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Conservation agriculture under climate change: Principles, processes, and prospects

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Abstract

Climate change poses a serious threat to global food security, agroecosystem stability, and rural livelihoods by intensifying temperature extremes, altering rainfall patterns, and increasing the frequency of droughts and floods. Conventional tillage-based agricultural systems have contributed significantly to soil degradation, greenhouse gas emissions, and declining resilience under climatic stress. Conservation Agriculture has emerged as a transformative and climate-smart production system that addresses these challenges through minimal soil disturbance, permanent soil cover, and diversified cropping systems. By improving soil physical, chemical, and biological properties, Conservation Agriculture enhances water retention, soil organic carbon sequestration, nutrient cycling, and crop stress tolerance. Evidence across tropical, subtropical, and temperate regions demonstrates its potential to stabilize yields, reduce greenhouse gas emissions, and strengthen adaptive capacity under climate variability. This review synthesizes current knowledge on the role of Conservation Agriculture in climate change adaptation and mitigation, emphasizing its impacts on soil health, crop productivity, nutrient use efficiency, and agroecosystem resilience, while highlighting the need for context-specific implementation to maximize benefits.

Keywords: Climate change, conservation agriculture, soil health, climate resilience, greenhouse gas mitigation, sustainable farming systems, nutrient use efficiency

Introduction

Adverse impacts of climate change increasingly threaten livelihoods and resilience across the globe, food security, and the stability of environmental resources. Current global food systems are not fit for purpose, necessitating transformative approaches such as Conservation Agriculture to mitigate climate change, regenerate soils, and ensure resilient food systems. Agricultural production represents one of the largest sources of environmental degradation, contributing between 21 and 37% of global greenhouse gas emissions through deforestation, depletion of soil carbon, emissions of nitrous oxide, and enteric fermentation. Without timely intervention, these emissions are projected to rise by approximately 30-40% by 2050, driven by population growth, rising incomes, and shifts in dietary preferences. Concurrently, the intensification of conventional tillage-based farming accelerates land degradation and environmental problems such as soil erosion, nutrient depletion, biodiversity loss, and pollution, thereby exacerbating the climate crisis. Consequently, producing sufficient food with finite natural resources while minimizing environmental footprints has become a critical challenge for the global scientific community. Conservation Agriculture has emerged as a sustainable production system that enhances soil health, productivity, and climate resilience through minimal soil disturbance, crop residue retention, and crop diversification. These principles act synergistically to improve soil structure, enhance water-holding capacity, and stimulate biological activity, leading to yield stability and restoration of ecosystem functions. As an integrated approach to sustainable soil management, Conservation Agriculture minimizes mechanical disturbance, maintains permanent organic soil cover, and promotes diverse crop rotations, thereby facilitating carbon sequestration, reducing greenhouse gas emissions, and strengthening climate resilience.

This paradigm recognizes agriculture as both a contributor to and a victim of climate change, offering pathways to reduce environmental impacts while enhancing food security. The urgency for climate action continues to intensify under rising global temperatures, underscoring the need for agricultural transformations that limit warming to sustainable thresholds while addressing the sector's dual role as a major emitter and a vulnerable system.

Climate Change and Agroecosystems

Trends in Climate Variability and Extremes

Climate change manifests through multiple interconnected patterns affecting agricultural systems globally. Rising temperatures have been documented extensively, with Ethiopia experiencing mean annual temperature increases of approximately 1.3 °C since 1960, at an average rate of 0.28 °C per decade Hailu *et al.*, 2024 ^[15]. This warming trend is accompanied by altered rainfall patterns, characterized by increased spatial and temporal variability that disrupts traditional farming cycles.

Drought and flood events are becoming more frequent and severe. Evidence indicates that dry spells of 3-4 weeks are manageable under conservation agriculture practices, but extreme scenarios of waterlogging and prolonged dry spells require additional management interventions Rusinamhodzi *et al.*, 2024 ^[33]. The frequency and intensity of extreme events are increasing, creating unprecedented challenges for agricultural systems that evolved under more stable climatic conditions. These climatic shifts create cascading effects throughout agroecosystems, with temperature extremes affecting crop physiology while erratic precipitation patterns disrupt soil-water dynamics and nutrient cycling processes Hailu *et al.*, 2024 ^[15].

Impacts of Climate Change on Crop Production

Climate change significantly affects crop growth, yield, and stability through multiple pathways. Simulation studies project substantial production losses, with teff, maize, and sorghum production expected to decline by 25.4%, 21.8%, and 25.2% respectively by 2050 compared to baseline periods Hailu *et al.*, 2024 ^[15]. These impacts result from shortened maturity periods, reduced crop quality and quantity, and altered distribution patterns.

Crop-soil-climate interactions are becoming increasingly complex under changing conditions. Climate change affects agricultural productivity by altering livestock feed availability, impacting animal health, growth and reproduction, and expanding desertification processes Hailu *et al.*, 2024 ^[15]. The interplay between rising temperatures, altered precipitation, and soil degradation creates feedback loops that amplify negative impacts on crop production systems. Meta-analytical evidence from sub-Saharan Africa reveals that yield benefits from conservation practices are highly context-dependent, with positive effects observed primarily under well-drained soils and moderate rainfall conditions, while poorly drained soils combined with excessive rains lead to depressed yields Rusinamhodzi *et al.*, 2024 ^[33]. This variability underscores the critical importance of understanding local crop-soil-climate interactions for effective adaptation strategies.

