.

What is Conservation agriculture?

Conservation Agriculture represents a sustainable farming system that focuses on increasing productivity and ensuring long-term soil and environmental health. It promotes production intensification and high yields while conserving the natural resource base by adhering to three core principles: minimal soil disturbance, permanent soil cover, and crop diversification. Complementing these with sound practices in nutrient and pest management enhances the system's effectiveness. According to the Food and Agriculture Organization (FAO), CA is not just a set of practices, but a holistic concept centered around preserving and enhancing natural biological interactions both on the surface and within the soil (Sarkar et al., 2022). The overarching goal of CA is to maximize farm productivity and profitability in harmony with environmental sustainability. It emphasizes that integrating ecological preservation into crop production provides more substantial social and economic returns than conventional production methods alone particularly by reducing labour, input costs, and environmental damage. Conventional agriculture, which relies heavily on mechanical tillage and extensive input use, has contributed to several environmental issues. These include soil erosion, water pollution (both surface and groundwater), and overconsumption of water resources. It has also been linked to land degradation, loss of biodiversity, decreased energy efficiency, and greenhouse gas emissions contributing to climate change. In contrast, CA serves as a more environmentally responsible alternative, addressing many of these shortcomings. The foundation of CA lies in keeping the soil covered with crop residues and minimizing tillage, thereby enhancing soil structure and reducing erosion. This approach transforms farming systems into more eco-friendly operations that benefit not just the farm but the broader community. These benefits include reduced use of synthetic chemicals, less reliance on fossil fuels, and improved ecosystem services. CA also emphasizes the judicious and integrated use of soil, water, and biological resources, aiming for maximum efficiency with minimal environmental impact. Conservation agriculture, through its resource-conserving and integrative approach, offers practical solutions to many of these modern agricultural challenges.

Principles of conservation agriculture

Conservation agriculture, widely adopted across various regions globally, is grounded in ecological principles aimed at promoting more sustainable land use. It represents a resource-efficient crop production approach that balances the need for profitable yields with the preservation and enhancement of environmental quality. At its core, CA seeks to boost natural biological processes both above and below the soil surface. The foundational practices of CA include maintaining adequate levels of crop residue on the soil for mulching, implementing diverse crop rotations and intercropping systems, and minimizing soil disturbance through practices like controlled traffic farming. CA is characterised by three core principles (Fig.1) which are linked to each other, viz. minimum soil disturbance, permanent soil cover and diversified crop rotations. These principles are very specific and economically viable in different agroclimatic and socio-economic conditions of the farmers.

✓ **Minimal mechanical soil disturbance**

Minimising mechanical soil disturbance is aimed at reducing tillage operations to the minimum necessary for ensuring a fine seedbed, proper germination and satisfactory crop stand. The soil biological activity produces very stable soil aggregates as well as various sizes of pores, allowing air and water infiltration. The introduction of ZT or minimum soil disturbance is to curb the negative impact of excessive tillage and to reduce soil erosion, which ultimately improves soil and water conservation. With mechanical soil disturbance, the biological soil structuring processes will disappear. Minimum soil disturbance provides/maintains optimum proportions of respiration gases in the rooting-zone, moderate organic matter oxidation, porosity for water movement, retention and release and limits the re-exposure of weed seeds and their germination. Minimising soil disturbance also maintains proper aeration in rooting zone, oxidation of organic matter, water movement in soil and exposing the weed seeds either for germination or as prey to beetles.

