CHAPTER FOUR

Conservation Agriculture in the Semi-Arid Tropics: Prospects and Problems

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Abstract

Relatively less attention has been paid on the use of conservation agriculture (CA) in the arid and semi-arid tropics (SAT), although a lot of information is available from humid and sub-humid regions globally. The objective of this review is to focus on the use of CA — its status, problems and prospects in the semi-arid tropical regions with emphasis on Asia and Africa. The information on the use of CA in SAT regions is summarized and put in context with the information available and lessons learnt on the use of CA in relatively vast tracts of land, especially in Brazil, North America, and Australia. Clearly, there are several bottlenecks in the use of CA in the SAT regions of Asia and Africa especially under rainfed agriculture. Among the major constraints to the use of CA in these regions include insufficient amounts of residues due to water shortage and degraded nature of soil resource, competing uses of crop residues, resource poor smallholder farmers, and lack of in-depth research in the SAT regions of Africa and to a lesser extent in Asia. The exception in the implementation of CA is of course the wheat—rice system in south Asia under irrigated conditions. The use of CA in the wheat—rice system of the Indo-Gangetic Plains (IGP) of south Asia has been relatively well researched during the last decade or so. However, in rainfed systems of the drier regions, relatively less attention has been given to develop research strategy to overcome the constraints to the adoption of CA. Examples are given from Brazil, Australia and North America as to how CA has been widely adopted in those regions as well as from Africa where CA is being promoted through active support of donor agencies. Obviously, there is need for strategic long-term research in the SAT regions for exploring the prospects in the face of major constraints faced to the adoption of CA, before CA could be taken to the farmers' door steps.

1. Introduction

The need to feed the burgeoning population and increasing use of fertile land for non-agricultural purposes has led policy makers shifting their attention to relatively less fertile lands in the arid and semi-arid areas as cradle of next green revolution. Today, about 560 million poor people live in rural areas in the semi-arid tropics (SAT) throughout the world. Agriculture in the semi-arid areas is afflicted with numerous constraints including water scarcity, soil degradation, low soil fertility, low risk bearing capacity of tenants, low farm mechanization, lack of interest from private sector to invest into agriculture due to its unreliable nature and expanding desertification, which results in very low crop productivity or crop failures in these areas. Adding to this bleak scenario, climate change is another major cause of concern for success of agriculture in the SAT. The main causes of soil degradation include not only intensive cultivation for soil preparation under conventional agriculture, but also the removal or burning of crop residues, inappropriate crop rotations that do not maintain vegetative cover on soil surface or allow appropriate buildup of organic matter, besides deforestation and poor rangeland management. Thus, these practices leave the soil resource vulnerable to the vagaries of climatic hazards such as wind, rain and sun by directly exposing to them. Continuing soil degradation is the main cause of declining farm productivity. This leads to no or very low economic returns to farmers pushing them into perpetual trap of poverty. The notion that "Farmer born in poverty, grows with poverty and dies in poverty" holds true for SAT farmers. This poor state of agriculture in the SAT is the cause of food insecurity and lack of sufficient livelihood opportunities for millions of farm households in these areas.

SAT regions across the world have problems related to wide variation in total rainfall and its distribution and relatively less fertile soils. . In temperate climates, in nineteen out of twenty years, annual rainfall is between 75 and 125% of the mean. In the SAT, at mean annual rainfall of 200—300 mm, the rainfall in nineteen out of twenty years, typically ranges from 40 to 200% of the mean, and for annual rainfall of 100 mm the range widens to 30—350% of the mean (FAO, 1981). Low rate of infiltration leading to high run-off is the reason for less effective utilization of the rainfall (Hudson, 1987). Surface crusting, which is widespread in semi-arid regions appears the primary reason for low infiltration (Valentin, 1985). Apart from the reduction in infiltration, surface crusting may hinder the emergence of seedlings. The deep cracking of Vertisols can lead to increased loss of moisture by evaporation and problems during cultivation (FAO, 1987). Water storage in the root zone may be limited by low intrinsic moisture-holding capacity of sandy soils. Due to erratic rainfall and low storage, even complete infiltration early in the season may not avoid moisture stress later. This underlines the importance of enhancing rain water use efficiency through improved infiltration and reduced evaporation losses for reducing the risk of crop failure in SAT regions.

Therefore, it is necessary to recommend crop production techniques to farmers that address the above mentioned problems faced by SAT agriculture particularly soil degradation, low soil fertility and vulnerability to climate change and variability so that agriculture may emerge as a source of farmers' prosperity. The objectives of this review therefore, are to evaluate the potential of conservation agriculture (CA) to redress the current problems faced in agricultural production in the SAT, and to enhance agricultural productivity and sustainability in the face of current and future climate variability and change.

2. Conservation Agriculture as a Part of Solution

Results from long-term studies have shown that continuous intensive plowing is undesirable as it leads to unsustainability particularly in the SAT where soils are prone to degradation. Therefore, an increasing number of farmers are reconsidering plowing and its relevance for successful crop production. Thus, issues related to resource conservation in the SAT have assumed importance in view of widespread natural resource degradation and the need to reduce production costs, and make agriculture profitable for small holders. During the past three decades or so rapid strides have been made all over the world to evolve and spread resource conservation technologies including zero and reduced tillage systems, better management of crop residues, planting methods and crop rotations or plant associations, which endorse conservation of soil and water and make agriculture resilient to climate change related risks. CA has also emerged a major way forward from the existing unsustainable conventional agriculture, to protect the soil from degradation processes and make agriculture sustainable. Empirical evidences have been accumulating to show that zero/minimum tillage based agriculture along with crop residue retention and adoption of suitable crop rotations can be highly productive, provided farmers participate fully in all stages of technology development and extension (FAO, 2001).

CA is being purported as a panacea to agricultural problems in smallholder farming systems in the tropics (Hebblethwaite *et al.*, 1996; Steiner *et al.*, 1998; Fowler and Rockström, 2001; Derpsch, 2003; Hobbs, 2007; Hobbs *et al.*, 2008; Foley, 2011). The CA specifically aims to address the problems of soil degradation due to water and wind erosion, depletion of organic matter and nutrients from soil, runoff losses of water, labor shortage and, moreover, it purports to address the negative consequences of climate change on agricultural production. CA permits management of soils for agricultural production without excessively disturbing the soil, while protecting it against the processes that lead to degradation e.g., erosion, compaction, aggregate breakdown, loss in organic matter, leaching of nutrients among others. Giller *et al.* (2009) argued that CA appears to offer great potential to address problems related to smallholder farming in the SAT. But region specific CA options need to be identified for implementation by resource-poor farmers (Fowler and Rockstrom, 2000).

3. Conservation Agriculture: Concept and Definition

According to Baker *et al.* (2002) conservation tillage is the collective umbrella term commonly given to no-tillage (NT), direct-drilling, minimum tillage and/or ridge-tillage, to denote that the specific practice has a conservation goal of some nature. Usually, the retention of 30% surface cover by residues characterizes the lower limit of classification for conservation-tillage.

CA is based on the integrated management of soil, water and agricultural resources in order to reach the objective of economically, ecologically and socially sustainable agricultural production. It relies on three major principles:

- Minimal soil disturbance by direct planting through the soil cover without seedbed preparation;
- Maintenance of a permanent vegetative soil cover or mulch to protect the soil surface;
- Diversified crop rotations in the case of annual crops or plant associations in case of perennial crops.

The concept of CA has evolved from the zero tillage (ZT) technique. In ZT, seed is put in the soil without any soil disturbance through any kind of tillage activity or only with minimal soil disturbance, with time soil life takes over the functions of traditional soil tillage like loosening the soil and mixing the soil components. In addition, increased soil biological activity creates a stable soil structure through accumulation of organic matter. As against this, mechanical tillage disturbs this process. In CA, mechanical tillage is avoided which helps to maintain the existing interactions between soil flora and fauna, which are necessary to release plant nutrients. Seeds are directly put in the soil without any prior tillage or minimal tillage. The biomass produced in the system is kept on the soil surface rather than incorporated into the soil or burnt, which provides physical protection for the soil against agents of soil degradation and food for the soil life. When the crop residues are retained on soil surface in combination with NT, it initiates processes that lead to improved soil quality and overall resource conservation. Therefore, zero/minimum tillage and maintenance of soil cover in the form of crop residues or cover crops are important elements of CA. At the same time varied crop rotations involving legumes, are important to manage pest and disease problems and improve soil quality through biological nitrogen fixation and addition of organic matter (Baudron *et al.*, 2009).

FAO defined goals of CA as follows: "CA aims to conserve, improve, and make more efficient use of natural resources through integrated management of available soil, water, and biological resources combined with external inputs. It contributes to the environmental conservation as well as to the enhanced and sustained agricultural production. Therefore, it can also be referred to as resource efficient or resource effective agriculture".

4. Conservation Agriculture Worldwide and Lessons Learnt

Since statistics is not available on specific use of the practice of CA, it is hard to quantify CA adoption statistics worldwide. Instead, the acreage of ZT is used as a proxy for CA (Hobbs and Govaerts, 2010). The latest statistics on adoption of ZT worldwide is 105 million ha (Derpsch and Friedrich, 2009). This figure is used as a proxy for CA, although not all of this land is permanently no-tilled or has permanent ground cover. The data in Table 1 show the distribution of NT agriculture country-wise. Increase in acreage under CA over the period of time in different parts of globe has been accounted by FAO (2008a,b) as shown in Fig. 1. Sangar *et al.* (2004) presented an account of the current status and perspectives of CA in different parts of the world. In the United States, where farmers during the 1990s were required to implement soil conservation plan on erodible croplands in order to be eligible for commodity price supports, the no-till area increased from 7 Mha in 1990 to 27 Mha in 2007, making USA a pioneer in adopting CA systems. The spread of CA in the US has been the result of a combination of public pressure to fight erosion, a strong tillage and conservation related research and education backup and public incentives to adopt reduced tillage systems. Other countries where CA practices have now been widely adopted for many years include Australia, Argentina, Brazil, and Canada. Now widely used in the production of corn and soybeans, no-till has spread rapidly in other parts of western hemisphere, covering 26 Mha in Brazil, 20 Mha in Argentina, and 13 million in Canada. Australia with 12 Mha under NT ranks 5th among the leading countries adopting no-till system. In many Latin American countries, CA systems are fast catching up. Some states in Brazil have adopted an official policy to promote CA. The continuous adoption of NT by farmers in different Brazilian regions has been due to cost reduction through savings on fuel, labor, and machinery and soil erosion control (Machado and Silva, 2001). In Brazil, the adoption has increased with time and the area under NT grew exponentially and more than 60% of the cultivated land is under CA (Mello and Raij, 2006). However, in contrast to Brazil, the

Table 1 Area (ha) under CA in different countries of the world: The area with >30% ground cover qualified for CA (1000 ha)

Country	Area (Year)
Argentina	25 553 (2009)
Australia	17 000 (2008)
Bolivia (Plurinational State of)	706 (2007)
Brazil	25 502 (2006)
Canada	13 481 (2006)
Chile	180 (2008)
China	3 100 (2011)
Colombia	127 (2011)
Democratic People's Republic of Korea	23 (2011)
Finland	160 (2011)
France	200 (2008)
Germany	5 (2011)
Ghana	30 (2008)
Hungary	8 (2005)
Ireland	0.1 (2005)
Italy	80 (2005)
Kazakhstan	1 600 (2011)
Kenya	33.1 (2011)
Lebanon	1.2 (2011)
Lesotho	2 (2011)
Madagascar	6 (2011)
Malawi	16 (2011)
Mexico	41 (2011)
Morocco	4 (2008)
Mozambique	152 (2011)
Namibia	0.34 (2011)
Netherlands	0.5 (2011)
New Zealand	162 (2008)
Paraguay	2 400 (2008)
Portugal	32 (2011)
Republic of Moldova	40 (2011)
Russian Federation	4 500 (2011)
Slovakia	10 (2006)
South Africa	368 (2008)
Spain	650 (2008)
Sudan and South Sudan	10 (2008)
Switzerland	16.3 (2011)
Syrian Arab Republic	18 (2011)
Tunisia	8 (2008)
Ukraine	600 (2011)

(*continued*)

Table 1 (*continued*)

Country	Area (Year)
United Kingdom	150 (2011)
United Republic of Tanzania	25 (2011)
United States of America	26 500 (2007)
Uruguay	655.1 (2008)
Venezuela (Bolivarian Republic of)	300 (2005)
Zambia	200 (2011)
Zimbabwe	139.3 (2011)
Total	124 795

(Source: FAO; http://www.fao.org/ag/ca/6c.html).

adoption of soil conservation practices by farmers in many low-income countries remains a major obstacle despite extensive technological options for improved soil management. A redeeming feature about CA systems in many of these countries is that these have come more as farmers' or community led initiatives rather than as result of the usual research extension systems efforts. Farmers practicing CA in many countries in South America are highly organized into local, regional and national farmers' organizations, which are supported by institutions from both South and North America. Spread of CA systems is relatively less

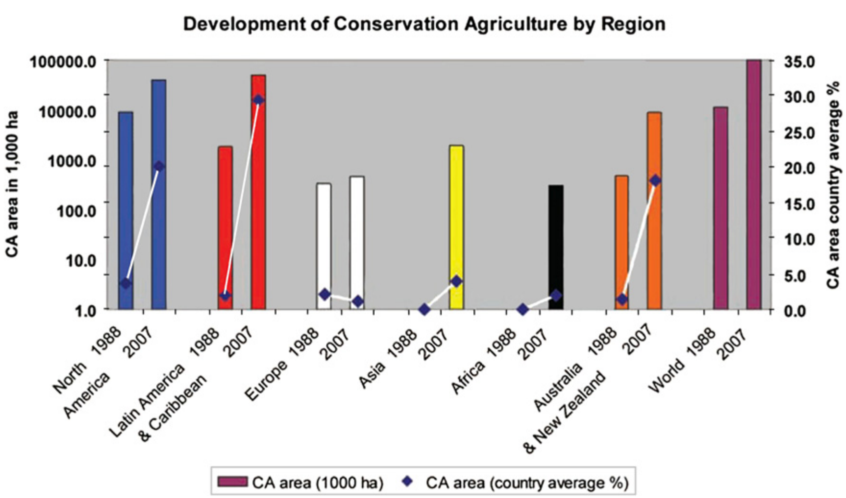

Figure 1 Expansion of area under CA in different parts of the world during 1998–2007. (Source: FAO, 2008a). For color version of this figure, the reader is referred to the online version of this book.

in Europe as compared to countries mentioned above. While extensive research over the past two decades in Europe has demonstrated the potential benefits of CA yet the evolution of practice has been slower in EU countries vis-à-vis other parts of the world possibly due to inadequate institutional support. France and Spain are the two countries where CA is being followed in about one Mha of area under annual crops. In Europe a European Conservation Agriculture Federation (ECAF), a regional lobby group has been founded. This body serves as a link among national associations in UK, France, Germany, Italy, Portugal, and Spain. The CA is adapted to varying degrees in countries of south-east Asia *viz*. Japan, Malaysia, Indonesia, Korea, the Philippines, Taiwan, Sri Lanka, and Thailand. Wang *et al*. (2010) based on the survey of 292 households reported that the adoption rates of CA technology (either in full or partial) in China is still low; especially the full adoption of CA is almost zero. The main factors behind slow pick up of CA by Chinese farmers are low labor cost and low share of machinery and fuel in the total cost of cultivation which gives little incentive to them to embrace CA technology. Since, at least in the first years of adoption, it is not clear if CA technology can result in higher yields; farmers do not have much enthusiasm to adopt CA in China (Wang et al., 2010). Central Asia is another prospective area for the CA (Gupta and Sayre, 2007).

In Africa unfortunately, despite nearly two decades of development and promotion by the national extension program and numerous other projects, adoption has been extremely low in the smallholder farming compared to in other continents such as South America, North America and Europe due to various constraints (Mashingaidze *et al*., 2006, Hobbs, 2007; Gowing and Palmer, 2008). The constraints identified included: a low degree of mechanization within the smallholder system; lack of appropriate implements; lack of appropriate soil fertility management options; problems of weed control under no-till systems; lack of access to credit; lack of appropriate technical information; blanket recommendations that ignore the resource status of rural households; competition for crop residues in mixed crop—livestock systems, and limited availability of household labor (Twomlow *et al*., 2006). There are instances where adoption claimed during the course of active promotion of technologies by NGOs and research later transpired to be due to the temporary influence of the project rather than a sustained change in agricultural practices (Giller *et al*., 2009). For example, the apparent success of Sasakawa Global 2000 program in promoting CA appears largely to have been due to its promotion within a technology package including inputs of fertilizers, pesticides and herbicides (Ito *et al*., 2007). ‘‘Dis-adoption'' (abandon of the technology after a few seasons of adoption) was recorded once incentives of input packages were stopped (Baudron *et al.* 2007). The widespread adoption of CA that was claimed through promotion programs appears to have suffered the same fate in South Africa (Bolliger, 2007) and in Zambia (Giller *et al.*, 2009).

In South Asia, CA systems would need to reflect on the unique elements of intensively cultivated irrigated cropping systems with contrasting edaphic needs and rainfed systems with monsoonal climate features. Concerted efforts of Rice-Wheat Consortium for the Indo-Gangetic Plains (IGP), a CGIAR initiative in partnership with the national research system of the countries of the region (Bangladesh, India, Nepal, and Pakistan) over the past decade or so is now leading to increasing adoption of resource conservation technologies like ZT mainly for the sowing wheat crop. In the rice—wheat (RW) areas of South-Asia, no-till planting of wheat has increased rapidly over the past 5 years with more than 2 Mha reported in the 2004/05 wheat season in the IGP (Rice-Wheat Consortium, 2006). In India, efforts to adapt and promote resource conservation technologies have been underway for nearly a decade, but it is only in the past 4—5 years that the technologies are finding rapid acceptance by the farmers growing rice—wheat system in the states of Haryana, Punjab and Western Uttar Pradesh. Efforts to develop and spread CA have been made through the combined efforts of several State Agricultural Universities, Indian Council of Agricultural Research (ICAR) institutes and the CG system promoted Rice-Wheat Consortium for the IGP. Unlike in rest of the world, in India spread of technologies is taking place in the irrigated regions of the IGP where rice—wheat cropping system dominates. CA systems have not been tried or promoted in other major agro-eco regions like rainfed semi-arid tropics, the arid regions or the mountain agro-ecosystems.

