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Conservation Agriculture: A Climate-Smart Path to Sustainable Farming

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Abstract

Soil degradation and an increasingly unpredictable climate threaten the productivity of farms worldwide, with conventional tillage accelerating erosion and loss of soil organic matter. Conservation Agriculture (CA) offers a climate-smart approach to sustainable food production that is built on three interlinked principles: minimal soil disturbance, permanent soil cover and crop diversification. Emerging from the lessons of the 1930s Dust Bowl and refined over decades of global adoption, CA can play a major role in improving soil structure, conserving moisture, reducing erosion, supporting soil carbon storage and strengthening resilience to climate stress. It can also contribute to climate- change mitigation through soil carbon sequestration and reduced fuel consumption. Despite these benefits, adoption remains constrained by machinery costs, residue management trade-offs and knowledge gaps among farmers. Targeted policy support, accessible technology through Custom Hiring Centres and stronger extension services can help bridge this gap. This article presents CA's scientific basis, historical development, climate benefits, major challenges and practical pathways for its wider adoption, positioning it as a scalable approach for building resilient and sustainable farming systems.

Keywords: Conservation Agriculture, Climate Change, Soil Carbon Sequestration, Climate resilience, Sustainable farming

1. Introduction

Every year, the Earth loses a staggering 24 billion tonnes of fertile soil, creating a silent crisis that affects nearly 25% of our global land area (Kumawat *et al.*, 2023). For smallholder farmers, this is more than just a statistic. It means declining soil productivity, greater vulnerability to erosion and drought, along with increasing pressure on the people who depend on it for their livelihoods. As climate change intensifies, this vulnerability is pushed to the brink. Rising temperatures, erratic rainfall patterns and prolonged droughts are no longer distant threats but daily realities that jeopardise global food security. Conventional farming practices, characterised by intensive tillage and the removal of crop residues, can accelerate soil degradation by disturbing soil structure, increasing erosion and reducing soil organic matter.

To feed a growing population in an increasingly volatile environment, we must reconsider how we manage our most fundamental resource, the soil. Conservation Agriculture (CA) offers a transformative, climate-smart pathway towards sustainable farming. It is built on three core principles: minimum mechanical soil disturbance, permanent soil cover and crop diversification. CA approach can help restore soil health and strengthen ecosystem resilience. Recent research indicates that CA practices can boost crop productivity and water productivity by up to 76% and 66%, respectively, while improving soil health and water infiltration under increasing climate stress (Kumawat *et al.*, 2023; Teng *et al.*, 2024). By protecting soil, conserving water and strengthening the resilience of farming systems, CA offers a practical, scalable and climate- smart path towards sustainable farming.

2. A Brief History: From Dust Bowl to Conservation Agriculture

Modern Conservation Agriculture (CA) emerged from necessity. In the 1930s, the United States' "Dust Bowl" turned millions of hectares of farmland into airborne dust, as intensive ploughing stripped away the soil's ability to hold itself together. So, the researchers began exploring no-tillage methods to prevent soil erosion.

By the 1970s, farmers in Brazil and Argentina picked up the thread and combined no-till methods with cover crops to fight their own land degradation crises. In India, the CA journey gained momentum in the 1990s with the adoption of zero tillage wheat in the Indo Gangetic Plains. Zero tillage helped farmers overcome delays in wheat sowing and reduce cultivation costs. It also helped address herbicide resistant weed *Phalaris minor* (Erenstein and Laxmi, 2008). The approach gradually expanded beyond zero tillage towards residue retention and diversified cropping, strengthening CA based systems across the region.

Recognizing its potential to transform global farming, the Food and Agriculture Organization (FAO) formally defined the three core principles of CA in the late 1990s. The global area under CA increased from 106.5 million hectares in 2008-09 to 205.4 million hectares in 2018-19. By 2024, it was estimated to have reached 250–270 million hectares, reflecting its rapid expansion across agricultural systems worldwide (Rockström *et al.*, 2026).

