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Conservation Agriculture in Dry land Farming: A Review

*Madhukumar S R, Sagar Chandaki, Sangayya Math and Anil Kumbar
M.Sc. Scholar, College of Agriculture, Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani-431402, Maharashtra, India
*Corresponding Author's email: madhukumar4157@gmail.com

Conservation agriculture (CA) has emerged as a transformative approach to ensuring sustainable crop production in the face of soil degradation, climate change, and water scarcity. Dryland farming systems, which contribute significantly to global food production, are increasingly vulnerable to erratic rainfall, high evapotranspiration, and declining soil fertility. In such environments, conventional tillage-based agriculture accelerates land degradation and reduces productivity, whereas CA offers a pathway to resilience. Based on three interrelated principles: minimum soil disturbance, permanent soil cover, and crop diversification. CA improves soil health, enhances water-use efficiency, and stabilizes yields. Globally, CA has been adopted across 205 million hectares, with significant successes in South America, Africa, and Australia. In India, adoption is gaining momentum, particularly in dryland states such as Maharashtra, Madhya Pradesh, and Rajasthan, supported by national initiatives like NICRA, RKVY, and research from institutions such as ICAR and CIMMYT. This review synthesizes global and Indian experiences of CA in dryland farming, highlighting agronomic, environmental, and socio-economic benefits while discussing challenges including residue management, equipment costs, and farmer awareness. Future prospects emphasize integration with climate-smart agriculture, precision tools, and crop breeding for CA systems. Strengthening institutional support, farmer training, and adaptive research is vital for mainstreaming CA in dryland regions.

Keywords: Conservation agriculture, dryland farming, soil health, crop diversification, water-use efficiency

Introduction

Agricultural sustainability has become a critical global issue, particularly in the context of climate change, land degradation, and water scarcity. Traditional agricultural practices often degrade natural resources, reduce biodiversity, and impair the long-term productivity of soils. As the global population continues to rise, the demand for food, fiber, and fuel is also increasing, placing immense pressure on already fragile ecosystems, especially in dryland areas. These regions, which account for over 40% of the Earth's terrestrial surface, are particularly vulnerable due to limited and erratic rainfall, poor soil fertility, and frequent droughts (UNCCD, 2020).

Dryland farming refers to agricultural methods specifically adapted for arid and semi-arid regions with minimal or no irrigation. This type of farming is often constrained by climatic unpredictability, nutrient-deficient soils, and a high risk of crop failure. In many developing countries, dryland agriculture supports a significant proportion of smallholder farmers who depend on rainfed systems for their livelihoods. However, conventional tillage-based farming systems in these regions often exacerbate soil erosion, decrease soil organic matter, and degrade water retention capacity, ultimately threatening food security and rural economies (Rockstrom *et al.*, 2010).

History and development of conservation agriculture:

In the 1930s for the first time tillage, as a soil management concept, was questioned, when the dustbowls devastated wide areas of the mid-west United States. The idea of conservation tillage was introduced for erosion control through reduced tillage and keeping the surface soil covered with crop residues. In true sense, only in the 1960s no-tillage was introduced in farming practices in the USA. In western Indo-Gangetic plains (IGP), during the mid-1990s on-farm testing of the zero-till drill was started with the introduction of an inverted T opener on Pantnagar zero-till drill. Many resource-conserving technologies (RCTs) like ZT, bed planting, laser levelling, dry seeding, etc. are being developed and made available to the farmers in Indian IGP. In the first decade of the twenty-first century, many CA-based component technologies have been developed, tested, and refined to address the issues of resource conservation, soil health, water, labour, crop establishment, etc. in rice and wheat crops of IGP. From the year 2012, CA is increasingly being promoted in the region as Climate Smart Agriculture Practices (CSAPs) by integrating it with precise water and nutrient management with the aim of increasing resilience to climate change and enhancing the mitigation potential of cropping systems.

The increase in the area under CA has been especially significant in South America (69.9 M ha) mainly in Argentina, Brazil, Paraguay and Uruguay followed by North America (63.2Mha) mainly in USA and Canada. In Asia it is around 13.9 M ha (7.7%), corresponding to 4.1% of the cropland in the region. The total cropland area under CA in 2015/16 is about 180 M ha of arable cropland glob ally (12.6% of cropland) in more than 50 countries. Argentina, Australia, Brazil, Canada, and America cover more than 90% of the area under CA (FAO, 2015). CA systems are widely adaptable in different ecologies (Jat et al., 2014), in India it is practiced in 1.5 M ha area.