Despite successful in the upland soils in the humid and sub-humid tropics, limited benefits of NT however, have been reported in the semiarid or arid tropics throughout the world (Darolt, 1998; Hullugale and Maurya, 1991; Nicou *et al.*, 1993).

5. Conservation Agriculture for SAT: Perspective, Challenges and Opportunities

Rainfed semi-arid and arid regions are characterized by variable and unpredictable rainfall, structurally unstable soils and low overall productivity. The key challenge is to adopt strategies that will address the twin concerns of maintaining or even enhancing the integrity of natural resources and productivity, while improvement of natural resources taking a lead as it forms the very basis for long-term sustained productivity (Sangar, 2004). In light of the problems increasingly posed by the combination of climate change, population increase, soaring food prices, high input costs, energy deficit and resource degradation, the adoption of the systems like CA need to be promoted with greater efforts of all involved. However, to move from conventional tillage (CT) agriculture to effective CA requires much alteration in conventional thinking and attitudes about how agriculture should be undertaken not only on the part of the farmers but also of policy makers, scientific experts, and advisory staff. Retaining crop residues as mulch, using unfamiliar crops in rotation, changes in needed implements, all may pose great operational and financial uncertainty to farmers, some of whom may nevertheless decide to start out without important advisory support or appropriate legislation to facilitate the transition. From the results of most research station studies as well as prediction by models such as DSSAT, it has been found that zero/reduced tillage systems without crop residues left on the soil surface have no particular advantage because much of the rainfall is lost as runoff probably due to rapid sealing of the soil surface (ICRISAT, unpublished data). It would therefore, appear that NT alone in the absence of soil cover is unlikely to become a favored practice. However, overall productivity and residue availability being low and demand of limited residues for livestock feed being high pose major limitation for residue use as soil cover in the arid and semi-arid regions. An argument often heard in the discussion on CA is that it is only feasible in the humid and sub-humid tropics and that the generation of sufficient biomass in the semi-arid regions is the limiting factor to start implementing CA (Bot and Benites, 2005a). However, recent research findings have shown that even in the semi-arid areas of Morocco, the application of the principles of CA bears its fruits. Mrabet (2000) reported higher yields under CA due to better water use and improved soil quality; the latter caused by an increase in soil organic C and N and a slight pH decline in the seed zone (Mrabet *et al.*, 2001a, 2001b; Bessam and Mrabet, 2003). It would appear that there is need to identify situations where availability of even moderate amount of residues can be combined with reduced tillage to enhance soil quality and efficient use of rainwater (Guto *et al.*, 2011).

The potential of CA to reverse the process of soil degradation and make agricultural production more secure is so significant a factor that farmers need to be encouraged and supported proactively in practical ways to start and complete the transition to CA for the benefit of themselves, their local and national communities, and the future generation (FAO, 2001; Lal, 2010). Figure 2 shows the potential benefits of CA at eco-system level which are important to achieve the twin targets of food security and sustainability.

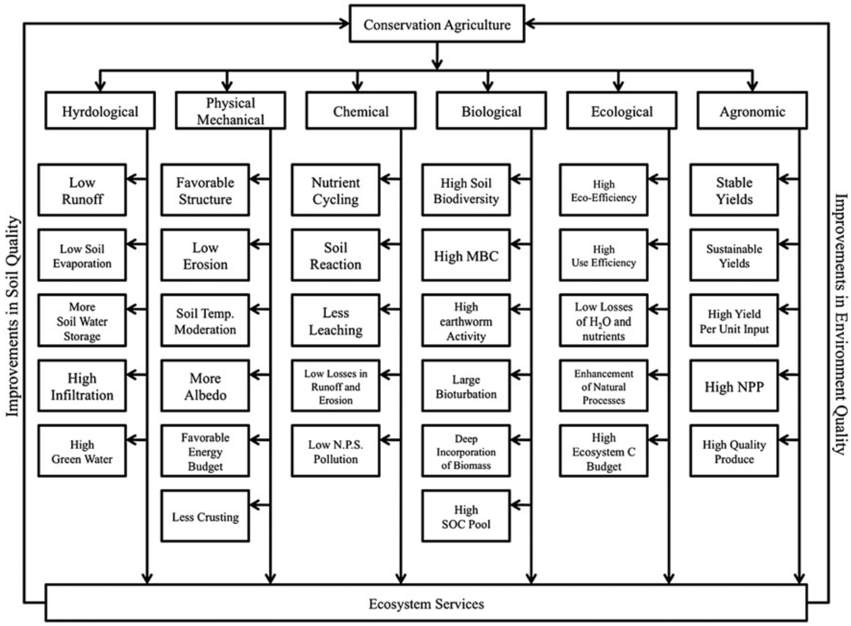

Figure 2 Ecosystem services generated through adoption of CA. (Source: Lal, 2010 with permission of the Author).

6. A Paradigm Shift in SAT Agriculture Through Conservation Agriculture

6.1. Conservation Agriculture and Soil Conservation

Cultivation of soils through intensive tillage can result in faster degradation of soils through water and wind erosion (Castro Filho *et al.*, 1991; Babalola and Opara-Nadi, 1993). CT causes more physical disruption coupled with less production of aggregate stabilizing materials (Bradford and Peterson, 2000). Besides, tillage removes the protective cover of crop residues from the soil surface thus/** exposing the soil to various degradation processes. This intensifies the process of land degradation. Halting accelerating land degradation, including the decline in SOC is one of the greatest challenges facing agricultural production in tropical and subtropical regions (Craswell and Lefroy, 2001). Reversing soil degradation process and restoring or enhancing soil quality is a pre-requisite for achieving significant productivity gains on sustainable basis in much of semi-arid tropics. More important than using physical barriers to control runoff, which is responsible for only 5% of erosion, research showed that the ideal solution is to maintain soils covered as much of the time as possible with growing plants or crop residues (FAO, 2001). CA has the potential to emerge as an effective strategy to address the increasing concerns of serious and widespread degradation of natural resources including soil degradation (Sangar, 2004). Castro (1991) compared water, soil and plant nutrient loss in conventional agriculture and direct seeding in a wheat–maize rotation and found that the losses were less under direct seeding due to the soil cover, which reduced the rainfall impact on the soil surface. In CA by avoiding the detachment of soil particles by raindrop impact, which accounts for 95% of erosion, soil losses are avoided or reduced, and at the same time the soil can be cultivated in conditions similar to those found in forests (FAO, 2000). Compared to CT, NT leaves more plant residues on the soil surface, which protect it against raindrop impact and allow improvement in soil aggregation and aggregate stability (Aina, 1979; Vieira, 1985; Derpsch *et al.*, 1986; Castro *et al.*, 1987; Carpenedo and Mielniczuk, 1990). Soil cover protects soil against the impact of raindrops and gusty winds, and also protects the soil from the heating effect of the sun (Moldenhaucer *et al.*, 1983; Knapp, 1983; Derpsch, 1997; FAO, 2000; Saxton *et al.*, 2001; Bot and Benites, 2005a; Govaerts *et al.*, 2006). At the same time, practices of minimum/zero tillage and direct sowing techniques as alternatives to the conventional practices lead to minimum disturbance of soil. The presence of crop residues over soil surface under CA prevents aggregate breakdown by direct raindrop impact as well as by rapid wetting and drying of soils (LeBissonnais, 1996) which can be of special importance for heavy textured soils in semi-arid tropics. Size distribution of soil structural units like stable aggregates has been proposed as a parameter to predict water retention and infiltration/runoff (Barthes and Roose, 2002). Govaerts *et al.* (2009a,b) and Verhulst *et al.* (2009) found that ZT with residue retention resulted in a high mean weight diameter and a high level of stable aggregates in rainfed systems of Mexico. However, ZT with residue removal led to unstable and poorly structured soils. They also observed that CT results in a good structural distribution, but the structural components were much weaker to resist water slaking than in ZT with residue retention. Indirectly, the residue lying on the soil surface in ZT with residue retention protects the soil from raindrop impact. Thus, plant nutrients and soil organic matter (SOM) remain in the soil. Under CT, there is no physical protection of soil and this increases susceptibility to further disruption (Six *et al.*, 2000a,b). Improved soil erosion control and greater crop yields under NT with a winter cover crop compared to CT were also reported in long-term studies on Oxisols in Brazil (Derpsch *et al.*, 1991).

In addition, maintenance of plant residues on soil surface provides protection against surface sealing and at the same time increase the water infiltration rate, two factors of utmost importance in the control of water erosion of acid tropical soils (Roth *et al.*, 1986; Glanville and Smith, 1988; Muzilli, 1994; Ruedell, 1994). Due to enhanced rain water infiltration under CA; soil erosion may be reduced to a level below the regeneration rate of the soil (Derpsch, 1997).

Under CA, the 30% threshold for soil cover (Allmaras and Dowdy, 1985) is thought to reduce soil erosion by 80%, but undoubtedly greater soil cover would suppress erosion even further (Erenstein, 2002). Increased soil cover can result in reduced soil erosion rates close to the regeneration rate of the soil or even lower, as reported by Debarba and Amado (1997) for an oats and vetch/maize cropping system. The results of soil loss measurement in 2003 and 2004 in the Jungsan Up farm, Korea showed that mulching with winter wheat or spring barley residues and planting the next crop on the covered soil without plowing reduces soil loss to 14–17% of the loss from the tilled fields (Mousques and Friedrich, 2007). According to them, this improvement is due to the protection from raindrop impact provided by crop residues. Soil erosion control is perhaps the clearest benefit of CA. There is a clear relationship between retention of mulch and reduction of runoff and soil loss by erosion (Lal, 1998; Erenstein, 2002). As erosion rates are greatest under high rainfall intensity, on steep slopes and on more erodible soils, it seems likely that these are precisely the conditions where CA can have the greatest benefits (Lal, 1998; Roose and Barthes, 2001). Organic matter contributes to the stability of soil aggregates and pores through the bonding or adhesion properties of organic materials such as bacterial waste products, organic gels, fungal hyphae and worm secretions and casts, which ultimately enhances water infiltration and retention in the soil (Bot and Benites, 2005b). The fungal hyphae and bacteria slime, even if formed and decay again rapidly, play an important role in connecting soil particles. A strong relationship exists between the soil carbon content and an increase in aggregate size (FAO, 2001). Castro Filho *et al.* (1998) found an increase in soil carbon content under ZT resulting in a 134% increase in aggregates of >2 mm and a 38% decrease in aggregates of <0.25 mm compared to under CT. In an Oxisol from Southern Brazil, after 14 years of cultivation compared with disc plough followed by two light harrowing, the NT system improved the state of soil aggregation, particularly at 0–10 cm depth (Castro Filho *et al.*, 1998). The authors reported that soil aggregation had a tendency to increase when crop rotation included plant species with higher C/N ratio (i.e., maize). Roth *et al.* (1992) looking at the significance of fractions of organic matter for aggregation in an Oxisol, found that aggregate stability was best correlated with humic acid carbon. Capriel *et al.* (1990) also reported high correlation coefficient between the aliphatic hydrophobic component of organic matter and aggregate stability ($r = 0.91$) of a temperate soil. NT increases (SOM) and aggregation, but the aggregate stability seems to be more influenced by the quality of the (SOM) indicating again, that NT combined with adequate cover crops can improve aggregation and aggregate stability.

The mulch used in CA promotes more stable soil aggregates as a result of increased microbial activity and better protection of the soil surface. Higher SOC content in conservation tillage may lead to higher and stable aggregation (Horne *et al.*, 1992; Lal *et al.*, 1994; Karlen *et al.* 1994) because of several mechanisms including (i) fungal dominated microflora (Beare *et al.*, 1993; Beare *et al.*, 1997), (ii) higher earthworm activity (Mousques and Friedrich, 2007), and (iii) formation of platy structure with greater bulk capacity. Carter (1992) found that ZT and residue retention in the long-term can improve soil structure. A well-granulated soil that is somewhat water-stable allows movement of air and water and directly determines the soil's capacity to infiltrate water, which in turn decreases runoff (Blevins *et al.*, 1998). The larger organic matter content in the top layers of zero tilled soils with residue retention promotes aggregate stability and is associated with an increase of the 1−2 mm aggregate fraction (Weill *et al.*, 1989). SOM can increase both soil resistance and resilience to deformation (Kay, 1990; Soane, 1990), decrease soil compactness (Kemper and Derpsch, 1981a,b), and improve soil macro-porosity (Carter, 1990) which ultimately helps in soil conservation.

6.2. Conservation Agriculture and Soil Quality

Studies reveal that CA leads to significant improvement in soil quality over time. A successful adoption of CA for sufficient period of time can improve soil quality and thereby agronomic sustainability (Lal, 2010; Verhulst *et al.*, 2010). Soils under NT are physically and chemically stratified (Muzilli, 1983; Centurion *et al.*, 1985; Eltz *et al.*, 1989), compared to tilled fields. CA studies in both Korea and China have also demonstrated that CA technology plays an important role in rapidly improving the physical, chemical and biological properties of the topsoil (Mousques and Friedrich, 2007). Improvement in soil physical and chemical properties under NT compared to CT was reported by Hargrove *et al.* (1982) also on highly weathered Ultisols in the southeastern United States. Soil microbial population and enzyme activities are greater under no-till and the amount of potentially mineralizable N in the surface of no-till soils averaged 35% greater than in conventional till soils, thereby indicating a greater conservation of N in CA plots (Nurbekov, 2008). Nhamo (2007) also reported that there is more abundance and activity of soil biota under maize-based CA cropping systems than under conventional practice in the sandy soils of Zimbabwe. The increased biological activity creates a stable soil structure through accumulation of organic matter. Hobbs *et al.* (2008) also observed that under CA the soil biota "take over the tillage function and soil nutrient balancing" and that "mechanical tillage disturbs this process". Several workers including Hendrix *et al.* (1986), Lee and Foster (1991); Roth and Joschko (1991), Lavelle *et al.* (1994) and Balota *et al.* (1998) also reported favorable effects of soil fauna on physical properties (e.g., diminution of runoff by earthworm channels and aggregate formation by soil fauna and microorganism interactions). Greater microbial biomass and abundance of earthworms and macro-arthropods (e.g., termites and ants) in soils under NT exert beneficial effects on soil fertility. Protease activity of the soil was found higher in the field with crop residue than in the field without crop residue (Nurbekov, 2008).

The leaves that fall from pigeonpea before harvest provide a mulch and can add as much as 90 kg N ha^{-1} to the soil that then mineralizes relatively slowly during the subsequent season, releasing N for the next maize crop (Adu-Gyamfi *et al.*, 2007; Sakala *et al.*, 2000). Thomas *et al.* (2007) reported significantly higher total N in 0–30 cm soil depth and exchangeable K in 0–10 cm soil depth under no-till compared to conventional till plots. Sisti *et al.* (2004) reported that when C and N stocks were calculated to a depth of 30 cm, it was found that there was no significant difference in the quantity of SOM under ZT and CT in wheat–soybean system, but there was significantly greater C and N stocks in the soil under ZT compared to CT under the other two rotations of wheat/soybean–hairy vetch/maize (2 years) and wheat/soybean–white oat/soybean–vetch/maize (3 years), amounting to differences of 5.3 and 9.1 Mg C ha^{-1} and 0.31 and 1.38 Mg N ha^{-1}, for wheat/soybean–hairy vetch/maize and wheat/soybean–white oat/soybean–vetch/maize, respectively. The reason that C stocks did not increase under ZT compared to CT under the wheat/soybean rotation could be attributed to the fact that for there to be an accumulation of SOM there must be not only C input from crop residues but also a net external input of N. In this case, no extra amount of N was added externally other than the total demand of the crops and N added through biological nitrogen fixation due to soybean was exported out of field in the form of grain. In wheat/soybean–hairy vetch/maize and wheat/soybean–white oat/soybean–vetch/maize rotations the N_2-fixing green-manure crop, vetch, was included and the entire crop was left as residues for the subsequent maize crop which led to increase in C and N stocks in these rotations. It therefore, seems reasonable to conclude that N input through green manuring with vetch is the key to the observed SOM accumulation or conservation under ZT. Green-manure legumes are known to increase C stocks significantly when included in rotation under ZT (Sidiras and Pavan, 1985; Bayer and Bertol, 1999; Amado *et al.*, 1999, 2001; Bayer *et al.*, 2000a,b) Further, Sisti *et al.* (2004) argued that under CT this N input was not apparent either because the BNF input was reduced by soil mineral N released by the disc plowing that preceded this crop (Alves *et al.*, 2002), and/or N from mulch was lost by leaching (NO_3^-) or in gaseous form (*via* NH_3 volatilization or denitrification) again due to SOM mineralization stimulated by tillage.

Calegari and Alexander (1998) reported that after nine years, the phosphorus (P) content (both inorganic and total) of the surface layer (0–5 cm) was higher in the plots with cover crops. Depending on the cover crop, the increase was between 2 and almost 30%. This indicates that different cover crops have an important P-recycling capacity and this was even improved when the residues were retained on the surface. This was especially clear in the fallow plots where the CT plots had a P-content 25% lower than that in the ZT plots.