Vulnerability of Conventional Tillage-Based Systems

Conventional tillage-based agriculture has created widespread soil degradation, erosion, and moisture loss across global agricultural landscapes. Most of the world's agricultural

soils have been depleted of organic matter and soil health under tillage-based agriculture compared to their state under natural vegetation Pisante *et al.*, 2015 ^[32]. In Ethiopia, soil erosion rates average 12 tons/ha/year, with extreme cases exceeding 300 tons/ha/year on steep slopes where vegetation has been removed Hailu *et al.*, 2024 ^[15]. Intensive agriculture causes multiple environmental problems including pollution, soil erosion, fertility loss, biodiversity decline, and greenhouse gas emissions, which exacerbate climate change Francaviglia *et al.*, 2023 ^[11]. Tillage disturbance is a major factor that reduces carbon stabilization in fine-textured soils and promotes soil organic carbon breakdown Hailu *et al.*, 2024 ^[15].

Reduced resilience under climate extremes represents a critical vulnerability of conventional systems. Traditional farming practices contribute to declining vegetation cover through increased farming on steep slopes, degrading and depleting soils and making soil degradation a widespread environmental issue Hailu *et al.*, 2024 ^[15]. Inappropriate farming methods account for 28% of soil degradation, creating systems that are increasingly vulnerable to climate variability and extreme events. The economic implications are substantial, with land degradation causing minimum annual costs ranging between 2-3% of agricultural growth and GDP in countries like Ethiopia, representing enormous losses for agricultural sectors that form the backbone of national economies Hailu *et al.*, 2024 ^[15]. This economic vulnerability, combined with environmental degradation, creates urgent imperatives for transitioning toward more resilient agricultural systems that can withstand increasing climate pressures while maintaining productivity and environmental sustainability ^[15].

Conceptual Framework and Principles of Conservation Agriculture

Definition and Core Principles

Conservation Agriculture (CA) represents a paradigm shift from conventional agricultural practices, defined by the Food and Agriculture Organization as “a sustainable agricultural production system for the protection of water and agricultural soil that integrates agronomic, environmental and economic aspects” Francaviglia *et al.*, 2023 ^[11]. This comprehensive approach is built upon three fundamental, interconnected principles that work synergistically to enhance agroecosystem sustainability.

Minimum Soil Disturbance

The first principle involves minimum mechanical soil disturbance through conservation tillage, encompassing practices such as no-tillage (NT) and minimum tillage systems Francaviglia *et al.*, 2023 ^[11]. No-tillage represents the most advanced form, consisting of a one-pass planting and fertilizer operation where soil and surface residues are minimally disturbed, with only a narrow 2-3 cm wide strip opened for seed placement Francaviglia *et al.*, 2023 ^[11]. This approach eliminates all pre-planting mechanical seedbed preparation, fundamentally altering soil-plant-environment interactions.

Conservation tillage practices demonstrate significant benefits for soil health. Studies show that minimum tillage helps conserve soil moisture through enhanced infiltration and reduced runoff compared to conventional tillage Hailu *et al.*, 2024 ^[15]. The practice maintains crop residue, significantly reduces soil temperature, and enhances nutrient accumulation in the surface soil layer, resulting in improved crop growth and production

Hailu *et al.*, 2024 ^[15]. Research indicates that conservation tillage reduces soil disturbance and soil moisture evaporation while crop residue application increases soil moisture and soil nutrients returned from added crop residue Hailu *et al.*, 2024 ^[15].

Permanent Soil Cover

The second principle emphasizes permanent soil organic cover with crop residues and/or cover crops Francaviglia *et al.*, 2023 ^[11]. This practice involves maintaining plant cover that protects soil for extended periods without causing competition for water and nutrients with the main crop. Cover crops can be spontaneous (wild species growing according to local conditions) or seeded species selected for specific benefits, including leguminous crops for nitrogen improvement or forage crops for multiple uses Francaviglia *et al.*, 2023 ^[11]. Permanent plant cover provides multiple ecosystem services. Meta-analytical evidence shows SOC sequestration rates ranging from 0.27 to 1.03 t C ha⁻¹ yr⁻¹, with highest values achieved for woody crops under warm temperate conditions at around 1.0 t C ha⁻¹ yr⁻¹. Francaviglia *et al.*, 2023 ^[11]. Cover crops improve soil physical properties (aggregate stability, water infiltration, bulk density), chemical properties (N, P, K contents), and biological properties (microbial diversity, abundance, activity), leading to decreased wind and water erosion effects and higher, more stable yields Francaviglia *et al.*, 2023 ^[11].

Crop Diversification

The third principle involves crop diversification through rotations and associations involving at least three different crops, including a legume crop. Francaviglia *et al.*, 2023 ^[11]. This encompasses various implementation strategies: crop rotations (different crops in different years), multiple cropping (different crops in succession during the same year), and intercropping (crops grown together on the same field) Francaviglia *et al.*, 2023 ^[11]. Global data analysis from 97 paired treatments demonstrates that enhancing rotation complexity increases SOC by 0.15 ± 0.11 t C ha⁻¹ on average Francaviglia *et al.*, 2023 ^[11]. European studies show SOC increases of 18% when adopting more complex rotations and introducing legume crops, with greater increases in semiarid climates (11%) compared to humid conditions Francaviglia *et al.*, 2023 ^[11]. Crop diversification provides additional benefits including improved soil structure, enhanced biological properties through different C: N ratios, and the “break-crop effect” that increases wheat yields by 0.5 to 1.2 t ha⁻¹ when cultivated after unrelated species Francaviglia *et al.*, 2023 ^[11].

