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FEATURE

# Sequestering carbon and increasing productivity by conservation agriculture

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The quantum jump in food production and progress toward elimination of mass starvation have been driven by mechanization of plowing and other farm operations, introduction of input-responsive varieties, use of chemical fertilizers along with herbicides and pesticides, increase in supplemental irrigation, and reliance on information and communication technology. Notable among the consequences of the agricultural revolution between 1960 and 2015 are increase in (1) human population from 3 billion to 7.3 billion (United Nations 2014); (2) atmospheric concentration of carbon dioxide ($CO_2$) from 316 ppm to 400 ppm (IPCC 2014); (3) global temperature by 0.12°C (0.22°F) per decade (IPCC 2014); (4) problems of soil degradation by erosion, salinization, depletion of soil organic matter (SOM), and nutrient imbalance (Bai et al. 2008); (5) depletion, pollution, and eutrophication of natural waters; and (6) risk of extinction of soils (Tenseson 2014) and species. Yet, food production must be increased by another 1 billion t (1.1 billion tn) by 2050, while also restoring the degraded soils and ecosystems, reducing net anthropogenic emissions, and improving the environment.

Plow-based agriculture has exacerbated the problems of accelerated soil erosion by water and wind, oxidation of SOM, and decline in soil structure (aggregation) and tilth. The plow-related problems of environmental degradation were highlighted by the Dust Bowl of 1930s in the United States (Steinbeck 1939) and in China since 2000; soil degradation and desertification in Sub-Saharan Africa (SSA), South Asia, the Caribbean, etc. (Bai et al. 2008); and the excessive withdrawal of water from aquifers such as of the Ogallala (United States), Indo-Gangetic Plains (South Asia), and the Huang-Huai-Hai Plains (China). Thus, there has been a growing interest in developing a plowless agriculture with possibility of lesser impact on soil and the environment (Lal et al. 2007; Lal 2009).

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While some traditional farmers (e.g., in SSA, the Andean region, and the Caribbean) have been sowing crops in undisturbed field by using a digging stick or a hand-held hoe for millennia, sowing crops in an untilled soil on commercial farms originated in the US Corn Belt during late 1950s, primarily in response to the severe problem of soil erosion by water and wind. In the 1940s, discussions on pros and cons of plowless agriculture or no-till (NT) farming started with the publication of two books, *Plowman's Folly* (Faulkner 1943) and the *The Furrow and Us* (Jack 1946). In the wake of ruinous Dust Bowl, Faulkner blamed the moldboard plow for disastrous pillage of the soil, and Time Magazine termed the Folley-Jack debate as "the hottest farming argument since the tractor first challenged the horse" (Jack 2007).

Because of the strong impact of tillage or its elimination on soil organic carbon (SOC) pool and its dynamics, objective deliberations on this theme must continue, especially during 2015 International Year of Soil, because of its critical role as a source/sink of atmospheric $CO_2$, methane ($CH_4$), and nitrous oxide ($N_2O$); the urgency to feed an ever growing and increasingly affluent world population; the need to minimize risks of water contamination, eutrophication, and nonpoint source pollution from agricultural runoff; and the importance of enhancing biodiversity. The fact that present agriculture is more reliant on input rather than on efficiency increase raises the stakes even higher. Therefore, a holistic and system-based approach to soil management as the engine for increasing productivity by improving efficiency and making agriculture environmentally compatible is more important now than ever before.

As anthropogenic greenhouse gas (GHG) emissions increase due to global economic and population growth and the atmosphere and oceans warm, there is a strong need to identify potential C sinks of storing atmospheric $CO_2$. The terrestrial C cycle is an important sink of the anthropogenic C emissions (LeQuéré et al. 2014; Running 2008), and soil C pool is a critical component of this sink. While improving productivity and advancing food security, SOC storage in depleted and degraded agricultural lands can also partly offset anthropogenic emissions and improve the environment.