Conservation Agriculture started in Punjab, India with direct seeding of wheat (*Triticum aestivum* L.) in 1980s. In 1990s, the International Maize and Wheat Improvement Centre (CYMMYT) launched the CA programme in India, Bangladesh, Nepal, Pakistan, Afghanistan and China. Subsequently rice–wheat consortium (RWC) was established by the Consultative Group for International Agri cultural Research (CGIAR) in 1994 to deal with rice wheat farming systems practiced widely in Indo–Gangetic plains and Himalayan mid–hills region. The CA based technologies are being practiced over nearly 1.5 Mha in irrigated regions of India, particularly in Indo–Gangetic plains (Kassam *et al*., 2019). This history of research on CA technologies was from irrigated cropping systems particularly in rice–wheat system. The research on typical CA involving tillage levels, crop–residue retention on soil surface and N management under rainfed conditions with sorghum–castor (*Ricinus communis* L.) rotation was initiated in 1995 at the ICAR–CRIDA farm. Subsequently several experiments on typical CA with anchored crop–residues involving zero till planters under major rianfed crop rotations were started from 2005 onwards at CRIDA, Hyderabad. Under Consortium Research Platform on CA (CRP–CA), CA experiments were extended to selected centres of All India Coordinated Research Project on Dry land Agriculture (AICRPDA) and farmers' fields in 2012-13. The research work done in India on CA in rainfed and dryland ecosystems is reviewed critically here, to identify suitable CA practices, prospects and potential benefits of CA, and issues and opportunities for adoption of CA practices in rainfed areas over large scale.

Global and Indian Scenario of Conservation Agriculture

Globally, conservation agriculture is practiced on over 205 million hectares (FAO, 2022). South America leads adoption, with Brazil, Argentina, and Paraguay pioneering no-till and residue retention technologies in soybean, maize, and wheat systems. In Africa, Zambia and Kenya have promoted CA through smallholder-focused projects, though adoption remains uneven due to labor, knowledge, and equipment constraints. Australia demonstrates large-scale adoption in dryland wheat–sheep systems, where CA has been instrumental in sustaining yields under highly variable rainfall (Kassam et al., 2019).

In India, CA is expanding through government initiatives, ICAR-led research, and NGO interventions. Adoption has been particularly visible in the Indo-Gangetic Plains with rice–wheat systems using zero-till drills. However, in dryland regions such as Maharashtra, Karnataka, and Rajasthan, adoption is slower due to resource limitations. Here, CA practices such as in-situ moisture conservation, residue mulching, and intercropping of pulses with cereals show promise for stabilizing yields under water scarcity (Jat et al., 2020).

Principles of Conservation Agriculture

The foundation of CA rests on three principles, each of which plays a critical role in dryland farming systems:

1. Minimum Soil Disturbance: This principle involves minimizing soil disturbance to maintain soil structure, health, and biodiversity. No-till or reduced tillage practices help preserve soil organic matter, reduce erosion, and enhance water retention. By avoiding frequent and deep plowing, the soil's natural ecosystem is less disrupted, promoting beneficial soil organisms and reducing soil compaction.

- Conventional Tillage leaves < 15 % residue on soil surface
- Conservation Tillage leaves at least 30% residue on soil surface
- No Till leaves the soil covered 100% of the time

2. Permanent Soil Cover: Maintaining a continuous cover on the soil surface with living plants or plant residues is crucial. This cover protects the soil from erosion, suppresses weeds, conserves soil moisture, and enhances soil organic matter. Cover crops, such as legumes, grasses, or mixtures, can be planted during off-seasons to keep the soil covered and improve soil health.

- Cover crops contribute to the accumulation of organic matter
- Permanent soil cover is vital for protecting the soil from the beating action of rain drops and direct sun shine effect.
- Alters the micro climate of the soil.

3. Crop Diversification: Implementing diverse crop rotations or intercropping systems helps break pest and disease cycles, reduces the risk of crop failure, and improves soil fertility. Different crops have varying root structures and nutrient requirements, which can lead to more efficient use of soil nutrients and improved soil structure. Crop diversity also enhances biodiversity, both above and below ground, contributing to a more resilient agricultural system. By adhering to these principles, conservation agriculture aims to create a more sustainable and productive farming system that is resilient to environmental stresses and capable of supporting long-term agricultural productivity.

Adoption of CA in Dryland Farming Systems

Global Experiences

In South America, the adoption of zero-till systems in Brazil has significantly improved both productivity and sustainability, with maize and soybean yields increasing by 15–20% while soil erosion was reduced by nearly 80% (Derpsch et al., 2019). In Africa, conservation agriculture has shown similar promise, with evidence from Zambia indicating a 40% improvement in maize yields under erratic rainfall conditions (Nyamangara et al., 2020). Likewise, in Australia, dryland wheat systems managed under CA have consistently reported yield stability even during severe drought years, largely due to enhanced soil water retention and improved resilience.

