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Global Status and Adoption of Conservation Agriculture for Resilient Agro-Ecosystems

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ABSTRACT

Conventional tillage-based agriculture-which involves an intensive soil disturbance and monocropping has resulted in soil degradation, biodiversity loss, reduced resource-use efficiencies, and heightened vulnerability to climate variability. Conservation agriculture has emerged as a sustainable agro-ecological approach that addresses these challenges while ensuring resilient and productive farming. This article reviews the global status, guiding principles, trends in adoption, constraints, and future prospects of conservation agriculture on diverse agro-ecological regions. Conservation agriculture is underpinned by three interlinked principles: minimal or no mechanical soil disturbance, permanent soil cover through crop residues or cover crops, and diversified cropping systems. Applied as an integrated system, CA enhances soil structure, improves infiltration of water, increases soil organic carbon sequestration, and optimizes nutrient and water use efficiency, culminating into stable or increased crop yields with time. Global adoption of CA has rapidly expanded onto more than 150 million hectares worldwide, with significant expansion observed in developed and developing countries. Nevertheless, constraints associated with weed management, residue competition, equipment availability, and site-specific conditions limit wider adoption, especially among smallholder farmers.

INTRODUCTION

Low-input farming methods dominated by cereal monoculture and intense tillage have a significant detrimental effect on pressure from diseases, weeds, and pests across Eastern Europe and Central Asia, which lowers profit margins. The agricultural model that relies on mechanical soil tillage, exposed soils, and continuous monocropping typically has detrimental effects on agriculture's natural resource base to the point where future agricultural productive potential is compromised. This type of farming is thought to be a significant contributor to the decline of biodiversity and to hasten soil erosion by accelerating the mineralization of organic materials. A significant portion of the region's theoretically accessible land is either locked up in other valuable uses that are essential to the proper operation of ecosystems (such as forests, grasslands, protected areas, human settlements, and infrastructure) or is not particularly good for agriculture. Therefore, improving productivity per unit area of farmed land is becoming increasingly important for the great majority of crop production.

Conservation agriculture is a sustainable agro-ecological approach to resource-conserving agricultural production that avoids or minimizes soil mechanical disturbance (no-till) in conjunction with crop variety and soil cover. Although the region has created conservation agriculture farming techniques that can increase production, farmers face a perceived and occasionally actual risk of failure when they switch to new systems and business practices. Because of this, the Guide identifies two essential elements for the creation of successful Conservation Agriculture systems: first, the development of multidisciplinary scientific and technical capacity; and second, and perhaps most crucially, close cooperation with farming communities, rather than just farmers, to leverage their traditional and existing knowledge. Agriculture, notably conservation agriculture, is not a single, standardized technique that can be used instantly, anyplace, and in a consistent way. Instead, it is a collection of interconnected ideas that promote the development of regionally tailored procedures, strategies, and techniques. The agriculture industry, which contributes theleast to the national economy, employs the majority of India's workforce **(Khan *et al.*, 2025)**.

1. Three principles form the foundation of CA :

Principle 1: Continuous no or minimal mechanical soil disturbance (implemented by direct planting material placement into tillled soil and no-till seeding or broadcasting of crop seeds and causing minimum soil disturbance from any cultural operation, harvest operation, or farm traffic);

Principle 2: Preserving crop biomass, root stocks, stubble, cover crops, and other sources of ex situ biomass in order to maintain a permanent biomass soil mulch cover on the ground surface;

Principle 3: Crop species diversification (executed by implementing a cropping system with crops in rotations, sequences, and/or relationships incorporating annual and perennial crops, including a balanced mix of legume and non-legume crops).

