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FEATURE

A system approach to conservation agriculture

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Dwight D. Eisenhower, 34th US President (1953 to 1961), summarized the plow dilemma by stating, “Farming looks mighty easy when your plow is a pencil and you are a thousand miles from corn field” (Eisenhower 1956). Despite great progress in agriculture since the 1950s, farming may now pose even bigger challenges because of the increasing demand for food, feed, fiber, and fuel in the 21st century. The challenges of farming are exacerbated by a changing and uncertain climate, increase in risks of soil degradation by erosion and other processes driven by decline in soil organic carbon (SOC) concentration and pool, increase in dependence on energy-based inputs such as fertilizers and pesticides, high risks of shifts in spectrum of pests and pathogens, and decrease in availability of soil and water resources because of diversion to nonagricultural uses. Hence, there is a growing emphasis on sustainable intensification, climate-resilient and eco-efficient agroecosystems, and the linkage of farming and soil management to sustainable development goals (United Nations 2014).

Research on and adoption of conservation agriculture (CA) started during the 1960s. Presently, the literature is replete with merits, limitations, and uncertainties of no-till (NT) systems (table 1). It is because of these limitations and uncertainties of NT that the focus now is on CA as a system. Increasing adoption of CA requires prudent strategies to address limitations and uncertainties of NT. Therefore, the objective of this article is to deliberate a system approach to CA for minimizing uncertainties and limitations while maximizing merits and ecological benefits.

SYSTEM APPROACH

The American naturalist John Muir, said, “When we try to pick out anything by itself, we find it hitched to everything else in the universe” (Muir 1911). Indeed, the success of CA depends on harnessing the benefit of interconnectivity, or the nexus concept. The strategy is of enhancing eco-efficiency, improving consistency/stability of production, and producing more with less. Four basic components of CA (Lal 2015a)—residue mulch, minimal soil disturbance, cover cropping and rotations, and integrated nutrient management—must be interconnected (figure 1) to (1) replace whatever nutrients and other resources are removed, (2) respond wisely to changes in pedospheric processes, (3) anticipate changes in soil/environment quality that may occur over time, and (4) formulate an appropriate action plan.

Crop Residue Mulch. Retention of crop residue mulch is essential to conserving soil and water, creating a positive soil C budget, moderating microclimate, improving activity and species diversity of soil macro- (earthworms and termites) and microfauna (microbes), recycling nutrients, and sustaining agronomic yield. Whereas the importance of stubble mulching to hold soil and water and improve productivity of dryland farming in the United States dates back to the 1930s (Albrecht 1938; Duley and Russel 1948; Zingg and Whitheld 1957), its role for erosion control was recognized following the work on soil splash by impacting raindrops by W.D. Ellison (1944, 1947, 1948). Merits of mulch-based CA are especially critical to erosion control in humid, subhumid, and semiarid tropics (Lal 1975, 1976a, 1976b,

