

13. Carbon Sequestration Potential of Conservation Agriculture Systems under Climate Change Scenarios

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Introduction: Climate Change and the Role of Agriculture

Conventional agricultural practices based on intensive tillage and monocropping have led to soil structure degradation, loss of soil organic matter, increased erosion, and higher CO₂ emissions. In response, conservation agriculture (CA) has emerged as a key sustainable management framework to address land degradation, food security, and greenhouse gas mitigation while maintaining crop productivity (IPCC, 2019). Soil organic carbon (SOC) in agricultural systems depends on the balance between carbon inputs from crop residues and organic amendments and losses through erosion and decomposition. Increases in SOC are widely used as an indicator of CA effectiveness because of their benefits for soil health and climate change mitigation (Bossio *et al.*, 2020). However, long-term monitoring and robust reporting systems are essential to reliably assess SOC changes under CA. Climate change will strongly influence SOC dynamics, as elevated CO₂ may enhance biomass inputs, while rising temperatures can accelerate SOC decomposition. Soils are increasingly recognized for their role in

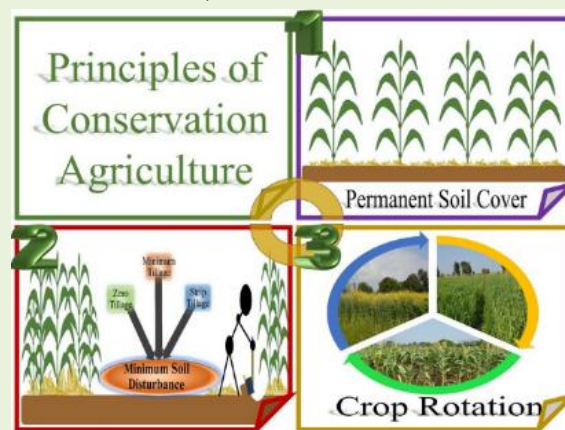
providing ecosystem services linked to the Sustainable Development Goals and climate policy agendas. Agriculture therefore faces the dual challenge of ensuring food security while sustaining soil functions such as carbon sequestration, nutrient cycling, and water regulation. Despite global progress, food insecurity remains widespread and is expected to intensify under climate change. These challenges are particularly acute in India and other climate-vulnerable regions, where rising temperatures, erratic rainfall, and extreme events threaten agricultural productivity and livelihoods (Ranjan *et al.*, 2021). Agriculture is also a major source of methane and nitrous oxide emissions, yet it holds significant mitigation potential through improved soil management and carbon sequestration (FAOSTAT, 2020). In this context, CA is widely promoted as a practical approach to enhance resilience, reduce soil degradation, and contribute to climate-smart and sustainable agriculture, especially in South Asia and Sub-Saharan Africa.

Carbon Sequestration and Soil Health

A consistent body of evidence shows that shifting from intensive conventional tillage to conservation agriculture (CA) practices such as reduced tillage, permanent soil cover, and diversified cropping enhances soil organic carbon (SOC) stocks across agroecosystems worldwide. Increased SOC under CA improves soil physical, chemical, and biological properties, including aggregate stability, water infiltration, nutrient availability, and microbial diversity, which together underpin soil health and productivity. Organic matter derived from crop residues provides energy for soil microorganisms, stimulating nutrient cycling and enhancing crop nutrient uptake. Higher SOC also strengthens soil resilience by physically protecting organic matter within stable aggregates, thereby improving carbon storage and resistance to climatic stresses. Through these mechanisms, SOC interacts with water and air systems and supports multiple ecosystem services, including climate regulation, land degradation neutrality, and greenhouse gas mitigation, aligning closely with several Sustainable Development Goals. Consequently, SOC is widely regarded as a robust indicator of sustainable agricultural management and climate mitigation potential.

Soil health worldwide is increasingly threatened by erosion, compaction, salinization, nutrient depletion, and pollution (FAO and ITPS, 2015). Healthy soils are essential for sustaining food production while maintaining ecosystem services such as nutrient cycling, water regulation, and biodiversity conservation. Conservation agriculture systems improve these functions by

enhancing soil structure and biological activity. Within CA, cover crops play a central role by supplying organic inputs, suppressing weeds, improving water retention, reducing nutrient losses, and regulating soil biota. Over time, cover cropping contributes to SOC and nitrogen accumulation and reduces net CO₂ and N₂O emissions, supporting climate change mitigation (Cates *et al.*, 2019).