Evolution of Conservation Agriculture

Global Adoption Trends

Conservation agriculture has experienced remarkable global expansion since its conceptual origins in the 1930s following Edward Faulkner’s questioning of conventional plowing practices and subsequent development during the 1960s in the mid-western United States as a response to the Dust Bowl ecological disaster Francaviglia *et al.*, 2023 ^[11]. By 2015-2016, global analysis revealed that CA was practiced on 180.4 million hectares, equivalent to 12.5% of total global cropland Francaviglia *et al.*, 2023 ^[11]. Regional adoption patterns show significant variation in both absolute area and proportional coverage. South America leads with 69.9 million hectares (38.7% of global CA area), representing 63.2% of the region’s cropland under CA practices Francaviglia *et al.*, 2023 ^[11]. North America follows with 63.2 million hectares (35.0% of global

CA), covering 28.1% of regional cropland. Australia/New Zealand and Asia account for 22.7 and 13.9 million hectares respectively, representing 45.4% and 4.1% of their respective regional croplands Francaviglia *et al.*, 2023 ^[11].

Adoption rates vary significantly across regions, with Russia/Ukraine, Europe, and Africa showing lower implementation levels from 5.7 to 1.5 million hectares, representing only 3.6 to 1.1% of these regions’ total cropland areas Francaviglia *et al.*, 2023 ^[11]. This variation reflects diverse biophysical, socio-economic, and policy contexts influencing CA adoption worldwide ^[11].

CA in Tropical, Subtropical, and Temperate Systems

Conservation agriculture demonstrates remarkable adaptability across diverse climatic zones, though implementation strategies and outcomes vary significantly. In tropical conditions, SOC sequestration rates oscillate between 0.12 and 1.56 t SOC ha⁻¹ yr⁻¹ depending on crop type and climate regime, with higher rates in moist compared to dry conditions and generally higher rates for arable compared to woody crops Francaviglia *et al.*, 2023 ^[11]. Sub-Saharan Africa presents unique challenges and opportunities for CA implementation. Meta-analysis of 933 observations from 16 countries shows average yields under CA were only 4% higher than conventional practices, with largest yield increases of 8.4% possible when all CA principles were practiced under low rainfall conditions with herbicide use Rusinamhodzi *et al.*, 2024 ^[33]. Benefits are most pronounced on loam-textured, well-drained soils where yield benefits reach 16% higher than conventional practices, while poorly drained soils show yield depressions up to 33% Rusinamhodzi *et al.*, 2024 ^[33].

Temperate systems show different response patterns. In Mediterranean woody cropping systems, SOC sequestration rates range from 0.27 to 1.1 t ha⁻¹ yr⁻¹, with average values approximately five times higher for woody compared to arable crops Francaviglia *et al.*, 2023 ^[11]. Under boreal conditions, SOC sequestration rates range between 0.28 and 0.39 t ha⁻¹ yr⁻¹ across different soil types Francaviglia *et al.*, 2023 ^[11]. The success of CA across different systems depends on proper targeting to agroecologies and local conditions. Moisture conservation benefits are relevant in mildly water-limited environments (dry spells of 3-4 weeks) but may be irrelevant or negative in high rainfall environments Rusinamhodzi *et al.*, 2024 ^[33].

Conservation Agriculture as a Climate-Smart Practice

Adaptation and Mitigation Dimensions

Conservation agriculture embodies both adaptation and mitigation dimensions of climate-smart agriculture, providing comprehensive responses to climate change challenges. The adaptation dimension focuses on enhancing agricultural systems’ resilience to climate variability and extremes, while the mitigation dimension addresses greenhouse gas emissions and carbon sequestration.

Climate Change Adaptation through CA operates through multiple mechanisms. The practice enhances soil moisture conservation, with minimum tillage helping conserve soil moisture through enhanced infiltration and reduced runoff compared to conventional tillage Hailu *et al.*, 2024 ^[15]. Conservation tillage maintains crop residue, significantly reduces soil temperature, and enhances nutrient buildup in surface soil layers, leading to higher crop growth and production, thus helping as adaptation to climate change Hailu *et al.*

et al., 2024 ^[15]. CA fosters climate resilience by improving agricultural systems' ability to cope with climate-related shocks such as droughts, floods, and temperature extremes. By retaining soil cover and organic matter, CA helps crops withstand harsh weather conditions Hailu *et al.*, 2024 ^[15]. The practice creates resilient agricultural and food systems through improved soil health, fertility, and water management, which are critical for determining food production quantity and quality Hailu *et al.*, 2024 ^[15]. Climate Change Mitigation through CA addresses greenhouse gas emissions and carbon sequestration. Conservation agriculture is among non-substitutable options to reduce greenhouse gas emissions Hailu *et al.*, 2024 ^[15]. Key mitigation strategies include crop diversification, improved nitrogen use efficiency, crop rotation, enhanced soil carbon sequestration strategies, crop residue retention, reduced soil disturbance, and integrated farming systems Hailu *et al.*, 2024 ^[15]. Research demonstrates that conservation agriculture practices have positive impacts on soil organic carbon (SOC), soil aggregation, and carbon in aggregates, improving soil health Hailu *et al.*, 2024 ^[15]. Studies show significant differences in SOC between conservation agriculture (1.8 ± 0.07) and conventional tillage (1.6 ± 0.05), with no-till and reduced tillage showing substantial impacts on soil organic carbon (12.9 to 19.4% increase) and soil aggregates (20.77 to 25.97% increase) compared to conventional tillage Hailu *et al.*, 2024 ^[15].