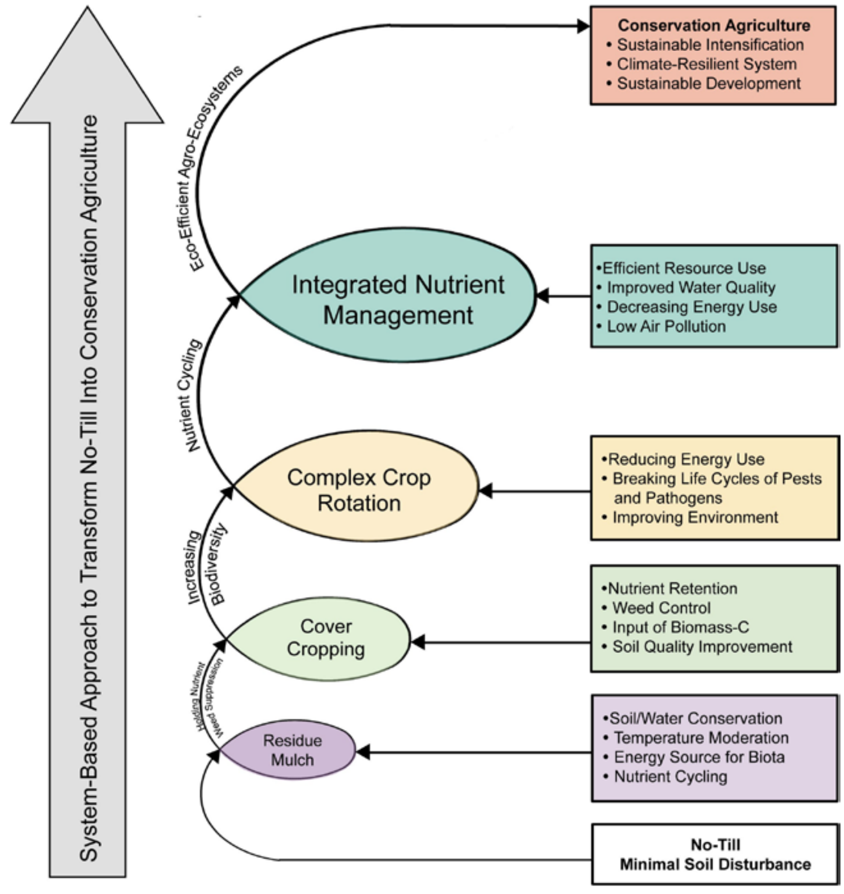

Figure 1

Integrating four basic components for transforming no-till into conservation agriculture.

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Table 1

Limitations and uncertainties of no-till (NT) farming which must be addressed through a system-based approach to enhance merits of conservation agriculture to advance climate resilience and promote sustainable intensification.

Merits	Limitations	Issues and uncertainties (for small landholders)
1. Erosion control and reduced sedimentation	1. High incidences of weeds, especially perennials	1. Land tenure and economic factors
2. Water conservation and high water use efficiency	2. Greater use of pesticides, including herbicides	2. Access to market and credit
3. Savings in time and labor	3. Need for new seed drill and other farm machinery	3. Availability if inputs
4. Low energy use	4. More insects, pests, and pathogens	4. Changing and uncertain climate (extreme events)
5. Less equipment used	5. High risks of soil compaction	5. Nutrient management (N, P, and Ca) and fertilizer placement
6. Low wear and tear of machinery	6. High level of management skills	6. Soil acidification
7. Less non-point source pollution	7. More emission of N_2O	7. Lack of proper tools and equipment
8. Soil quality improvement and better structure	8. Poor quality of seed placement, low crop stand	8. Shift in weed spectrum
9. Soil carbon sequestration	9. Risks of yield reduction (5% to 10%)	9. Time required for NT to become fully functional
10. Better environment	10. Sub-optimal soil temperatures in spring	10. Poorly drained soils inhibit seedling growth
11. Climate-resilient system	11. Slow internal drainage in clayey soils	11. Harvesting residues for cellulosic ethanol and other uses
12. Sustainable intensification	12. Competing uses of crop residues	12. Nutrient (N) and water interaction on crop yield
13. Low production cost and high net profit	13. Increased fertilizer immobilization and low uptake	13. Ammonia volatilization
14. Enhanced fungal hyphae network and increased glomalin	14. Sulfur (S) deficiency at seeding stage	14. Low efficacy of pesticide/herbicide use with mulch
15. High activity and diversity of soil biota including microbial biomass carbon	15. Build up of soil P in the surface and enhanced risks of eutrophication	15. Changes in soil fertilizer recommendation over time

1983, 1987). Crop residue mulching in the tropics tends to stabilize and even enhance crop yields and improve use efficiency of water (Rockstrom et al. 2009; Thierfelder and Wall 2009) and of inputs (Erenstein 2002, 2003). As the habitat and energy source for soil fauna, retained crop residue mulch also increases recycling of plant nutrients (nitrogen [N], phosphorus [P], potassium [K], calcium [Ca], magnesium [Mg], etc.) and of carbon (C). Therefore, removal of crop residues exacerbates risks of water runoff and accelerated erosion, aggravates depletion of SOC and plant nutrients, and increases the need for input of chemical fertilizers.