Soils of agroecosytems have lost a large part of the antecedent SOC pool by erosion, decomposition, and leaching. The magnitude of SOC loss from cultivated soils is estimated at 15 Mg $ha^{-1}$ (13,390 lb $ac^{-1}$) in China (Song et al. 2005), but may be much higher for soils in SSA and South Asia (Lal 2004). Discussions on the importance of terrestrial C cycle and its changes since the ice age gained momentum in the 1990s (Crowley 1995). Yet, our knowledge is grossly insufficient (Falkowski et al. 2000), especially to describe the impact of agricultural perturbations (plowing) on the soil C pool and dynamics at local, regional, and global scales. Therefore, critical questions which must be addressed include the following:

1. Does conversion from plow tillage (PT) to conservation agriculture (CA) merely redistribute SOC in the profile, or can the SOC pool be increased on long-term basis, especially in the subsoil where it is away from the zone of intense natural and anthropogenic perturbations?
2. What land use and soil management systems can create a positive soil C budget?
3. Is CA a viable option for increasing the SOC pool (Schlesinger 2000; Powlson et al. 2014) and sustaining agronomic yield (Pittelkow et al. 2014) in a changing and uncertain climate?
4. What policy interventions may facilitate adoption of best management practices (BMPs) of land use and soil/crop management (Hammons 2009)?
5. What makes sense and nonsense in application of CA (Kirkegaard et al. 2014) to achieving long-term sustainability of agroecosystems (Rasmussen et al. 1998; Bockstaller et al. 2008)?

The objective of this article is to answer these questions and explain how to judi-

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ciously and prudently use CA to harness its potential as a conservation-effective technology, climate-resilient agriculture, and a viable option for sustainable intensification of agroecosystems for advancing food and nutritional security, and for adaptation/mitigation of climate change.

## DEFINITIONS AND TERMINOLOGY

The awareness during 1940s regarding the need for the elimination of plowing and retention of crop residue mulch on the surface led to several practices and the associated terminology to describe the new concept of seedbed preparation based on the need for reducing soil disturbance and retaining of crop residue mulch for soil and water conservation (figure 1). During the 1960s and 1970s, a range of terms (NT, zero tillage, direct seeding, conservation tillage, minimum tillage, mulch tillage, and strip tillage) were used. However, indiscriminant use of these terms, often using the same term to describe different practices, has exacerbated confusions and controversies. Therefore, standardization of terminology is important.

## CONSERVATION AGRICULTURE: A SYSTEMS APPROACH

Since the late 1990s, there has been a greater emphasis on a system approach to NT farming, and this is called "conservation agriculture" (CA). Conceptually, CA encompasses four basic principles (figure 2): (1) retaining crop residues as surface mulch, (2) including cover crops in the rotation cycle, (3) improving soil fertility by integrated nutrient management (INM) for healthy crop growth and biochemical transformation of biomass C into SOM or humus (Lal 2014), and (4) causing minimal or no soil disturbance (NT). Additional supporting criteria are (1) adopting a holistic approach to sustainable management of agroecosystems, (2) providing three to five years of soil restoration phase while converting from long-term conventional PT to CA so that soil quality is sufficiently restored to fully harness its agronomic and ecological benefits, and (3) including improved crop varieties and genotypes that can also emit molecular-based signals under biotic/abiotic stresses detectable by remote sensing for targeted interventions.

Based on these criteria, CA is defined as a farming system comprised of crop residue mulch, cover cropping, INM, and NT techniques in a rotation cycle for effective soil and water conservation, SOC sequestration, sustainable intensification, and climate change adaptation and mitigation. The seemingly tall order is not only essential to advancing food and nutritional security but also critical to reducing GHG emissions by agriculture—presently estimated at 30% of global total emissions (IPCC 2014, 2015; LeQuéré et al. 2014)—and minimizing the severe problems of nonpoint source pollution and contamination of surface waters including hypoxia (Diaz and Rosenberg 2008) and algal bloom (Michalak et al.

**Figure 1**

Historical evolution of plowing and conservation agriculture.