Soils constitute one of the largest terrestrial carbon reservoirs, storing about 1500 Pg of carbon in the upper metre nearly twice the carbon in the atmosphere. Past land-use change and intensive cultivation have depleted this pool, contributing significantly to atmospheric CO₂ emissions. Enhancing SOC through CA-driven carbon sequestration defined as the transfer of atmospheric CO₂ into stable soil carbon pools via plant biomass and residues offers a cost-effective strategy to mitigate climate change while improving soil fertility, water retention, erosion control, and overall agricultural sustainability.

Conservation Agriculture: An Overview

Conservation agriculture (CA) emerged in the 1930s as a response to severe soil degradation

caused by intensive tillage, gaining wider recognition after the Dust Bowl in the United States. Since then, CA has been adapted to diverse agroecosystems worldwide. The Food and Agriculture Organization defines CA as a sustainable production system that enhances food security and farm profitability while conserving soil, water, and biological resources. CA is based on three interlinked principles: minimum or zero soil disturbance, permanent soil cover through crop residues or cover crops, and crop diversification through rotations, intercropping, or associations (FAO, 2020). These principles enhance soil biological activity, protect soil from erosion, improve water infiltration, and strengthen soil organic carbon (SOC) dynamics, thereby increasing system resilience. Crop diversification, in particular, improves ecosystem functioning and SOC accumulation while reducing vulnerability to climatic stresses.

Three core principles of conservation agriculture enhancing soil carbon sequestration and climate resilience.

Conventional agriculture has historically focused on maximizing yields through intensive inputs and tillage, often resulting in soil structure degradation, compaction, and loss of soil health. In contrast, CA mitigates these impacts by maintaining soil cover and reducing disturbance, thereby improving soil structure and biological processes (Indoria *et al.*, 2017). While CA is widely recognized as a pathway to sustainable agriculture, its adoption particularly among smallholders in mixed crop–

livestock systems can be constrained by competing uses of crop residues as livestock feed.

Carbon Sequestration Potential of Conservation Agriculture under Climate Change

Soils are among the largest terrestrial carbon reservoirs, storing about 1500 Pg of carbon in the upper metre, nearly twice the amount in the atmosphere. However, intensive cultivation and land-use change have led to substantial SOC losses and increased CO₂ emissions. Conservation agriculture enhances SOC sequestration by reducing soil disturbance and increasing carbon inputs through residues, cover crops, and diversified rotations (Alvaro-Fuentes *et al.*, 2012). Reported SOC sequestration rates under CA range from 0.27–1.10 t ha⁻¹ yr⁻¹ in Mediterranean systems and 0.12–1.56 t ha⁻¹ yr⁻¹ in tropical regions, with higher rates generally observed in moist climates (Powlson *et al.*, 2016). Crop diversification alone can increase SOC stocks by about 0.15 ± 0.11 t C ha⁻¹, with greater gains in complex rotations and legume-based systems.

In the Indo-Gangetic Plains, CA practices have resulted in modest but significant SOC gains, with average sequestration rates of 0.37 Mg C ha⁻¹ yr⁻¹, while Sub-Saharan Africa shows wider variability (0–1 Mg C ha⁻¹ yr⁻¹) depending on climate and management (Powlson *et al.*, 2016). These gains are typically highest during the initial years of CA adoption and in soils with low initial SOC stocks, but are ultimately limited by soil carbon saturation. Climate change is expected to influence future SOC sequestration. Simulation studies indicate

lower sequestration rates under high-emission scenarios (e.g., RCP8.5) compared with low-emission pathways (Huang *et al.*, 2020). Nevertheless, the IPCC recognizes CA as a key strategy for mitigating greenhouse gas emissions, improving soil health, and enhancing climate resilience (IPCC, 2019). Although global cropland SOC sequestration potential is finite (0.4–1.2 Gt C), CA remains a cost-effective and scalable approach for climate-smart agriculture, especially when combined with broader mitigation strategies.