Mousques and Friedrich (2007) reported that CA practices improved soil pH, organic matter and available nutrient contents in most of the farms compared to CT: organic matter content was raised by an average of 0.2%, the available N was raised by 20–25 mg kg^{-1} soil, available P increased by 10 mg kg^{-1} soil; and in Songmun Farm, available P increased by a maximum of 30–40 mg kg^{-1} due to the use of nutrient-rich cover of maize residue and hairy vetch. This could be the result of increased P mobilization by organic acids resulting from the build-up of SOM; the available potassium (K) content was also improved by 10–15 mg kg^{-1} soil. It was also observed that straw decomposed better and faster in the wheat–paddy field than in the wheat–maize–rape–cotton field. Umar *et al.* (2011) reported that soils from the conventionally farmed plots were more acidic than those under CA. However, Thomas *et al.*, (2007) observed that soil pH in the 0–10, 10–20 and 20–30 cm depths was not affected by tillage and stubble retention treatments. They also observed that at the end of 9 years mean soil pH had not changed significantly in the 0–10 cm depth compared to initial levels, but had increased in the 10–20 and 20–30 cm depths. It is necessary to identify regionally, which crop rotations increase SOM with simultaneous improvement in soil characteristics and plant nutrient supply (Machado and Silva, 2001).

Growing legumes in rotation under CA helps to replace the loss of N through biological fixation of atmospheric N. According to Amado *et al.*, (1998) reduced tillage and addition of N by legumes in the cropping system increases the total N in the soil. They reported that after five years, the 0–17.5 cm soil layer contained 490 kg ha^{-1} more total soil N than in the traditional system of oats–maize under CT. After nine years, the system even resulted in a 24% increase in soil N compared to that under CT (Amado *et al.*, 1998). Inclusion of legumes as cover crops in CA leads to higher soil cation exchange capacity (CEC) due to increased organic matter content. Especially systems with pigeonpeas (*Cajanus* *cajan*) resulted in a 70% increase in CEC compared to a fallow–maize system (FAO, 2001).

Intensive mechanized agriculture has been reported to cause soil compaction in the tropics (Castro Filho *et al.*, 1991; Kayombo and Lal, 1993; Verhulst *et al.*, 2010). Despite difficulties in relating maximum rooting or length density to crop yield, long-term use of disc tillage equipment (e.g., disc plough) can compact the subsurface layer, inhibiting deep rooting of some crop plants and reducing crop productivity (Castro Filho *et al.*, 1991; Fageria *et al.*, 1997). CA has been found to reduce soil compaction due to reduced traffic and application of crop residues. Besides, deep root system of legumes used as cover crops in CA performs biological tillage without affecting delicate structure created by soil life. Crop rotation involving cover crops such as the deep-rooted hairy vetch may promote biological loosening of compact soils, an effect that has been already reported for Brazilian and African soils (Kemper and Derpsch, 1981a,b; Kayombo and Lal, 1993). However, to know the degree to which NT in combination with cover crops can reduce soil compaction and affect soil flora and fauna, there is need to implement well-designed long-term experiments in the SAT regions. Fleige and Baeumer 1974) observed that as in the case of temperate soils, NT systems in the tropics can also show similar results as reported in non-cultivated ecosystems. Compared to the forest soil, 11 years of agriculture on an Oxisol in Passo Fundo, State of Rio Grande do Sul, Brazil led to an increase in the bulk density mainly in 0–20 cm depth (Machado and Silva, 2001). But they also reported that the bulk density of soils cultivated with soybean–wheat/hairy vetch–maize under NT tended to be lower than in the CT. Blevins *et al.* (1983) also reported decrease in bulk density under NT compared to CT. However, Acharya *et al.* (1988) reported that bulk density was lower when crop residue was incorporated compared to when they are retained on the soil surface as mulch.

CA can also be helpful in ameliorating sodicity and salinity in soils (Govaerts *et al.*, 2007c; Hulugalle and Entwistle, 1997; Sayre, 2005; Du Preez *et al.*, 2001; Franzluebbers and Hons, 1996). Compared to CT, values of exchangeable sodium (Na), exchangeable Na percentage and dispersion index were lower in an irrigated Vertisol after nine years of minimum tillage (Hulugalle and Entwistle, 1997). Also, Sayre (2005) reported reduced sodicity and salinity in soil under permanent raised beds with partial or full residue retention compared to under conventionally tilled raised beds. The combination of ZT with sufficient crop residue retention reduces evaporation from the topsoil and salt accumulation (Nurbekov, 2008; Hobbs and Govaerts, 2010). Inclusion of legumes in crop rotations in CA may reduce the pH of alkaline soils due to intense nitrification followed by NO_3^- leaching, H_3O^+ excretion by legume roots, and the export of animal and plant products (Burle *et al.* 1997). No-till system helps in lowering down the pH of surface soil compared to CT, which is mainly ascribed to the fact that in no-till the entire N is placed on the soil surface and the N acidifies the soil. Similar results were also reported by Blevins *et al.* (1983). According to Govaerts *et al.* (2007a) ZT on its own does not induce better soil health, but the combination of ZT with residue retention is essential for desirable benefits in terms of improved soil quality.

Thus, it can be seen from the review that CA has profound effects on soil quality through its positive effects on soil physical, chemical, and biological properties.

6.3. Conservation Agriculture and Carbon Sequestration

Dwindling SOM and consequently declining soil fertility of cultivated lands is a major concern particularly in the tropics and subtropics as this results into lower crop productivity and resource use efficiency. In most tropical and subtropical areas, there is demand for increasing agricultural production, which warrants cultivation on marginal lands (Greenland *et al.*, 1997) but this needs restoration of their fertility first. After evaluating many different long-term experiments all over the world, Reeves (1997) stated that soil organic carbon (SOC) is the most consistently reported soil attribute from long-term studies and is a keystone soil quality indicator, being inextricably linked to other physical, chemical, and biological soil quality indicators, and thus, an indicator of sustainability. Restoring carbon into the soils is important not only for climate change mitigation but also to improve the soil quality for agricultural uses. Calegari *et al.* (2008) opined that patterns of organic carbon decline and nutrient depletion in Oxisols that have been under cultivation for many years calls into the question of sustainability of production on these soils in tropical and subtropical regions. Rates of decline in SOM (SOM) when land is converted from forest or grassland to agriculture is rapid, with up to 50% of the SOM being lost within 10–15 years (Diels *et al.*, 2004; Zingore *et al.*, 2007). Many long-term studies have shown that continuous cropping results in decline of SOC, although the rate is climate and soil dependent, and can be ameliorated by the choice of soil management practices. A common claim by the proponents of CA is that NT with residue mulching will halt this decline and leads to accumulation of SOM. But there is difference of opinion as to whether it is cover crops and residue retention or NT which contribute to SOM increase and if both then, degree to which they contribute. Corbeels *et al.* (2006) observed that although it is often difficult to separate the effects, it appears that reported increases in SOM are mainly due to increased biomass production and retention in CA systems rather than reduced tillage or NT. Similarly, Giller *et al.* (2009) reported that benefits of enhanced SOM and soil fertility with CA are more a function of increased inputs of organic matter as mulch. Readers are referred to more references on this issue (West and Post, 2002; Roldan *et al.,* 2003; Alvear *et al.*, 2005; Riley *et al.*, 2005; Madari *et al.*, 2005; Diekow *et al.*, 2005; Metay *et al.*, 2006).

However, a comparative analysis of soil organic content under ZT and CT from different medium to long-term studies revealed that ZT recorded higher organic carbon content ranging from 3.86—31.0% compared to CT (Fig. 1). Analysis also revealed that ZT recorded higher carbon content over CT when practiced for longer period of time (Balota *et al.*, 2004; Calegari *et al.*, 2008; Govaerts *et al.*, 2007). However, Machado *et al.* (2001) could record only 3.86 and 5.72% increase in carbon content due to ZT compared to CT even after practicing ZT for 11 and 21 years, respectively. Castro Filho *et al.* (1998) found a 29% increase in SOC in NT compared to CT in the surface 0—10 cm soil layer, irrespective of the cropping system. Nurbekov (2008) reported significantly higher SOM in 0—10 cm soil depth under no-till system, but it was lower in the 10—15 cm depth compared to conventional system in Uzbekistan. This is caused by differentiation of soil fertility under CA when soil is not turned up. However, some studies; as shown in Fig. 3; have reported increase in carbon content due to ZT even up to depth of 40 cm compared to CT (Acharya *et al.*, 1998; Aziz, 2008; Balota *et al.*, 2004). Machado and Silva (2001) reported that the distribution pattern of organic carbon under NT in an Oxisol from Passo Fundo, State of Rio Grande do Sul, Brazil was closer to the adjacent secondary forest than in conventionally tilled soils.

Some other studies indicate that crop rotations also play important role in deciding improvement in SOM due to CA. Some reports from Brazil indicated that where no legume was included in the rotation (Muzilli, 1983) or the only legume in the system was soybean [Glycine max (L.) Merr.] (Machado and Silva, 2001; Freixo *et al.*, 2002), no difference in SOC was found between NT and CT. However, when a legume cover crop was included in the rotation, SOC under NT was significantly higher than under CT (Sidiras and Pavan, 1985; Bayer *et al.*, 2000a, 2000b; Calegari *et al.*, 2008). Amado *et al.* (2005) also reported that more carbon can be stored by adding leguminous cover crops to the rotation cycle in CA. Besides addition of C to the soil, legumes add a substantial quantity of N to the soil, which results in increased biomass production of the succeeding crops.

The results from long-term experiments have shown a high potential for carbon sequestration with NT management coupled with the use of cover crops and crop rotations (Bolliger *et al.*, 2006). Systems based on high crop residue addition and NT tends to accumulate more carbon

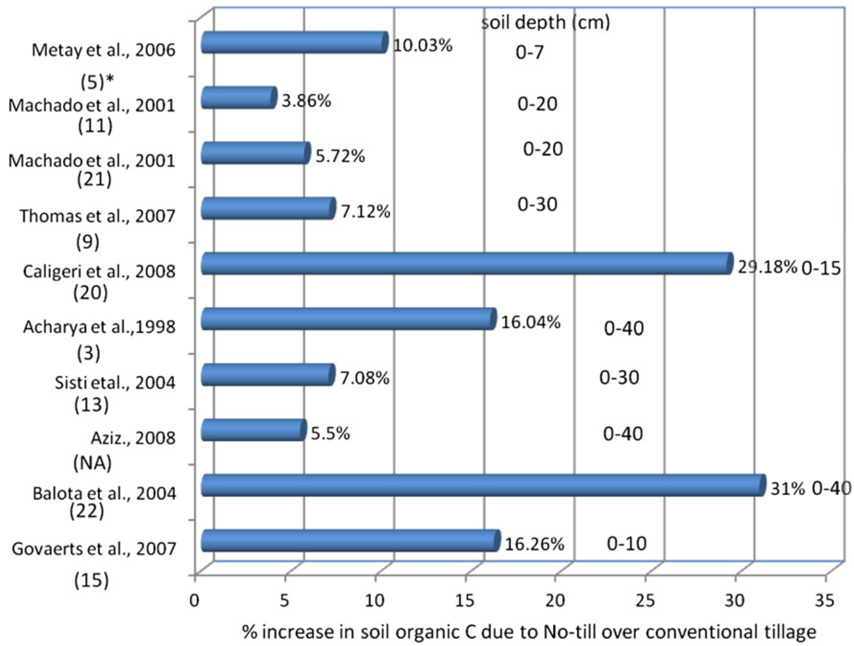

Figure 3 Differences in soil organic carbon content (%) due to adoption of zero-tillage over conventional tillage. * The values in parenthesis are the number of years study was conducted. (Source: figure drawn from data from published literature). For color version of this figure, the reader is referred to the online version of this book.

in the soil than is released into the atmosphere (Greenland and Adams, 1992). West and Post (2002) concluded that soil carbon sequestration was generally increased by NT management, but had a delayed response, with significant increases in 5 through 10 years. Havlin (1990) observed that high amount of crop residues in combination with NT increased SOC, while SOC declined with low residue-producing crops like soybean in combination with moldboard plowing (Edwards *et al.*, 1992). Calegari *et al.* (2008) reported that the NT treatment with winter cover crops resulted in the greatest SOC content, most closely mimicking the effect provided by native undisturbed forest. Another attribute related to greater SOC resulting from NT management and winter cover crops is greater N availability. N input from legume cover crops is important to nutrient cycling and SOC accumulation under both NT and CT systems. Lal *et al.* (1998) citing results reported by Franzluebbers and Arshad (1996a, 1996b) observed that there may be little to no increase in SOC in the first 2–5 years after a change in management practice, but it will be followed by a larger increase in the next 5–10 years. Campbell *et al.* (2000) found that measurable gain in SOC could be observed in 6 years or less when weather conditions were favorable. Ghosh *et al.* (2010) reported around 71% increase in SOC due to double no-till over the CT at the end of four cropping cycles from North-East India.

Under dryland conditions on the sandy soils of West-Africa, simulation model predictions using the CENTURY and RothC models suggest that conversion to NT will result in small increases in soil C contents ($0.1-0.2\ t\ ha^{-1}\ yr^{-1}$) (Farage *et al.*, 2007). Chivenge *et al.* (2007) demonstrated that reduced tillage is only likely to have a strong positive effect on SOM in finer-textured soils. This is due to the lack of physical and structural protection of SOM in sandy soils in which the organic matter contents depend strongly on amounts of crop residue added regularly to the soil. Thus, the effect of NT is likely to be larger on heavier-textured soils that have a larger equilibrium content of SOM for a given C input (Feller and Beare, 1997). A recent meta-analysis of soil C storage under CA drawing largely on experience from North America revealed that C contents were increased by CA compared with CT in roughly half of the cases, CA showed no change in 40%, and a reduction in soil carbon in 10% of the experiments (Govaerts *et al.*, 2009a,b). For some soils, especially those with coarse texture and in arid climate, conversion to CA when soil has been under cultivation for a long time may, however, have little effect on SOC content (Powlson and Jenkinson, 1981; Haynes and Knight, 1989; Zingore *et al.*, 2005; Chivenge *et al.*, 2006). In coarse-textured soils, significant carbon sequestration through CA or other biomass-enhancing practices might not be feasible.

CA increases SOM due to reduced rate of decomposition of crop residues and plant roots and the continued accumulation of organic matter in the soil by fauna and flora. As the level of SOC is a function of the quantity of crop residues, plant roots, and other organic material returned to the soil, and the rate of their decomposition (Lal *et al.*, 1998), it seems that carbon sequestration and soil conservation can be combined if satisfactory and sustainable crop production is the intention. A principal mechanism of C sequestration in soil is through the formation of stable micro-aggregates (Skjemstad *et al.*, 1990; Lal, 1997; Six *et al.*, 2000a,b). As conversion to CA may increase micro-aggregation and aggregate stability (Elliott, 1986; Haynes and Swift, 1990; Haynes *et al.*, 1991; Lal *et al.*, 1994), therefore, higher C sequestration under CA is probable. Bayer (1996) found a smaller effect of soil management system on SOC in clayey Oxisols, compared to that in Red-Dark Podzolic and Red–Yellow Podzolic soils (Alfisols and Ultisols). He rationalized the effect due to physical stabilization of organic matter in micro-aggregates (structural stability), through stable combination of organic matter with mineral surfaces by "coordination junction" (colloidal stability). Duxbury *et al.* (1989) reported that the stability of micro-aggregates is not affected by plowing.

A review of 67 long-term experiments that included 276 paired treatments indicated that a change from CT to NT can sequester $57 \pm^{-} 14$ g C m^2 yr^{-1} (West and Post, 2002). According to Amado *et al.* (2001) the maize/Mucuna system showed a positive balance of almost 20 t CO_2 ha^{-1} compared to fallow/maize. These results confirm the potential of CA for carbon sequestration. However, the "simple" change from CT to ZT is not enough. According to Lovato *et al.* (2004), a minimum addition of 4.2 t ha^{-1} yr^{-1} of carbon through vegetative residues in cropping systems and 4.5 t ha^{-1} yr^{-1} in mixed systems of pastures and crops (Nicoloso *et al.*, 2005) is necessary for maintaining SOM at stable higher levels. It means below these values CO_2 emission will or can take place and thus, for promoting CA as an effective tool for carbon sequestration, it is necessary to include crops and cover crops in the rotation that add large quantities of biomass.

Carbon sequestration in managed soils occurs when there is a net removal of atmospheric CO_2 because C inputs (crop residues, litter, etc.,) exceed C outputs (harvested materials, soil respiration, C emissions from fuel and the manufacture of fertilizers, etc.,) (Izaurralde and Cerri, 2002). For a positive change in SOC to take place, there must be either increased organic matter inputs to the soil, decreased decomposition/oxidation of SOM, or a combination of the two factors (Paustian *et al.*, 2000; Follet, 2001). As in case of CA residues are retained on soil surface rather than mixing into the soil as under CT, the organic materials decompose slowly, and thus, CO_2 emission into the atmosphere is also slow. Thus in the total balance, net fixation or sequestration of C takes place; the soil becomes a net sink of C (Bot and Benites, 2005b).

Additionally, for tropical soils with a predominance of kaolinitic clay and high amounts of Fe and Al, some results show that highly aggregated soil with these characteristics have contributed to organic matter protection and reduction in SOC loss (Bayer, 1996). Assuming an average carbon accumulation of 0.5 t $ha^{-1}yr^{-1}$, an area like southern Brazil (Rio Grande do Sul, Santa Catarina and Paraná) under CA would have the potential to sequester 5 million t of C annually, which corresponds to 18 million t of atmospheric CO_2 (Bot and Benites, 2005b).