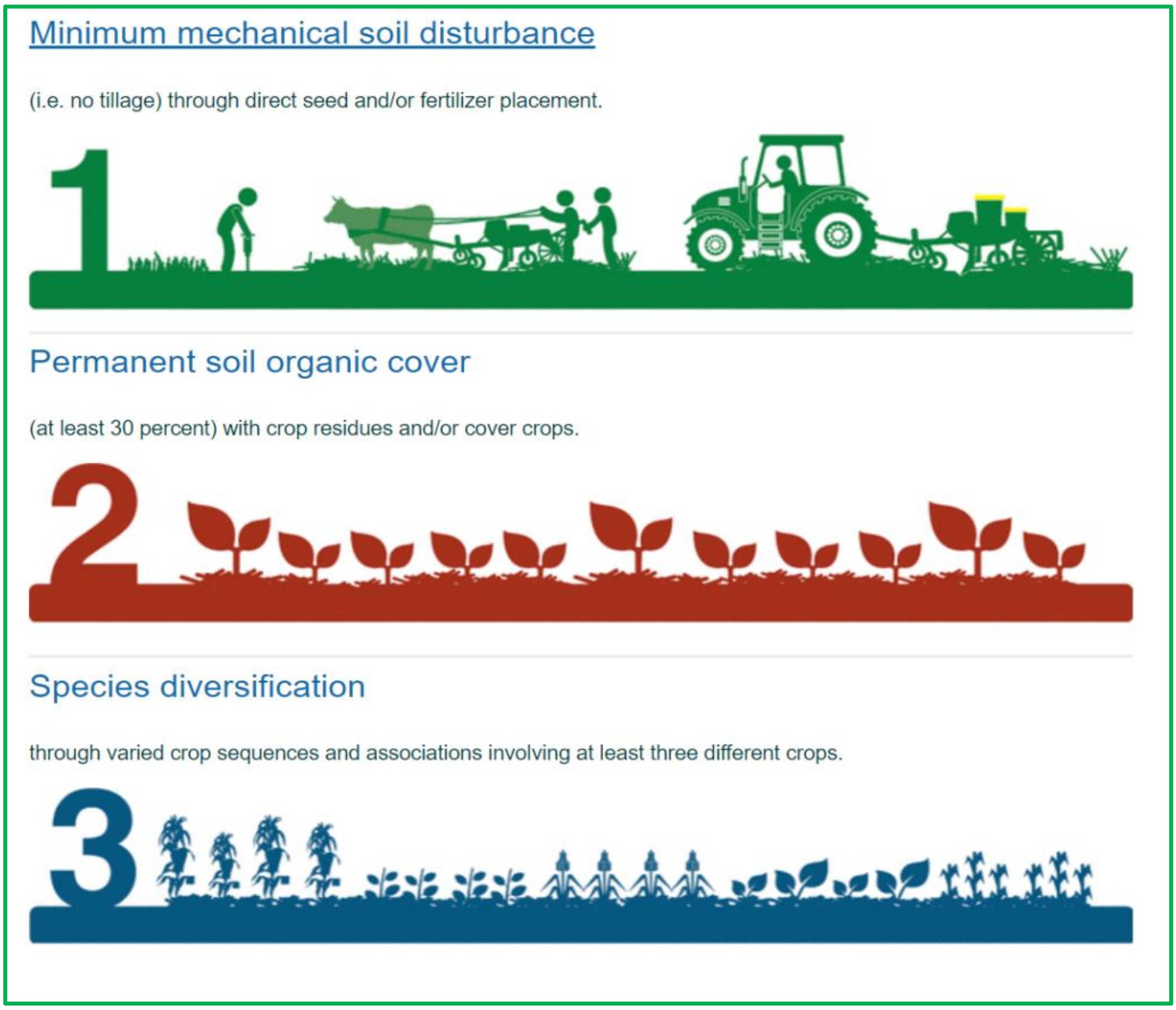

Fig 1. Principles of conservation agriculture (Source: FAO, 2025)

✓ **Permanent organic soil cover**

A permanent soil cover is important to protect the soil against the deleterious effects of exposure to rain and sun and provide micro- and macroorganisms in the soil with a regular supply of food and alter the soil's physical environment for optional growth and development of soil organisms. Crop residue is the principal component of soil cover to protect soil and water erosion from topsoil and plays an important role in building soil organic matter, nutrient recycling, and improving soil quality (Sarkar and Bandyopadhyay, 2021). Crop residues are the principal sources of carbon, and it has a significant effect on soil physical, chemical, and biological soil properties.

✓ **Diversified crop rotations**

Diversified crop rotation is of paramount importance in mitigating the biotic and abiotic problems, arising in monoculture, particularly in rice-wheat cropping system. Furthermore, a diversity of crops in rotation leads to a diverse soil flora and fauna. Cropping sequence and rotations involving legumes help in minimal rates of build-up of the population of pest species, through life cycle disruption, biological nitrogen fixation, control of off-site pollution, and enhancing biodiversity. It must be suited to different agroclimatic and farmers' socio-economic conditions. Inclusion of legume crops in rotation can also play an important role in conserving groundwater and soil water. Moreover, the quality of these crops (higher protein content) is better than wheat and other cereals in rice–wheat-grown areas. Particularly in wheat, crop rotation addresses the problems of insect, pest and diseases by integrating crop rotations, which help to break the cycle that perpetuates crop diseases such as wheat rust and pest infestations, resulting in higher yield.