Adverse effects of residue removal on soil properties (Juo and Lal 1977; Blanco-Canqui and Lal 2008; Govaert et al. 2005) and agronomic productivity (Juo and Lal 1977; Verhulst et al. 2011) have been widely reported. No-till without mulch cover drastically reduces crop yields in semiarid regions (Rusinamhodzi et al. 2011), strongly reduces the C sink potential (Wu et al. 2015), and decreases the SOC pool (Blanco-Canqui 2013).

Retention of residues can improve the efficacy of C stabilization by strengthening aggregation (Tisdall and Oades 1982; Six et al. 2000; Wang et al. 2013). In a 10-year experiment in Mongolia, He et al. (2009) observed the largest yield improvement in wheat (*Triticum aestivum*)–oat (*Avena sativa*) and the highest water use efficiency (WUE) when crop residues were retained, and in the Loess Plateau of China, Huang et al. (2008) concluded that NT with stubble retention resulted in higher and more efficient use of water and nutrients. Straw mulching also increases WUE under rainfed (Shen et al. 2012) and irrigated agriculture (Baunhardt et al. 2013a, 2013b). Mulch type (live vs. dead) can also affect soil biological functioning and crop yield (Djigal et al. 2012). However, the rate of mulch required may vary with soil type, cropping system, and the climate (Stagnari et al. 2014). CA with residue mulch and crop rotations is a viable option even for European agriculture from the viewpoint of productivity (Van de Putte et al. 2010).

Cover Cropping. Recommendations of cover cropping date back to 3000 years BP in the Zhou dynasty of China (Lipman 1912) and to Roman Philosopher Cato in 3rd Century BC (Lal 2015b). However, importance of cover cropping had been forgotten since the 1960s because of the cheap availability of chemical fertilizers. The renewed interest in cover cropping since 2000 is attributed to its environmental and sustainability benefits. Cover crops conserve N for grain crops; reduce soil erosion; and increase crop yield, especially in developing countries (Pretty 2008; Lal et al. 1979; Wilson et al. 1982). Deep-rooted cover crops can alleviate soil compaction in NT systems (Williams and Weil 2004) and suppress weeds (Moyer et al. 2000; Triplett and Dick 2008; Mirksky et al. 2011; Lal 2015b). Rather than by herbicides, cover crops can be suppressed by roller crimper (Kornecki et al. 2009). Cover crops also impact soil chemical properties (Calegari and Alexander 1998; Lal et al. 1978) and affect N mineralization and availability (Schomberg and Endale 2004).

Cover cropping in CA on a Brazilian Oxisol indicated benefits on grain yield and SOC concentration (Calegari and Alexander 1998) while contributing N and enhancing soil fertility. Increases in SOC sequestration in Brazilian studies were also observed by Bayer et al. (2006), Boddey et al. (2010), and Metay et al. (2007). Based on a 13-year study in Southern Brazil, Sisti et al. (2004) observed SOC sequestration with NT only when used in conjunction with vetch (*Vicia villosa*) as a cover crop in the rotation. The increase was attributed to a greater root density in the subsoil than under a PT system. In general, SOC accumulation rate peaks during the fifth to ninth year after the adoption of CA (Zanatta et al. 2007). Thus, Calegari et al. (2008) recommended that NT combined with cover crops is the management system of choice to achieve sustainable crop production on Oxisols in subtropical and tropical regions of the world.

Agricultural intensification with CA can improve SOC even in seasonally dry agroecosystems of the Mediterranean (Aguilera et al. 2013), South Asia (Iqbal et al. 2011), and Central Mexico (Fuentes et al. 2012). Positive effects of cover cropping on increase in SOC pool even to 75 cm (2.46 m) depth under NT were reported from a 12-year cover crop experiment in southern Illinois, United States (Olson et al. 2014). For cotton (*Gossipium hirsutum*) and sorghum (*Sorghum bicolor*)-based systems in southeastern United States, cover cropping may enhance SOC and microbial biomass C (Sainju et al. 2006, 2007). The ecosystem C budget is also favorable in CA because of reduced energy use in farm operations (Lal 2004; Jayasundara et al. 2014).

