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REVIEW ARTICLE

Conservation agriculture for sustainable crop production: A comprehensive review of soil health, climate resilience and productivity

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Abstract

Conservation Agriculture (CA) is a sustainable farming approach that focuses on reducing soil disturbance, retaining crop residues and promoting crop diversity to enhance productivity and environmental health. This review examines the diverse benefits of CA, emphasizing its role in enhancing nutrient use efficiency through improved soil nutrient retention, increased soil organic carbon and stimulating microbial activity. Additionally, CA contributes to climate resilience by lowering greenhouse gas emissions and thereby enhancing carbon sequestration. It also improves soil structure and water retention, while mitigating issues such as sodicity, thereby enhancing both the physical and chemical properties of soil. CA practices increasing energy efficiency, reducing production costs and improving farmers' economic returns. Furthermore, CA helps manage pests, diseases and nematodes by promoting healthier soil ecosystems. However, its adoption faces challenges, including technical difficulties, limited access to appropriate machinery and socio-economic barriers. This review emphasizes the transformative potential of CA in creating sustainable agricultural systems. It also highlights the need to address existing barriers to fully harness its benefits for ensuring food security and combating climate change.

Keywords: CA; climate change; enzyme activity; growth and yield; residue-retention; soil health; sustainability

Introduction

The Green Revolution of the 1960s brought significant transformations to crop cultivation in India by introducing high yielding varieties of rice and wheat, expanding irrigation infrastructure encouraging increased use of chemical fertilizers and pesticides. While these modern practices such as intensive ploughing, monocropping and clearing of crop residues contributed to increased food production, they also resulted in environmental damage, soil degradation and high energy consumption, making them unsustainable in the long run.

In response to these challenges, CA has emerged as a sustainable alternative (1). CA emphasizes minimal soil disturbance, permanent soil cover, crop diversification, offering a resource-efficient strategy that supports long-term productivity, enhances soil health and mitigates climate change (1,2). CA improves soil microbial activity, nutrient cycling and air quality by reducing the burning of crop residues (3).

By harmonizing productivity with sustainability, CA strengthens the resilience of agroecosystems and reduces environmental impacts. This review explores the multifaceted role of CA in enhancing soil health, mitigating climate change, improving farm productivity and supporting the long-term sustainability of agricultural systems.

Principles of CA

Three basic principles serve as the foundation for CA: (i) Reduced Tillage (RT) or Zero Tillage (ZT) for little soil disturbance; (ii) maximal crop cover or crop residue retention; and (iii) crop diversification.

Minimum mechanical soil disturbance

Minimum soil disturbance involves practices like no-tillage and direct seeding. The disturbed area is less than 15 cm wide or less than 25 % of the cropped area, whichever is smaller (4). Direct planting entails cultivating crops with minimal soil disturbance following the previous crop's harvest. It can be applied to all annual and perennial crops and vegetables. This method can be implemented manually using tools like likoti or jab planters or mechanically with animal or tractor-drawn no-till drills (5). This machine cuts and lifts crop residues, sows seed directly into the soil and spreads the straw as mulch (1).

No-tillage farming reduces fuel, time and labor costs over the long term. It has the potential to maintain or increase soil carbon and nitrogen stocks by minimizing the loss of soil organic matter, it also reduces greenhouse gas emissions (6).

Permanent soil cover

Mulch made of organic matter such as leaves or compost enriches and insulates the soil. Live mulch involves intercropping to offer soil cover. Crop residues or live cover shield the soil from the direct impact of erosive raindrops, reduce evaporation and suppress weed growth (5). The area with less than 30 % residue cover is not considered a CA (4). This residue retention protects the soil from harmful rain and sunlight exposure, provides continuous nutrients to microorganisms and modifies the soil microclimate, promoting the growth of soil organisms and plant roots. This also enhances soil aggregation and carbon sequestration (7). No-tillage with mulch enhances water infiltration, reduces runoff and increases yield compared to tilled soils (8). Ground cover promotes biodiversity both above and below ground, while also attracting beneficial insects that aid in pest control (9).

Species diversification

Crop rotation involves alternating different types of crops within fields and across different growing seasons. For instance, it includes shifting between cereal crops like maize and wheat, followed by legume crops such as beans (4). Crop rotation enhances soil fertility and yield by utilizing crops with diverse root systems, allowing for efficient nutrient absorption from various soil depths. It also enhances water use efficiency. Leguminous crops, in symbiosis with nitrogen-fixing bacteria, enrich the soil with biologically available nitrogen-benefiting subsequent non-leguminous crops. In addition nutrient cycling, rotation breaks pest and disease cycles, thereby reducing dependency on chemical control methods (5).

Status of CA

Since 1970, there has been a massive increase in the use of CA worldwide, from less than 1 million hectares across 8 countries to a staggering 205 million hectares in 102 countries by 2019, making up about 15 % of the world's cropland. In India, the area under CA rose from 1.5 million hectares during 2013-2014 to 3.5 million hectares in 2018-2019. Brazil has been particularly successful in adopting CA, with a significant 43 million hectares, making up nearly 80 % of its annual cropland, implementing various forms of no-till agriculture (10). Since approximately 2008-2009, CA adoption has significantly expanded across multiple continents. For instance, the rapid spread of CA practices, particularly in regions where smallholder farmers are increasingly harnessing the benefits of sustainable farming methods. There has been a considerable increase in CA cropland areas across South America, North America, Australia and New Zealand, Russia and Ukraine, Europe, Asia and Africa. These increases range from 64.8 % in North America to a staggering 6800 % in Russia and Ukraine. Notably, Europe (including Russia and Ukraine), Africa and Asia have experienced a fourfold increase in the global share of CA expansion (11). The regional breakdown of CA expansion over the years 2008-2009, 2014-2015 and 2018-2019 is illustrated in Fig. 1 & 2 (12).