CA principles are universally applicable to all agricultural landscapes and land uses with locally developed and adapted practices is supported by the existence of CA systems in all land-based agriculture across all continents. Increased need for funds to support the agricultural industry and enhance farmers' well-being is a defining feature of the 2024–2025 decade **(Khan *et al.*, 2025)**. The ecological basis of CA systems is formed by the simultaneous application of the three separate principles. The three principles do not form a CA system if they are implemented independently. For instance, unless it is combined with the use of the other two practices of soil mulch cover and diverse cropping, the adoption of no-till practice alone does not classify the production system as CA based. External inputs like agrochemical and plant nutrients of mineral or organic origin are applied optimally and in ways and quantities that do not interfere with or disrupt the biological processes, and soil interventions like mechanical tillage are minimized or avoided. In this way, CA enhances total land husbandry for rain-fed and irrigated crops and promotes effective agronomy, such as timely operations. CA is a foundation for sustainable agricultural output intensification when combined with other well-known best practices, such as the use of high-quality seeds and integrated pest, fertilizer, weed, and water management. Yield values under established CA systems are on par with or even greater than those under traditional intensive tillage systems. Yield penalties are not always the result of CA. Additionally, compared to tillage-based management, the total crop and biomass production within a season rises over time with CA management because soil moisture and carbon are preserved and unproductive times spent on tillage and land preparation are eliminated. At the same time, CA adheres to the widely recognized concepts of ecological sustainability as, when applied, the three principles behave like naturally vegetated land. **[Dumansky, J., Reicosky, D.C. and Peiretti, R.A. 2014, Kassam, A.H., Friedrich, T., Shaxson, F. and Pretty, J.2009, Shaxson, F., Kassam, A., Friedrich, T., Boddy, B. and Adekunle, A.2008, Kassam, A.H., Derpsch, R. and Friedrich, T. 2014a, Basch, G., Kassam, A., Friedrich, T., Santos, F.L., Gubiani, P.I., Calegari, A., Reichert, J.M. and Dos Santos, D.R., 2012].** Long-term increases in water and nutrient retention and utilization as well as a decrease in the use of pesticides, including herbicides, and mineral fertilizers can result from increased cropping system diversity, stimulation of biological processes in the soil and above the soil surface, and decreased erosion and leaching. Improved water infiltration and less surface runoff restore groundwater supplies. Reduced levels of pesticide contamination and soil nutrient contamination due to decreased leaching and soil erosion improve water quality **[Bassi, L., 2000].**

Table 1. Comparison of the principles and practices that underlie conservation agriculture compared to conventional agriculture

Conventional agriculture	Conservation agriculture
➢ Using science and technology to control nature while cultivating land.	➢ Utilizing composts and in-situ organics.
➢ Burning or elimination of residue (bare surface).	➢ Brown cover crops and manuring (surface retention).
➢ There is little water infiltration.	➢ In the early phases of adoption, weeds are a concern, but they eventually go away.
➢ Soil erosion and excessive mechanical tillage.	➢ Minimal disruption of natural processes.
➢ Utilizing composts and ex-situ FYM. Green manuring (incorporated).	➢ The rate of water infiltration is high.
➢ Soil erosion and strong winds.	➢ Biological tillage, or no-till or very reduced tillage.
➢ In addition to killing existing weeds, it encourages the germination of new weed seeds.	➢ Soil erosion and wind are minimal.

2. History of Conservation Agriculture

Global empirical data demonstrates that farmer-led agricultural production system transformation from tillage-based to CA is currently a global occurrence. As a new paradigm for "sustainable production intensification" and an illustration of "climate smart agriculture," the spread has gained even more traction in recent years. The updated data on the adoption of CA in 2013 that is presented in this paper only applies to arable cropland and is based on a number of sources, including official statistics (e.g., Canada and the USA); survey estimates by agroindustry and no-till farmer organizations (e.g., Australia, Brazil, Argentina, Paraguay, and Uruguay); Ministry of Agriculture (e.g., China, Malawi, Zimbabwe); NGOs (e.g., Europe, Russia, Madagascar, Zambia); and knowledgeable individuals from research and development organizations (e.g., India, Kazakhstan, and Ukraine). With the exception of Africa, where a large portion of the data is still from the 2010 database, it has been able to update the database for the majority of countries. **Kassam *et al.* (2009) and Derpsch and Friedrich (2009a)** provide a helpful summary of the adoption of CA in several nations in 2008/2009; in 2010/11, **Kassam *et al.* (2010) & Friedrich *et al.* (2012)**. **Jat *et al.* (2014) and Farooq and Siddique (2014)** provide a global state of the arts review of CA.

According to **Kassam *et al.* (2009)**, the estimated global extent of CA agriculture in 2008–09 was around 106 M hectares, or 7.5% of all cropland worldwide. It was approximately 157 M ha (11% of the world's cropland) in 2013, a change of nearly 51 M ha (47%) over the course of five years (Table 2). CA has developed into a rapidly expanding production system in recent years. Although CA was only applied to 2.8 million hectares globally in 1973–1974 (Figure 1), the area increased to 6.2 million hectares in 1983–1984 and 38 million hectares in 1996–1997 **(Derpsch, 1998)**. The global adoption rate increased from 45 million hectares in 1999 to 72 million hectares in 2003. The area of agriculture in California has increased from 72 to 157 M ha during the past ten years at an average annual pace of about 8.3 M ha.The rate of change has been roughly 10 M ha since 2008/09, indicating the growing interest of farmers in the CA farming system approach, primarily in North and South America and Australia, and more recently in Kazakhstan with large farms, as well as in India and China with small farms, where significant increases in the adoption of CA are anticipated and are actually happening.