3. What is Conservation Agriculture?

Imagine a farm where the plough rarely touches the soil, the ground is always covered and no single crop dominates the field year after year. That is CA in a nutshell, a farming system built around working with nature's processes rather than against them. Instead of being a single farming practice, CA is an integrated approach to manage land, water and biological resources to make farming more efficient and resilient (Hossain *et al.*, 2021). According to Richards *et al.* (2014), CA is characterised by three interconnected principles:

a) Minimum soil disturbance

This means reducing soil disturbance to the minimum necessary for crop establishment, often through reduced or zero tillage. Under reduced tillage, no more than 20-25% of the soil surface should be disturbed.

b) Permanent soil cover

The soil should remain protected by crop residues, mulch or living cover crops. A minimum soil cover of around 30% must be kept, although the appropriate level depends on the local soil, climate and cropping system.

c) Crop diversification

Instead of planting the same crop year after year (monoculture), farmers must incorporate crop rotations, intercropping or other diversified cropping sequences. For example, a farmer might rotate maize with legumes like beans or peas, which naturally improves soil fertility and disrupts the life cycles of pests and diseases.

These three principles are designed to work together rather than in isolation. Reduced soil disturbance protects soil structure, soil cover helps in conserving moisture and crop diversification supports a more balanced and resilient cropping system. Collectively, they build a stronger foundation for sustainable farming in an increasingly unpredictable climate.

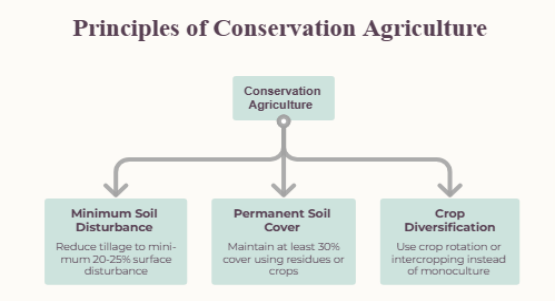


Fig. 1. Principles of Conservation Agriculture

4. CA: Building Climate Resilience for Sustainable Farming

Climate resilience refers to the capacity of a farming system to withstand, absorb and recover from climatic stresses such as drought, erratic rainfall and extreme heat while maintaining its productivity (Khan *et al.*, 2024). In agriculture, this resilience begins beneath our feet, where soil structure provides the foundation for stable crop production. When soil is protected by crop residues and subjected to minimal disturbance, its particles bind together to form stable aggregates. By prioritising soil health, CA fundamentally transforms how land interacts with water. Instead of allowing rains to wash away topsoil, the undisturbed earth and its protective residue cover maintain structural integrity. An eight-year field study on Vertisol in Central India found that no-till soils developed water-stable aggregates covering 79.4% of the surface layer, compared to just 63.8% under conventional tillage (Naorem *et al.*, 2023). These stable aggregates help the soil withstand the impact of water, reduce erosion and maintain a structure that supports water infiltration and storage. However, resilience also comes from crop diversification. Diversification of crops can help improve how efficiently water and nutrients are used, promote better soil health and lower the chances of pest and disease incidence, which in turn supports a sustainable production system. Evidence from India shows that crop diversification can cushion the adverse effects of rainfall deficits and heat stress on agricultural productivity, with its adaptation benefits becoming more pronounced under

severe climatic fluctuations and over the long term (Birthal and Hazrana, 2019).

Beyond strengthening climate resilience, CA contributes to climate change mitigation through greater soil carbon storage and reducing energy consumption in farming operations. Conventional ploughing releases stored carbon into the air as CO_2, whereas reduced soil disturbance and increased residue retention under CA can promote soil carbon accumulation. By reducing soil disturbance, farmers can see an increase in soil organic carbon stocks of up to 19.4% in the surface layers (Jayaraman *et al.*, 2022). Furthermore, by cutting out unnecessary tractor passes, CA has been shown to slash farm fuel consumption by 35 to 40%, while decreasing the farm mechanized operations by 30 to 45% and increase the profitability by 15 to 35% (Zbancă *et al.*, 2025). Altogether, these benefits show how CA can strengthen soil resilience, contribute to climate change mitigation, conserve resources and improve economic returns, helping to build farming systems that remain productive and sustainable over the long term.