Alignment with CSA Framework

Conservation agriculture aligns comprehensively with the Climate-Smart Agriculture (CSA) framework, which aims to sustainably increase agricultural productivity and incomes, adapt and build resilience to climate change, and reduce greenhouse gas emissions where possible. This alignment operates across multiple dimensions and scales. CA contributes to sustainable productivity increases through improved soil health indicators including soil aggregation, soil organic carbon storage, soil enzymes, and microbial biomass, which enhance the carbon-nitrogen cycle, soil stability, and overall crop productivity Hailu *et al.*, 2024 ^[15]. When tillage practices integrate with crop rotation and residue management, they offer long-term sustainability for soil management Hailu *et al.*, 2024 ^[15]. The framework's resilience component is addressed through CA's enhancement of soil structure and water retention capacity. Conservation agriculture reduces adverse impacts associated with conventional agriculture, such as soil erosion, soil organic matter decline, water loss, and soil physical deterioration, while increasing biodiversity Hailu *et al.*, 2024 ^[15]. The practice improves agricultural systems' buffer capacity against temperature extremes, making soils more resilient to extreme rainfall events, droughts, and warming Francaviglia *et al.*, 2023 ^[11].

CA aligns with CSA's mitigation goals through multiple pathways. The reduction in tillage operations mitigates direct CO₂ emissions from machinery and prevents peaks of CO₂ emissions from soils that typically occur after tillage operations Francaviglia *et al.*, 2023 ^[11]. Improved nitrogen management reduces N₂O emissions from soils or achieves decreases in yield-scaled N₂O emissions Francaviglia *et al.*, 2023 ^[11]. CA's alignment with CSA extends to broader agroecosystem services. The practice contributes to achieving multiple Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land) Hailu *et al.*, 2024 ^[15]. This multi-goal contribution demonstrates CA's comprehensive alignment with

climate-smart approaches that address interconnected challenges of food security, environmental sustainability, and climate change ^[15].

The evidence demonstrates that conservation agriculture represents a mature, scientifically-validated approach to climate-smart agriculture, offering integrated solutions for adaptation and mitigation while supporting sustainable intensification of agricultural systems across diverse global contexts.

Conservation Agriculture and Soil Physical Properties under Climate Change

Soil Structure, Aggregation, and Bulk Density

Conservation agriculture fundamentally transforms soil physical architecture through enhanced aggregation processes and reduced mechanical disturbance. Soil aggregation represents a critical indicator of soil health improvement under conservation tillage practices, with research demonstrating substantial improvements in aggregate stability and formation Hailu *et al.*, 2024 ^[15]. Studies show that conservation agriculture practices have positive impacts on soil aggregation, with no-till and reduced tillage systems showing 20.77 to 25.97% increases in soil aggregates compared to conventional tillage Hailu *et al.*, 2024 ^[15]. The mechanisms underlying improved aggregation involve complex interactions between organic matter inputs, reduced mechanical disruption, and enhanced biological activity. Conservation tillage maintains crop residue and enhances nutrient accumulation in surface soil layers, creating favourable conditions for aggregate formation Hailu *et al.*, 2024 ^[15]. Research demonstrates that reducing tillage improved soil aggregation and protection of organic carbon within aggregates against erosion or ploughing in organic rainfed almond orchards under semiarid Mediterranean conditions Francaviglia *et al.*, 2023 ^[11].

Bulk density modifications under CA systems reflect improved soil structure and porosity. The presence of plant cover improves soil structure, porosity, aggregate stability, and water infiltration compared to bare soil Francaviglia *et al.*, 2023 ^[11]. Conservation agriculture enhances soil aggregation, thus improving protection of soil organic carbon against erosion, tillage operations, and abrupt soil temperature and moisture fluctuations Francaviglia *et al.*, 2023 ^[11]. Studies in various cropping systems demonstrate that CA practices lead to overall improvement in soil structure resulting from aggregation of mineral particles and organic materials, facilitating germination and rooting of crops through higher resistance of soil aggregates to physical stress Francaviglia *et al.*, 2023 ^[11]. Long-term structural improvements become more pronounced with time. Research indicates that soil health indicators such as soil aggregation improve under conservation tillage practices, potentially enhancing soil stability and overall crop productivity Hailu *et al.*, 2024 ^[15]. The aggregation process is enhanced by the continuous input of organic matter from crop residues and cover crops, creating stable micro- and macro-aggregates that resist breakdown under climatic stresses.

Soil Moisture Conservation and Water Infiltration

Water conservation represents one of the most critical benefits of conservation agriculture, particularly under climate change scenarios with increased precipitation variability. Minimum tillage assists in conserving soil moisture through enhancing infiltration and reducing runoff compared to conventional tillage Hailu *et al.*, 2024 ^[15]. The practice reduces soil disturbance and soil moisture evaporation, while crop

residue application helps increase soil moisture and soil nutrients returned from added crop residue Hailu *et al.*, 2024 ^[15]. Infiltration enhancement mechanisms operate through multiple pathways under CA systems. Conservation tillage influences water regulation through increased soil water infiltration, which fosters groundwater storage and lessens surface runoff, improving water availability for crops Francaviglia *et al.*, 2023 ^[11]. The presence of permanent soil cover and improved soil structure creates preferential flow paths that facilitate rapid water movement into the soil profile, reducing surface runoff and enhancing water storage capacity. Moisture retention benefits are particularly pronounced in water-limited environments. In Ethiopia, where soil moisture is a challenge, conservation agriculture can improve soil moisture status and enhance crop resilience to moisture stress Hailu *et al.*, 2024 ^[15]. The potential benefits of CA are largely linked to moisture conservation of crop residues, reduced run-off and erosion, increased infiltration, and reduced evaporative losses Rusinamhodzi *et al.*, 2024 ^[33]. Research demonstrates that planting basins and early planting serve as key mechanisms for climate change adaptation through their moisture retention capacity Rusinamhodzi *et al.*, 2024 ^[33].