Greenhouse Gas Mitigation through Conservation Agriculture

Conservation agriculture (CA) not only supports carbon sequestration but also contributes significantly to the reduction of other major greenhouse gases (GHGs), notably nitrous oxide (N_2O) and methane (CH_4). Modest reductions in these gases can yield substantial climate benefits (Sarkar et al., 2023a). CA influences GHG emissions through multiple pathways. Reduced tillage diminishes soil aeration and microbial turnover, leading to a slower nitrogen mineralization rate. This in turn can lower N_2O emissions from nitrification and denitrification processes, especially when combined with precision fertilizer management and crop diversification. Residue retention, a key CA component, can also affect GHG dynamics. While it contributes to carbon buildup, its interaction with nitrogen cycling is complex. In aerobic conditions, residues improve soil structure and water infiltration, which suppresses N_2O emissions. However, in poorly drained or waterlogged soils, excessive residue loads may create anaerobic pockets conducive to denitrification, potentially increasing N_2O. Context-specific residue management, therefore, is crucial. Methane mitigation is particularly relevant in rice-based systems, which are significant CH_4 emitters due to anaerobic decomposition of organic material in flooded paddies. CA-based rice cultivation through practices such as alternate wetting and drying (AWD), direct-seeded rice (DSR), and crop residue mulching has demonstrated considerable CH_4 mitigation potential. By minimizing mechanical tillage and irrigation needs, CA can lower CO_2 emissions from fossil fuel combustion. Life-cycle assessment studies in South Asia show a 15-25% reduction in overall carbon footprint for CA-based rice-wheat systems compared to conventional farming (Jat et al., 2021). Cumulatively, these effects make CA a valuable component in climate mitigation portfolios.

Conservation Agriculture and Climate Resilience

In the face of increasing climate variability and extreme weather events, enhancing the resilience of agricultural systems has become an urgent priority. Conservation agriculture (CA) offers a viable pathway to climate adaptation by improving soil health, water retention, and agroecosystem stability. These co-benefits of CA are particularly crucial for smallholder farmers and rainfed systems, which are highly vulnerable to climatic shocks. By maintaining permanent soil cover and minimizing soil disturbance, CA enhances soil structure and promotes the formation of stable aggregates. This improves infiltration and reduces runoff, thereby increasing water-holding capacity and mitigating drought stress. Residue mulching and cover crops act as thermal buffers, moderating soil temperature fluctuations and protecting seedlings from heatwaves and frost. Diversified crop rotations and intercropping under CA systems also support pest and disease regulation, reduce weed pressure, and improve nutrient cycling. These biological synergies enhance crop vigour and stability, resulting in more consistent yields under variable climatic conditions. Moreover, CA reduces dependence on external inputs such as water, synthetic fertilizers, and energy, which are often constrained during climate extremes. This input efficiency contributes to economic resilience and sustainability, especially in regions facing frequent droughts, erratic rainfall, or escalating production costs. Resilience also extends to ecosystem-level services. CA fosters greater microbial diversity and soil biological activity, which are essential for nutrient transformations, carbon stabilization, and long-term soil fertility. These qualities improve the overall adaptability of the farming system to both short-term shocks and long-term climatic trends.

Implementation Challenges and Context-Specific Outcomes

Despite the many advantages of CA, adopting it widely remains difficult due to several technical, social, and economic challenges. A fishbone diagram of implementation challenges and context-specific outcomes in CA is shown in Fig. 2. A major issue is the lack of awareness and training among farmers. Shifting from traditional farming methods to CA involves learning new practices that rely on understanding soil biology, crop interactions, and residue management. Unfortunately, many farmers do not have access to quality extension services, training programs, or decision-making tools needed to support this transition. Limited access to suitable equipment is another major obstacle. Tools like zero-tillage seeders, residue spreaders, and direct planters are often unavailable or unaffordable especially for small-scale farmers in developing regions. Without proper machinery, CA practices can become time-consuming and labour-intensive. Additionally, the supply chains for agricultural equipment often do not promote CA-compatible tools due to a lack of demand or incentives. Managing crop residues is also a challenge, particularly in mixed farming systems where residues are used for fodder, fuel, or bedding. Leaving them on the field, as CA recommends, may conflict with traditional uses, making it socially and economically unfeasible for many farmers. Effective solutions require community-based approaches and integration with livestock needs. The success of CA also depends on local conditions such as soil type, climate, and resource availability. In areas with sandy soils, for example, carbon buildup is often minimal due to low soil aggregation. High rainfall zones may face increased pest and disease problems under heavy residue retention. Similarly, in low-input systems, the benefits of CA may take years to appear, discouraging farmers from sticking with the practice. Perceived risk is another barrier. Farmers with limited land or capital may avoid CA due to fears of lower yields during the transition phase. Without strong support systems like crop insurance, input subsidies, or assured markets, they are unlikely to adopt such practices. In conclusion, while CA offers a promising path to sustainable and climate-resilient farming, its success depends on adapting the approach to specific local needs. Policymakers must address these challenges through targeted subsidies, flexible guidelines, farmer-friendly extension services, and community engagement to ensure CA adoption is both feasible and beneficial for farmers.