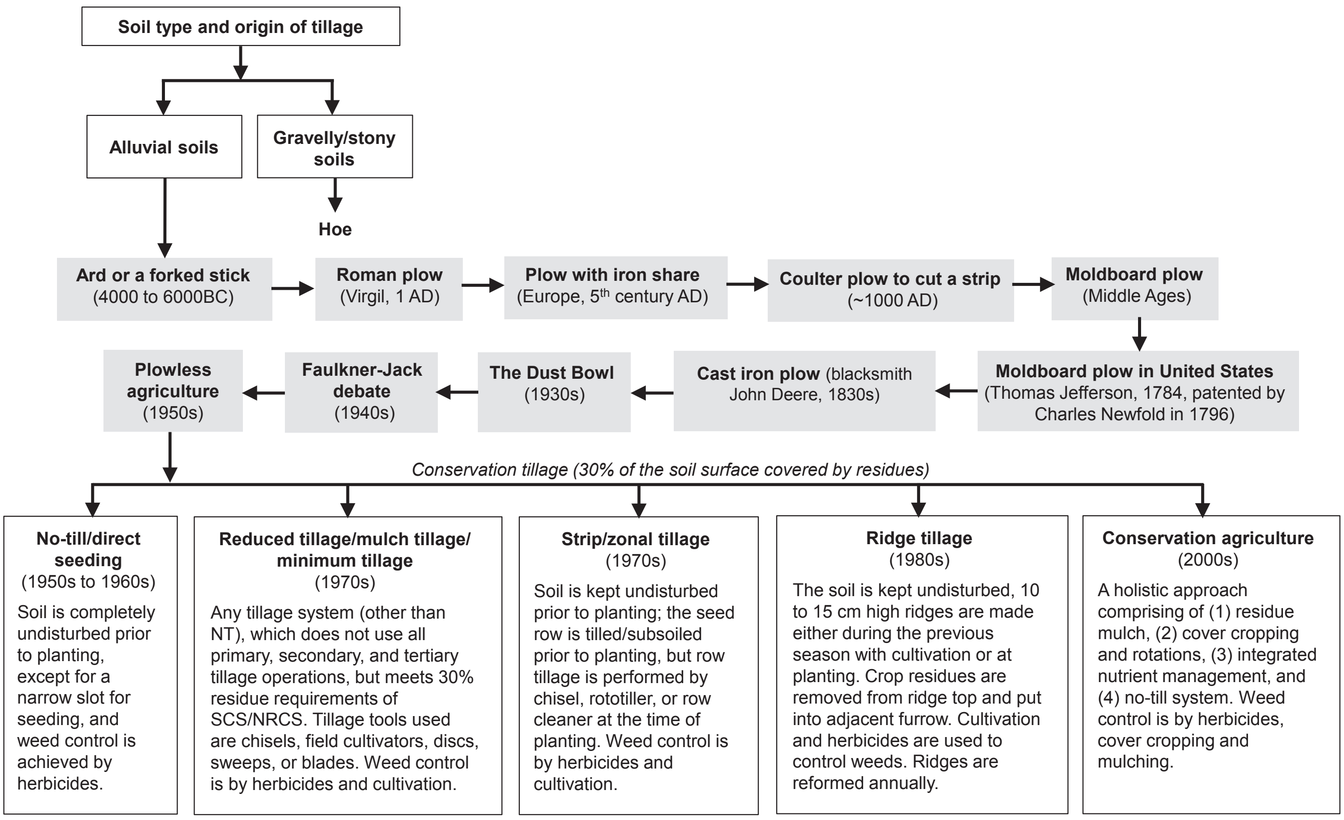
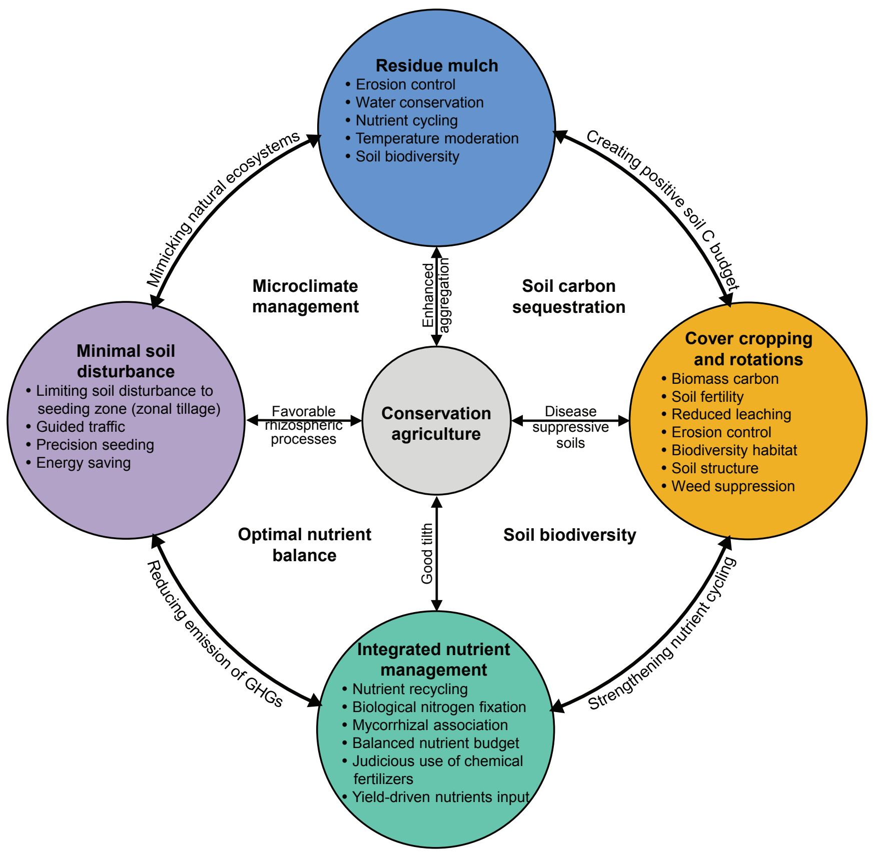