Management practices of CA

Precise sowing machinery in CA

Sowing is the process of placing the seeds in the soil to initiate crop growth. Ensuring the ideal plant population is crucial for maximizing potential productivity in CA systems. Hence, precision sowing using suitable machinery is essential in CA. Machine sowing under conservation tillage is essential for sustainable agriculture, as it minimizes soil disturbance, preserves soil health and improves water retention. By precisely placing seeds without extensive tilling, this approach supports uniform crop establishment, reduces labor and fuel costs and contributes to environmental conservation. In addition to the Happy Seeder, various other seeders have been developed and utilized for sowing under CA practices. The BARI CA seed planter

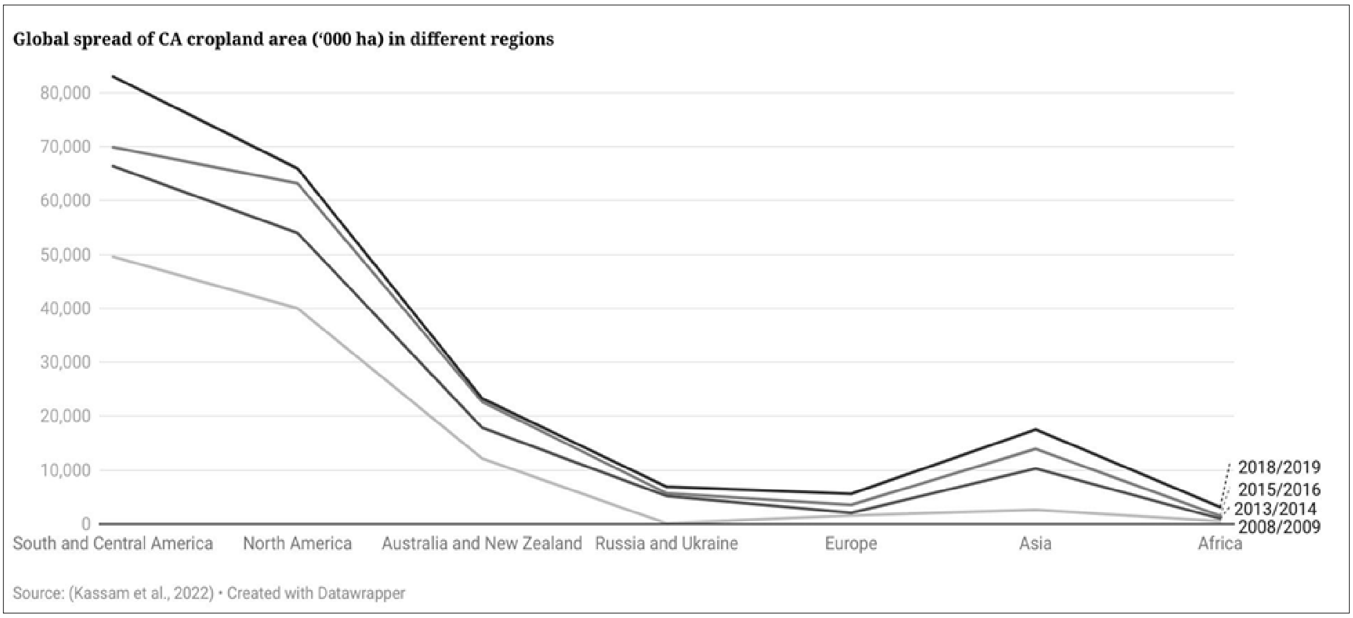

Fig. 1. Global spread of CA cropland area in different regions for 2008-2009, 2014-2015 and 2018-2019.

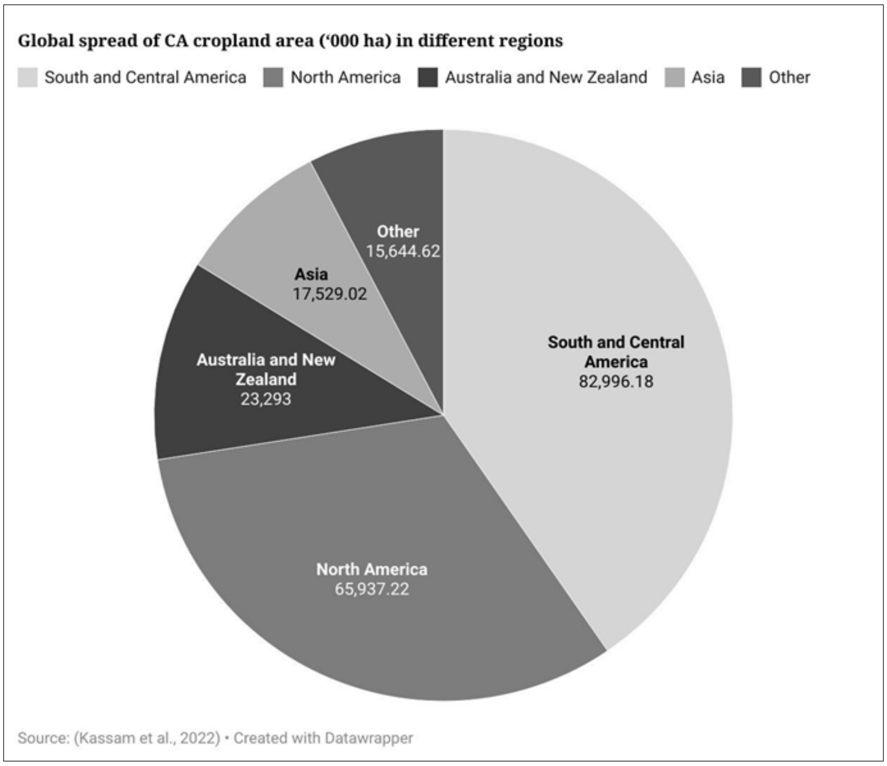

Fig. 2. Global spread of CA cropland area in different regions for 2018-2019.

is used for the direct sowing of oilseeds, pulses, wheat, jute and maize, which performs three tasks that can be completed in one pass: leveling, cum pressing and seed placement in a furrow. It also performs multiple tillage operations, such as RT, ZT and strip tillage (13). CA seed planter significantly outperformed conventional methods such as broadcasting and dribbling as it efficiently manages crop residue, saves time and reduces costs and carbon emissions (14).