Evidence from Indian Studies and Field Experiences

Soil degradation across cropping systems is a major socioeconomic and environmental concern, and climate change is expected to further threaten food production, making soil-conserving practices increasingly important. Field evidence shows that reduced soil disturbance improves soil quality, environmental performance, and soil water conservation particularly under rainfed conditions. In India, long-term studies from the Indo-Gangetic Plains (IGP) demonstrate clear biophysical gains from conservation agriculture (CA). In maize-based systems, no-tillage and permanent raised beds reduced soil penetration resistance by 15.9% and 30.7%, respectively, compared with conventional tillage. Under semi-arid rainfed conditions in western India, no-tillage reduced surface runoff by 16.2% and soil loss by 37.2%. In the western IGP, CA-based maize–wheat systems also improved resource-use efficiency and reduced

irrigation water requirements by up to 64% relative to conventional management (Jat *et al.*, 2020).

Zero-tillage wheat sown into rice residue in the Indo-Gangetic Plains, demonstrating permanent soil cover and



residue retention for improved soil health.

Indian evidence further indicates that CA components zero tillage, residue retention, and crop diversification can increase soil organic carbon (SOC) and lower greenhouse gas emissions. Long-term wheat-based studies report consistent SOC gains under reduced tillage. While residue retention alone may produce smaller SOC gains due to faster decomposition in tropical conditions, combining residue retention with zero tillage increased SOC accumulation to about 0.45 Mg C ha⁻¹ yr⁻¹. Residue retention also supports mitigation by reducing residue burning, a major source of carbon emissions. For comparison, evidence from Sub-Saharan Africa largely reflects combined CA practices (especially reduced tillage + residue retention), with mean SOC increases of 0.54 Mg C ha⁻¹ yr⁻¹ but much higher variability than the IGP; several on-farm studies show no detectable change due to soil heterogeneity and sampling limitations (Powlson *et al.*, 2016).

Multiple Benefits for Farmers and Environment

Conservation agriculture (CA) delivers broad on-farm and environmental benefits alongside soil carbon gains. Reduced or conservation tillage improves soil structure, porosity, aggregate stability, and water infiltration, strengthening overall soil functioning. It also substantially reduces water- and wind-driven soil erosion, with runoff reductions of 30–65% and erosion losses reduced by 63–80% across diverse systems (Martínez-Mena *et al.*, 2020). These gains translate into better water conservation and resilience to drought and temperature stress. CA enhances nutrient cycling and efficiency: improved soil conditions support nitrogen availability, while better nitrogen management can reduce N₂O emissions and lower emissions linked to machinery and field operations. Residue retention is especially important for reducing runoff and soil loss, improving soil moisture, moderating soil temperature, and raising water-use efficiency (Zhao *et al.*, 2020).

Cover crops (including spontaneous plant covers) further improve infiltration, nutrient availability, and microbial biomass and diversity, while reducing erosion and suppressing weeds in subsequent crops (Muhammad *et al.*, 2021). Crop diversification improves aggregation, root development, microbial diversity, and yields through break-crop effects; legume inclusion can reduce fertilizer needs and associated N₂O emissions, while also spreading labour demand and reducing market risk. By combining reduced tillage

with residue retention and cover crops, CA protects organic carbon within soil aggregates, reduces erosion-related carbon losses, and can increase SOC stocks down to about 30 cm. Overall, CA supports soil health and ecosystem services food and fibre production, water and air quality regulation, and biological pest suppression while enabling sustainable intensification when adapted to local conditions (Jat *et al.*, 2020). In many contexts, these adaptation and resilience benefits can be more pronounced than direct mitigation where SOC gains are modest.

Challenges in Adoption

Although conservation agriculture (CA) can deliver clear soil and climate benefits, these often appear gradually and vary with soil, climate, crop type, and management; in many cases, measurable improvements may take 3–7 years after adoption. Adoption is particularly difficult in dry regions where biomass production is low and crop residues are scarce or diverted for livestock feed and household fuel. Barriers to CA adoption are multi-dimensional biophysical, technical, economic, and socio-institutional. Biophysical constraints include water and nutrient competition under arid and semi-arid conditions, waterlogging risks in heavy soils or high-rainfall zones, and potential increases in N₂O emissions where high inorganic nitrogen is used (Guenet *et al.*, 2020). In some settings, CA may increase bulk density, cause surface sealing where residue cover is insufficient, or delay crop development in cooler climates due to reduced soil temperature under mulch. Cover crops can also

compete for water under low rainfall conditions if not carefully managed.