**Figure 2**

Four conceptual principles of conservation agriculture systems.



2013). In this context, the question is not whether CA works or not, but how to make it work by a strategy of identifying site-specific components. CA is a mission, a goal, and a long-term strategy of sustainable intensification of arable lands. The objective is not to produce the highest yield, but a sustainable optimum yield, especially during bad growing seasons. Thus, sustainability of a technology is judged not by the highest yield in a good season, but a respectable/stable yield in a poor season. This is the criterion of a climate-resilient management system.

## SOIL CARBON SEQUESTRATION

An answer to whether conversion from PT to CA merely redistributes SOC in the profile rather than enhances it lies in a critical assessment of the equilibrium SOC pool under new management and its depth-distribution in relation to several exogenous (climate, physiography, and biome) and endogenous (soil properties) factors. Differences in input of biomass C is a main factor explaining variability in SOC sequestration under CA vs. PT (Virto et al. 2012). Differences in soil moisture and temperature regimes, and susceptibility to erosion among systems are other factors. Given favorable soil and climate and adoption of the holistic and farming system approach, there are examples from around the world of measurable gains in the SOC pool with conversion of PT to CA, not just in the surface (0 to 15 cm [0 to 6 in]) layer but also in subsoil to 50 cm (20 in) depth or more (table 1).

However, low rates of SOC sequestration are observed in arid regions and in seasons affected by drought. In South Dakota, United States, Clay et al. (2012) observed an SOC sequestration rate of 181 kg C ha$^{-1}$ (161 lb ac$^{-1}$) during the drought seasons compared with 368 kg ha$^{-1}$ (328 lb ac$^{-1}$) for the long-term average. In addition to drought, temperature-sensitivity of SOC is also a factor whose response is not well understood (Davidson and Janssens 2006). Lower summertime soil temperatures in a CA system may reduce $CO_2$ flux compared with that under PT (Sainju et al. 2008).

There are also several studies where a consistent and measurable increase in SOC under CA has not been observed. In contrast to the positive trends described above, review of literature on depth-distribution and total profile in relation to tillage methods indicates four distinct patterns: (1) no significant differences in SOC profile SOC pool among tillage treatments (Ludwig et al. 2011); (2) more SOC under PT than NT when assessed to 1 m (3 ft) depth or more (Li et al. 2007); (3) increase of SOC in the surface but decrease below the plow layer, indicating redistribution of the SOC pool because the cumulative totals are similar (Angers et al. 1997; Diaz-Zorita and Grove 2000; Doran et al. 1998; Xu et al. 2007); and (4) decrease in the SOC pool in both PT and CA systems as in landscapes prone to severe erosion (Olson et al. 2013). Declines in the SOC pool under NT are related to lower input of biomass C into the system, either because of low productivity or harvesting of residues (Kim et al. 2009). A study in southern Brazil on grain-based cropping systems and grazing indicated a linear relationship between SOC concentration and the annual C supply through plant biomass (Nicolso et al. 2008). The amount of biomass C required to maintain the SOC at the antecedent level differs among soils, climates, management systems, etc.