CA practices like ZT and strip tillage are suitable for areas susceptible to drought stress which utilize leftover soil moisture from the monsoon season for seeding and early plant growth (15). In this region, the sowing of mung bean using a zero till planter and strip-till planter exhibited higher effective field capacities and field efficiencies compared to bed planter and power tiller operated seeder. The highest plant populations were statistically observed in plots planted using different conservation machinery such as zero till planter, strip-till planter, bed planter and power tiller operated seeder followed by those planted with conventional tillage (16). A wet-resistant rotary strip-till seeder (WR seeder) is an efficient method to improve sowing efficiency and seedling establishment thereby enhancing wheat grain yield and overall benefits in wet clay fields with heavy residue loads within the rice-wheat rotation system (17). Innovative no-till seeding technology has advantages over typical rotary-till seeding, including higher wheat yield, nitrogen uptake and nitrogen use efficiency. It also enhanced the recovery of applied nitrogen, leading to lower N losses and improved N retention in soil-crop systems over multiple growing seasons (18).

Cover crop termination in CA

Cover crops are defined as crops, including grasses, legumes and forbs, grown for seasonal cover and other conservation purposes (19). The cover crop may be terminated by natural causes such as frost or intentionally terminated through the chemical application, crimping, rolling, tillage or cutting. Disc chain harrows as a sustainable alternative to conventional methods for cover crop termination in shallow soil tillage. Hairy vetch (cover crop) termination and seedbed preparation for soybean establishment utilizing a disc chain harrow exhibited good operating performance, characterized by a low mechanical force required to pull, energy requirement and fuel consumption. This would enable the formation of a dry vegetation layer that can cover and shield the moist underlying surface and break the soil crust (20). Apart from this, it also improves soil porosity and aeration and increases water-holding capacity.

Nutrient management in CA

CA, which aims to sustainably manage nutrients and maintain soil fertility, is a key strategy for increasing crop yields while reducing their negative effects on the environment (21,22). This involves practices such as balanced fertilization, incorporating organic amendments, soil testing for precise nutrient application and employing technologies for efficient nutrient use (21). Integrated Nutrient Management (INM) is particularly important, as it involves the use of both natural and man-made sources of plant nutrients to maintain and improve soil fertility (23). The role of plant nutrition in CA systems is crucial for increasing yield, nutrient use efficiency and profitability (22). The integration of CA with precision nitrogen and water management emerges as the most effective approach, leading to increased grain yields, increased gross returns and impressive energy outputs. It not only boosts maize productivity and net returns but also promotes sustainable and resource-efficient agricultural practices in the Indo-Gangetic Plains (IGP) (24). In rice-wheat cropping systems, conventional tillage combined with inefficient fertilizer application often results in poor productivity. Zero-till direct-seeded rice with conservation tillage, residue retention and smart fertilizer management improves water and nutrient use efficiency. The Nutrient Expert® and soil test-based NPK systems significantly boost the benefit-cost ratio and seed and biomass yields (25).

In eastern India, maize farmers typically focus on applying nitrogenous fertilizers without considering a balanced nutrient approach, resulting in poor nitrogen-use efficiency. Low-cost RGB sensors help assess crop health for precise nutrient application, while tools like Nutrient Expert® and GreenSeeker™ support site-specific nutrient management-together enhancing nutrient use efficiency and promoting sustainable agriculture. (26-28). Implementing Site-Specific Nutrient Management (SSNM) through Nutrient Expert® software can enhance crop yields by delivering nutrients at optimal times and dosages (29). Regarding nutrient management, SSNM using Nutrient Expert® software is identified as the superior option for enhancing soil chemical and biological properties (30). The combined use of precision nutrient management tools such as Nutrient Expert® and GreenSeeker™, along with fertilizer drilling using a disc planter, enhances the effectiveness of permanent bed-based maize-wheat systems. This integrated approach can significantly boost crop yields, nutrient use efficiency and profitability. Additionally, it helps reduce greenhouse gas emissions from CA -based maize-wheat systems in the eastern IGP (31). Improving nitrogen fertilization efficiency is crucial for smallholder farmers in CA. Combining residue application with top-dressed nitrogen fertilizer significantly boosts yields. While leaf-based chlorophyll measurements are reliable but time-consuming, canopy-based RGB (Red Green Blue) indices via digital photography provide a cost-effective and efficient alternative, with drones enhancing measurement efficiency (32). Farmyard Manure (FYM) application boosted phosphorus (P) mineralization, while residue application enhanced nitrogen (N) mineralization. The combined use of NPK fertilizer and FYM in CA maximizes crop yields, improves soil health and delivers economic benefits (33).

Soil fertility management in CA

Integrated Soil Fertility Management (ISFM) is effective for maintaining soil fertility. Minimum tillage with crop residue enhances soil aggregate properties and increases the storage of carbon, nitrogen, phosphorus and sulfur. Minimum tillage utilizes production resources more efficiently than conventional tillage and maintains soil fertility by enhancing organic matter and nitrogen inputs. It also aids in soil aggregation and prevents soil compaction (34). Trichocompost and bio-slurry improve nitrogen uptake in rice compared to standard fertilizers in mustard-rice-rice rotations. *Trichoderma* bio-compost shows potential for boosting crop production and soil health without accumulating heavy metals (35). Use of crop residues, rock phosphate and *Tithonia diversifolia* (cover crop), increased soil fertility and maize productivity (36). Long-term ISFM treatments, including the application of organic and mineral fertilizers, improve soil chemical properties and organic matter dynamics (37).

Weed management in CA

One of the biggest obstacles to CA is weed control. The increased proliferation of weeds in no-till conditions results in significant losses in production and quality. Crop rotation, stale seedbed adoption, appropriate sowing time and geometry, crop residue retention, a higher seed rate and competitive crop cultivars control the weed population in CA (38). Combining cover crops with glyphosate herbicide is an effective weed control strategy for transgenic direct-sown soybeans and corn under no-till conditions. This approach significantly reduces weed pressure and minimizes herbicide dependence in field crop production (39). ZT with residue retention combined with two hand weedings (30 and 50 DAS) or pre- and post-emergence herbicides (Atrazine 0.75 kg ha^{-1} fb 2, 4-D 0.75 kg ha^{-1} and tembotrione, 0.075 kg ha^{-1} or 0.1 kg ha^{-1} respectively) control weeds effectively in pearl millet (40).