According to Table 2, the number of nations that have implemented and promoted CA has grown from 36 in 2008/09 to at least 55 in 2013. However, Table 2 does not include a number of nations where CA is known to be performed. These include Ethiopia, Burkina Faso, and Cameroon in Africa, Vietnam, Cambodia, and Laos in Asia, and Denmark and Sweden in Europe. Additionally, the area of CA systems based on perennial crops or a combination of annual and perennial crops is growing in many nations across all continents and is not included in the total CA area presented in this research.

Table 2. Extent (ha) of adoption of CA worldwide by countries (Kassam *et al.*, 2018)

Sl. No	Country	2008-09	2013-14	2015-16
1	USA	26,500.00	35,613.00	43,204.00
2	Brazil	25,502.00	31,811.00	32,000.00
3	Argentina	19,719.00	29,181.00	31,028.00
4	Canada	13,481.00	18,313.00	19,936.00
5	Australia	12,000.00	17,695.00	22,299.00
6	Paraguay	2,400.00	3,000.00	3,000.00
7	Kazakhstan	1,300.00	2,000.00	2,500.00
8	China	1,330.00	6,670.00	9,000.00
9	Bolivia	706.00	706.00*	2,000.00
10	Uruguay	655.10	1,072.00	1,260.00
11	Spain	650.00	792.00	900.00
12	South Africa	368.00	368.00*	439.00
13	Germany	354.00	200.00	146.00
14	Venezuela	300.00	300.00*	300.00
15	France	200.00	200.00*	300.00
16	Finland	200.00	200.00	200.00
17	Chile	180.00	180.00	180.00
18	New Zealand	162.00	162.00*	366.00
19	Colombia	102.00	127.00	127.00
20	Ukraine	100.00	700.00	700.00

21	Italy	80.00	380.00	283.92
22	Zambia	40.00	200.00	316.00
23	Kenya	33.10	33.10*	33.10
24	United Kingdom	24.00	150.00	362.00
25	Portugal	25.00	32.00	32.00
26	Mexico	22.80	41.00	41.00
27	Zimbabwe	15.00	90.00	100.00
28	Slovakia	10.00	35.00	35.00
29	Sudan	10.00	10.00*	10.00
30	Mozambique	9.00	152.00	289.00
31	Switzerland	9.00	17.00	17.00
32	Hungary	8.00	5.00	5.00
33	Tunisia	6.00	8.00	12.00
34	Morocco	4.00	4.00	10.50
35	Lesotho	0.13	2.00	2.00
36	Ireland	0.10	0.20	0.20
37	Russia	–	4,500.00	5,000.00
38	India	–	1,500.00	1,500.00
39	Malawi	–	65.00	211.00
40	Turkey	–	45.00	45.00
41	Moldova	–	40.00	60.00
42	Ghana	–	30.00	30.00
43	Syria	–	30.00	30.00
44	Tanzania	–	25.00	32.60
45	Greece	–	24.00	24.00
46	Korea, DPR	–	23.00	23.00
47	Iraq	–	15.00	15.00
48	Madagascar	–	6.00	9.00
49	Uzbekistan	–	2.45	10.00
50	Azerbaijan	–	1.30	1.30

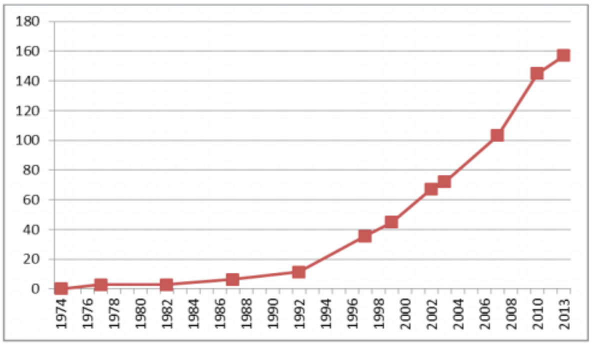

Figure 1. Global uptake of CA in M ha of arable cropland

Table 3. Factors that determine a soil guide for conservation agriculture systems (Lal, R. 2015)