Different trends in depth distribution can partly be explained on the basis of the duration of tillage methods because NT takes three to five years or more to restore soil structure and enhance activity of soil biota. For a short period after conversion (less than five years), NT increases SOC concentration and pool compared to PT methods only in the surface layer but not for the entire soil profile (Deen and Kataki 2003; Powlson et al. 2014). Marked stratification of SOC in the surface layer under NT is attributed to application of crop residues and other biomass on the surface and incorporation within the plow layer. Thus, more SOC pool in PT below the plow layer than at equivalent depth has been commonly observed. In addition, subsoil properties (e.g., acidity, aluminum [Al] toxicity, phosphorus [P] and calcium [Ca] deficiency, pan or compaction, anaerobiosis, and water logging) have a strong impact on agronomic productivity (Pittelkow et al. 2014), the SOC pool, and its depth distribution. Specifically, P deficiency and low availability of Ca inhibit root development in the subsoil (Ritchey et al. 1980; Pavan et al. 1984) and decrease the SOC pool. In this regard, alleviation of root-restrictive attributes of subsoil is critical to increasing the SOC pool in the deeper horizon, which is also an important strategy to enhance the mean residence time of the SOC pool and enhance crop yield and total production.

Strong differences in the SOC pool among tillage methods and of trends in depth distribution are also caused by erosional processes. Globally, accelerated soil erosion by water leads to an estimated emission by as much as 1.1 Pg C y$^{-1}$ (1.21 billion tn C yr$^{-1}$) (Lal 2003). Erosion-induced breakdown of aggregates and alterations in soil moisture and temperature regimes aggravate the depletion of the SOC pool onsite and emission of GHGs offsite (Lal 2003). Therefore, assessment of tillage-induced alterations in the SOC pool must take into account preferential removal of the SOC pool through erosion by water, wind, and other agents of erosion. The data from a 24-year conservation tillage experiment in southern Illinois showed that no SOC sequestration occurred in the sloping and eroding NT plots (Olson et al. 2013). For an Oxisol in the Brazilian Cerrado, Bayer et al. (2006) also observed that the SOC pool was maintained on cultivated land except when the soil had been subjected to erosion, which caused 15% loss of the SOC pool. A modeling study on the effect of erosion on the SOC pool at the regional scale in Germany showed that mean SOC losses by erosion were up to 0.45 Mg C ha$^{-1}$ y$^{-1}$ (402 lb C ac$^{-1}$ yr$^{-1}$) in agroecological zones covering the state territory of 35,742 km$^2$ (13,800 mi$^2$) (Gaiser et al. 2008). Gaiser and colleagues also estimated the $CO_2$-C mitigation rate for this state upon conversion from PT to NT in the range of 0.08 to 1.83 Mg C ha$^{-1}$ y$^{-1}$ (71 to 1,634 lb C ac$^{-1}$ yr$^{-1}$) even with accounting for the losses by erosion.

Therefore, it is important to identify which soil types, managements, and agroecoregions enhance or deplete SOC pools, why, and by what processes. This information is essential to developing systems which alleviate soil-related constraints, enhance soil C sink capacity, and create a positive soil/ecosystem C budget.

## CROP YIELD AND AGRONOMIC SUSTAINABILITY

Food and nutritional insecurity are global issues, but they are especially severe in developing countries because of population growth and declining availability of land, water, and other resources (Ray et al. 2015). Thus, sustainability of agronomic practices and increase in total production are essential to meeting the goals of increasing food supply. The challenge is especially daunting because of the changing and uncertain climate (Wilke and Morton 2015; Tubiello et al. 2007) and the attendant increase in risks of soil degradation (Bai et al. 2008). Because even a slight reduction in agronomic yield is not acceptable, a critical evaluation of crop response to a CA system is urgently warranted.