5. Challenges in Adoption of CA

Despite its clear benefits, transitioning to CA is far from a simple switch for most farmers. One of the primary hurdles is access to suitable machinery for farmers shifting to zero- tillage systems because resource-conserving technologies require specialized equipment and involve substantial initial costs. In the Indo-Gangetic Plains, 70.37% of farmers reported the high cost of zero-till machinery like the zero-till seed drill and happy seeder as a constraint, while 80.74% reported limited knowledge of machine adjustments (Kumar *et al.*, 2026).

Crop residue management poses another challenge in CA. Although retaining residues on the soil surface is central to CA, farmers may depend on straw as livestock feed or burn it to clear fields quickly for the next crop. Residue burning not only removes the protective soil cover required for CA but also loses valuable organic matter and nutrients. Weed management also becomes more complex without the traditional "reset" provided by the plough, as weed populations may shift and require more precise herbicide use and greater technical knowledge (Sahoo *et al.*, 2025). Many farmers also hesitate during the transition period, when yields can dip temporarily before soil structure and fertility fully recover. This uncertainty can discourage adoption, even when long-term benefits are well documented. The extent of these challenges, however, varies with local soil conditions, water availability, farm size and access to machinery and support services. Implementing all three principles of CA simultaneously requires a systemic shift that can be daunting without strong extension support, training and practical knowledge. However, identifying these challenges is the first step toward creating tailored solutions that can make CA more accessible and effective for farmers. This understanding of current barriers paves a clear path toward the innovations needed for the way forward.

6. The Way Forward: Making CA Work for Farmers

To turn the potential of CA into widespread reality, the gap between scientific promise and field-level practice must be bridged. The primary economic barrier can be dismantled through Custom Hiring Centres (CHCs) and machinery sharing models that let smallholder farmers to rent zero till technology rather than buy it outright, thus reducing the cost of field operations. Government support can further improve access to such technologies. Under India's Crop Residue Management Scheme, financial assistance of 50% is provided to individual farmers for eligible machinery, while assistance of up to 80% is available for eligible organizations establishing CHCs. Since the scheme began in 2018–19, more than 3.54 lakh crop residue management machines such as happy seeders, straw choppers, balers etc. have been distributed and more than 43,500 CHCs have been established (MoA&FW, 2026).

Beyond machinery, wider adoption will also depend on farmer training, efficient extension services and practical alternatives to residue burning. Policy support should promote an integrated CA approach based on minimal tillage, residue retention and crop diversification, rather than treating zero tillage as a stand-alone practice. CA is not a rigid template but a dynamic system that can be customized to the resources and requirements of each farm. With accessible technology, appropriate policy support and locally pertinent expertise, CA can become a practical pathway towards productive, resilient and sustainable farming.

7. Conclusion

Conservation agriculture is more than just a set of farming techniques; it represents a move toward more sustainable management of soil and agricultural inputs. By combining minimal soil disturbance, soil cover and crop diversification, CA can strengthen soil resilience, conserve moisture, reduce soil erosion, support

soil carbon storage and thus help in mitigating climate change. At the same time, farm profitability can also be increased by using less fuel and paying less for field operations. Even if obstacles like access to machinery, residue management and technical expertise still exist, these can be addressed with the help of appropriate policy support, farmer training and locally tailored strategies. As climate uncertainty increases, CA offers a practical, climate-smart strategy to maintain agricultural productivity, while safeguarding soil and other natural resources that are the cornerstone of resilient and sustainable farming for future generations.

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