Climate adaptation implications of improved water management are substantial. CA systems demonstrate greater infiltration, moisture retention, and support for early planting as key adaptation strategies Rusinamhodzi *et al.*, 2024 ^[33]. However, targeting is important because moisture conservation is relevant in mildly water-limited environments (dry spells of 3-4 weeks) but may be irrelevant or negative in high rainfall environments Rusinamhodzi *et al.*, 2024 ^[33]. The effectiveness varies with soil drainage characteristics, with well-drained soils showing 16% higher yield benefits than conventional practices, while poorly drained soils combined with excessive rains lead to depressed yields Rusinamhodzi *et al.*, 2024 ^[33].

Temperature Moderation and Microclimate Regulation

Thermal regulation represents a crucial but often underappreciated benefit of conservation agriculture systems. Conservation tillage retains crop residue and significantly reduces soil temperature, contributing to improved crop growth and production Hailu *et al.*, 2024 ^[15]. The presence of plant covers all year round increases soil buffer capacity against temperature extremes, making soils more resilient to extreme rainfall events, droughts, and warming Francaviglia *et al.*, 2023 ^[11].

Microclimate modification mechanisms operate through surface cover effects and altered energy balance. Permanent soil cover minimizes temperature fluctuations at the soil surface, creating more stable thermal conditions for biological processes Francaviglia *et al.*, 2023 ^[11]. The mulch layer acts as an insulating barrier, reducing diurnal temperature variations and protecting soil organisms from thermal stress. This thermal buffering is particularly important under climate change scenarios with increased frequency of extreme temperature events ^[11].

Seasonal temperature dynamics are substantially modified under CA systems. During hot periods, surface residues reduce soil heating and maintain cooler root zone temperatures, while during cold periods, the insulating effect prevents excessive heat loss. This temperature moderation extends growing seasons and reduces thermal stress on crops, contributing to improved yield stability under variable climatic conditions. Evapotranspiration regulation through microclimate modification provides

additional benefits. Leaving crop residues on soil surface reduces evapotranspiration, improving water use efficiency Francaviglia *et al.*, 2023 ^[11]. The combined effects of temperature moderation and reduced evaporative losses create favorable microclimatic conditions that enhance crop performance and resilience to climatic variability.

Soil Erosion Control under Extreme Rainfall

Erosion control represents one of the most immediate and visible benefits of conservation agriculture, particularly critical under climate change scenarios with intensified precipitation events. Conservation tillage greatly reduces erosion, improves soil structure, and conserves organic matter in soil Hailu *et al.*, 2024 ^[15]. Research demonstrates that plots under conservation tillage showed lower average soil losses and runoff compared to conventional tillage systems Hailu *et al.*, 2024 ^[15]. Quantitative erosion reduction under CA systems is substantial across diverse environments. A comprehensive overview of soil and water conservation practices indicates that annual runoff and soil loss rates can be reduced by 20-74% when CA practices are adopted Francaviglia *et al.*, 2023 ^[11]. Specific studies show reductions in runoffs between 30-65% and erosion reductions between 63-80% with decreasing tillage intensity Francaviglia *et al.*, 2023 ^[11]. Research demonstrates that shifting from conventional moldboard plowing to minimum tillage reduced soil erosion by 65% and 85% in cereal and almond fields respectively Francaviglia *et al.*, 2023 ^[11].

Mechanisms of erosion control operate through multiple protective pathways. Vegetation management practices such as cover crops and mulching are most effective in reducing annual runoff and soil loss rates, followed by mechanical techniques and soil management practices Francaviglia *et al.*, 2023 ^[11]. The permanent soil cover intercepts rainfall, reducing raindrop impact energy and surface sealing, while improved soil structure enhances infiltration capacity and reduces surface runoff generation.

Extreme event resilience is particularly important under climate change. The more erosion-prone conditions are (erodible soils, steeper slopes, areas with low-frequency occurrence of high-intensity rainfall events), the more effective CA practices become in reducing runoff and soil erosion rates Francaviglia *et al.*, 2023 ^[11]. In Ethiopia, where average annual soil loss rates are estimated at 12 tons/ha/year and can exceed 300 tons/ha/year on steep slopes, conservation agriculture provides critical erosion control benefits Hailu *et al.*, 2024 ^[15].

Conservation Agriculture and Soil Chemical Properties Soil Organic Carbon Dynamics and Stability

Soil organic carbon enhancement represents the cornerstone of conservation agriculture's chemical benefits, with profound implications for soil fertility and climate mitigation. Research consistently demonstrates that conservation agriculture practices have positive impacts on soil organic carbon (SOC), with studies showing significant differences between conservation agriculture (1.8 ± 0.07) and conventional tillage (1.6 ± 0.05) Hailu *et al.*, 2024 ^[15]. No-till and reduced tillage systems demonstrate substantial impacts on soil organic carbon, with increases ranging from 12.9 to 19.4% compared to conventional tillage Hailu *et al.*, 2024 ^[15]. Carbon sequestration rates vary significantly across climatic zones and management systems. Under Mediterranean conditions, SOC sequestration rates range from 0.27 to 1.1 t ha⁻¹ yr⁻¹ when conservation tillage is adopted in woody cropping systems, with average values approximately

five times higher for woody compared to arable crops Francaviglia *et al.*, 2023 ^[11]. Under tropical conditions, SOC sequestration rates oscillate between 0.12 and 1.56 t SOC ha⁻¹ yr⁻¹ depending on crop type and climate regime, with higher rates in moist compared to dry conditions Francaviglia *et al.*, 2023 ^[11].