Soil quality is a strong determinant of agronomic yield. Thus, CA systems that enhance soil quality (such as those practiced in Brazil and elsewhere in South America) also improve and sustain productivity. There are examples from around

**Table 1**

**Several studies that demonstrate an increase in soil organic carbon (SOC) under conversion to conservation agriculture.**

| Location | Study duration (y) | Crop | Depth measured (cm) | SOC (Mg C ha$^{-1}$) or rate of change of SOC pool (kg C ha$^{-1}$ y$^{-1}$)* | Reference |
|---|---|---|---|---|---|
| Huan Province, China | 4 | Rice | 80 | NT (129.4), PT (126.3), RT (122.5) | Xu et al. (2013) |
| Georgia, United States | 41 | Corn, sorghum | 200 | NT (60), CR (52), FS (62) | Devine et al. (2011) |
| Global (24 studies) | >5 | Grain crops | >30 | NT (100.3), PT (95.4) | Angers and Eriksen-Hamel (2008) |
| Mediterranean Dryland | 16 | Barley | 40 | NT (50.5), PT (47.5) | Alvaro-Fuentes et al. (2008) |
| Andes-Colombia (Andisols) | 7 | Potato | 117 | NT (1636), PT (1224) | Quintero and Commerford (2013) |
| Southern Brazil | 11 to 20 | Grain crops | 100 | +640 to 1,170 | Sá et al. (2013) |
| Southern Brazil | 22 | Grain crop | 40 | +994 | Sá et al. (2001) |
| Central Brazil (Cerrado) | 1 to 13 | Soybean | 40 | +400 to 1,700 | Blanchart et al. (2007) |
| Madagascar Highlands | 7 | Corn–soybean | 20 | +590 to 1,050 | Sá et al. (2008) |
| North Central United States | — | Cotton | — | +430 | Causarano et al. (2005) |
| United States | 5 | Corn–soybean | — | +900 | Hollinger et al. (2005) |
| Southeastern United States | — | Cotton | — | +428 | Causarano et al. (2005) |
| Michigan, United States | 12 | Corn–soybean–wheat | 100 | +330 to 500 | Syswerda et al. (2011) |
| Western Canada and United States | 10 to 40, 4 to 56 | Wheat, barley | — | +80 to 460 | Liebig et al. (2005) |
| Canada, Prairies | — | Grain crops | — | +312 to 544 | West and Post (2002) |
| Southeastern Australia | 20 | Grain crops | — | +180 to 315 | Grace et al. (2010) |
| Global (67 studies) | 5 to 60 | Grain crops | — | +300 | Janzen et al. (1998) |
| Global (52 Studies) | — | Grain crops | — | +47 to 620 | Puget and Lal (2005) |

Notes: NT = not-till. PT = plow tillage. RT = rotary tillage. FS = Forest system.

* Above the horizontal rule are measured SOC pools; below the horizontal rule are rates of change in the SOC pool.

the world where properly implemented CA systems have improved soil quality and agronomic yields, including some from the US Central Great Plains (Mikha et al. 2012) and Corn Belt (Al Kaisi et al. 2005; Triplett and Dick 2008) region. Positive effects on soil physical quality (structure and water infiltration rate) are especially relevant to erosion control in erosive climate and erodible soils of the tropics (Lal 1976a, Lal 1976b; Choudhury et al. 2014) and elsewhere (Li et al. 2011; Kheyrodin and Antoun 2011). Soil moisture conservation by NT is an important advantage even in industrial agriculture, as was the case during the summer drought of 2012 in the US Corn Belt (Lal et al. 2012; Goode 2015). In these situations, conversion to CA can also improve soil biological quality with respect to microbial communities (Gupta et al. 2008; Zhang et al. 2012; Mathew et al. 2012), microbial growth and decomposition processes (Franzluebbers et al. 1995), soil food web and C dynamics (Minoshima et al. 2006), earthworms (Lal 1975, Lal 1976a; Edwards et al. 1988; Parmelee et al. 1990), and other macrofauna (Mutema et al. 2013). The CA-caused increase in SOC concentration even in the surface layer and reduction in soil erosion and improvement in biological properties also enhance soil fertility and chemical attributes (Lal 1975; Triplett and Dick 2008; Kheyrodin and Antoun 2011), ameliorate sodic soils (Choudhury et al. 2014), and improve agronomic productivity. With proper implementation, there are examples of better yield in NT than in PT, especially in well-drained soils prone to water runoff and accelerated erosion (Zhang et al. 2009; Liao et al. 2015; Moraru and Rusu 2013).