Nitrogen immobilization in CA occurs when soil microorganisms decompose crop residues, temporarily reducing N availability for crops (41). This process involves both biotic and abiotic mechanisms, with microbes incorporating N into their biomass and N being fixed in soil organic matter (42). CA practices lead to increased organic matter stratification in topsoil, affecting carbon and nitrogen mineralization patterns (43). While initial N immobilization can reduce crop biomass, it may not significantly impact final yields (44). Applying 100 % nitrogen initially followed by 75 % N on zero-till permanent beds with residue retention can enhance wheat productivity and weed suppression (45). ZT with residue retention reduced the weed population in green gram. Pre-emergence pendimethalin and post-emergence imazethapyr provided effective weed control (46). Conventional tillage in rice, followed by ZT in wheat, reduced weed emergence, distribution and biomass through integrated weed management. This reduction in weeds improved crop performance, yields and profitability across the cropping sequence (47).

Recent advancements in computer vision and machine learning have enabled precise weed control through Site Specific Weed Management (SSWM). Methods like the weed patch detection model and weed species classification model target specific weed patches. Using the ISOBUS protocol based on ISO 11783, herbicide application is done with the aid of georeferenced weed patch maps, ensuring precise spraying only in infested areas. This approach significantly enhances weed control, reduces herbicide usage and promotes sustainable farming practices, with accuracy rates between 89 % and 98 % for various weed species (48). In the no-till field, weed patches were more stable over time due to reduced mechanical disturbance. Field margins significantly influenced weed infestation in the no-till field, indicating the need for targeted weed control near margins. Understanding weed spatial dynamics through Unmanned Aerial Vehicles (UAVs) can aid in developing precision weed management strategies (49).

Effects of CA on agricultural sustainability

Agronomic response of CA

Crop growth: Annual wheat demonstrated greater above-ground biomass productivity compared to intermediate wheatgrass and tilled annual wheat, which was accompanied by enhanced soil microbial biomass and carbon stabilization. These improvements indicate better crop growth in cereals, attributed to higher nutrient availability, improved moisture retention and increased root biomass. Collectively, these factors boosted seedling vigor and grain yields (50,51).

Additionally, when annual wheat was preceded by legume crops, maize growth was enhanced due to increased ear leaf area, 1000-grain weight and harvest index, ultimately resulting in higher yields (17). Cover cropping, especially with legumes like vetch and cowpea, significantly enhanced yields under no-till systems by improving soil nutrient status, biomass production and nitrogen availability. These practices not only supported plant growth but also promoted the formation of soil aggregates, which retained moisture and nutrients. Moreover, they increased microbial activity, facilitating nutrient cycling and fostering healthier crop development (52,53). In terms of water management, cover cropping also improved soil water accumulation by reducing evaporation and enhancing infiltration, which benefited crops (wheat) requiring consistent moisture for optimal growth (54). Similarly, when combined with plastic film mulching, it optimized water use, improved nitrogen translocation and minimized soil evaporation, leading to healthier crops and higher yields (55).

Incorporating crop residues into the soil proved beneficial by enhancing soil organic carbon levels, which improved soil health and nutrient availability. In contrast, traditional tillage practices depleted soil organic carbon, highlighting the superiority of residue management and no-till systems for promoting sustainable crop growth (56). Thus, CA practices foster robust crop growth by improving soil structure, moisture dynamics and biological activity.

Leaf area index: Leaf Area Index (LAI) is a critical measure for understanding plant canopy structure and function, representing the total leaf area relative to the ground surface and used to assess plant productivity, gas exchange and canopy dynamics (57,58). No-tillage practices significantly impact LAI by improving soil conditions. Enhanced soil structure and increased porosity under no-tillage lead to better water infiltration and retention, supporting healthier leaf growth and expansion, which results in a higher LAI (59-61). Furthermore, the increase in soil organic matter and fertility associated with no-tillage boosts nutrient availability, supporting more vigorous leaf growth and contributing to a higher LAI (62). Increased nitrogen and potassium availability under NT enhances photosynthetic activity, ultimately improving LAI and grain yield (63).

Nutrient management practices also play a significant role in influencing LAI. The application of potassium fertilizer, both as a basal treatment and foliar spray, has been shown to enhance LAI in lentils by promoting nutrient uptake and plant health (64). Other nutrient-related factors, such as crop residue mulching and increased nitrogen availability, improve LAI by supporting better leaf development and enhancing photosynthetic capacity in wheat (65).

The relationship between LAI and photosynthesis is evident, as LAI is positively correlated with carbon isotope discrimination ($\Delta^{13}C$), indicating improved photosynthetic efficiency and yield potential in summer maize under different tillage and straw management practices (66). Additionally, experimental warming using infrared heater has significantly increased LAI, improving pre-anthesis growth and photosynthetic performance, which contributes to higher biomass accumulation and grain yield in winter wheat (67). Ridge tillage can further optimize LAI by improving canopy structure and reducing leaf senescence, which helps to mitigate the negative effects of waterlogging on photosynthesis and grain yield in summer maize (68). Increased LAI under no-tillage and MT practices is primarily due to enhanced soil moisture retention, which reduces water stress during critical growth periods and improves crop growth rates (69). Overall, no-tillage and related practices improve LAI by enhancing soil conditions, retaining moisture and increasing nutrient availability, leading to healthier plant growth, higher photosynthetic efficiency and greater agricultural productivity. Together, these changes underscore the critical role of NT and nutrient management in enhancing canopy development and photosynthetic efficiency.

Crop yield: CA practices, including no-till farming, cover cropping and crop rotation, significantly impact crop yield by improving soil health, enhancing moisture retention and increasing nutrient availability (21,70-72). For instance, no-tillage with straw mulching has been shown to boost grain yields by reducing soil water evaporation, enhancing water retention and improving water storage across cropping systems (73). Additionally, NT practices doubled rice yields over time (around 24 years), reaching 12 mg ha^{-1}, primarily due to improved Soil Organic Carbon (SOC) accumulation, which enhances soil health and supports long-term productivity (74). Similarly, no-till practices increased organic matter and improved water retention, resulting in a 116 % rise in corn yields over 20 years (75). ZT combined with hydrogel application and residue retention/mulching significantly enhanced rainfed maize yields, highlighting the importance of soil moisture management (76). Wheat grain yield also increased under improved tillage practices due to better spike formation and enhanced root activity. These practices created optimal soil conditions, including higher nutrient availability and stable moisture levels, which collectively supported robust crop growth.