Considering only the upper 10 cm of soil depth, NT sequestered 64.6% more organic carbon than the system under CT (Calegari *et al.*, 2008). These data are similar to those reported by Sá *et al.* (2001). Conversely, below this layer (10–20 cm) the CT system stored more organic carbon (23.6% higher than NT). However, the comparison at 20–40 cm soil depth showed no difference between the soil management systems. Considering the surface 40 cm of soil, the NT system sequestered only 6.7 Mg C ha^{-1} higher compared to CT. The rates of C sequestration were 1.24 and 0.96 Mg ha^{-1} yr^{-1} to NT and CT systems, respectively (Calegari *et al.*, 2008). These results are similar to those reported by

Roscoe and Buurman (2003) who, even after 30 years of cultivation, found no differences in SOC levels between NT and CT in a Dark Red Latosol (TypicHaplustox) in the Cerrado area of Minas Gerais State, Brazil. They attributed this lack of difference to the high clay contents and Fe + Al oxi-hydroxides concentration and physicochemical protection of organic C under CT. Working in the tropical central savanna region of Brazil, Centurion *et al.* (1985) and Corazza *et al.* (1999) found higher soil C stocks under NT than under CT in the surface 0–20 and 0–30 cm soil layers, but when the evaluation was extended to 100 cm soil depth, these differences disappeared due to lower C content in the 30–100 cm layer under NT. Kern and Johnson (1993) from the analysis of results from 17 experiments, concluded that a change from CT to NT sequesters the greatest amount of C in the top 8 cm of soil, a lesser amount in the 8- to 15-cm depth, and no significant amount below 15 cm. In some cases, mixing and soil turnover by plowing may enhance formation of organo-mineral complexes and aggregation as was observed in soils of the semi-arid regions of the West African Sahel (Charreau and Nicou, 1971), and consequently more C sequestration compared to that under CA. Tan *et al.* (2007) were of the view that the response of SOC to tillage practices depends significantly on baseline SOC levels, the conversion of CT to NT had less influence on SOC stocks in soils having lower baseline SOC levels but had higher potential to mitigate C release from soils having higher baseline SOC levels.

6.4. Conservation Agriculture and Crop Productivity

Review of the available literature on CA provides mixed indications of the effects of CA on crop productivity. While some studies claim that CA results in higher and more stable crop yields (African Conservation Tillage Network, 2011), on the other hand there are also numerous examples of no yield benefits and even yield reductions particularly during the initial years of CA adoption. Short-term yield effects have been found to be variable (positive, neutral, or negative yield response) (Lal, 1986; Mbagwu, 1990; Gill and Aulakh, 1990; Lumpkin and Sayre, 2009). CA has been reported to enhance yield level of crops due to associated effects like prevention of soil degradation, improved soil fertility, improved soil moisture regime (due to increased rain water infiltration, water holding capacity and reduced evaporation loss) and crop rotational benefits. Baudron *et al.* (2009) noted that benefits of CA at a plot level are encouraging, often increased yield obtained as a result of enhanced water and nutrient use efficiency. Even though the short-term yield effect of CA is variable over space and time, productive benefits accumulate over time as mulching arrests soil degradation and gradually improves the soil in physical, chemical and biological terms (Erenstein, 2002). Under conditions where moisture is limiting, improved rainwater use efficiency through improved infiltration and reduced water loss by evaporation under CA may improve crop yields in the short-term (Lal, 1986; Vogel, 1993), although the full yield benefits of improved water availability are not realized unless nutrient deficiencies, common in the soils of the semi-arid, are also addressed (Rockström and Barron, 2007; Rusinamhodzi *et al.*, 2011). Calegari *et al.* (2008) reported that the mean annual seed yield of soybean in a nine- year study were 2.54 and 2.41 Mg ha^{-1}, respectively for NT and CT. They also reported that annual corn grain yields over eight seasons were 5.82 and 5.48 Mg ha^{-1}, respectively for NT and CT. Lal (1991) reported from two eight years or longer studies that larger maize grain yields were maintained with a mulch-based NT system than in a plow-based system. Gupta *et al.* (2010) reported that wheat grain yields were 5393, 5056 and 4537 kg ha^{-1} under zero-till with residue retention, zero-till without residue and CT with rotavator broadcast, respectively.

CA practices were widely adopted during the 1990s in the commercial farming sector in Zimbabwe, and a meta-analysis of maize (*Zea mays* L.) yields indicated that yields were equal or improved with respect to conventional production systems in 'normal' or dry years, but tended to be depressed during seasons with above-average rainfall (Giller *et al.*, 2009). Grain yields under no-till were generally higher (+19%) in dry years but lower (−7%) in wet years in Northern China as reported by Wang *et al.* (2011). CA-based technologies (zero till seeded maize in rotation with wheat with surface retention of all crops residues) provided consistently superior rainfed maize yields over 10 years, as compared to the normal, tillage-based, farmer practice for maize production in the central highlands of Mexico (Lumpkin and Sayre, 2009).

FAO (2001) reported that CA systems achieve yield levels as high as conventional agricultural systems but with less fluctuations due, for example, to natural disasters such as drought, storms, floods, and landslides. When crops are grown in a rotation which is one of the underlying principle of CA, they usually do better than when the same crop is grown in the same field year after year. The rotational soil fertility benefits of grain legumes to subsequent crops can be substantial, giving double the yield of subsequent cereal crops in some cases (Martin and Touchton, 1983; Kasasa *et al.*, 1999; Giller, 2001). One approach that has proved to be inherently attractive to farmers and is standard practice in much of southern Malawi is intercropping maize with the grain legume pigeonpea (*Cajanus cajan* (L.) Millsp.) (Giller *et al.*, 2009). If pigeonpea is sown between planting stations on maize rows, the plant population and yield of maize can be maintained, whilst reaping the advantage of yield from the pigeonpea harvest (Sakala, 1998). Higher yields of wheat and maize (Govaerts *et al.*, 2005) are the result of an increase in soil quality, especially in the topsoil under CA (Govaerts *et al.*, 2006). Better and stable yields under CA occur due to timely planting or buffering of moisture stress, improved soil physical and biological properties, improved water infiltration, less soil and wind erosion, and a potential for biological control and less incidence of disease and pest disease (Hobbs and Govaerts, 2010). Acharya *et al.* (1998) observed that minimum tillage in combination with mulching significantly increased rooting density and grain yield of wheat as compared to that in CT and no-mulching (farmers' practice).

With the cropping period in most semi-arid regions being relatively short, the timing of field operations is critical (Twomlow *et al.*, 2006). Moreover, shortage of animal traction may severely limit the land area that can be plowed within the short window at the start of the growing season when the first rains fall and the soil is wet enough to be tilled. This can lead to strong delays in the time of planting which results in strong yield penalties (Tittonell *et al.*, 2007a). Thus, CA can provide a major benefit by, removing the need for tillage and allowing a larger proportion of the land to be cropped. Yields in the rice—wheat (RW) systems of the IGP in South Asia are higher with no-till because of timelier planting and better stands. Yield increases as high as 200—500 kg ha^{-1} are found with no-till wheat compared to conventional wheat under rice—wheat system in IGP (Hobbs and Gupta, 2004). Similarly, because majority of African farmers do not have direct access to animal or motorized traction, seedbeds are often prepared too late, the cropping season shortened, and crop yields reduced (Ellis-Jones and Mudhara, 1997). Therefore, NT can help farmers to ensure early, on time sowing. Nurbekov (2008) argues that lower evaporation loss of soil moisture and consequently lower salt accumulation in surface layers as the main reasons for higher yield of wheat under no-till system in Uzbekistan. This is explained as the evaporative loss of water from no-till plots was lower than that from conventional till plots as a result accumulation of salts in root zone decreased, facilitating proliferation of roots, which in turn led to greater yields. In the long run, no-till practice with retention of crop residues helps in lowering down the salinity levels due to combined effects of reduced evaporation and recycling of organic matter. Increased SOM levels improve the water holding capacity and enable plants to get through extended drought periods.

Presence of crop residues on soil surface can help in better germination and emergence of seedlings in light-textured soils where formation of surface crusts and seals due to breakdown of soil macro-aggregates are the major constraints to crop productivity (LeBissonnais, 1996; Lal and Shukla, 2004).

Bot and Benites (2005a) discussed the effect of high temperature on plant growth and development and how CA can be helpful in mitigating the adverse effects of high temperature on plants. According to them, soil temperature adversely influences the absorption of water and nutrients by plants, seed germination and root development, as well as soil microbial activity and crusting and hardening of the soil. High soil temperature is a major constraint to crop production in much of the tropics. Maximum temperature exceeding 40 °C at 5 cm soil depth and 50 °C at 1 cm soil depth are commonly observed in tilled soil during the growing season, sometimes with extremes of up to 70 °C. Bot and Benites (2005a) further argue that such high temperatures have an adverse effect not only on seedling establishment and crop growth, but also on the growth and development of the microbial population. Experiments have shown that temperature exceeding 35 °C reduce the development of maize seedlings drastically and that temperature exceeding 40 °C can reduce germination of soybean seed to almost nil. Mulching with crop residues or cover crops regulates soil temperature. The soil cover reflects a large part of solar energy back to the atmosphere, and thus, reduces the temperature of the soil surface, resulting in a lower maximum soil temperature in mulched compared with un-mulched soil with reduced fluctuation in temperature. The higher residue accumulation in zero till fields leads to lower soil temperature compared to that in conventionally tilled fields (Fabrizzi *et al.*, 2005).

Giller *et al.* (2009) concluded that although the introduction of CA can result in yield benefits in the long-term, in the short-term (and this may be up to nearly 10 years) yield loss or no yield benefits are just as likely. Mashingaidze *et al.* (2009) observed no significant differences in both maize and sorghum yield due to residue retention in hoe- based minimum tillage systems in semi-arid Zimbabwe during the initial two years.

6.5. Conservation Agriculture and Nutrient Use Efficiency

CA helps to improve nutrient use efficiency as it reduces soil erosion thereby preventing nutrient loss from the field. Nutrient loss may be minimized in CA due to reduced runoff and through appropriate use of deep-rooting cover crops that recycle nutrients leached from the topsoil (FAO, 2001). It leads to greater availability of both native and applied nutrients to the crops. CA resulted in improved fertilizer use efficiency (10−15%) in the rice-wheat system, mainly as a result of better placement of fertilizer with the seed drill as opposed to broadcasting with the traditional system (Hobbs and Gupta, 2004). In some reports, lower

N fertilizer efficiency was recorded as a result of microorganisms tying up the mineral N (immobilization) in the crop residues. However, in other longer-term experiments, release of nutrients increased with time because of microbial activity and nutrient recycling (Carpenter-Boggs *et al.*, 2003). Increased aggregation and SOM at the soil surface led to increased nutrient as well as water use efficiency (Franzluebbers, 2002). Phosphorus efficiency and availability to plants can be improved if crop residues are added to soils (Iyamuremye and Dick, 1996 and Sanchez *et al.*, 1997) and this effect can be boosted if combined with NT (Sidiras and Pavan, 1985; De Maria and Castro, 1993; Selles *et al.*, 1997). But there is need for generating information on the effects of different plants utilized as cover crops combined with tillage systems on N mineralization and release and P sorption as there are limited experimental results on these aspects. According to Fontes *et al.* (1992), adsorption sites of goethite can be blocked by organic matter fractions such as humic acids, reducing P sorption. Compounds of low molecular weight such as oxalate and malate can also have similar effects in blocking the P-sorption sites, but these effects are only transient (Afif *et al.*, 1995; Bhatti *et al.*, 1998). Compared to low-molecular weight organic acids, humic substances can be more efficient because of their higher stability and persistence in agricultural soils. As pointed out by Iyamuremye and Dick (1996), despite considerable evidence on the positive effects of organic amendments on the decrease in P sorption by soils, there is very little field-based research to determine whether the results from more basic studies under controlled conditions are applicable to field conditions. Inclusion of legumes in CA leads greater to nutrient availability to plants. Burle *et al.* (1997) reported highest levels of exchangeable K, calcium (Ca), and magnesium (Mg) in systems with pigeonpea and lablab (*Dolichos lablab*) and lowest in systems containing clover. Similarly, Govaerts *et al.* (2007c) observed higher C, N K, and lower sodium (Na) concentration with residue retention compared to residue removal in a rainfed permanent raised bed planting system in the subtropical highlands of Mexico.

However, increased infiltration may translate into increased deep drainage and increased leaching of mobile nutrients, which may counterbalance advantages of retaining them *in situ* (Erenstein, 2003; Scopel *et al.*, 2004), though "by-pass flow" may occur so that most applied N is retained in the topsoil and N leaching is limited (e.g., in south-western Kenya, Smaling and Bouma, 1992).

6.6. Conservation Agriculture and Rain Water Use Efficiency

CA has been found to retain and store more rain water compared to conventional agriculture and therefore is helpful to get higher yield in the SAT where plants face water stress during most of their life cycle. Experimental results show that runoff decreases exponentially with the proportion of soil surface effectively covered by residues, a 30% cover of soil surface usually implying a reduction of runoff by >50% (Findeling *et al.*, 2003; Scopel *et al.*, 2004). CA has been found to positively affect the water balance of soils by improving rain water infiltration (Calegari *et al.*, 1998; Avila-Garcia, 1999; Govaerts *et al.,* 2007b; Shaxson *et al.*, 2008), water holding capacity (Hudson, 1994; Acharya *et al.*, 1998; Govaerts *et al.,* 2007b; Mousques and Friedrich, 2007; Nurbekov, 2008; Govaerts *et al.*, 2009b), and reducing evaporative loss (Scopel *et al.*, 2004). Infiltration of water is generally higher in ZT with residue retention compared with ZT with residue removal (Hobbs and Govaerts, 2010). Govaerts *et al.* (2009b) reported that ZT with residue retention had higher soil moisture content compared to the other treatments, especially in the dry mid-season period, i.e., 65–85 days after sowing of maize and wheat, albeit to lesser extent in wheat. Wheat stubble had higher time-to-pond (direct surface infiltration) compared to plots with maize. These results are similar to those reported by McGarry *et al.* (2000) who obtained higher time-to-ponds both under low as well as high-energy rainfall in ZT with residue compared to CT. Similarly, Roth *et al.* (1988) reported that soil with 100% soil cover facilitated complete infiltration of a 60-mm rainfall, whereas only 20% of rain infiltrated when the soil was bare. In the short run, residue heaps act as a succession of barriers giving the water more time to infiltrate, while in the long run (>5 years) it leads to average infiltration rates up to 10 times higher than in CT through impeding crust formation (Scopel and Findeling, 2001). These authors also reported that residue intercepts rainfall and releases it more slowly afterwards, which helps to maintain higher moisture level in soil, leading to extended water supply for plants. Blevins *et al.* (1983) reported greater saturated hydraulic conductivity in no-tilled soils attributed to better porosity and increased earthworm activity compared to under CT. Changrong *et al.* (2009) reported from China, one to more than 20% increase in water availability in dryland fields due to zero or reduced tillage with residue retention. Dixit *et al.* (2003) reported 22.8% higher moisture content in 0–50 cm soil depth in NT compared to that in CT from a study made in Haryana, India.

Thierfelder and Wall (2009) reported higher rain-water infiltration and soil moisture content in CA plots than in the plowed plots. They found infiltration three to five times in CA compared to plowed plots. The greater numbers of worms, termites, ants, and millipedes combined with a higher density of plant roots result in more large pores, which in turn increase water infiltration in CA plots (Roth, 1985). In an experiment in southern Brazil, rainwater infiltration increased from 20 mm h^{-1} under CT to 45 mm h^{-1} under NT (Calegari *et al.*, 1998). Soil moisture storage and availability is also improved by both soil cover (less evaporation, more infiltration) and SOM (FAO, 2001). Infiltration rates under well-managed CA are much higher over extended periods than in traditional agriculture due to better soil porosity (Shaxson *et al.*, 2008). In Brazil, a six-fold difference was measured between infiltration rates under CA (120 mm h^{-1}) and traditional agriculture (20 mm h^{-1}) (FAO, 2008a). CA thus, provides a means to maximize effective rainfall and recharge of groundwater as well as reduces risks of floods due to improved water infiltration. In CA plots most or all of rainfall is harnessed as effective rainfall, with no runoff and no soil erosion, leading to longer and reliable moisture regime for crop growth, and improved drought proofing (Shaxson *et al.*, 2008).

The residues maintained on the soil surface reduce the loss of stored soil moisture through evaporation, besides increased infiltration. In the SAT regions, mulching has been shown to be effective in reducing the risk of crop failure at field level due to better capture and use of rainfall (Kronen, 1994; Scopel *et al.*, 2004; Bationo *et al.*, 2007). Nurbekov (2008) reported an increase of 28% in moisture content in surface (0−10 cm) soil with residue maintenance on surface compared to without residues.