Technical barriers include limited availability of suitable, affordable no-till seeding machinery especially for small and medium farmers and, in some systems, increased reliance on herbicides and complex weed control during the transition period (Costantini *et al.*, 2020). Economic constraints include high machinery costs, limited incentives, short-term yield penalties in some environments, and market uncertainty. Social and cultural barriers such as low awareness, limited training, and traditional preferences for intensive tillage also slow adoption. These constraints are often amplified for smallholders due to weak institutional support, limited access to inputs and credit, and labour limitations.

From a climate perspective, outcomes are context-specific: in semi-arid environments, no-till without adequate fertility management has been linked to yield reductions and negligible SOC gains, while strong sunlight can accelerate residue breakdown (photodegradation) and reduce SOC benefits if residues are poorly managed (Martínez-Mena *et al.*, 2020). Moreover, SOC sequestration potential is finite, varies widely by site, and remains limited by knowledge gaps and a shortage of long-term datasets; permanence of SOC gains is another concern. Finally, in some cases CA may increase N₂O emissions, potentially offsetting part of the mitigation benefit underscoring the need for locally adapted, integrated nutrient and residue management (Yigezu *et al.*, 2021).

Policy Support and Way Forward

Conservation agriculture (CA) must be locally adapted, as outcomes vary with climate, soil, crop type, and management; the goal is to reduce degradation without sacrificing yields and agroecosystem stability. CA integrates agronomic, environmental, and economic objectives, but adoption remains limited where incentives, supportive subsidies, and enabling regulations are weak (FAO, 2023). Strengthening extension systems especially through training technical advisors can accelerate dissemination of diversified rotations and locally suitable CA packages. A strong “way forward” is to invest in long-term experiments and monitoring to quantify SOC changes credibly and support carbon accounting and evidence-based policy; early SOC net-balance assessments can directly inform decision-making and incentive design. Soil health assessment should rely on a practical minimum dataset of physical, chemical, and biological indicators that are easy to measure, management-sensitive, and linked to ecosystem functions.

Policies should support site-specific CA design, improve access to appropriate machinery (especially no-till seeders) for both small and large farmers, and provide sustained technical backstopping (Yigezu *et al.*, 2021). Long-term viability also depends on sound crop rotations, residue management, and where needed strategic/occasional tillage, combined with measures such as cover crops and traffic control to limit compaction, runoff, and erosion. From a

climate-policy perspective, CA should be promoted primarily for soil health, resilience, and sustainable intensification, because SOC sequestration under CA can be limited, variable, and reversible. Evidence from high-input systems shows that improved nitrogen management can deliver greenhouse gas reductions comparable to or greater than SOC sequestration, reinforcing the need for integrated packages that combine CA with efficient nutrient management, diversification, and residue strategies especially under Indian conditions (Jat *et al.*, 2016). Internationally, policy packages (e.g., the EU Soil Thematic Strategy, CAP reforms, and the European Green Deal) and initiatives such as “4 per 1000” illustrate how incentives and coherent strategies can support SOC-focused soil protection and climate action (European Commission, 2019).

Conclusion

Conservation agriculture (CA), through minimum soil disturbance, permanent soil cover, and crop diversification, offers modest and variable increases in soil organic carbon (SOC) sequestration while significantly enhancing soil health improving soil structure, water retention, and nutrient cycling reducing greenhouse gas emissions, and building resilience to climate variability. Although its direct contribution to climate change mitigation should not be overstated, CA's primary strength lies in sustaining agricultural productivity, improving agro-ecosystem services, and supporting adaptation in the face of changing climate scenarios. Widespread adoption requires

overcoming barriers through targeted training, site-specific management, robust monitoring frameworks, and integrated policy support linking agriculture, climate, and biodiversity goals ensuring long-term food security and environmental sustainability without compromising yields.

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