Enhanced nutrient management also plays a vital role in increasing crop yields. Phosphorus (P), for example, is crucial for soybean growth, as it enhances root establishment and grain quality. Applying 30 kg ha^{-1} of P resulted in the highest soybean yield, improving nutrient uptake and efficiency compared to higher rates (77). Nitrogen fertilization further boosted maize yields by improving nutrient content and nitrogen accumulation, especially when intercropped with *Urochloa ruziziensis* under a no-tillage system (78). Similarly, nitrogen topdressing of up to 120 kg ha^{-1} significantly enhanced common bean yields by increasing nitrogen availability and soil health, particularly when intercropped with corn and *Urochloa ruziziensis*, achieving a yield of 3025 kg ha^{-1} (79). Furthermore, NT increased winter wheat yields by 5 % on average, with higher nitrogen rates amplifying the effect, suggesting that nutrient management is essential for maximizing yield potential under conservation tillage systems (80).

Moreover, cropping system diversity improves yields by enhancing soil health and nutrient cycling. Crop rotation boosted soybean yields, while NT outperformed other tillage systems by improving moisture retention (81). Similarly, intercropping maize with *Urochloa ruziziensis* under NT enhanced soil coverage, moisture retention and soil health, contributing to increased straw and grain yields (79). Crop diversity further increased yields by improving nutrient uptake and suppressing plant diseases, demonstrating the importance of integrating diverse cropping systems into CA (75). CA effectively enhances crop yields through improvements in soil health, nutrient management and moisture retention. These practices, supported by innovative approaches like strip tillage and intercropping, offer sustainable solutions for boosting agricultural productivity across diverse ecosystems. The percentage increase in yield under conservation tillage compared to conventional tillage is presented in Table 1. In summary, CA boosts crop yields by enhancing water retention, improving nutrient use efficiency and fostering resilient cropping systems.

Root development

Root parameters are essential for assessing plant growth, nutrient uptake and overall plant health. These include root length, diameter, surface area, volume, number of tips and structural characteristics (87,88). CA practices enhance soil structure, increase organic matter and improve water infiltration, creating ideal conditions for root development. These practices can reduce sub-surface soil strength by 20-25 %, increase total porosity by 17 % and improve soil aggregation and organic carbon levels in the topsoil, supporting better root development, especially in wheat grown in rice-wheat systems. This leads to better absorption of water and nutrients, particularly nitrogen (89,90).

Cover crops with deep and robust roots (stylo) enhance soil structure and improve water and air conductivity through the formation of biopores, which facilitate deeper root growth in subsequent crops (91). For instance, integrating cover crops such as hairy vetch (*Vicia villosa*) enhances deep-root growth in succeeding crops like soybeans (92). Root distribution shifts notably, with a larger proportion of roots concentrated in the top 0-10 cm of the soil when soil disturbance is minimized (93). The presence of mesopores in minimally disturbed soils creates additional niche space for microbes, further increasing microbial diversity (94).

Root Length Density (RLD) measures root growth per unit volume of soil and higher RLD improves plant access to water and nutrients, thus boosting yield (95). Roots improve soil structure by creating channels that reduce compaction, enhancing water infiltration and aeration. In particular, cover crop roots penetrate compacted layers, reducing soil resistance over time and improving soil health (96). In contrast, deep ploughing and harrowing increases RLD by improving soil structure, which in turn boosts yields. Additionally, systems that minimize soil disturbance also promote strong root development and effective growth (97). Effective fertilizer placement, especially phosphorus application on the soil surface, increases root biomass and surface area in the topsoil, though it may reduce root length under drought (98).

Long-term practices that minimize soil disturbance also improve macroporosity and pore connectivity in the topsoil, facilitating easier root penetration and promoting root growth. This allows roots to access deeper soil layers for water and nutrients, enhancing overall plant development (99). Furthermore, these practices reduce the formation of a plow pan, which can inhibit root penetration. Roots can grow more freely and access deeper soil layers, thereby supporting better crop growth and yield potential (100). A consistent root diameter across soil layers indicates balanced soil compaction and structure, promoting uniform root development and efficient water and nutrient uptake (101). This uniformity suggests a stable environment for roots to grow, which contributes to efficient root function. Under warming conditions, root biomass in systems with minimal disturbance increases significantly, primarily in the surface layer (0-10 cm), suggesting limited deep root extension compared to conventional tillage (102).

Systems that minimize soil disturbance significantly enhance root biomass in the top 5 cm of soil, supporting improved nutrient and water uptake while contributing to soil carbon sequestration (95). While RLD may be lower in such systems compared to conventional tillage, these systems exhibit 9.6 % higher root biomass in the top 100 mm, likely enhancing root surface area. This increased surface area supports better nutrient and water uptake efficiency (99). Moreover, these systems improve soil structure and porosity, enhancing root surface area by allowing for better root penetration (103). Studies have shown that these systems promote greater root surface area due to improved soil structure and higher organic matter, facilitating better nutrient uptake, especially phosphorus, as roots can explore more soil volume (104). Improved soil structure and moisture retention further support deeper root systems that can access more nutrients and water. Additionally, larger soil pores and increased organic matter provide a more favorable environment for root growth (105). Therefore, CA not only improves above-ground crop performance but also enhances below-ground architecture, leading to better resource uptake and long-term soil health.