Mousques and Friedrich (2007) reported that CA improved soil moisture in Korea and China. In Korea, soil moisture analysis of soil samples taken in 2003, 2004 and 2005 showed that the soil moisture content of fields under CA practice was higher than in fields with CT. In 2005, straw mulching increased the soil moisture by 10−20% at different soil depths. This can be explained by the greater water infiltration and the reduced evaporation from the soil surface because of the soil cover. NT and mulching allowed a better soil porosity and biological activity, with soil organisms creating macro-pores enabling water to penetrate deeper into the soil (Mousques and Friedrich, 2007; Hobbs *et al.*, 2008), allowing efficient water harvesting and moisture availability in the soil profile for crop growth. In China, the CA fields contained more soil moisture than the traditional fields 15 days after the rains, and the difference was significant to 0.5 m soil depth (Mousques and Friedrich, 2007). Water-use efficiency increased in the no-till wheat following rice because often the first irrigation could be dispensed with, and when the first irrigation was given the water moved faster across the field (Hobbs, 2007). Systems using no-till and permanent ground cover showed reduced water runoff (Freebairn and Boughton, 1985), better water infiltration (Fabrizzi *et al.* 2005), and more water in the soil profile throughout the growing period (Kemper and Derpsch, 1981a). The biological activity combined with the previous crop's root channels results in interconnected soil pores that lead to improved water infiltration (Kay and VandenBygaart, 2002). The improved pore space is a consequence of the bio-turbating activity of earthworms and other macro-organisms and channels left in the soil by decayed plant roots (Bot and Benites, 2005b). No tilled soils with surface cover mulch had higher surface water content than conventional tilled fields because mulch acts as a porous media developing a top soil structure with worm channels, macro-pores, and plant root holes, producing higher infiltration rates (Mielke *et al.*, 1986; Zachmann and Linden, 1989; Rao *et al.*, 1998; McGarry *et al.*, 2000). Water infiltrates easily in CA plots, similar to that observed forest soils (Machado, 1976). The consequence of increased water infiltration combined with a higher organic matter content, is increased storage of water in the soil profile (Gassen and Gassen, 1996). Moreover, organic matter intimately mixed with mineral soil materials has a considerable influence in increasing moisture holding capacity, especially in the topsoil, where the organic matter content is greater and more water can be stored. Bot and Benites (2005b) observed that conserving fallow vegetation as a cover on the soil surface, and thus reducing evaporation, results in 4% more water in the soil. This is roughly equivalent to 8 mm of additional rainfall. This amount of extra water can make the difference between wilting and survival of a crop during temporary dry periods. Hudson (1994) showed that for each 1% increase in SOM, the available water holding capacity in the soil increased by 3.7%. Blevins *et al.* (1971) reported that short periods of drought stress occurred in crops growing on plowed soils, whereas no drought occurred in ZT with residue retention. Therefore, ZT with residue retention decreases the frequency and intensity of short mid-season droughts (Bradford and Peterson, 2000). CA may improve the water budget at field level and reduce drought-spell related risk of crop failure, therefore creating or reinforcing the rationale to invest in external inputs (Rockström *et al.*, 2002).

Different studies on the implementation of various components of the CA have reported beneficial effects with respect to improved rain water use efficiency which underlines the need to evaluate the effect of different components on rain water use efficiency as also stressed by Giller *et al.* (2009). Across a set of experiments in semi-arid and dry sub-humid locations in east and southern Africa, Rockström *et al.* (2008) demonstrated that minimum-tillage practices increased water productivity and crop yields, even when little or no mulch through crop residues was achieved. Instead, the yield improvements were attributed to the water-harvesting effects of minimum- tillage practices and improved fertilizer use from concentrated application along the ripped and sub-soiled planting lines. ZT practices have proven effective in helping to increase plant available water under drought and to improve crop water use efficiency (Bradford and Peterson, 2000). However, other studies revealed that maintenance of crop residues on the soil surface can be an effective mean for improving plant available water (Laddha and Totawat, 1997; Arshad *et al.*, 1999 and Biamah *et al.*, 1993). According to Ruedell (1994) the proportion of rainwater that infiltrates into the soil depends on the amount of soil cover provided. On bare soils (cover = 0 t ha^{-1}), runoff and soil erosion is greater than when the soil is protected with mulch. Crop residues left on the soil surface lead to improved soil aggregation and porosity, and an increase in the number of macro-pores, and thus to greater infiltration rates. Increased levels of organic matter and associated soil fauna lead to greater pore space with the immediate result that water infiltrates more readily and can be held in the soil (Roth, 1985). The residue left on the topsoil acts as a barrier, reducing the runoff velocity and giving the water more time to infiltrate; the residue intercepts rainfall, absorbs its energy and releases it more slowly for infiltration into the soil. Unger (1978) showed that high wheat-residue levels resulted in increased storage of fallow precipitation, which subsequently produced higher sorghum grain yields. High residue levels of 8–12 t ha^{-1} resulted in about 80–90 mm more stored soil water at planting and about 2 t ha^{-1} more of sorghum grain yield compared to no residue management. In the rainfed trial, soil moisture content in the top 60 cm of the zero till plots was lower when residue was removed compared to when residue was retained (Verhulst *et al.*, 2009).

6.7. Conservation Agriculture and Other Input Use Efficiency

The adoption of CA not only helps in improving the soil quality and higher nutrient and rain water use efficiency, but also in the long run provides a range of benefits to the farmers through less demand for chemical fertilizers, fuel, labor and probably pesticides (Machado and Silva, 2001; Sangar, 2004; Mariki and Owenya, 2007). The long-term experience with CA shows that in commercial farming, the need for operations and purchased farm inputs decreases as the understanding of the system grows with the management capacity of the farmer (Derpsch, 1997). The benefits of CA include reduction of the amount and costs of labor and energy required for land preparation, and sowing due to the fact that the soil becomes soft and easy to work. Sowing directly into the soil without any prior tillage operations implies less labor requirement under CA. In fact, the reduction in cost and time required are usually the most compelling reasons for farmers to adopt conservation tillage (FAO, 2001). Farmers see NT systems as a less laborious and less risky procedure enabling fuel and machinery saving and cost reduction (Machado and Silva, 2001). Rotations can also spread labor needs more evenly during the year. Not tilling the soil and planting directly into a mulch of crop residues can reduce labor requirements at a critical time in the agricultural calendar, particularly in mechanized systems when a direct-seeding machine is used (Giller *et al.*, 2009). Conservation tillage reduces the energy (for example fuel for machines and calories for humans and animals) and time required. A large-scale trial at the IITA (International Institute of Tropical Agriculture) in Nigeria found that ZT required 52 MJ energy and 2.3 h labor ha compared to 235 MJ and 5.4 h on CT (Wijewardene, 1979). Mousques and Friedrich (2007) reported that in DPRK (Democratic People Republic of Korea); CA practices allowed input savings of 30–50%. An average of 15.5 kg fuel ha^{-1} was saved by following the CA system, and the labor hours ha^{-1} were reduced to half to one-third. They also found that in China, CA technologies such as direct seeding without tillage and inter-planting reduced inputs requirement and increased farmers' net income.

The soil cover also inhibits the germination of many weed seeds, minimizing weed competition with the crop FAO (2001), which reduces the number of weeding operations required. Weeding accounts for more than 60% of the time a farmer spends on the land. In the first few years, however, herbicide may still need to be applied, making a location-specific knowledge of weeds and herbicide application important. Use of pre- and post-plant herbicides in no till in Ghana required only 15% of the time required for seedbed preparation and weed control with a hand-hoe, while the reduction in labor days required in rice in Senegal was 53–60% (Findlay and Hutchinson, 1999). According to FAO for mechanized farms, CA reduces fuel requirements by 70% and the need for machinery by 50%.

However, Giller *et al.* (2009) concluded that in the short-term and without the use of herbicides, which will be the case for most smallholder farmers, CA is unlikely to result in significant net savings in total labor requirements. At the same time, CA may result in a transfer of the labor burden from men, traditionally in charge of land preparation, to women, traditionally in charge of weeding, whilst changes in total labor demand may be small (Baudron *et al.*, 2007). In the long-term and with the use of herbicides net savings appear to be possible. However, Mashingaidze *et al.* (2009) reported that in both maize and sorghum retaining the available crop residue (at a rate of 2.5 t ha^{-1} or less) did not result in significant weed suppression.

6.8. Conservation Agriculture and Inset-Pest, Disease and Weed Dynamics

The studies on insect-pest dynamics under CA have produced varying results. Generally as tillage is reduced, the number of insect pests increases

(Musick and Beasely, 1978). However, reduced tillage also tends to increase diversity of predators and parasites of crop damaging insects (Stinner and House, 1990). Similarly, under CA crop rotations can help break insect-pest (disease and weed also) cycles. Consequently, the switch from conventional agriculture to CA often has no net effect on insect damage in the long run, but during initial years of CA there may be greater crop loss due to insect-pests when the predators/parasites are not sufficient in number. A diversified double-cropping system in CA is an effective way to tackle the problems of insect-pests including diseases and weeds and herbicide resistance (Mousques and Friedrich, 2007). The minimal soil disturbance and soil cover will protect the biological component of the soil and help with biological tillage, keeping pests and disease under control through biological diversity processes (Hobbs and Govaerts, 2010). Besides, functional and species diversity are increased, creating more possibilities for integrated pest control under CA. According to FAO (2001), pest management can also benefit from conservation practices that enhance biological activity and diversity, and hence competitors and predators, as well as alternative sources of food. For instance, most nematode species (especially the pathogens) can be significantly increased by application of organic matter, which stimulates the action of several species of fungi attacking nematodes and their eggs. For detailed account on how crop residue retention and tillage systems affect insect pests and their management readers are referred to Forcella *et al.* (1994). A review of 45 studies by Stinner and House (1990) showed that 28% of the pest species increased with decreasing tillage, 29% showed no significant influence of tillage and 43% decreased with decreasing tillage.

Similarly, a reduction in tillage influences various pathogens in different ways, depending on their survival strategies and life cycle (Bockus and Shroyer, 1998). Singh *et al.* (2005) reported from Haryana, India that the fungal population in conventional plots was 2.1 × 102 and 4.9 × 102/g dry soil at CRI and dough stages in wheat relative to 1.4 × 102 and 4.6 × 102/g dry soil in ZT plots while in rice it was 12.2 × 102 and 2.2 × 102/g dry soil in conventional and zero till plots at the tillering stage of the crop. Reduced tillage indirectly defines the species composition of the soil microbial community by improving retention of soil moisture and modifying soil temperature (Krupinsky *et al.*, 2002). Crop rotation is crucial to neutralize the tendency under ZT to increase pathogen numbers (Barker and Koenning, 1998). Crop rotations may reduce pathogen carryover from one season to next season. Enhanced surface-soil microbial activity accompanying reduced tillage may create an environment that is more antagonistic to pathogens due to competition (Cook, 1990). The cooler soil temperatures associated with reduced tillage may favor such antagonistic soil microbial population (Knudsen *et al.*, 1995). Species that pass one or more stages of their life cycle in the soil are most directly affected by tillage. Combination of residue retention with ZT could also cause population of beneficial soil micro-flora to increase and compete with the pathogenic microbial community. Residue management indirectly influences the balance of beneficial and detrimental microbial residents in soil (Cook, 1990). The advantage of ZT with residues in the long run is the creation of favorable conditions for the development of predators, by creating a new ecological stability. ZT with residues thus, offers potential for biological control of plant diseases.

Some crop residues reduce pathogen damage to crops. According to Forcella *et al.*, (1994), there may be several mechanisms for this phenomenon: (1) inhibitory chemicals may leach from decomposing residue, (2) stimulatory chemicals leach from residues and promote populations of beneficial microbial control agents, (3) high C: N ratios enhance populations of highly competitive non-pathogenic species in-lieu of non-competitive pathogenic species, and (4) higher soil water contents increase vigor of crops making them less susceptible to diseases. The biomass acts as source of food for microbes including various bacteria, fungi, nematodes, earthworms, and arthropods, which can induce major changes in disease pressure in CA systems (Hobbs and Govaerts, 2010). Pankhurst *et al.* (2002) found that ZT with direct seeding into crop residue increased the build-up of organic C and microbial biomass in the surface soil and intensified its suppression towards two introduced fungal pathogens. General suppression is related to total soil microbial biomass, which competes with pathogens for resources or causes inhibition through more direct antagonism (Weller *et al.*, 2002). Therefore, better disease control can be expected in ZT and CT with residue retention compared to other treatments (Govaerts *et al.*, 2007a). Sturz *et al.* (1997) provided a list of the impacts of minimum tillage on specific crops and their associated pathogens. Crop residue and its subsequent breakdown result in biological and chemical processes that can directly affect a pathogen's viability by restricting nutrients and releasing natural antibiotic substances with various inhibitory properties (Cook, 1990). Cook (2003) reviewed the take-all decline phenomenon in wheat and provided evidence that antibiotics are produced in the soil and play a role in the ecology of soil organisms. However, our level of understanding of the mechanisms involved is still limited (Bailey and Lazarovits, 2003), and the time required for microbial communities to achieve a new balance may sometimes be too long for farmers' economic requirements (Kladivko, 2001; FAO, 2001). However, Govaerts *et al.* (2007b) reported that CA may increase or decrease disease incidence in different crops, for example, in maize, residue retention increased the incidence of root rot, while in wheat, residue decreased the incidence.

According to Mousques and Friedrich (2007), CA controls weeds by a combination of crop rotation, mulching and efficient, but reduced herbicide use if and where needed. They have experienced in DPRK that the weed infestation decreases when CA is used for a longer period. The farmers reported reduced weed pressure after only one year. Positive effect of mulch has been observed in terms of reduced numbers and weight of weeds in maize fields of Jungsan Up Farm since the first year of the project. However, in China no difference in pest or weed incidence was observed in upland crops between the CA and conventional plots (Mousques and Friedrich, 2007). Nurbekov (2008) observed that weed menace may be reduced as weed seed is not incorporated into the soil and seed bank gets exhausted, residues impede weed germination and growth and increased biological activity results in lower weed seed viability. Weed germination under CA is lower, for example in rice-wheat systems (50–60% less) because the soil is less disturbed and less grassy weed (*Phalaris minor*) seeds germinate than in tilled soils (Hobbs, 2007). There is also evidence of allelopathic properties of cereal residues in respect to inhibiting surface weed seed germination (Steinsiek *et al.* 1982; Lodhi and Malik 1987; Jung *et al.*, 2004). Weeds are also controlled when the cover crop is cut, rolled flat, or killed by herbicides. ZT often favors perennial (broadleaf and grass) species compared to CT (Carter *et al.*, 2002) as tillage destroys and prevents these plants from setting seed, but ZT has been reported to successfully control annual broadleaf weeds over time when the right weed control practices are implemented and the seed bank gets depleted by not tilling the soil (Blackshaw *et al.*, 2001). Also, the mulch residue cover can control weeds by excluding light (Ross and Lembi, 1985). In South Asia where ZT wheat is planted after rice, the germination of grassy weed *Phalaris minor* was reduced because of less soil disturbance (Hobbs and Gupta, 2003). Introduction of herbicide tolerant crops such as soybeans, maize, cotton, and canola has helped to reduce the problems of weeds associated with ZT in many countries around the world where CA has significant acreage. Additionally, crop rotation, one of the pillars of CA, leads to diversification of cropping practices and therefore, changes weed populations and species composition, leaving less opportunity for an individual weed to become dominant (Hobbs and Govaerts, 2010). Kennedy (1999) also observed that farming practices that maintain soil microorganisms and microbial activity, which is common in CA, can also lead to weed suppression by biological agents.

However, the net effect of crop residues retained in CA on weed control is somewhat contradictory. In some cases, crop residue retention lessened herbicides efficacy (Erbach and Lovely, 1975; Forcella *et al.*, 1994); in other cases, rainfall washed intercepted herbicides into the soil and efficacy remained high (Johnson *et al.*, 1989); and still in other instances, crop residue suppressed weed seed germination and/or seedling growth and thereby complemented the effects of herbicides (Crutchfield *et al.*, 1986).

In an ongoing experiment on CA at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, we have observed severe weed infestation in CA plots even in third year of the experiment. However, application of pre-emergence herbicides may be helpful in controlling the weeds in CA fields. Rains sometime prove detrimental in application and efficient use of pre-emergence herbicides. Therefore, to make CA a success, particularly in the semi-arid tropics, there is need for post-emergence herbicides for intercropping systems involving crops of different botanical nature (e.g., maize/pigeonpea, sorghum/pigeonpea).

6.9. Conservation Agriculture and Climate Change- Mitigation and Adaptation

CA has the potential to improve adaptation to climate change mainly due to enhanced water balance in CA managed fields and to climate change mitigation through possible C sequestration and reduced emission of CO_2 to the atmosphere (Fig. 4). NT is also seen as an important soil management practice in the context of global climate change as it may increase C sequestration in soil due to improved crop residue management (Batjes and Sombroek, 1997; Lal, 1997). The CO_2 emission from the conventionally managed soils is due to plowing, mixing crop residues and other biomass into the soil surface and burning of biomass (FAO, 2001). Conversely, practices such as reducing tillage intensity, decreasing or eliminating the fallow period, using a winter cover crop, retention of crop residues on soil surface, changing from mono-cropping to rotation, or altering soil inputs to increase primary production (fertilizers, pesticides, irrigation, etc.,), all could contribute to greater organic C storage in the soil (West and Post, 2002). These practices result in increasing SOC to reach new SOM equilibrium (Johnson *et al.*, 1995). Detailed review on carbon sequestration due to CA has been made in this article under 'conservation agriculture and C sequestration'.