Climate	Land forms and physiography	Soil type	Human dimensions
1. Rainfall amount and seasonal distribution	1. Slope characteristic (e.g., gradient, length, aspect, and shape)	1. Texture, structure, mineralogy, pH, and electrical conductivity	1. Farm size and tenure rights
2. Temperature and the growing season duration	2. Drainage (surface and internal)	2. Profile, horizonation, depth, and drainage	2. Infrastructure (market)
3. Probability of drought stress during the growing season	3. Susceptibility to erosion (water, wind, and tillage)	3. Soil organic carbon concentration and depth distribution	3. Institution support
4. Soil temperature regime (0 to 10 cm depth) and diurnal fluctuations	4. Vegetation cover	4. Nutrient reserves	4. Education and gender

There is a need, therefore, to establish a compatibility guide depending on site conditions within these geographical hotspots (table 3). Climate, land topography, soil types, socioeconomic factors, among others, also matter **(Lal 1985)**. There are soils that were naturally suited to CA, including drained soils that are prone to erosion, calcareous soils, poorly structured silt loam, silty-clay loam, among others. Soils that have root-restricting subsoils, soils that have electrical imbalances, including acidity, aluminum toxicity, and Ca and P deficiencies, need modification prior to the implementation of CA. Some heavy soils that have poor internal drainage, in addition to soils found in higher latitudes, which have suboptimal spring soil temperatures, make up soils that are not suitable for CA implementation. Thus, a serious assessment concerning the types that can be most suitable for the application of CA is required, especially concerning small landholder agriculture within SSA, Asia, and other developing countries **(Giller *et al.* 2011)**. **Chivenge *et al.* (2006)** offered strategies for reducing SOC degradation in fine-textured soils and designing functional CA systems for the establishment of C inputs management in coarse-textured soils in Zimbabwe. In identifying potential niches for CA adoption, it is important to consider the community, cultural, and social issues apart from biophysical considerations related to soil, climate, and physiography.

CA, when properly employed, is one of the techniques that can distinguish carbon from the soil, conserve the soil, conserve the water, or sustain the productivity. Through the development of packages specifically designed for sites, as well as making people aware of the benefits derived from CA, the use can be improved.

Table 4. Limitations and Uncertainties in No-Till Systems

Merit	Limitations	Issue of uncertainties
Reduced sedimentation and erosion management	An abundance of weeds, particularly perennials	Economic variables and land tenure
High water use efficiency and water conservation	Increased application of herbicides and other pesticides	Market and credit accessibility
Time and labor savings	The need for new farm equipment, including a seed drill	Accessibility of inputs
Minimal energy consumption	An increase in infections, pests, and insects	A shifting and unpredictable climate (extreme events)
Less machinery	Elevated soil compaction hazards	Fertilizer application and nutrient control (N, P, and Ca)
Minimal machine wear and tear	Excellent managerial abilities	Acidification of the soil
Reduced pollution from non-point sources	Increased N_2O emissions	Inadequate tools and equipment
Improved soil structure and quality	Low crop stand and poor seed positioning	Change in the spectrum of cannabis
Carbon sequestration in soil	Risk of reduced yields (5% to 10%)	The time required for NT to operate at its fullest potential
Improved environment	Non-ideal soil temperature for spring	Seedling development in poorly drained soil

3.Future vision

Decades ahead, the best possible efforts of all players should work towards the shift of tillage agriculture to CA. There are many ways to support immediate and wide spreading scaling up CA **(World Bank, 2012; Kassam *et al.*, 2014)**:

- ✧ All new agriculture development projects should use CA as a technology for sustainable production intensification and involve stakeholders for a positive outcome, including developing an enabling environment for private sector engagement.
- ✧ Promote initial government aid in terms of incentives to ensure appropriate farming equipment becomes more accessible while minimizing risks of any unfruitful productivity losses during initial years when CA systems are adopted.
- ✧ Design large-scale programs to provide incentives for CA farmers in the form of payments for ecosystem services like carbon sequestration, watershed services to enhance the quality and quantity of water resources, control of soil erosion, and reduction of flood risks, and sustaining pollination services.
- ✧ Reformulate the agricultural curricula of universities to teach the next generation of farmers and practitioners in agriculture development that CA is an alternative and sustainable method of farming.Supply agricultural universities and schools with literature and publications relevant to CA in local language.
- ✧ Support more innovative practical research to tackle soil, agronomic, and livestock husbandry challenges through universities and research centers.

CONCLUSION

Conservation agriculture, with its principles of reduced soil disturbance, permanent soil cover, and crop rotation, has been identified as a viable approach for sustainable intensification and climate change resilience. Long-term experience has shown that conservation agriculture leads to an improvement in soil structure, carbon sequestration, water use efficiency, and yield stability. Yet, its adoption is limited by site-specific soil-climatic conditions, weed management, machinery constraints, and socio-economic factors. A system-level and adapted approach is required to promote conservation agriculture.

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