Table 1. Percentage (%) of yield increased under conservation tillage practices compared to conventional tillage

Crop	Practices	Yield increased	References
Rice-wheat cropping system	ZT + crop residues in wheat	Rice - 17 % Wheat - 13 %	(82)
Wheat and pea	No-till straw mulching	Wheat - 14.3 % Pea - 29.5 %	(83)
Intensive rice-based cropping system	Strip tillage with high residue retention (50 cm) and high dose of potassium (K)	23-35 %	(84)
Maize-wheat-mungbean rotation	ZT with a permanent broadbed, crop residues and 100 % required nitrogen (N)	31.1 %	(85)
Rice-wheat cropping system	Early sowing of a long-duration wheat variety (second fortnight of October) under conservation tillage	5.5 %	(86)

Physiological response of CA

No-Tillage (NT) farming, a practice within CA, leads to notable changes in plant physiological responses like, photosynthetic rate, water use efficiency etc., when compared to Conventional Tillage (CT) methods. NT systems can result in changes to root architecture, which may enhance the plant's ability to absorb water and nutrients (106). The undisturbed soil structure and organic mulch in NT systems also impact plant physiology, leading to an improved plant water status, as evidenced by higher stomatal conductance and better photosynthetic rates (107,108). Additionally, NT fosters beneficial soil microbiota Arbuscular Mycorrhizal Fungi (AMF) that can enhance plant defense mechanisms (109). Together, these physiological enhancements contribute to improved plant growth, drought resilience and crop yield under NT systems (107,110). In light of the increasing adoption of sustainable agricultural practices, understanding plant physiological responses under NT systems is crucial for optimizing productivity and minimizing environmental impacts.

Photosynthetic rate

NT practices improve soil water content, supporting higher stomatal conductance and photosynthetic rates, particularly in crops like common beans, without compromising water use efficiency (111). Improved moisture availability supports greater stomatal conductance and higher photosynthetic rates in crops like common beans, without reducing water use efficiency. Furthermore, NT fosters the accumulation of soil organic matter, which boosts soil fertility (107), encourages deeper root growth and increases earthworm populations, thereby improving soil structure and water retention (112). Light interception is typically greater in CT systems, especially during early growth stages. However, NT can improve light penetration within the canopy due to a lower photosynthetic photon flux density extinction coefficient (113). Additionally, NT with straw mulch enhances soil moisture retention and light interception, boosting wheat photosynthesis and dry matter accumulation (114). Further, no-till cultivation of winter wheat results in a more developed photosynthetic apparatus, characterized by higher pigment content and prolonged operation, leading to increased yields compared to traditional tillage (115). In maize-wheat cropping systems, double zero-tillage combined with foliar phosphorus application and bio-inoculants has also been shown to improve photosynthesis and enhance crop resilience to nutritional and environmental stresses (116). Recent research indicates that NT with wheat straw mulch can boost maize yield by 15.6 % over CT primarily by enhancing photosynthesis and water use efficiency (117). Thus, NT practices enhance photosynthetic characteristics and crop yields, though their effectiveness varies depending on the crop and prevailing environmental conditions.

Water use efficiency

NT practices enhance Water Use Efficiency (WUE) primarily through reduced evaporation and improved infiltration (118,119). NT promotes soil aggregation, especially in the upper layers, which improves water retention and reduces the energy plants need to access water (120). While NT may slightly reduce total porosity, it substantially boosts mesoporosity and microporosity, which are vital for water storage (103). Long-term NT use leads to lower bulk density and higher total and effective porosities, particularly in systems with more crop residue return (121). These structural enhancements improve water infiltration and decrease runoff. Modeling studies confirm that improvements in soil structure under NT contribute more significantly to increases plant-available water than surface disturbance reduction alone (122). However, the effect of NT on crop yield and WUE depends on factors such as climate, crop type and management practices. In China, NT boosted maize WUE by an average of 5.9 %, while its impact on wheat varied based on rainfall (123). Under dryland conditions, long-term NT with straw mulch enhances soil moisture, photosynthesis, WUE and dry matter accumulation in winter wheat (114). These findings indicate that NT can be an effective approach for improving WUE across various crops and environmental settings, especially when integrated with suitable management practices. Collectively, these enhancements make NT a valuable strategy for optimizing WUE, particularly in water-limited environments.

Leaf water potential

Leaf Water Potential (LWP) serves as a key indicator of a plant's water status and its stress response (124). NT practices offer significant benefits for soil and plant water management, making them a valuable approach to sustainable agriculture. These practices have been shown to improve soil properties by reducing bulk density and penetration resistance after initial establishment, which in turn facilitates better root growth and enhances plant water status (110). Additionally, the use of cover crops and mulches in NT systems can increase soil moisture content by 3-5 % compared to control plots, promoting water conservation through their mulching effect (125,126). This increased soil moisture leads to higher LWP and reduces drought stress symptoms in crops like maize and soybeans (125). Integrating straw and plastic mulches in NT systems minimizes soil- LWP gradients, thus facilitating improved water transfer, biomass accumulation and yield (127). Mulch-based NT systems reduce labor and fuel requirements while also preventing soil erosion (128). Another critical benefit of NT is its ability to moderate soil temperatures and minimize thermal stress on plant roots. (129) observed consistently lower soil temperatures under NT, which alleviated heat shock and decreased root heat stress in wheat. This temperature regulation improves root water uptake efficiency (130). NT systems improve root development by reducing bulk density and penetration resistance, which enhances water uptake and raises LWP (110). Similarly, greater biomass accumulation and leaf area in cowpeas under NT compared to CT has been reported (131). NT practices significantly enhance LWP by improving soil moisture retention and alleviating thermal and drought stress, resulting in improved plant water status and resilience. This promotes sustainable crop development and boosts agricultural productivity. Overall, NT significantly improves LWP and mitigates thermal and drought stress, thereby enhancing plant resilience and contributing to sustainable crop production.

Effects on nutrient use efficiency

In CA fields, the use of suitable deep-rooting cover crops helps to minimize nutrient losses (132). Under NT, the surface soil had significantly higher exchangeable Ca, Mg and K levels than the ploughed soil (133). Reduced soil disturbance and higher retention of residues improved potassium balance (134). Strip-tillage led to higher nitrogen content in the sowing strip compared to the inter-rows. Additionally, this technique increased the nitrogen and potassium levels in the topsoil (0-20 cm), enhancing the plants' uptake of these nutrients (135). NT combined with residue, recommended levels of nitrogen (N) and potassium (K) and 17.2 kg of phosphorus (P) per hectare along with Phosphorus-Solubilizing Bacteria (PSB) culture significantly improved phosphorus agronomic efficiency and recovery efficiency in wheat (136). Crop residues slow down the release of nutrients, preventing denitrification or leaching of nutrients. Residue retention modulates nutrient release, reducing denitrification and leaching losses, particularly of nitrate nitrogen (137). The short-term immobilization of mineral nutrients by microbes may lead to decreased fertilizer use efficiency. On the other hand, microbial activity and nutrient recycling produce an increase in nutrient availability with time (138).