6.9.1. Climate change mitigation

Review of available literature suggests that CA can prove as an important climate change mitigation strategy mainly due to greater retention of C in the soil, and less use of fossil fuels thereby leading to reduced CO_2 emission into the atmosphere. For example, farmers practicing rice-wheat

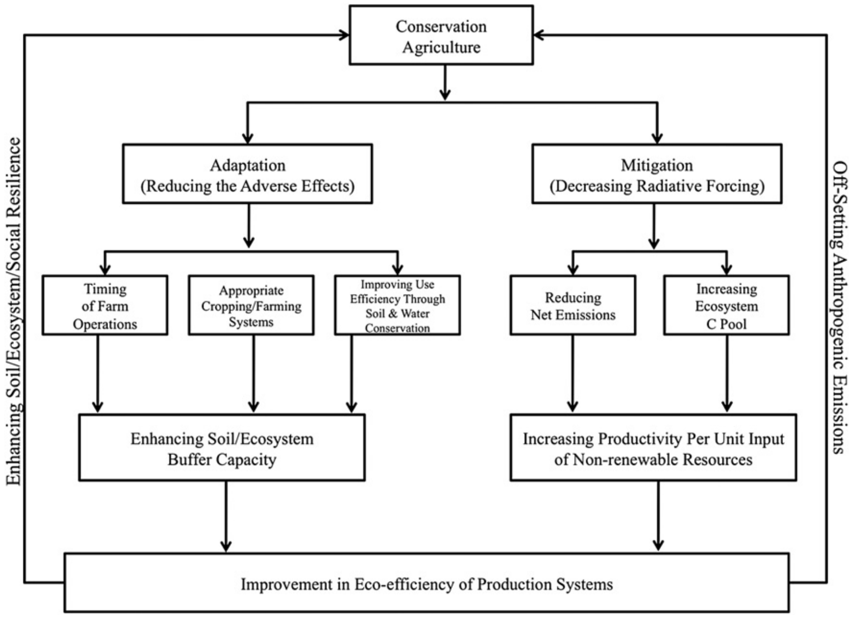

Figure 4 Mitigation and adaptation to climate change and variabilities through CA. (Source: Lal, 2010 with permission of the Author).

system in the IGP tend to burn the crop residue after crop harvest which is a significant source of air pollution; however, CA can help to avoid such environmental pollution as it retains the crop residues on soil surface. Reduced fuel consumption in farming for tillage, water pumping, reduced residue burning, and reduced loss of nutrients especially N under CA practices lead in remarkable reduction in emission of greenhouse gases (GHGs) (Nurbekov, 2008). Further, minimal soil disturbance results in less exposure of SOM to oxidation and hence, lower CO_2 emission to the atmosphere compared to tilled soils (Hobbs and Govaerts, 2010). Due to avoidance of tillage operations under CA, it saves considerable amount of diesel and thus, reduced CO_2 emission, one of the gases responsible for global warming (Robertson *et al.*, 2000; West and Marland, 2002; Wang and Dalal, 2006; Erenstain *et al.*, 2008). Hobbs and Gupta (2004) reported that farmers were able to save 40–60 L diesel fuel per ha in zero till wheat grown after harvesting of puddled rice as farmers can forego the practice of plowing many times to get a good seedbed for wheat. According to a survey of farmers adopting ZT in Haryana (India) and Punjab (Pakistan) during 2003–04 by Erenstain *et al.* (2008), farmers were able to save 35 L diesel for land preparation, or 98 kg C ha^{-1}. One litre diesel contains 0.74 kg C and emits 2.67 kg CO_2 (Environmental Protection Agency, 2009). Lifeng *et al.* (2008) reported that CO_2 flux were 135% and 70% more from soil in plowed field for residue cover and no cover plots respectively, compared to no-till field. Hutsch (1998) suggested that a reduction in tillage intensity could help minimize the adverse effects of cultivation on soil CH_4 uptake. But according to Omonode *et al.* (2007), anaerobic conditions are frequent under ZT and consequently there will be an emission of CH_4. CA applied to rice could be a way to reduce CH_4 emissions since it would eliminate the puddling and encourage more percolation of water through the soil profile and help aerate the soil (Hobbs and Govaerts, 2010). Soils under NT, depending on the management, might also emit less nitrous oxide (Izaurralde *et al.*, 2004).

Patiño-Züñiga *et al.* (2009) observed in a laboratory incubation experiment that the N_2O emission from CT with residue retention was 2.3 times larger compared to NT with residue retention. Jacinthe and Dick (1997) observed that the seasonal N_2O emission from ZT was significantly lower than from CT (chisel tillage) under continuous maize, maize-soybean rotation and maize-soybean/wheat—hairy vetch rotation in Ohio, USA. Kessavalou *et al.* (1998) demonstrated that the application of tillage during fallow increased the N_2O flux by almost 100% relative to the NT treatment.

However, Robertson *et al.* (2000) reported that N_2O emission from ZT was similar to or slightly higher than that from CT under maize—wheat—soybean rotations in the mid-west USA. Similarly, Rochette *et al.* (2008) demonstrated in a 3-year study in East Canada that the average N_2O emission from ZT was more than double than that from CT in a heavy clay soil. They concluded that N_2O emission only increased in poorly drained fine textured agricultural soils under ZT located in regions with a humid climate, but not in well-drained aerated soils. Six *et al.* (2004) concluded that in humid and dry climates, differences in N_2O emissions between the two tillage systems changed over time. In the first 10 years, N_2O fluxes were higher in ZT compared to in CT, regardless of climate. After 20 years however, N_2O emissions in humid climates were lower in ZT than in CT and were similar between tillage systems in the dry climate. As pointed out by Hobbs and Govaerts (2010), the key for the implementation of CA as a climate change mitigation strategy is the understanding of the integrated effect of the practice on all GHGs and developing the necessary component technologies and fertilization practices to reduce the emission of N_2O, since any gains in reduction of CO_2 and CH_4 emissions could be lost if these practices resulted in increased N_2O emissions.

6.9.2. Climate change adaptation

As CA improves water availability and soil quality, besides other advantages, it is likely CA may emerge as an important climate change adaptation strategy. Hobbs and Govaerts (2010) also observed that the resulting improved soil quality and improved nutrient cycling due to CA can improve the resilience of crops to adapt to changes in local climate. CA can help to adapt to climate change induced water stress through increased water infiltration (Pikul and Aase., 1995; Cassel *et al.*, 1995; McGarry *et al.*, 2000; Thierfelder *et al.*, 2005; Zhang *et al.*, 2007; Govaerts *et al.*, 2007a; Govaerts *et al.*, 2007c;Verhulst *et al.*, 2009), improved soil water holding capacity (Kemper and Derpsch, 1981; Hulugalle *et al.*, 2002; Anikwe *et al.*, 2003; Fabrizzi *et al.*, 2005; Bescansa *et al.*, 2006; Govaerts *et al.*, 2007c., Li *et al.*, 2007; Govaerts *et al.*, 2009b) and reduced evaporation of stored soil moisture (Nurbekov, 2008; Gupta *et al.*, 2010; Hobbs and Govaerts., 2010) .Govaerts *et al.*, (2007a) reported that soils under ZT with residue retention generally have higher surface soil water contents compared to tilled soils in the highlands of Mexico. ZT with residue retention has been reported to decreases the frequency and intensity of short mid-season droughts (Blevins *et al.*, 1971; Bradford and Peterson, 2000). Similarly, the increased infiltration under CA in combination with the permanent raised-bed system can help mitigate the effects of temporary waterlogging which is likely to increase in some parts due to climate change induced aberrant weather conditions (Hobbs and Govaerts, 2010). Mulch cover reduces soil peak temperature that can increase with global warming thus, favoring biological activity, initial crop growth and root development during the growing season (Acharya *et al.*, 1998; Oliveira *et al.*, 2001). In CA, soil-surface-retained residue affects soil temperature through its effects on the energy balance; while tillage operations increase the rates of soil drying and heating because tillage disturbs the soil surface and increases the air pockets in which evaporation occurs (Licht and Al-Kaisi, 2005). Soil temperature in surface layer can be significantly lower (often 2 and 8 °C) in the day in summer in zero-tilled soils with residue retention compared to that under CT (Oliveira *et al.*, 2001). Acharya *et al.* (1998) found that the presence of crop residues as mulch in the minimum tillage treatment raised the minimum soil temperature, measured at 0.05 m depth, by 0.5−2 °C compared to no mulch treatment during wheat growth. The maximum temperature under minimum tillage treatment however, was lowered at this depth by 0.3−2 °C. As recent studies have shown that soil temperature is one of the main climate factors that influence CO_2 emission from the soil, there therefore, there is possibility that CA may help further reduce CO_2 emission from soil by lowering soil temperature. High soil temperature increases soil respiration and thus, increase CO_2 emission (Brito *et al.*, 2005). Gupta *et al.* (2010) reported that under zero-till drilling with residue retained keeps canopy temperature lower by 1−1.5 °C during the grain filling stage in wheat because of cooling due to more transpiration owing to sustained soil moisture availability to the plants for reasons like higher water retention in the soil, reduced water losses due to weeds and evaporation. They further observed that this helps in mitigating the terminal heat stress in wheat. In the absence of residue retention, farmers need to apply irrigation at grain filling stage to avoid terminal heat stress. Jacks *et al.* (1955) also reported that surface residue will reduce early spring and summer soil temperatures at the wheat crown depth by as much as 6 °C.

Thus, it can be seen from the review of literature that CA can help a great deal in climate change mitigation and adaptation.

6.10. Conservation Agriculture and Biodiversity

Under CA increased soil cover due to cover crops and crop residues and no disturbance of their habitats unlike under CT, leads to an increase in the variety and variability of animals, plants and micro-organisms both above and below ground, which are necessary to sustain key functions of the agro-ecosystem. Such observations have also been reported by Rodgers and Wooley (1983). CA provides supportive conditions for soil life by providing sufficient food to soil inhabiting organisms (like bacteria, fungi, actinomycetes, earthworms, arthropods etc.,) and protecting them against mechanical and possibly chemical disturbances thus, giving more natural conditions of life.

Under CA, there is a protective blanket of crop residues on the surface which has great influence on the activity and the population of soil micro-organisms (FAO, 2001). For ZT systems in southern Brazil, differences of about 50% in soil biomass and *Rhizobia* population compared to CT were reported (Hungria, *et al.*, 1997). Selected crop rotations along with ZT favor *Bradyrhizobia* population, nodulation and thus, greater nitrogen fixation and yield (Voss and Sidirias, 1985, Hungria, *et al.*, 1997, Ferreira, *et al.*, 2000). Govaerts *et al.* (2007a) from a long-term study in the semi-arid rainfed subtropical highlands at CIMMYT reported that retention of crop residues increased microbial biomass and micro-flora activity, and that the continuous, uniform supply of C from crop residues served as an energy source for microorganisms. Further, when residue was retained ZT showed similar or higher microbial biomass and micro-flora activity compared with CT, and higher microbial biomass and micro-flora activity than in ZT without residue, especially for maize crop.

Several studies reported that CA favors greater microbial activity in surface soil layers than in the deeper layers. As crop residue is concentrated in soil surface in ZT, microbial biomass and microbial activity at the surface of zero-tilled soils is significantly greater compared to in conventionally tilled soils (Arshad *et al.*, 1990; Angers *et al.*, 1993a,b;

Kandeler and Böhm, 1996). Results from several other studies also reported that soil microbial biomass (SMB) was significantly higher in the surface of no-till than in conventional tilled soils (Doran, 1980; Linn and Doran, 1984; Buchanan and King, 1992; Angers *et al.*, 1993 a, b; Ferreira *et al.* 2000). However, taking into account the whole plow layer, smaller differences existed as shown by Franzluebbers *et al.* (1995), where a 75–146% greater SMB-C concentration under no-till than CT at a 0–50 mm depth existed, but only 12–43% greater SMB-C concentration was observed in the 0–200 mm depth under wheat cultivation.

According to FAO (2001), CA improves above ground biodiversity also as it provides more habitats and food for birds, small mammals, reptiles, earthworms, insects etc., which in turn lead to an increase in species diversity and population. Use of winter wheat straw as mulch or winter hairy vetch as cover crop under CA resulted in significant increase in beneficial fauna such as spiders (and earthworms) in DPRK (Mousques and Friedrich, 2007). Thus, CA results in increased biological activity both above and below the ground, due to the continuous presence of the residues as a food source and favorable habitats. Increased below-ground biological activity is vital for improved soil quality. Similarly, increased above ground biological activity may result in more pests, but generally results into higher populations of predators and parasites and thus, promotes biological pest control (Jaipal *et al.*, 2002; Kendall *et al.*, 1995). In a study conducted in Spain that looked at the effects of tillage on soil-borne arthropods found that no-till resulted into more arthropods in some cases (Rodriguez *et al.*, 2006). In another study in Australia, more earthworms were found in no-till treatments (Chan and Heenan, 1993). CA often leads to increase in earthworm activity compared to areas where deep tillage is practiced. In general, earthworm abundance, diversity and activity have been found to increase under CA as compared to under conventional agriculture (Acharya *et al.*, 1998; Verhulst *et al.*, 2010; Kladivko, 2001). Earthworm activity is reported to increase soil macro-porosity, especially when population is significant (Shipitalo and Protz., 1988). McCalla (1958) reported that bacteria, actinomycetes, fungi, earthworms, and nematodes populations were higher in residue mulched fields than in plots where the residues were incorporated. Other studies also showed greater numbers of soil fauna in no-till, residue retained management treatment compared to in tilled plots (Kemper and Derpsch 1981b; Nuutinen 1992; Hartley *et al.*, 1994; Karlen *et al.*, 1994; Buckerfield and Webster 1996; Clapperton 2003; Birkas *et al.*, 2004; Riley *et al.*, 2005). As surface mulch also helps to moderate soil temperature and moisture, it may provide more favorable environment for microbial activity in the soil.

Macro-aggregates which tend to improve in ZT fields compared to conventionally till fields (Castro Filho *et al.*, 2002) and probably provided an improved microhabitat for microorganisms since macro-aggregates have been reported to be associated with greater enzyme activities, respiration and MBC than in micro-aggregates (Gupta and Germida, 1988; Dick, 1992; Miller and Dick, 1995; Franzluebbers and Arshad, 1997; Mendes *et al.*, 1999). Verhulst *et al.* (2010) reported that the effect of CA on soil mesofauna is variable, but in general macro-fauna abundance is stimulated.

6.11. Conservation Agriculture and Off-Site Environmental Benefits

It has been found that CA not only provides benefits in the field where it is practiced but provides many ecological benefits in the surroundings also. CA helps to reduce leaching of plant nutrients and other agrochemicals into the surface and subsurface water bodies compared to conventional agriculture thereby conserving the quality of precious water resources (Becker, 1997). Conservation agricultural practices lead to a significant reduction in erosion, and thus, to a reduction in water pollution and contamination which can be measured with indicators like water turbidity and the concentration of sediments in the suspension and thereby reduction in water treatment costs (FAO, 2001). CA helps increase availability of cleaner water because pollution, erosion, and sedimentation of water bodies are reduced. Reduced erosion can lead to regional benefits such as reduced rate of siltation of water courses and increased recharge of aquifers (Jarecki and Lal, 2003; Lal *et al.*, 2007). It is also being claimed that when practiced over a considerable large area, CA may lead to more constant water flows in rivers /streams and improved recharge of the water table with re-emergence of water in defunct wells. In NT system channels created by decaying plant roots are not disturbed (macroporosity is increased) which helps in increasing deep percolation of water (Barley, 1954; Disparte 1987; Green *et al.*, 2003), leading to recharge of ground water. This function of CA is more pronounced when deep rooted legumes like pigeonpea are included in the cropping systems. CA helps in reducing flooding in downstream areas because most of the water is absorbed in the soil *in-situ*. Due to improved growing season moisture regime and soil quality, crops under CA are healthier, require less fertilizers and pesticides to feed and protect the crop, thus reduce emission of harmful gases and chemicals into soil, water, air and food at both production and field level (FAO, 2008). According to Baudron *et al.* (2009), CA is expected to increase productivity and mitigate negative environmental impacts traditionally associated with agriculture through increased water and nutrient use efficiency. Due to such varied environmental benefits associated with CA, sometimes it is described as a win–win strategy for agriculture and the environment (Lal et al., 1998). Moreover, CA may help to impart increased environmental awareness and better stewardship in community for conserving and respecting natural endowments.

6.12. Conservation Agriculture and Farm Profitability

Adopting CA helps increase farm profitability in the long-term as it reduces variable costs because number of operations and probably external inputs are also reduced. Similarly, under CA mechanical equipments have longer life span, lower repair costs, and consume less fuel due to reduced use than in conventional agriculture. One of the major benefits of CA, which makes it popular among farmers is it costs less in terms of not only money but also time and labor. Agriculture is facing shortage of labor worldwide. Decrease in labor use was considered to be the main reason for the adoption of conservation tillage at large scale in Parana, Brazil (Darolt and Ribeiro, 1998). In the rice-wheat systems of South Asia (Hobbs and Gupta, 2004), no-till wheat significantly reduced the cost of production; farmers estimate this at about Rs. 2500 ha^{-1} (US$ 60 ha^{-1}), mostly due to use of less diesel fuel, less labor, and less pumping of water. Since planting can be accomplished in one pass of the seed drill, time for planting is also reduced thus; freeing farmers to do other productive work (Hobbs, 2007). The increased production and profitability can be the major driving factor for farmers to implement CA and thus, go beyond ineffective and expensive directive incentives like subsidy on diesel (Govaerts et al., 2009a). Mousques and Friedrich (2007) also reported that the net income under CA was twice than that under CT (4100 against 1900 RMB ha^{-1}), mainly because of the reduced inputs. Farmers using Conservation tillage reduced the production costs of soybean per ha by US$67 in Argentina, by US$35 in the USA and by US$27 in Brazil (FAO, 1998). Weeds are smothered due to soil cover with residues, leading to labor saving in weed control. As a result in North Cameroon, net returns to land were calculated to be on average €76 ha^{-1} more with cotton produced under CA than with cotton produced conventionally, which yielded an average of €225 ha^{-1} (Raunet and Naudin 2006). A comparative analysis of the returns on investment in conventional agriculture and CA in Kenya showed a potential of doubling benefits by using CA (FAO, 2009). Experiences from Punjab, Sindh, and Baluchistan provinces in Pakistan showed that with ZT technology farmers were able to save on land preparation costs by about Rs. 2500 ha^{-1} and reduce diesel consumption by 50–60 L ha^{-1} (Sangar et al., 2004).