Leguminous cover crops can deliver several ecosystem services (Jensen et al. 2010, 2012), including increase in soil N fertility. Thus, cropping patterns in the Canadian prairies and US northern Great Plains have justifiably shifted from fallow-based to legume-based systems (Lupwayi and Kennedy 2007). Strong adverse impacts of summer fallowing on SOC budget have also been observed for grain farming in northern Kazakhstan, where Funkawa et al. (2004) reported the net soil respiration rate in the fallow plot of 2.9 Mg C ha^{-1} (1.29 tn ac^{-1}), or 4% of the total SOC pool in the 0 to 30 cm (11.8 in) layer. In southern Brazil, 10 years of intensive farming with legume-based CA systems resulted in a 24% increase in soil N as compared to PT (Amado et al. 1998). Additional research should focus on increasing the legume component in the cropping system in sub-Saharan Africa (SSA) (Batino et al. 2006) and elsewhere in developing countries.

Crop Rotations. Because of low soil moisture and short growing seasons in the arid and semiarid regions, crop rotations can strongly impact SOC concentration and soil quality (Sainju et al. 2006; Balkcom et al. 2013). A rotation cycle (wheat, chickpea [*Cicer arietinum*], barley (*Hordeum vulgare* L.), and lentil [*Lens culinaris*]) with early sowing in a CA system can be attractive cropping technology in West Asia and the Middle East (Piggin et al. 2015), and can increase production of food legumes (Siddique et al. 2012). Biannual crop rotations (wheat–sunflower [*Helianthus annuus*], wheat–chickpea, wheat–faba bean [*Vicia faba*]) in a CA system can improve soil quality in a Mediterranean Vertisol (Melero et al. 2011) and Zambian Alfisols (Thierfelder and Wall 2010). A meta-analysis of corn (*Zea mays* L.) -based CA system under rainfed conditions in southern Africa showed an increase in yield over time in practices that include rotation and high input (Rusinamhodzi et al. 2011). In Zimbabwe, rotating corn with cowpea (*Vigna unguiculata*) and sorghum in a CA system increased crop yield (Mupangwa et al. 2012). Productivity benefits of crop rotations in CA may also be due to reduction in root rot and nematode populations (Govaerts et al. 2006), and decline in weed and other pests. Forage-based rotations in CA are useful in integrated crop-livestock systems (Sanderson et al. 2013; Hutchinson et al. 2007).

Integrated Nutrient Management and Soil Fertility Improvement. Several issues and uncertainties about plant nutrient management in NT farming can be effectively addressed through integrated nutrient management (INM) in CA. Low soil fertility is one of the reasons for low crop yields in resources-poor farmers in SSA (Sanchez 2015). The vicious cycle of low nutrient input causing low crop yield, which results in lower biomass input into soil, lower humification efficiency, and a lower SOC pool, can only be broken by the strategy of INM and the creation of a favorable elemental balance (N, P, sulfur [S], Ca, Mg, and micronutrients) in the root zone. Some of the apparent discrepancies in SOC pool under NT are also attributed to the low soil fertility and unfavorable elemental balance (Campbell et al. 2001).

The importance of applying N, P, and manure on increasing SOC pool is widely recognized (Jenkinson and Raynor 1977; Lal 2014). Experiments in the North China Plain (Kong et al. 2013, 2014) indicated an increase in SOC pool with improvement in soil fertility since the 1980s. Adequate application of fertilizers, along with retention of crop residues and growing cover crop, must be combined into a management system to improve soil quality (Liu et al. 2006). Wang et al. (2013) reported that the application of both inorganic and organic fertilizers significantly increased SOC concentration in the top 20 cm (8 in) layer in different regions of China.

An effective nutrient management in CA cannot be independent of the consideration of N use by weeds (Wortman et al. 2011). Similarly, rainfall distribution/amount and water availability strongly impact agronomic yield and must be appropriately considered (Sinclair and Rufty 2012), especially in semiarid regions of SSA. In Burkina Faso, Zougmore et al. (2004) observed that combining water-harvesting practices with input of organic and mineral fertilizers created synergistic effects in enhancing sorghum yield under Sahelian rainfed conditions. Thus, a flexible system of fertilization to vary nutrient input according to the rainfall pattern may enhance resource capture (N, P, K, etc.) and recovery efficiencies in semiarid regions (Chikowo et al. 2010).