In contrast, there are also numerous examples of significant reductions in agronomic yields with NT. This declining yield trend sets-in-motion a vicious cycle of decreasing biomass causing low SOC pools, which result in lower yields, low biomass input, lower soil quality, and finally, even lower yields. Thus, it is utterly important, to identify the cause and effect relationship, determine site-specific soil and ecosystem-related constraints, and develop strategies to alleviate the yield-limiting barriers so that ecologic, climatic, and environmental benefits of CA systems can be fully harnessed. In degraded soils, a successful adoption of CA without prior amelioration can be a myth rather than a reality, especially for resource-poor farmers and small landholders of the tropics and subtropics.

Indeed, there are several known reasons for reduction in crop yield under NT, particularly within two to three years after conversion from PT to NT (table 2). Important among these are (1) low crop stand due to insufficient seed-soil contact and poor seeding equipment that accumulates residues in front of the seeder rather than cutting through it, (2) stunted seedling growth because of suboptimal soil temperatures during cold and wet springs in higher latitudes, (3) soil compaction in the row zone, (4) immobilization of N by residues of large C:N ratio and low availability of other plant nutrients, (5) ineffective weed control and a shift towards perennial weeds, and (6) increase in incidence of pests and pathogens under NT including seedling damage by slugs in a damp and cold spring (Wahlen et al. 2010).

With examples of some of these constraints outlined in table 2, it would be presumptuous to accept that agronomic practices developed for PT methods of seedbed preparation can be used for the CA system. The need for development of BMPs specific to CA system has been recognized since the 1980s (Lal 1983) and must be objectively considered and actively pursued.

## DEVELOPING A HOLISTIC SYSTEM APPROACH

Daunting and challenging task as it may seem, there is little choice but to integrate four basic/conceptual components into a system for the success of CA (figure 3) (Lal 1987). Implementing CA as a single element (eliminating plowing but removing crop residues) rather than a package is not acceptable. A sufficient quantity of crop residue mulch, use of a cover crop (preferably leguminous with a deep root system), adequate soil fertility, and proper crop rotations are essential components of a complete CA package. There are economic, ecologic, and social costs involved

**Table 2**

Some examples of specific causes of yield reductions under no-tillage systems.

| Country/region | Agroecosystem | Crop | Cause of yield reduction by NT/CA | Reference |
|---|---|---|---|---|
| Australia | Grain crops | Wheat | Reduced early seedling growth | Kirkegaard (1995) |
| Burkina Faso | Ferruginous tropical soil | Cotton, sorghum, maize | N deficiency | Soler et al. (2011) |
| China | Loess Plateau | Wheat, peas | Stubble removal | Huang et al. (2008) |
| Japan | Andosol | Wheat, barley, rape | P deficiency | Tsuji et al. (2006) |
| Mediterranean | Arid | Maize, sunflower | Poor establishment | Farina et al. (2011) |
| Mexico | Rainfed | Maize | Stubble removal | Verhulst et al. (2011) |
| United States | Tenessee Vallet | Cotton, corn, rye | N availability | Reddy et al. (2009) |
| Northwestern United States | Palouse (Northern Idaho) | Wheat | Greater root disease pressure | Hammel (1995) |
| Pacific Northwest, United States | Colombia Basin | Wheat | Downy brome weed | Camara et al. (2003) |
| Western Great Plains, United States | Semiarid | Wheat, maize, sorghum | N management and use efficiency | Kolberg et al. (1996) |
| Uzbekistan | Grain crops | Wheat | Partial crop residue retention, not using the full system | Kienzler et al. (2012) |

Notes: N = nitrogen. P = phosphorus.

in each of these inputs. Carbon sequestration in soil can happen only when CA or any other system can create a positive soil C budget, which has additional inputs and costs associated with residue mulch, fertilizers, herbicides, etc. Farmers must be fairly compensated for the societal value of humus or SOC sequestered (Lal 2014). Input of C from crop residues and cover crops are important to offset losses by decomposition, erosion, and leaching.