Carbon stability mechanisms involve complex interactions between physical protection, chemical stabilization, and biological processes. Conservation agriculture enhances soil aggregation, thus improving protection of soil organic carbon against erosion, tillage operations, and abrupt soil temperature and moisture fluctuations Francaviglia *et al.*, 2023 ^[11]. The practice minimizes oxidation of soil organic matter and CO₂ loss while maintaining supply of organic matter as substrate for soil biota Francaviglia *et al.*, 2023 ^[11]. Long-term carbon dynamics show temporal variations in sequestration rates. Research indicates that SOC sequestration rates can reach up to 20 per 1000 within the first 5 years after adoption of sustainable management practices, up to 10 per 1000 after 20 years, then becoming limited to 4 per 1000 after 40 years Francaviglia *et al.*, 2023 ^[11]. This temporal pattern reflects the approach toward carbon saturation levels in soils under sustained CA management.

Nutrient Availability and Stratification

Nutrient stratification represents a characteristic feature of conservation agriculture systems, with important implications for nutrient management and crop nutrition. Conservation tillage enhances nutrient accumulation in surface soil layers, resulting in increased crop growth and production Hailu *et al.*, 2024 ^[15]. This stratification pattern reflects the concentration of organic matter and associated nutrients in surface horizons under reduced tillage systems. Nitrogen dynamics are particularly influenced by CA practices. Conservation agriculture has been proven to improve nitrogen availability, with the presence of plant cover enhancing nitrogen levels in the root zone Francaviglia *et al.*, 2023 ^[11]. Cover crops, particularly leguminous species, contribute to nitrogen fixation and cycling, with mixed grass-legume cover crops showing 75% higher extractable nitrogen than control treatments and 17% greater plant-available nitrogen than legumes alone Francaviglia *et al.*, 2023 ^[11].

Phosphorus and potassium availability are enhanced through improved soil biological activity and organic matter decomposition. Cover crops and permanent plant covers improve chemical properties including N, P, and K contents, leading to higher and more stable yields Francaviglia *et al.*, 2023 ^[11]. The enhanced microbial activity under CA systems facilitates nutrient mineralization and cycling, improving overall nutrient availability for crop uptake. Nutrient cycling efficiency is improved through enhanced biological processes. Conservation agriculture practices increase and maintain nitrogen levels in the root zone while increasing cation exchange capacity (CEC) of the root zone Francaviglia *et al.*, 2023 ^[11]. The practice recycles nutrients more effectively through enhanced decomposition of organic residues and improved soil biological activity ^[11].

Conservation Agriculture, Crop Physiology, and Stress Tolerance

Root System Architecture and Water/Nutrient Uptake

Conservation agriculture fundamentally modifies soil physical properties that enhance root development. Zero tillage with

residue retention increases soil structural stability, improving porosity and creating favourable conditions for deeper root penetration Francaviglia *et al.*, 2023 ^[11]. Reduced soil disturbance allows development of continuous macropores, facilitating water movement to deeper layers where roots access moisture during drought periods Ghosh *et al.*, 2020 ^[12]. The accumulation of organic matter at the soil surface enhances arbuscular mycorrhizal colonization and phosphate-solubilizing microbial populations, improving nutrient availability pathways Hussain *et al.*, 2021 ^[17]. Root biomass production increases significantly under conservation agriculture, with deeper rooting depths enabling access to water and nutrients beyond conventional root zones Begum *et al.*, 2029 ^[5].

Crop Responses to Heat and Drought Stress

Crops cultivated under conservation agriculture exhibit enhanced drought tolerance through improved soil water availability. Rice varieties with reduced stomatal density grown under conservation agriculture use approximately 60% less water while maintaining equivalent or improved yields under heat stress exceeding 40 °C. Absciscic acid production increases under conservation agriculture during drought stress, triggering adaptive stomatal closure and osmotic adjustment responses. Plant growth-promoting rhizobacteria populations expand under conservation agriculture, producing volatile compounds that induce systemic stress responses enhancing heat and drought tolerance. Proline and glycine betaine accumulation increases in crops under conservation agriculture, providing cellular protection against oxidative stress.

Yield Stability under Climate Variability

Conservation agriculture combined with residue retention increases crop yield stability across rainfall variability. Meta-analysis demonstrates that residue retention achieves productivity gains of 4.0-28.0% with median benefit of 8.2%, substantially exceeding no-till effects alone. Soil water retention increases 13-23% under conservation agriculture with surface mulching, reducing yield variability during drought years (Boillat *et al.*, 2019) ^[6]. Zero-till wheat with rice residue retention in the Indo-Gangetic Plain increased grain yield by 9.8-11.3% while reducing yield variation across seasons (Korav *et al.*, 2024) ^[24]. Improved soil aggregate stability under conservation agriculture reduces wind and water erosion, protecting nutrient stocks essential for sustained productivity (Ghosh *et al.*, 2020) ^[12].

Crop-Specific Responses to Conservation Agriculture

Cereal crops respond strongly to conservation agriculture, with wheat and maize achieving yield increases of 5-15% in most systems. Legume crops benefit disproportionately from conservation agriculture through improved nitrogen fixation nodule development and persistence, accessing water from deeper soil layers through enhanced infiltration (Stagnari *et al.*, 2017) ^[40]. Pigeonpea and common beans exhibit 13-29% productivity advantages when grown in intercropping systems under conservation agriculture compared to monocultures (Mwila, Mhlanga and Thierfelder, 2021) ^[30]. Deep-rooted crops access moisture from deeper soil layers improved by conservation agriculture-enhanced infiltration, while shallow-rooted crops benefit more from surface residue moisture conservation (Mwila, Mhlanga and Thierfelder, 2021) ^[30].