CONSERVATION AGRICULTURE FOR SMALL LANDHOLDERS

Small landholders, numbering 500 to 600 million, are principal food producers in developing countries. Low agronomic yields are attributed to degraded/depleted soils and low input. Severe depletion of SOC pool is also caused by social, economic, and policy dimensions (Ayuk 2001). It is precisely in these conditions that properly implemented CA can reverse soil degradation, restore soil quality, enhance productivity, and advance food/nutritional security. While soil fertility restoration in SSA can be achieved by adoption of CA (Mateete et al. 2010; Shaxson and Kassam 2015), the uptake of CA in these regions is low (Farooq et al. 2011). Development of a system-based approach and of equipment to facilitate farm operations can help (Sims et al. 2012). Lessons from CA success in Mexico and southern Africa can promote adoption in SSA (Erenstein et al. 2012; Ito et al. 2007; Marongwe et al. 2011). There are examples of successful adoption of CA for small landholders in Asia and SSA (Vance et al. 2014), and Kassam et al. (2012) reported significant productivity, economic, social, and environmental benefits of CA in dry Mediterranean climates, central and west Africa, and north Africa. Further, tools and practices are now available to implement CA for small landholder rainfed farming (Johansen et al. 2012).

However, overcoming social and cultural factors may also be essential for extensive adoption of CA by small landholders (Ngwira et al. 2012). Further, soil and water conservation may not be as influential in farmers' decisions to adopt CA in Europe as are economic factors (Van den Putte et al. 2010). A study in mountainous slopes of Vietnam showed that possible social constraints at the community level must also be overcome (Affholder et al. 2010).

SUCCESS STORY OF CONSERVATION AGRICULTURE IN SOUTH AMERICA

Several countries in South America are global leaders in adoption, with 64 million ha (158 million ac or 60% of all arable land) under CA in 2014 (Kassam et al. 2014). An important factor behind the success of CA in South America is the incorporation of cover crops in the rotation cycle, and the holistic approach, which has increased the rates of SOC sequestration. For a 22-year experiment on an Oxisol in Parana State, southern Brazil, Sá et al. (2001) reported the SOC sequestration rate under CA of 806 kg C ha^{-1} y^{-1} (719 lb C ac^{-1} yr^{-1}) for 0 to 20 cm (7.9 in) depth and 994 kg C ha^{-1} y^{-1} (887 lb C ac^{-1} yr^{-1}) for 0 to 40 cm (15.7 in) depth. In another study, Sá et al. (2008) compared PT and CA systems for four tropical soils, three in the Cerrado region of Brazil and one in the highlands of central Madagascar. The mean SOC sequestration rate of CA was 1.66 Mg C ha^{-1} y^{-1} (0.74 tn C ac^{-1} yr^{-1}) with a range of 0.59 to 2.60 Mg C ha^{-1} (0.26 to 1.16 tn C ac^{-1}), and indicated that 14.7% of each additional Mg (tn) of biomass-C input per hectare was sequestered as SOC. In the Cerrado region of Brazil, Bayer et al. (2006) reported that in comparison with PT, SOC in CA increased at the rate of 0.30 Mg C ha^{-1} y^{-1} (0.13 tn C ac^{-1} yr^{-1}) in a sandy clay loam Oxisol and 0.60 Mg C ha^{-1} y^{-1} (0.27 tn C ac^{-1} yr^{-1}) in the clayey Oxisol. The mean rate of C sequestration with CA system for all of Brazilian tropical soils has been 0.35 Mg C ha^{-1} y^{-1} (0.16 tn ac^{-1} yr^{-1}). Similar to results in Brazil, NT systems are also successful in the Pampean region of Argentina (Diaz-Zorita 1999; Diaz-Zorita and Duarte 2001; Diaz-Zorita et al. 2004). Steinbach and Alvarez (2006) reported an increase in SOC pool by CA but warned that nitrous oxide (N_2O) emissions were greater with a mean increase of 1 kg N ha^{-1} y^{-1} (0.89 lb N ac^{-1} yr^{-1}) in denitrification rate for humid Pampean scenario of climate change. The success story of CA in South America needs to be replicated in North America, Europe, Australia, China, etc.