Climate resilience through CA

According to the IPCC's analysis, 13.5 % of the world's greenhouse gas emissions come from agriculture (139). Agricultural soil management is one of the major causes of greenhouse gas emissions. Soil and root respiration play a significant role in CO_2 and CH_4 emissions (140). Therefore, soil is both a source and a sink for greenhouse gases. CA practices reduce GHG emissions while enhancing agroecosystem resilience under climate variability (141). This is enabled through no-till or reduced-till methods and crop residue retention, key components of CA. Carbon dioxide (CO_2) from the atmosphere is gradually absorbed into soil carbon with the help of CA (142). With an estimated 89 % contribution to the technical potential, soil carbon sequestration (better sinks) is the mechanism responsible for most of the mitigation potential. Also, reduction of N_2O and CH_4 emissions from soil makes up 2 % and 9 % of the total, respectively (143). NT reduced the carbon footprint by around 40 % in comparison to CT (91). The average reductions in CO_2, N_2O, CH_4 emissions and global warming potential that result from NT are 15.1 %, 7.5 %, 19.8 % and 22.6 %, respectively (144). Thus, CA significantly contributes to climate mitigation by enhancing soil carbon sinks and reducing emissions of CO_2, N_2O and CH_4.

Effects on soil physical and chemical properties

In an agroecosystem, soil health can be defined as the soil's capacity to adapt agricultural practices in a way that sustainably supports both agricultural production and the provision of other ecosystem services. CA as a sustainable system to combat the negative effects of conventional farming on soil health, prevent soil degradation and guarantee food security (145). The soil water content remained consistent in both conventional and conservation tillage. The addition of manure to conservation practices led to lower bulk density and penetration resistance. Manure integration in CA practices lowers bulk density and enhances aggregation, improving water retention and aeration (146). Under CA, there was an improvement observed in both aggregate stability and water-holding capacity (147). Strip tillage exhibited significantly higher values of pore characteristics, including macroporosity, network density, length density and interconnectivity, these are used to evaluate soil structure and hydraulic properties (148).

CA often results in elevated organic matter levels in the upper soil layers, which can enhance the Cation Exchange Capacity (CEC) of these layers. Additionally, CA practices have proven effective in mitigating sodicity and salinity issues in soils. CA enhances nutrient-holding capacity through higher CEC and mitigates salinity by balancing cation exchange processes (149). CA- based Subsurface Drip Irrigation (SDI) scenarios substantially lower the Exchangeable Sodium Percentage (ESP), increase beneficial cations (Na^+, Ca^{2+}, Mg^{2+}) and decrease harmful anions (O_3^{2-}, HCO^{3-}, Cl^{-}). Additionally, these practices demonstrated superior water and nitrogen use efficiency, along with higher crop productivity and profitability. Thus, integrating CA practices with SDI is a viable strategy for reclaiming degraded sodic lands and ensuring sustainable agricultural productivity in arid and semi-arid regions (150). Therefore, CA practices not only enhance soil structure and fertility but also offer a practical approach to reclaiming degraded lands, especially in arid and semi-arid regions.

Effects on SOC and microbial activity

Soil carbon is a critical component of soil health. In both micro-aggregates and bulk soil, NT increases the soil's carbon content, microbial biomass and nutrient availability. In comparison to CT, it also improved enzymatic activity for the acquisition of carbon and phosphorus, raised the C: N enzymatic ratio and increased crop production. Long-term conservation tillage increased carbon content and enzyme activity, which improved soil aggregates (151). No-till with legume cover cropping is an effective method for promoting carbon accumulation and stabilization in heavily weathered agricultural soils in subtropical climates (152). The application of biochar enhances the native SOC levels in calcareous soils (153). Similarly, growing direct-seeded rice followed by zero-till wheat with residue retention significantly increases SOC, which serves as a key indicator for evaluating soil fertility, carbon sequestration capacity and overall soil health (154). The total organic carbon, active organic carbon and Microbial Biomass Carbon (MBC) of the soil were all considerably raised by maize grown with straw mulch. MBC plays a crucial role in maintaining soil fertility, nutrient cycling and overall soil health. Maize-peanut rotation enhanced the amount of dissolved organic carbon in the rhizosphere by encouraging root growth and increasing maize production (155).

Incorporating *Urochloa* (cover crop) into no-till agricultural systems, especially when it stays in the field for longer periods, boosts microbial activity and promotes the presence of AMF. This contributes positively to soil health by increasing β-glucosidase activity, soil basal respiration and AMF abundance while reducing microbial stress ratios (156). Practicing maize-peanut rotation system increases the beneficial Plant Growth Promoting Rhizobacteria (PGPR) like *Bacillus, Streptomyces, Rhizobium* and *Pseudomonas* in the rhizosphere soil, it is due to elevated soil rhizosphere dissolved organic carbon levels (155). Conservation tillage substantially boosted overall soil microbial biomass by 37 %, including a 31 % increase in fungal biomass and an 11 % increase in bacterial biomass, particularly in the top 20 cm of soil. This practice was also linked to significant rises in soil total carbon and nitrogen and reduction in soil pH. The increase in soil total carbon was positively correlated with the rise in both fungal and bacterial biomass (157).