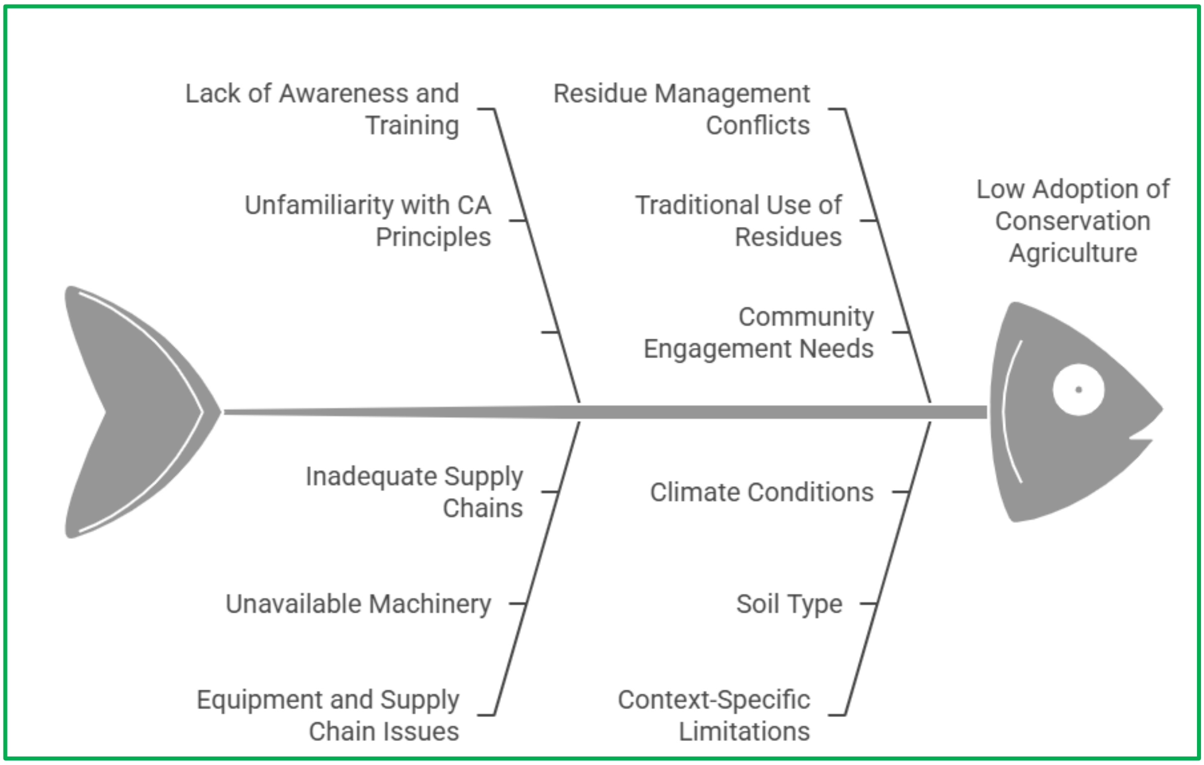

Fig. 2: Implementation Challenges and Context-Specific Outcomes in Conservation Agriculture (CA)

Conclusion and Way Forward

Conservation agriculture (CA) stands at the nexus of agricultural productivity and climate action. As a carbon farming strategy, it offers a compelling pathway to mitigate greenhouse gas emissions, sequester atmospheric carbon, and enhance the resilience of farming systems in the face of escalating climate variability. Through practices such as zero tillage, residue retention, and diversified crop rotations, CA not only stabilizes and increases soil organic carbon stocks but also contributes to broader ecosystem services like improved water retention, biodiversity enhancement, and soil health. Scientific evidence increasingly supports the climate mitigation potential of CA, especially when implemented in conjunction with integrated nutrient and water management. Furthermore, CA helps smallholder and commercial farmers alike adapt to climate stresses, offering a buffer against drought, heatwaves, and erratic rainfall. However, the pathway to mainstreaming CA is neither linear nor universal. Context-specific challenges ranging from access to mechanization and competing residue uses to variations in soil response highlight the need for nuanced, locally adapted solutions. Transitioning to CA demands long-term commitment, investment in capacity-building, and enabling policy environments that support innovation and risk mitigation. For CA to serve as a scalable climate solution, it must be embedded within broader sustainability frameworks and supported through international climate finance, agricultural subsidies, and inclusive governance structures. This includes empowering farmer cooperatives, enhancing public-private partnerships, and strengthening extension networks.

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