Surveys of farmers' fields adopting no-till wheat systems in India (Malik *et al.*, 2004) and Pakistan (Khan and Hashmi 2004) showed that farmers who have adopted no-till planting of wheat after rice had definite economic and social benefits accruing from this technology. Derpsch (2005) also reported yield, economic and social gains from other countries due to CA. By adopting the no-till system, Derpsch (2005) estimates that Brazil increased its grain production by 67.2 million t in 15 years, with additional revenue of US$ 10 billion. Profitability of farmers adopting CA may be further increased if provisions are made for giving carbon credits to them for sequestering additional carbon into the soil due to CA. Besides, crop rotation which is an important practice in CA, allows the cultivation of more than one crop so that farmers can spread the risk of fluctuating prices. Changrong *et al.* (2009) from China reported that with CA the total cost of cultivation may decrease by 15−20% and the net income due to CA can increase by 5.8−8.3%. According to them CA is associated with the reduction of cost on crop production inputs such as labor, fuel and use of farm machinery.

It is also quite possible that CA may decrease the farm profitability due to decreased yields mainly during the initial years and increased labor and pesticide requirement for weed and insect-pest and disease control in CA fields. As interculturing with man or bullock drawn implements is prohibited in CA fields which are sometimes cheaper than the costly herbicides and their application costs; the cost of cultivation may increase due to CA. Besides, crop residues maintained on soil surface may lead to carry over of insect-pests and disease pathogens from one season to the next season thus, increasing the severity of their incidence in succeeding crop in rotation in fields under CA. This may require application of higher amount of pesticides to protect the crops thereby increasing the cost of cultivation and reducing the net profitability. Moreover, the environmental cost of applying pesticides for weed, insect-pest and disease control in CA fields may be much higher and many a times unaccountable with severe ecological hazards and consequences.

7. Constraints in Scaling Up Conservation Agriculture in SAT

In spite of several advantages CA offers, there is very slow adoption of CA worldwide except in countries like Brazil, Argentina, Australia, and the USA due to various problems encountered during its adoption. In Brazil for example, CA was first introduced to farmers in the mid-1970s, but it took almost 15 years before the CA acreage reached 1 Mha in 1990 (Derpsch, 2005). The long lag phase is related to the challenges to the adoption of

CA due to which its adoption has not been spectacular worldwide as envisaged by its proponents. The major problems identified are discussed below.

7.1. Competitive Uses of Crop Residues

While benefits of CA are most directly attributed to the mulch of crop residues retained in the field, limited availability of crop residues is under many farming conditions an important constraint for adoption of CA practices (Asefa *et al.*, 2004; Giller *et al.*, 2009) because crop residues, and in particular cereal and legume residues provide highly valued fodder for livestock in smallholder farming systems such as in subtropical countries. In such regions, fodder/feed is often in critically short supply, given typical small farm size and limited common land for grazing. Given the cultural and economic value of livestock (Dugue *et al.*, 2004) – as an investment and insurance against risk (e.g., Dercon, 1998), for traction (e.g., Tulema *et al.*, 2008), for the manure produced (Powell *et al.*, 2004; Rufino *et al.*, 2007) and for milk and meat – livestock feeding takes precedence over use for mulching. As a result mulching materials are often in critically low supply, which makes the application rates of 0.5–2 t ha^{-1} reported to be needed to increase yield, unrealistic particularly in arid and semi-arid tropics (Wezel and Rath, 2002). In the highlands of Kenya, smallholder milk production by stall-fed cows (under zero-grazing) has expanded rapidly in the past decades (Bebe *et al.*, 2002). This has been accompanied by development of a market for maize stover as a valuable feed resource, again providing competition for potential residues for mulch (Tittonell *et al.*, 2007b). Moreover, with the increasing middle class population in the developing countries demand for animal products will be increased in near future and in fact high demand for livestock products along with fruits, vegetables, and fish has been the cause of soaring food inflation in recent years in the countries like India and China. This is likely to result into increased livestock population in the near future and consequent demand for fodder. However, this can be solved through improving the productivity of pastures and fodder crops. Strategies need to be developed to ensure sufficient fodder, while at the same time leaving enough residues on the land for conservation practices. One prerequisite for the adoption of CA practices if residues are to be used for both purposes (CA and fodder), it is important to know that if the quantity of residues produced by the system is enough for both objectives (Choto and Saín, 1993). This may be achieved by increasing the production of crop residues through crop selection or crop rotation. For example, selected crop rotation systems can produce large amount of residue (14 t ha^{-1} per year dry matter) under direct seeding and accumulate about 11 t ha^{-1}; in comparison, accumulation may only be

6.5 t ha^{-1} per year under conventional agriculture with monoculture systems (Bayer, 1996). In Guaymangoin, in order to produce enough crop residues to use as cover crop and for livestock feed, farmers decided to use local sorghum varieties with a low grain-residue ratio rather than hybrids (Choto *et al.*, 1995). This led to production of almost 10 t of crop residue ha^{-1} through maize-sorghum system. At the end of the dry season, after grazing, 6–7 t of residue ha^{-1} remained for use as mulch. Scopel *et al.*, (2004, 2005) reported that even small amounts of surface residues (<1.5 t ha^{-1}) can be effective in reducing water loss, soil erosion and increasing yield. Another solution may be to improve crop residue management. A successful initiative promoted by Selian Agricultural Research Institute is the sorting and compaction of maize residues for livestock feed. By separating palatable from unpalatable residues and compacting them, maize stalks (unpalatable part) are left on the land to protect the soil, while the cost of transporting the palatable part is reduced (FAO, 2001).

There are some other typical problems also encountered when crop residue is maintained on the soil surface like in Mozambique Giller *et al.* (2009) observed that the mulch is often removed in a matter of weeks after application by termites. In a study carried out in southern Burkina Faso, Ouédraogo *et al.* (2004) found that 80% of sorghum residue disappeared after 4 months in the presence of macro-fauna (termite), while only 1% disappeared in the absence of macro-fauna. Besides, community grazing rights is a critical issue for the adoption of conservation practices. Individual farmers cannot restrict grazing even on their own land without challenging the traditional rights of others in the community (Giller *et al.*, 2009; Umar *et al.*, 2011). Indeed, in semi-arid areas, residual biomass is considered a public good as it represents the main source of forage during the dry season (Schelcht *et al.*, 2005). If farmers who do not own livestock wish to opt to keep their residues as mulch they would need to fence their fields, which is expensive for them. This would require re-negotiation of the traditional rules or local by-laws governing free-grazing outside the cropping season (Martin *et al.*, 2004; Mashingaidze *et al.*, 2006). Umar *et al.* (2011) reported the typical problem of burning of crop residues lying in the fields of cultivators by mice hunters in Zambia.

7.2. Weed Preponderance

Even though, some proponents of CA argue that with good ground cover resulting from mulching or cover crops, there is less weed pressure under CA. But higher weed intensity during initial years is a reality as also observed by us (ICRISAT unpublished results) in ongoing long-term experiment on CA at ICRISAT, Patancheru, India. Severe weed infestation particularly during initial years of adoption is one major hindrance to motivate the farmers to adopt CA as not tilling the soil commonly results in increased weed pressure (Vogel, 1994, 1995; Blackshaw *et al.*, 2001; Kayode and Ademiluyi, 2004; Umar *et al.*, 2011). In one of the few long-term assessments of conservation tillage practices, Vogel (1995) found that CA system subjected to continuous maize production led to unacceptable infestation with perennial weeds within 6 years. This reflects the experience in North America, where perennial broad-leaved and grass weeds became increasingly problematic with reduced tillage despite the use of herbicides (Locke *et al.*, 2002). Vogel (1995) concluded that traditional hoe weeding proved inadequate to control the rapid buildup of perennial weeds in CA plots. Mousques and Friedrich (2007) observed that in winter wheat, there was a higher weed infestation in the CA plots, which was difficult to control with herbicides because of the residue cover. Weed management in the lowland paddy areas requires special attention under CA, including appropriate conditioning of the straw residues and timing of chemical weed control.

With the adoption of ZT, growers may expect greater changes in agricultural weed communities with concurrent changes in their weed management strategy being needed (Blackshaw *et al.*, 2001). Weeding before seed setting is essential to reduce weed intensity in the longer-term. Similarly, controlling weeds growing on field bunds and periphery is a must as they are important source of weed seed bank. Weed management in CA requires more herbicides application which is many times beyond the capacity of poor farmers of the SAT. Moreover, sometimes continuous rainfall may not allow the application of herbicides or reduce the efficiency of applied herbicides as experienced at the ICRSAT center, Patancheru, India (Unpublished observations). Wall (2007) reported that weed control is often laborious and costly in the initial years, with a greater requirement for herbicides than in CT at least in the initial years. Many low-income countries may depend on importation of herbicides which are required in higher amount mainly during initial 4–5 years of adoption, and the high cost is one important reason for low adoption of NT in such countries (Machado and Silva, 2001). According to Giller *et al.* (2009) restricted access to agricultural inputs such as herbicides due to the cost and the lack of effective input supply chains represents a major limitation for the implementation of CA. At the same time tremendous increase in herbicide use; when CA is followed at large scale; may lead to serious repercussions on health of local people and eco system. Export of herbicide residues in water streams will make their water unfit for human and animal consumption besides, having adverse impacts on marine life.

Plowing remains the single most cost-effective weed control method, and extension agents in southern Zambia confirmed that CA using permanent planting basins almost doubles the required weeding effort compared with conventional plowing (Baudron *et al.*, 2007). Even if the marginal return is high for these extra investments, most smallholders may not be able to undertake them due to limited resources and labor constraints (Erenstein, 2002; Giller *et al.*, 2001).

For labor constrained farmers, it is difficult to frame a strategy on how to allocate more of their activities towards weeding (Umar *et al.*, 2011). We experienced at the ICRISAT center farm that the increased amount of labor required for weeding in CA plots may outweigh the labor-saving gained by NT, unless herbicides are used to control weeds. Besides, CA results in shift of labor burden from men who perform activities such as hand tillage or ox-drawn plowing to women who generally perform manual weeding (Giller *et al.*, 2009; Baudron, 2007). A case study from Zimbabwe (Siziba, 2008) clearly shows the change in labor use profiles from planting to weeding with the adoption of the CA practice. Without a reallocation of the gender-division of these roles in agricultural production, this may lead to an unacceptable increase in the burden of labor on women. Besides, heavy use of herbicides in CT may cause herbicide carryover thus, adversely affecting crops in succession (Hinkle, 1983; Smika and Sharman, 1983) and the chemicals can move with runoff water leading to pollution of water bodies.

Promoters of CA however, often argue that increased investment in the form of extra inputs and/or extra labor is required only in the first few years of adoption. The early and continuous weeding decreases the weed seed bank over time and ultimately reduce the labor required in CA (CFU, 2003). Research at the GART station in Zambia supported this view, as it demonstrated that labor for weeding is reduced by 50% after 6 years in trials during which weeds were not allowed to grow beyond 5–6 cm (Baudron *et al.*, 2009). Mariki and Owenya (2007) have also reported that growing cover crops in the inter row space reduces labor requirement for weed control in CA plots.

7.3. Lower Crop Yields

There are many reports on reduced yield under CA particularly during conversion phase which are mainly due to high weed infestation, poor crop stand due to low germination, nutrient immobilization, higher insect-pest and disease attack, waterlogging in poorly drained soils, lack of skills in adopters during initial years etc., Issues like higher weed infestation, nutrient immobilization, insect-pest and disease attack in CA fields have been discussed at relevant places in this article. Absence of tillage in itself can result in adverse effects including higher run-off and lower infiltration, leading to lower yields (Tadesse *et al.*, 1996; Akinyemi *et al.*, 2003; Alabi and Akintunde, 2004; Abdalla and Mohamed, 2007). The negative effects of NT occur especially on the clay-poor, structurally weak soils of the arid areas, which are widespread throughout Sub-Saharan Africa (SSA) (Aina *et al.*, 1991). On such soils, the beneficial effects of mulching may not always be sufficient to offset the negative effects of NT resulting in lower yields during the first few years under no-till compared to plowing even if a mulch of crop residues is applied (Nicou *et al.*, 1993; Ikpe *et al.*, 1999; Mesfine *et al.*, 2005; Guto *et al.*, 2011). Poor crop stand has been observed in no-till plots with crop residues compared to conventional management on ongoing experiment in black watershed at the ICRISAT farm, Patancheru, India (unpublished data). Similarly, Mesfine *et al.* (2005) and Dabney *et al.* (1996) have reported reduction in sorghum stand in zero-till plots compared to conventional-till plots. Lower crop yield in CA, has been identified as major hindrance to motivate the farmers to adopt CA. Most smallholder farmers are risk-averse and cannot afford reductions in farm productivity to try a new system (Lumpkin and Sayre, 2009). However, even in cases where yield increases are small, CA advocates argue that the concept remains attractive among farmers in sub-Saharan countries as it enables a quick and easy establishment of crops (Baudron *et al.*, 2009). This is particularly true with planting basins that can be dug throughout the dry season.

During high rainfall intensity events on poorly drained soils, waterlogging aggravated by residue retention can result into crop damage to waterlogging sensitive crops like maize and legumes. Thierfelder and Wall (2009) also observed adverse effects of waterlogging on maize grain yield in CA plots. Evidence from temperate North America (Logan *et al.*, 1991) indicates cereal yields are larger under conventional than ZT during the initial years with or without moderate rates of mineral N fertilizer, but larger yield responses were observed under ZT as N fertilizer rates increase.

7.4. New Implements and Operating Skills Required

As CA involves different set of operations and management, it requires different implements and management skills than those used in conventional agriculture. The purchase of specialized equipment (e.g., ripper, direct-seeder) is critical for successful adoption of CA (Hobbs *et al.*, 2008), but represents an almost impossible investment for many resource-poor farmers in the SAT. The presence of crop residues on the soil surface and NT in CA pose a big challenge for seeding and planting of crops by farmers. A major requirement of the CA system is the development and availability of equipment that promotes good germination of crops planted into soil that is not tilled and where residue mulch occurs on the soil surface (Hobbs, 2007). Besides, machinery should also be able to place fertilizers at desired depth simultaneously with seeding. But unavailability of such implements is one of the major hindrances for the adoption of CA. For example, Machado and Silva (2001) observed the deficiency of NT seeding machines or hand planters in Brazil. Some advanced countries import or develop heavy, expensive equipment based on disk openers to address these requirements. But less developed countries have smaller tractors or bullocks as source of traction that necessitates different designs of equipment (Hobbs, 2007). Mousques and Friedrich (2007) reported that Brazil imported SA-7300 no-till seeder presented a challenge for the lifting capacity of the Korean Cholima tractors owned by the farmers in the DPRK. It may require purchasing new tractors which may be many times beyond the capacity of resource strained farmers. Therefore, development of machinery which can put the seeds and fertilizers at desired depth by cutting the surface retained residue in no tilled fields for satisfactory germination and higher nutrient use efficiency is vital to make this technology acceptable among farmers. Besides, farmers need to be properly guided and trained for use of new machinery. CA is a knowledge intensive process which demands time and commitment from the would-be or the farmers already practicing CA (Umar *et al.*, 2011). A lack of proper knowledge may result in misallocation of inputs, poor soil fertility management consequently resulting into low crop yields. As Mousques and Friedrich (2007) observed that zero till machinery imported from Brazil was not known to Korean farmers previously, they found it difficult to accept the new equipment at the start of the project. Besides, problems of maintenance of machinery has been observed, and appropriate training in the use of the machines is necessary to avoid premature equipment wear.

7.5. Nutrient Immobilization

Addition of large amount of crop residues particularly with low C: N ratio in CA fields may lead to net immobilization of plant nutrients in the soil more particularly during the initial years of adoption of CA when a new equilibrium is not reached. It may lead to lower crop yields unless extra amount of nutrients is added into the soil to offset the nutrient immobilization. According to Duxbury *et al.* (1989), SOC dynamics and nutrient cycling are strongly related through the microbial driven process of nutrient immobilization and mineralization. The ratio of available C and available N is the main factor determining whether N mineralization or immobilization will take place during the decomposition of organic matter (Paul and Juma, 1981). Because of its ability to serve as both a source and sink of soil nutrients, the soil microbial biomass plays a key role in these processes (Jansson and Persson, 1982). This is mainly the case for N, for which the addition to soil depends on the amount and quality of organic matter, crop rotation, how long NT has been conducted and rainfall regime (Santana, 1986; Sá, 1998). Increased soil microbial population, stimulated by the addition of large amount of organic matter and improved soil water content with CA, could compete with the crops for available plant nutrients. The influence of residue management on N availability is well-known, particularly during the first five years of conversion from CT to NT (Muzilli, 1994; Sá, 1998). Large amounts of cereal residues with a high C: N ratio that are left on the soil surface temporarily cause a net immobilization of mineral N in the soil, although it is expected that N immobilization will be less than when residues are incorporated (Abiven and Recous, 2007). Giller *et al.* (2009) observed that strong interactions exist between the amounts and quality of the crop residues and the soil characteristics, which determine the degree of N immobilization due to the surface mulching and hence in turn the need for additional N fertilizer. Farmers without access to mineral fertilizer cannot compensate for such N deficiency and will suffer yield reductions as a direct result (Giller *et al.*, 2009). However, if repeated additions of large amounts of crop residues lead to a greater soil C content with time, this may lead to a greater net N mineralization once a new equilibrium is achieved (Erenstein, 2002). The length of time required to achieve net N mineralization depends on rates of residue addition, rates of N fertilizer added and the environmental conditions — particularly on the length and 'dryness' of the dry season (Giller *et al.*, 2009). They also observed that if soil N availability decreases under CA with a mulch of crop residues — and some studies indicate that this does not always occur (Lal, 1979; Mbagwu, 1990) — a larger amount of N fertilizer will be needed to achieve equivalent yields as compared without crop residues. Further, the amount of fertilizer required will depend on the rates of crop residues added and their quality (Giller *et al.*, 2009). Nurbekov (2008) observed that because of N immobilization, higher amount of fertilizer is needed to be applied to crops (maize, wheat, sorghum) at sowing to achieve high yields, but the application of urea through broadcasting on the mulch layer has not been successful because of loss of N through ammonia volatilization. He also reported that soil denitrifiers population under no-till soils are significantly greater than that of conventional till soils. However, inclusion of legume cover crops can ameliorate N supply to crops (Heinzmann, 1985; Debarba and Amado, 1997). Burle *et al.* (1997) found that in legume-based systems without N fertilization, maize yields reached 6.6 t ha^{-1} producing at least 3 t ha^{-1} more grain than the traditional fallow/maize system.