GLOBAL BRIGHT SPOTS FOR CONSERVATION AGRICULTURE

While CA may not be universally applicable on all 300,000 soil series and highly diverse agroecoregions, it is important to identify global bright spots where it can be readily adapted. Being a knowledge-intensive technology, institutional support (e.g., extension services and access to market) is critically essential. Global bright spots with a potential for high impact include the following areas.

Regions of Degraded Soils and Low Agronomic Productivity. These include arable lands in SSA, South Asia, the Caribbean, the Andean region, and North Africa. Prior to implementing CA, it is critically important to restore soil physical quality by establishing cover crops, applying organic amendments, promoting activity of soil fauna, strengthening nutrient cycling, and improving soil fertility. Recent technological developments and seeding machinery can adapt traditional tillage methods into CA systems (Mrabet 2002). Indeed, an agrarian revolution based on CA can take roots in SSA (Fowler and Rockström 2001).

East Asia, Southeast Asia, Central Asia, and the Pacific. Infrastructure, access to market, and institutional support are relatively well developed in these regions. Thus, policy interventions and incentives (e.g., payment for ecosystem services or trading C credits) are needed to promote the adoption of CA. Long-term experiments must be established to adapt and fine-tune site- and soil-specific packages.

North (and South) America. The CA movement in the United States started during the 1960s and was triggered by the devastating effects of the Dust Bowl. However, CA is practiced in the United States on component basis rather than as an integrated system based on a holistic approach with cover cropping, INM, and complex rotations. Rather than every season, NT is used on a rotational basis.

Middle East. The arid climate of Middle East can also benefit from the judicious application of CA, provided that forages (cover crops) and food legumes are integrated into farming systems (Mrabet et al. 2012; Kassam et al. 2012).

SOIL SUITABILITY GUIDE

Within each of these geographical bright spots, it is critical to develop a soil suitability

Table 2

Determinants of a soil guide for conservation agriculture systems.

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
		5. Water retention and transmission	5. Availability of inputs (seed drill, seed, and agro-inputs)
		6. Root-restrictive issues (physical, chemical, and nutritional)	

guide based on site-specific factors (table 2). Important among these are climate, physiography and land form, soil type and profile characteristics, and socioeconomic factors (Lal 1985). Some soils are naturally suited to CA (i.e., well-drained soils prone to surface runoff and erosion, and weakly structured soils of silt loam and silty-clay loam texture). Soils with root-restrictive subsoil horizons, and those characterized by elemental imbalance (e.g., acidity, aluminum (Al) toxicity, and Ca and P deficiency) must be amended to alleviate these constraints prior to implementation of CA. Some soils in higher latitudes/altitudes with suboptimal soil temperatures in spring and those of heavy texture with poor internal drainage are not suited for CA. Thus, there is an urgent need for a critical appraisal of which soil types and which agroecoregions are best suited for CA, especially in case of small landholder farming in SSA (Giller et al. 2011), Asia, and elsewhere in the developing world. In Zimbabwe, Chivenge et al. (2006) proposed development of viable CA systems for the maintenance of C inputs to coarse-textured soils, and techniques to reduce SOC decomposition in fine-textured soils. In addition to biophysical factors related to soil, climate, and physiography; social, cultural, and community factors must also be considered in identifying appropriate niches for CA adoption.

CONCLUSIONS

Identifying bright spots (soil type and agro-ecoregions) where CA can be readily adopted is important. Demonstrating success in these bright spots is more critical than making indiscriminate universal recommendations of CA adoption. Socioeconomic, cultural, and ethnic/gender constraints to adoption of CA are important to small landholders in SSA, Southeast Asia, Central America, and the Caribbean. Small landholders have immediate priorities (e.g., poverty, food and nutritional security, harsh climate, lack of input, and poor knowledge) that are more important than long-term stewardship of natural resources. A possible mismatch between technology and the capacity of the resource-poor farmer must be addressed. Increasing adoption of CA will require dynamic policy approaches. Unwavering institutional and government support is essential for strengthening research, education, and outreach.

Properly implemented, CA is one of the options with a potential to sequester C in soil, conserve soil and water, and sustain productivity. Its application can be improved by developing site-specific packages, and educating the farming community and general public about the merits of CA and stewardship of soil resources.

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