Conservation Agriculture and Nutrient Use Efficiency

Nitrogen Dynamics and Loss Pathways

Global nitrogen use efficiency improved from 43% in 1988 to 55% in recent years, with conservation agriculture contributing substantially through reduced volatilization and enhanced cycling (Ludemann *et al.*, 2024) [27]. Ammonia volatilization decreases approximately 50% under zero tillage compared to conventional systems owing to surface residue protection. Nitrous oxide emissions decrease by 16-24% under conservation agriculture in many systems, though responses vary with soil moisture regime and fertilizer form (Sadiq *et al.*, 2024) [35]. Residue retention creates persistent nitrogen sources through decomposition, with peak nitrogen release occurring 4-8 weeks after incorporation (Hou, 2023) [16]. Strategic split-nitrogen applications synchronizing with crop demand reduce leaching losses by 25-50% compared to single annual applications.

Phosphorus and Potassium Availability

Phosphate-solubilizing microorganisms increase substantially in the rhizosphere under conservation agriculture, enhancing available phosphorus through organic acid production (Sharma *et al.*, 2013) [37]. Available phosphorus increases 17-475% under zero tillage with residue retention depending on soil type and fixation capacity (Jiang *et al.*, 2024) [22]. Organic acids derived from residue decomposition compete for phosphorus binding sites on mineral surfaces, mobilizing fixed phosphorus pools (Valenzuela, 2024) [42]. Potassium availability initially declines immediately after transition to conservation agriculture on soils with high fixation capacity, requiring strategic management through organic amendments (Ludemann *et al.*, 2024) [27]. Biochar application increases potassium availability by 15-40% while simultaneously improving soil water retention and cation exchange capacity (Valenzuela, 2024) [42].

Interaction with Integrated Nutrient Management

Integrated nutrient management combining 75-100% of recommended fertilizer rates with organic amendments achieves nitrogen use efficiencies equivalent to or exceeding conventional systems (Ali *et al.*, 2025) [1]. Legume residue retention with 50% recommended nitrogen fertilizer achieves equivalent yields to 100% conventional fertilizer under no-till compared to conventional tillage. Slow-release fertilizers improve nutrient synchronization with crop demand under conservation agriculture where residue decomposition provides competing nitrogen sources (Ali 2025) [1]. Combined nitrogen-phosphorus-potassium-organic (NPKO) applications increase maize yields by 11.65-220.42% depending on baseline productivity (Jiang *et al.*, 2024) [22]. Farmyard manure combined with reduced mineral fertilizer reduces external input requirements by 30-50% while maintaining productivity (Hou, 2023) [16].

Fertilizer Optimization under Conservation Agriculture Systems

Precision variable-rate nitrogen application based on soil maps reduces fertilizer requirements by 15-30% while maintaining equivalent yields (Valenzuela, 2024) [42]. Sensor-based real-time monitoring of soil nitrate and crop nitrogen status enables responsive fertilizer adjustments reducing losses by 25-40% (Gupta *et al.*, 2023) [14]. Spatial nutrient heterogeneity increases under conservation agriculture owing to differential residue accumulation and microbial activity concentration in surface layers (Valenzuela, 2024) [42]. Omission studies demonstrate 30% nitrogen and 50% potassium savings in wheat

after four years of conservation agriculture implementation (Jat *et al.*, 2017) [20]. Split-application nitrogen timing synchronized with crop growth stages reduces total nitrogen requirement by 15-25% compared to single applications (Govindasamy *et al.*, 2023) [13].

Conservation Agriculture and Greenhouse Gas Emissions

CO₂ Fluxes and Soil Carbon Balance

Soil carbon sequestration under reduced tillage alone is modest (median 4.8%, range 2.0-10.0%), while residue retention achieves substantially higher sequestration (median 9.7%, range 0.1-12.8%). In wheat-maize systems, cumulative soil CO₂ emissions range from 39 g CO₂-C m⁻² yr⁻¹ under zero-till with residue to 65 g CO₂-C m⁻² yr⁻¹ under conventional tillage (Wu *et al.*, 2017) [43]. Soil organic carbon stocks increase by 1.9-2.3 tons ha⁻¹ annually under conservation agriculture with residue retention compared to decline under conventional practices (Dey *et al.*, 2020) [10]. After five years, zero-till with residue retention achieved soil carbon stocks of 5,940 mg C m⁻² compared to 3,635 mg C m⁻² under conventional practices (Wu *et al.*, 2017) [43]. Fungal necromass increased from 28% to 53% of soil organic carbon under conservation agriculture with experimental warming, emerging as strongest predictor of carbon sequestration.

N₂O and CH₄ Emissions under Conservation Agriculture

Nitrous oxide emissions decrease approximately 18-24% under conservation agriculture with residue retention compared to conventional tillage in many systems (Basheer *et al.*, 2024) [4]. However, N₂O emissions increase under conservation agriculture in poorly drained soils with restricted oxygen availability, demonstrating context-dependent responses. Methane emissions remain relatively unchanged or slightly decrease under conservation agriculture, with soil moisture regime determining whether methane production increases offset oxidation in aerobic surface layers (Lee *et al.*, 2025) [26]. Raising soil pH from 6.0 to 7.0 through liming enhances N₂O reductase activity, reducing N₂O emissions by 15-30% under conservation agriculture. Biochar combined with nitrogen fertilizer reduces N₂O, CH₄, and CO₂ emissions in 84%, 64%, and 61% of observations respectively (Shrestha *et al.*, 2023) [38].

Net Global Warming Potential and Greenhouse Gas Intensity

Net global warming potential at moderate nitrogen rates (112 kg ha⁻¹) decreases 30% under conservation agriculture compared to conventional tillage, while differences diminish at high rates (224 kg ha⁻¹) (Mosier *et al.*, 2006) [28]. Greenhouse gas intensity (emissions per unit production) decreases 20-35% under conservation agriculture in most systems, showing more consistent benefits than absolute GWP (Sadiq *et al.*, 2024) [35]. Initial transitions to conservation agriculture may increase N₂O emissions temporarily as soil moisture regimes adjust, with breakeven points averaging 3-7 years when cumulative carbon sequestration offsets initial emissions (Bai *et al.*, 2019) [2]. Amortizing GHG intensity over 10-year periods reveals net negative global warming potential in most conservation agriculture systems (Bai *et al.*, 2019) [2].