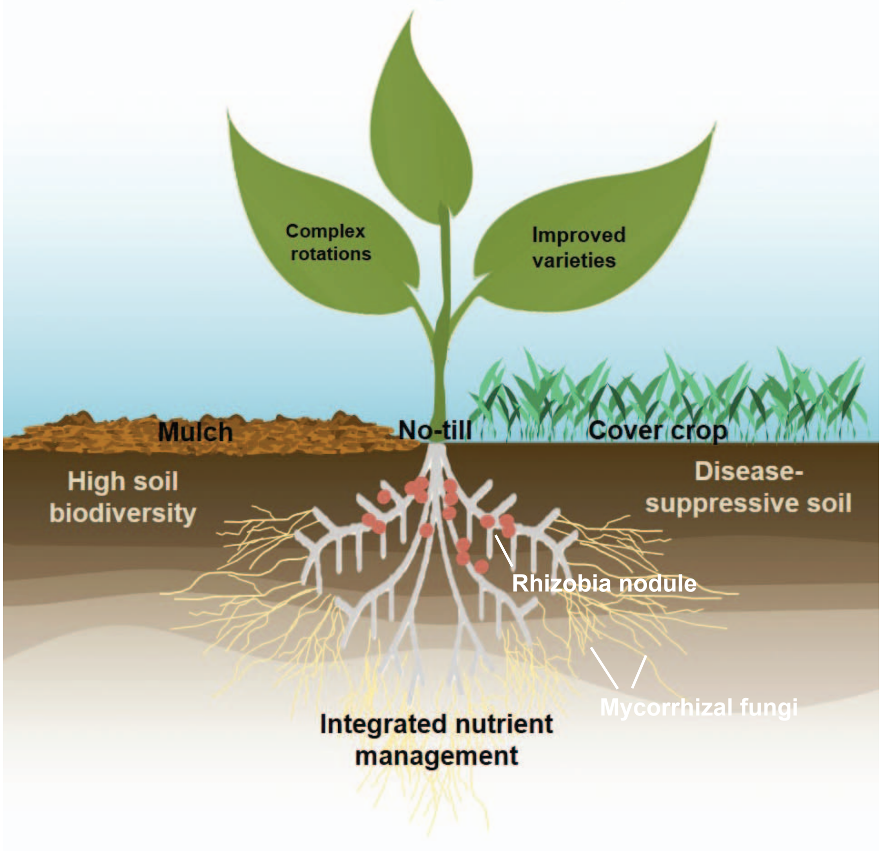
The humongous and complex problem of global warming necessitates critical review of all options (including geoengineering). Some of these strategies (i.e., CA) may cause only a modest reduction or drawdown of atmospheric $CO_2$. Thus, choice of these strategies must be based on additional co-benefits, cost-effectiveness, and social/cultural acceptability. In this regard, CA is an important mitigation option that deserves a serious and objective consideration. By itself, it cannot address climate change, but can make an incremental contribution along with other technologies and also produce several co-benefits.

Farmers are interested in feeding their families or making profit. If CA also helps in climate change adaptation and improves the environment, so be it, but that may not be among major goals of a farmer. Therefore, yield reduction from CA, especially during the initial stages of its implementation, must be objectively addressed. The yield-limiting constraints (e.g., weeds, pests, low crop stand, stunted seedling growth, subsoil compaction, and nutrient imbalance) must be alleviated, because even a slight yield reduction may be a major deterrent—for some farmers any amount of yield reduction is too much and is not acceptable.

Thus, it is pertinent to develop and implement an appropriate package of farm operations and cultural practices specifically designed for a CA system, along with the concept of the stewardship of soil resources. Soil stewardship and care must be embedded in every fruit and vegetable eaten, in each grain ground into the bread consumed, in every cup of water used, in every breath of air inhaled, and in every scenic landscape cherished. It is precisely in this context that CA is an important innovation and a mission for the 21st century.

**Figure 3**

**Conceptual outline of conservation agriculture based on four basic principles (mulch, cover crop, integrated nutrient management [INM], and minimal soil disturbance or no-till). The INM involves judicious use of chemical and biofertilizers and nutrient cycling (rhizobia nodules and mycorrhizal fungi). Improved varieties, including those which emit molecular signals under stress and detectable by remote sensing, allow for targeted interventions.**



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