Effects on enzyme activity

Enzyme activity in NT systems increases due to higher microbial biomass, boosting enzymes like dehydrogenase, fluorescein diacetate, β-glucosidase, urease and phosphatases, thereby enhancing soil health and nutrient cycling (158). Applying crop residue under NT systems further improves nitrogen availability by promoting microbial activity, influenced by residue rates, microbial biomass and soil pH (159). Calcium amendments (A mixture of sugar beet foam and red gypsum) also enhance protein breakdown, improving nutrient cycling (160). NT significantly boosts enzyme activities in the topsoil, with β-glucosidase and acid phosphatase showing up to 100 % higher activity compared to CT, driven by increased organic carbon and reduced disturbance (161). RT promotes the highest microbial biomass and acid phosphatase activity, while alkaline phosphatase and urease are maximized in NT systems for wheat and corn rotations, enhancing nutrient cycling and plant nutrient uptake (162). Cover crop decomposition under NT influences enzyme activities, with urease activity initially increasing but later declining, while β-glucosidase activity consistently decreases. These changes lead to increased soil ammonium concentrations and potential nitrogen immobilization in maize, necessitating adaptive nitrogen fertilization to sustain maize productivity in cover crop-based systems (163). ZT also enhances microbial viable counts and dehydrogenase activity in the surface soil across various cropping systems, further supporting nutrient cycling and plant growth (164).

Effects on energy use efficiency

Implementing CA in rice-based systems can greatly decrease the energy consumption from non-renewable fossil fuels used for irrigation and land preparation. This approach also improves ecosystem services and promotes cleaner production (165,166). In the IGP region where groundwater and soil quality are deteriorating, practices like zero-till transplanted rice followed by zero-till maize or wheat and zero-till direct-seeded rice followed by zero-till maize or wheat boost energy productivity and conserve non-renewable energy (167). NT cultivation saved approximately 2.33 MJ/kg of rice (168). RT in wheat cultivation can lower energy inputs and increase energy use efficiency and productivity. While maintaining grain yields like CT (169). Energy use efficiency was significantly higher with Green Seeker guided-N treatment in maize (170). Minimal energy use through CA practices significantly benefits production economies and the environment (167).

Effects on pests, disease and nematode management

High insect infestation rates pose a major threat to crop productivity because they can reduce output by 20 % annually. Soil management strategies are one approach to addressing this problem (171). Integrated pest management offers a comprehensive strategy for managing pests by combining chemical, mechanical, biological and cultural control techniques. In combination, they establish a balanced ecosystem that minimizes risks to the environment, reduces the need for agrochemicals and guarantees the long-term sustainability of agricultural systems (172). Practicing CA will alter the soil microbiomes, which will lead to reducing the size of Bt resistant western corn rootworm larvae while maintaining Bt toxin efficacy against susceptible larvae (173). It also reduces wireworm damage in maize. Adopting conservation practices can enhance pest management sustainably by promoting healthier soil ecosystems (174).

Disease management under CA relies on integrated strategies such as crop rotation, use of resistant varieties and biological control agents (175). For instance, ZT in wheat reduced *Fusarium* crown rot incidence without affecting its yield and quality (176). Winter oilseed rape is gaining popularity in crop rotations due to its economic benefits and its ability to reduce the occurrence of take-all fungal disease (caused by *Gaeumannomyces graminis)* in subsequent wheat crops under conservation strip tillage. This is mainly due to increasing the *phl*D gene and microbes in both roots and soil, which is crucial for producing the antifungal compound 2,4-diacetyl phloroglucinol (2,4-DAPG) (177).

CA has also shown potential in managing plant-parasitic nematodes. Nematodes such as *Meloidogyne* spp. and *Hirschmanniella* spp. are a significant threat to rice production in Asia. CA offers a promising solution to the above problem. CA reduced Plant Parasitic Nematodes (PPNs) in roots by 88 % through an increase in microbial richness and diversity and a notable rise in mycorrhizal fungi. The mature soil food web under CA correlated with reduced *Meloidogyne* spp. in roots. Effective regulation of PPN populations offers a viable alternative to nematicides for protecting rice crops (178).

Effects on economics

CA enhances farm profitability by boosting yields and reducing costs, resulting in higher net incomes and improved long-term sustainability for farmers (179). CA achieved a 36.15 % higher net return and a better benefit-cost ratio of 2.81, compared to CTs lower ratio of 2.16 in the rice-wheat cropping system (180). In strip planting, net income rose by 25-28 % for dry-season crops, while it matched CT net income for rice cropping systems (181). The total production costs for the wheat-sorghum-fallow system were highest for NT, followed by RT and CT. However, the NT system achieved the highest average return, approximately ₹6246 and ₹12191 ha^{-1} more than RT and CT, respectively (182). The benefit-cost ratio (3.2) of soybeans is higher under CA (164). In the zero till with raised bed method combined with crop residue retention, both gross returns (₹73104 ha^{-1}) and net returns (₹49992 ha^{-1}) were found to be higher for pigeon pea (183). These findings indicate that CA not only ensures ecological sustainability but also supports economic viability across diverse cropping systems.

Constraints of CA

Despite its benefits, CA faces several challenges that hinder its widespread adoption. Technical constraints include inadequate availability of suitable machinery for seeding and fertilizer placement, incomplete implementation of CA principles and poor weed and pest management strategies (184,185). In semi-arid areas, the short growing season, competition for biomass and limited investment capacity pose additional challenges (1). It highlights the need for targeted interventions and support systems to enable broader and more effective adoption of CA practices. Addressing these multifaceted constraints through targeted policy support, improved technology dissemination and farmer training is essential to unlock the full potential of CA.

Conclusion

CA provides a transformative approach to sustainable farming by tackling key challenges related to nutrient management, climate resilience, soil health and economic sustainability. By promoting healthier soil ecosystems and minimizing environmental impacts, CA boosts productivity while supporting long-term sustainability. Its ability to reduce greenhouse gas emissions, increase soil organic matter and encourage microbial activity makes it a critical tool in addressing climate change and ensuring the future viability of agriculture. However, for CA to be effectively adopted, it is essential to overcome barriers such as insufficient technical expertise, limited access to specialized machinery and socio-economic challenges. Integrating CA into national agricultural policies, research agendas and farmer support programs will be crucial to ensure resilient food systems and sustainable agricultural growth in the face of future challenges.

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Author's contributions

SV wrote the manuscript draft and SPS revised it. PMS, KSB, EP, KT, PY and KD verified the contents. All authors read and approved the final manuscript.

Compliance with ethical standards

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