Indian Experiences

In India, several states have demonstrated the potential of conservation agriculture in dryland systems. In Maharashtra, the practice of mulching in sorghum and pigeon pea cropping systems improved soil moisture availability by 25–30% and increased yields by 10–15% (Jadhav et al., 2018). In Madhya Pradesh, soybean–chickpea rotations under no-till practices enhanced farm profitability by lowering input costs while maintaining productivity. Similarly, in Rajasthan, conservation agriculture-based intercropping of pearl millet with mungbean improved overall system productivity and resilience, offering farmers greater stability under variable climatic conditions.

Benefits of Conservation Agriculture in Dryland Farming

Conservation agriculture (CA) provides multiple benefits in dryland ecosystems where water scarcity and soil degradation are major challenges. Agronomically, CA enhances soil moisture retention, raises rainwater-use efficiency by up to 30%, and improves soil organic carbon by 0.2–0.4% annually, resulting in 10–25% higher yields in cereals and pulses under rainfed conditions. Environmentally, CA reduces soil erosion by 50–70%, sequesters 0.3–0.5 t C ha^{-1} yr^{-1}, and lowers greenhouse gas emissions by minimizing tillage and fertilizer use, thereby contributing to climate change mitigation. Socio-economically, CA reduces production costs through savings in fuel and labor, supports higher cropping intensity and income diversification, and strengthens smallholder resilience to climate shocks. Collectively, these benefits establish CA as a vital strategy for enhancing productivity, sustainability, and livelihoods in dryland farming systems.

Challenges and Constraints

Despite its proven benefits, the adoption of conservation agriculture (CA) in dryland regions remains constrained by several barriers. One of the major challenges is residue management, as crop residues are often diverted for use as livestock fodder, limiting their availability for mulching and soil cover. The high initial cost of specialized equipment, such as zero-till drills and seeders, further discourages small and marginal farmers from investing in CA technologies. In addition, knowledge gaps and limited extension support restrict farmer awareness of CA practices and their long-term benefits. Short-term yield fluctuations also act as a deterrent, as farmers frequently expect immediate returns, whereas the advantages of CA—such as improved soil fertility and water-use efficiency—tend to accumulate gradually over time. Furthermore, socio-economic constraints, including land fragmentation, credit limitations, and resource scarcity, make it difficult for many dryland farmers to adopt and sustain CA practices.

Policy Support and Institutional Efforts

India has undertaken several initiatives to promote conservation agriculture (CA) in dryland regions through research, policy, and institutional support. The National Innovations on Climate Resilient Agriculture (NICRA) program emphasizes CA-based adaptation strategies in rainfed farming systems, focusing on enhancing resilience to climatic variability. The Rashtriya Krishi Vikas Yojana (RKVY) has played a significant role in funding farm mechanization and farmer training programs to encourage adoption of CA technologies. Additionally, ICAR–CIMMYT collaborations have introduced innovations such as zero-till seeders and residue management technologies, which are critical for sustainable dryland farming. At the global level, organizations such as the Food and Agriculture Organization (FAO) and the CGIAR consortium actively advocate for CA as a cornerstone of climate-smart agriculture, emphasizing soil conservation, sustainable intensification, and resource-use efficiency. Together, these national and international efforts highlight the importance of CA as both an adaptation and mitigation strategy for dryland agriculture.

Future Prospects and Research Needs

The future of conservation agriculture (CA) in dryland systems lies in adopting integrated and innovative approaches that enhance resilience and productivity. Climate-smart CA, when aligned with weather forecasting and crop modeling tools, can help farmers make timely decisions and mitigate climate risks. Digital agriculture technologies, including drones, sensors, and decision-support systems, are emerging as valuable tools for optimizing field operations and monitoring resource use efficiency. Equally important is crop breeding, which must focus on developing varieties specifically adapted to no-till and residue-retained environments, ensuring stable yields under stress conditions. Farmer capacity building through participatory extension approaches will play a crucial role in improving knowledge, building trust, and encouraging adoption of CA practices. Furthermore, supportive policy frameworks offering incentives such as subsidies for CA equipment, residue management, and carbon credit schemes can accelerate the widespread adoption of CA in dryland regions.

Conclusion

Conservation agriculture provides a sustainable pathway for enhancing productivity, resilience, and environmental health in dryland farming systems. Evidence from global and Indian contexts shows that CA improves soil quality, stabilizes yields, and supports climate resilience. However, widespread adoption requires overcoming challenges related to residue management, mechanization, and farmer capacity. Strengthening institutional support, policies, and research on locally adapted CA practices will be crucial for scaling its adoption. Integrating CA into national dryland development strategies can ensure food security and sustainable livelihoods under changing climates.

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