Trade-offs and Context-Specific Outcomes

Conservation agriculture in poorly drained soils without appropriate water management can increase both N₂O and CH₄ emissions through altered anaerobic conditions (Tan and

Kuebbing, 2023) ^[41]. Biochar combined with conservation agriculture and nitrogen fertilizer reduces CO₂, CH₄, and N₂O emissions simultaneously while improving soil properties (Shrestha *et al.*, 2023) ^[38]. Regional customization of conservation agriculture based on soil drainage, climate, and crop type is essential for maximizing climate mitigation while maintaining productivity (Kremen and Miles, 2012) ^[25]. Trade-offs between carbon sequestration and N₂O emissions occur in some systems, requiring management optimization for specific environmental outcomes.

Integration of Conservation Agriculture with Emerging Technologies

Precision Agriculture and Conservation Agriculture

Variable-rate nitrogen application based on remotely sensed soil nutrient maps achieves 15-30% reduction in fertilizer requirements while maintaining equivalent productivity (Jiang *et al.*, 2024) ^[22]. Spatial heterogeneity of soil properties under long-term conservation agriculture (differential residue accumulation, organic matter concentration in surface layers) makes precision targeting particularly valuable for nutrient management (Balafoutis *et al.*, 2017) ^[3]. Sensor-based soil monitoring enables responsive nitrogen application adjustments synchronizing fertilizer supply with crop uptake demand, reducing fertilizer requirements by 25-40% (Gupta *et al.*, 2023) ^[14]. Real-time monitoring of soil moisture, nitrate content, and crop nutritional status using capacitive and electrochemical sensors enables adaptive management optimizing conservation agriculture productivity (Valenzuela, 2024) ^[42]. Widespread adoption among smallholders remains limited owing to sensor costs, power requirements, and user complexity (Balafoutis *et al.*, 2017) ^[3].

Digital Decision Support Tools

Smartphone-based applications providing crop growth stage monitoring, pest and disease identification, and conservation agriculture-specific agronomic advice achieve substantial uptake in regions with high mobile phone penetration (Jayaraman and Dalal, 2022) ^[21]. Integration of decision support tools with weather forecasting, crop growth simulation models, and economic optimization algorithms enables farms to optimize conservation agriculture implementation for local conditions (Balafoutis *et al.*, 2017) ^[3]. Artificial intelligence applications remain in early development stages but show substantial promise for knowledge discovery in conservation agriculture systems (Balafoutis *et al.*, 2017) ^[3]. Computer vision systems enable automated weed detection and targeted herbicide application, reducing herbicide doses by 50-80% in pilot implementations (Balafoutis *et al.*, 2017) ^[3]. Machine learning models trained on extensive field datasets enable farms to optimize technology packages for unique circumstances.

Climate Forecasting and Conservation Agriculture-Based Advisories

Seasonal rainfall forecasts integrated with conservation agriculture management advice optimize crop variety selection, planting dates, and residue management for anticipated rainfall scenarios (Komarek *et al.*, 2021) ^[23]. Climate-informed conservation agriculture advisories improve climate adaptation effectiveness by 10-25% yield stability improvement over generic recommendations (Jayaraman and Dalal, 2022) ^[21]. Conservation agriculture-tailored climate advisory services combining seasonal rainfall forecasts with real-time crop

monitoring enable identification of high-risk periods requiring modified management (Jayaraman and Dalal, 2022) ^[21]. Integration of climate services with participatory farmer decision-making processes increases conservation agriculture adoption 15-30% among program participants compared to control communities (Jayaraman and Dalal, 2022) ^[21].

Mechanization Innovations

Light-weight, tractor-compatible zero-till seeders enable simultaneous crop establishment and residue retention without requiring large machinery investments (Chaudhary *et al.*, 2019) ^[9]. Motorized two-wheel tractors cost approximately one-quarter those of four-wheel tractors, expanding mechanization access for smallholder farmers managing 0.5-2 hectare plots (Somasundaram *et al.*, 2020) ^[39]. Combine harvesters equipped with residue retention systems reduce labor bottlenecks while enabling systematic residue management compatible with rapid planting cycles (Chaudhary *et al.*, 2019) ^[9]. Robotic weed removal systems using computer vision and precise herbicide application could reduce herbicide requirements by 80-90% while addressing herbicide resistance concerns (Balafoutis *et al.*, 2017) ^[3]. Autonomous agricultural vehicles adapted for conservation agriculture operations represent advanced concepts under development but require substantial cost reduction for smallholder deployment (Jayaraman and Dalal, 2022) ^[21].

Conclusions

Conservation Agriculture represents a scientifically validated and holistic approach for addressing the dual challenge of sustaining agricultural productivity while responding to climate change. By restoring soil structure, enhancing soil organic carbon, improving water and nutrient use efficiency, and moderating microclimatic extremes, Conservation Agriculture strengthens the resilience of cropping systems to climatic variability and extremes. Its integration with climate-smart agriculture principles, precision technologies, and adaptive nutrient management offers substantial opportunities to reduce environmental footprints and greenhouse gas intensity while maintaining yield stability. However, outcomes remain highly context-dependent, influenced by soil type, climate regime, crop choice, and management practices. Future efforts should prioritize site-specific adaptation, supportive policies, farmer-centered innovations, and long-term monitoring to fully realize the potential of Conservation Agriculture as a cornerstone of sustainable and climate-resilient food systems.

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