7.6. Carryover of Insect-Pests and Disease Pathogens

Favorable conditions created in CA fields due to higher soil moisture, temperature moderation, and ample food supply lead to increased incidence of insect-pest, diseases, rodents, nematodes on crop plants compared to fields under conventional management. Insects, rodents, nematodes, fungi, and other pests tend to increase with conservation tillage, requiring as much as a 30% increase in the use of pesticides over CT (Hinkle, 1983). According to Cook *et al.* (1978), colonization of seedlings of spring cereals may be greater in moldboard plowing than NT because the relatively low soil temperature in NT inhibits infection. But, seedlings of winter cereals are more at risk in NT than moldboard plowing because the relatively high soil water content at planting (late summer) in NT promotes infection. Reduced tillage often lowers soil temperature and increases soil water, leading to increased corn root rot (van Wijk *et al.*, 1959). However, some other studies indicate that the severity of crop diseases may increase, decrease, or remain stable with changing tillage systems (Cook *et al.*, 1978; Kirby, 1985). In an experiment on CA in China, Mousques and Friedrich (2007) reported heavy attack of *Laodelphaxstriatellus,* which transmits the rice stripe virus (RSP), in Jiangsu province. According to them although conventional fields were attacked as well, there were indications that the paddy under CA would be more affected because 1) the CT helps to reduce *Laodelphaxstriatellus* populations; 2) under conventional management the soil is not covered in winter, and *Laodelphaxstriatellus*are killed by the low temperatures so do not survive until next summer; 3) under the layer of straw and stubble, the effective use of insecticide or herbicides is difficult.

Giller *et al.* (2009) observed that the addition of large amounts of decomposable organic matter, as with grain legumes, legume green manures, forage legumes or improved tree fallows can have negative effects such as the stimulation of white grubs or cutworms that cut roots of cereals and can eliminate cereal growth – resulting in complete loss of the crop stand if incidence is severe. They reported that in Mozambique and Madagascar, the grubs of the black maize beetle (Heteronychusspp. – a scarab beetle) are recognized as major problems where large amounts of decomposable organic matter from legumes or maize straw are incorporated. In Zimbabwe, severe incidence of grubs of Agrotis spp. was stimulated by large inputs of readily decomposable litter from legume tree fallows in no-till systems (Chikowo *et al.*, 2004). In the eastern Corn Belt, USA especially in wet years, slugs are a major problem in NT, but not in the moldboard plowing (Forcella *et al.*, 1994). Cochran *et al.* (1977) have also reported phototoxic effects of residues.

7.7. Low Investment Capacity of SAT Farmers

Shift from conventional system to CA requires new investment in the form of machinery and inputs like herbicides, which majority of farmers in the SAT cannot afford due to their low socio-economic conditions. In practice, farmers have been found not to adopt all principles of CA due to various reasons such as limited access to inputs (herbicides, cover crop seeds), labor constraints or insufficient resources to grow cash crops, lack of residue supply, weed infestation etc., (see e.g., Baudron *et al.*, 2007; Kaumbutho and Kienzle, 2007; Shetto and Owenya, 2007). CA practices generally require investment, either in the form of purchased inputs or of labor, compared with conventional practices, which resource constrained farmers of SAT may not be able to spare. Farmers in SSA where efforts are on to promote CA seek substantial, visible and immediate benefits when considering adoption of CA practices (FAO, 2008b), but many of the benefits of employing CA are only realized in the longer term. Besides, the implementation of CA requires skills and a good understanding of crop rotation with cover crops and in weed control. Hence, the introduction of such CA will still face some difficulties in Africa or Asia, where the use of green manure or cover crops are economically nonviable as observed in southern India, central Tarai region of Nepal and northern Philippines (Ali and Narciso, 1996).

There is also the challenge of overcoming mindsets of farmers in relation to changing the traditional way of farming, where tillage is considered essential by farmers to get good yields (Hobbs, 2007). In fact, the change in mind-set not only by farmers but also by scientists, extension agents, private sector members, and policy makers may be the most difficult aspect associated with the development, transfer, and farmer adoption of appropriate CA-based technologies (Lumpkin and Sayre, 2009).

7.8. Lack of Sufficient Research on CA in the SAT

Another factor hindering the promotional efforts for widespread adoption of CA technologies is the lack of sufficient research outputs under different agro-climatic conditions particularly in Asia and Africa. There is need to pursue research vigorously on different aspects of CA to standardize the machinery, techniques, cropping systems, and residue management under CA in different agro-climatic conditions. As suggested by Lal (1997), further long-term studies in different soils and climates are needed to verify to what extent NT; which is one of basic constituent of CA, helps to sequester more carbon than under CT. Machado and Silva (2001) observed that similar to studies conducted by IAPAR in southern Brazil (Almeida, 1991), further investigations must exploit to the fullest the efficiency of different cover crops for weed control through allelopathy combined with herbicides and evaluate the potential hazards to surface and ground water caused by intensive use of herbicides. Research is needed to identify the causes of the often-observed short-term yield reduction and how they can be avoided or minimized (Giller *et al.*, 2009). It is important to develop and promote CA technologies in the context of well-defined natural resource/socio-economic domains and farming systems in different eco-regions around the world. For example, in countries like in India while good efforts have been made to popularize CA in irrigated rice–wheat-based cropping systems in IGP, other important ecologies such as dryland regions have not yet got such attention of policy makers and researchers. Machado and Silva, (2001) observed that investigations are needed to identify suitable strategies to improve the downward profile movement of surface applied lime in acidic soils under CA as soil acidity control is probably the first controversial aspect that is raised in NT systems in South American countries relative to the use of Oxisols in Brazil. Similarly, in SAT there is need to study the movement of surface applied gypsum which is needed for amelioration of soil alkalinity common in Aridisols.

Giller *et al.* (2009) noted that future emphasis on cereal–legume rotations under CA should focus on multipurpose grain and fodder legumes e.g., maize–pigeonpea intercropping is predominant in southern Malawi and in parts of central and southern Tanzania, but only in areas with small livestock densities as otherwise the crop is grazed after maize harvest before it reaches maturity. Similarly, during fallow period the left out crop residues on soil surface can be grazed by the cattle as the practice of communal grazing is common in SAT. This underlines the need for identifying suitable leguminous cover crops with multiple uses which are unpalatable to cattle and produce sufficient amount of crop residue for CA. Scope lies for utilizing the biotechnological tools to introduce in the existing legume crops such genes which can stimulate crops to synthesize the chemicals which prevent the cattle from browsing on such plants.

8. Up Scaling Conservation Agriculture in SAT

It has been demonstrated that CA can be quite helpful to achieve the goals of sustainability and improved productivity in different agro-ecologies, but promoting it in SAT is a challenging task before the stakeholders due to their typical agro-climatic, social and economic conditions. There is need to think upon the problems faced at the implementing level and devise a strategy involving all who are concerned. Most cases where changes in favor of CA have occurred are still only islands of success particularly in Africa. FAO (2001) have noted that this is partly because policy environments are not favorable, most agricultural policies still actively encourage farming that is relying largely, often almost exclusively, on external inputs and technologies that do not adequately internalize environmental and conservation costs, and so discriminate against locally adapted biological resources, technologies and practices, and sustainability. For the transition to more sustainable agricultural and other land use systems to occur, governments must facilitate the process with an appropriate range and mix of policy instruments and measures, including efforts to decentralize administration to interact better with local people; to reform land tenure to give individuals and communities the motivation to better manage and develop their local resources; to develop economic policy frameworks that encourage more efficient use of resources; to develop new institutional frameworks and set up training that would enable staff to be more sensitive to the needs of local people and instill a greater understanding of the ecological dynamics of different systems of land use (FAO, 2001). Although these constraints are common to other strategies for improvement of productivity, unless they are addressed there is little point in pushing CA as one more "silver bullet" (Giller *et al.*, 2009).

Hobbs and Govaerts (2010) however, noted that probably the most important factor in the adoption of CA is overcoming the bias or mindset about tillage. It is argued that convincing the farmers that successful cultivation is possible even with reduced tillage or without tillage is a major hurdle in promoting CA on large scale in SAT. In many cases, it may be difficult to convince the farmers of potential benefits of CA beyond its potential to reduce production costs, mainly by tillage reductions. It is therefore necessary to educate farmers on the links between excessive tillage and residue removal with soil sustainability problems, and how these problems can be alleviated through adoption of CA (Lumpkin and Sayre, 2009).

The remarkable growth of NT in Latin America, particularly in southern Brazil so far can be attributed to close collaboration between governmental institutions (research centers and extension service) and farmer associations, agrichemical companies, seed companies and agricultural machinery companies (Busscher, 1996). As FAO (2005) reported the challenge is for would-be advisers to develop a sense of partnership with farmers, participating with them in defining and solving problems rather than only expecting them to participate in implementing projects prepared from outside. Instead of using a top-down approach where the extension agent places CA demonstrations in farmer fields and expects the farmer to adopt, a more participatory system is required where the farmers are enabled through provision of equipment and training to experiment with the technology and find out for themselves whether it works and what fine-tuning was needed to make it successful on their land.

The obstacles in up scaling CA can be overcome through interaction among associations of interested people. The operational basis of such associations may be farmer-to-farmer exchange of experience on a regular basis and organization of promotional events such as field days. The other important thing for successful adoption of CA is the need to provide credit to farmers to buy the equipment, machinery, and inputs through banks and credit agencies at reasonable interest rates. At the same time government need to provide subsidy on purchase of such equipment by farmers. For example, Chinese government in recent years adopted a series of policy and economic measures to push CA techniques in Yellow River Basin and is providing subsidy on CA machinery and imparting effective training to farmers (Changrong *et al.*, 2009). This resulted into considerable increase in area under CA and currently in Shanxi, Shandong and Henan provinces over 80% area under maize cultivation depends on no till seeder. Management of crop residues and access to such inputs as seed and inorganic fertilizers need to be improved for farmers to achieve maximum benefits of CA (Mazvimavi and Twomlow, 2009). Sayre and Govaerts (2009) proposed that a network of decentralized learning hubs within different farming systems and agro-ecological zones should be developed. In such hubs, an intense contact and exchange of information can take place between different stakeholders of CA. Similarly, farmers who have already successfully adapted CA and gained sufficient experience can be motivated to help and train their fellow farmers through self-help groups (SHGs). Once lead farmers have adopted the technology, the promotional efforts required to popularize the system among other farmers are relatively small. FAO (2001) noted that the agricultural organizations have to promote experimentation; connectivity and group work based on roles rather than disciplines; and develop monitoring and self-evaluation systems to improve learning and awareness. National agricultural research and extension systems (NARES) need to assume coordination role for better functioning of the research and promotional activities with desired results in different agro-ecosystems.

Government agencies being relatively permanent institutions can become lasting and knowledgeable and independent sources of support. On-farm research and pilot projects can also be organized with the support of interested organizations. NGOs should be encouraged to work closely with government agencies rather than in isolation, with a view to helping government staff to develop their interests and skills in working with rural communities (at which NGOs are often more adept than government offices), using well developed and successful participatory programs as templates to study and learning (FAO, 2001). At the same time private sector support can be fundamental to the expansion of CA by supplying specialized implements required. Hobbs and Govaerts (2010) observed that because of the multifaceted nature of CA, technology development and extension; activities should be concentrated in a few well-characterized and defined locations representative of certain farming systems rather than having lower intensity efforts on a wide scale.

Given the complexity of the CA management packages, and the need to tailor the practices to local conditions, there is a need for strong capacity in problem-solving around CA practices among development agents (NGO and extension workers) as well as in local research capacity (Rockström *et al.*, 2001; Lahmar and Triomphe, 2008; Mazvimavi *et al.*, 2008). It is therefore, important that a non-linear, flexible approach is used when disseminating CA, with emphasis on capacity building and with room for adaptations to local conditions (Giller *et al.*, 2009). As Davis (2008) observed that the failures of extension in SSA are often due to a combination of a lack of relevant technology, failure by research and extension to understand and involve farmers in problem definition and solving, and weak linkages between extension, research, and farmers. Restrictive definitions of what constitutes CA rather than flexibility with consideration to the local conditions are therefore in the long run more likely to hamper rather than promote adoption of complex technologies such as CA (Baudron *et al.*, 2007). In the Conservation Agriculture in Africa Case Study Project (Triomphe *et al.*, 2007), it is recognized that there cannot be a linear transfer of CA technologies. There may be many adoption pathways and what farmers realistically can achieve at a given time and in a given farm context depends on factors and combinations thereof like environmental, socio-economic, institutional and political circumstances, and constraints. Aspects that need to be considered in tailoring CA systems to the local circumstances include farmers' production objectives, factors limiting production, expected relative costs (requirements in terms of inputs, equipment but also knowledge, labor, etc.,) and benefits (to the farmer, the community and/or the region) of CA approaches in the specific socio-ecological setting and institutions present which can assist with input supply, technical advice and marketing (Giller *et al.*, 2009). Knowler and Bradshaw (2007) concluded on the basis of a world-wide study that there was a lack of universal variables that explain the adoption of CA and that the effort to promote CA need to be tailored to local conditions. This confirms the conclusions of Erenstein (2002) and Kronen (1994) that the potential of CA and soil conservation technologies in general, is site-specific and depends on the local bio-physical and socio-economic environments.

Experiences can be shared between neighboring countries with similar agro-climatic and socio-economic conditions through networking. This has been particularly demonstrated in South Asia for the promotion of resource conservation technologies for wheat through rice-wheat consortium and national research system of the countries of the region (Bangladesh, India, Nepal, and Pakistan). FAO provides one such mechanism for inter-country networking, as do a range of other research and development networks. Fowler and Rockstrom (2000) describe that in April 2000, a group of primarily African promoters and practitioners initiated the African Conservation Tillage network (ACT) to identify, disseminate and promote the adaptation and adoption of resource-conserving tillage practices in Africa. The network sees as its primary task the opening up of channels of communication, but also plans activities to stimulate the establishment of national conservation tillage networks and the identification, adaptation and adoption of conservation tillage techniques.

To enhance the adoption level among farmers, it is important that CA should be profitable in short-term also. As smallholder farmers often attribute more value to immediate costs and benefits than those incurred or realized in the future due to the constraints of production and food security that they face (Giller *et al.*, 2011). For instance, experiences with small resource-poor farmers in Kenya, Costa Rica, El Salvador and Honduras show that in cases where conservation-effective farming can increase their cash incomes, they are keen to adapt and adopt such techniques, even if this may lead ultimately to a complete change in farming system (FAO, 2001).

Other stakeholders, especially equipment manufacturers, are also needed to be involved in order to modify the equipment as the farmers experiment, so that modifications can be made to the machinery under local situations for improved performance (Hobbs, 2007). To make CA a success there is need of availability of suitable equipments that can place seed and fertilizers at optimum depth through surface applied residues in zero tilled fields. The adoption of conservation technology following the dust bowl of the 1930s in USA was dependent on the development of seed drills that could cut the soil surface maintained residues and place the seed in the soil at the correct depth for satisfactory germination. Even though a wide range of equipments, mostly developed in developed countries, is available for planting in CA fields, these are power thirsty and not suitable for low powered tractors owned by farmers in SAT. Therefore, there is need to develop equipment that are cheaper, lighter and can be powered by smaller tractors or even by bullocks. To cater this need, there is need to have close interactions between farmers, technicians, machine builders, local private entrepreneurs, craftsmen, scientists. engineers etc., For example recently, multi-crop, zero-till ferti-seed drills fitted with inverted-T openers, disk planters, punch planters, trash movers or roto-disk openers have been developed for seeding into loose residues for zero till sown wheat in the rice-wheat system of IGP (RWC Highlights 2004–05).

As weed infestation is one of the major discouraging factors for the farmers to adopt CA, there is need to develop integrated weed management techniques to keep the yield loss due to weeds to minimum. This is particularly important in dryland areas where both nutrient and water stress reduce crop productivity. Herbicides may be used in some systems (Findlay and Hutchinson, 1999), hand hoes in others, and farmers who have animal-drawn plows can fit simple and inexpensive tines or subsoiling machine (Bwalya, 1999). However, indiscriminate use of herbicides under CA may lead to heavy environmental costs. The use of herbicides should be considered only as one of the options in an integrated approach of weeding and cover crop management. In both south Brazil and Paraguay, ZT systems for small farmers that eliminate the need for herbicides have been developed (FAO, 2001). But still there is growing realization that to promote CA particularly among small and marginal farmers, there is need to make available suitable herbicides at affordable prices particularly for intercropping systems which are popular in SAT due to their resilience to climatic as well as market related shocks. Mariki and Owenya (2007) recommended integrated weed management including agronomical/biological practices such as crop rotation, closer row spacing, intercropping and mulching (dead and live mulch) to suppress weeds and reduce some of the noxious weeds like *Digitaria* and *Cyperus*. For standing crops, mechanical methods like use of scrapers, hand rouging and slashing to minimize soil disturbance were recommended. Mariki and Owenya (2007) also reported that cover crop (*Mucuna* and Lablab) treatments had low weed counts ranging from 2 to 5 plants m^{-2} and differed significantly from the no cover crop treatment which had highest weed counts of 16—18 counts m^{-2} for all three species (*Digitaria, Cyperus,* and *Argemone mexicana*), respectively. Crop diversification in CA also allows greater choice of herbicides from different chemical families that will aid in overall improved weed management and may reduce the risk of herbicide resistance (Blackshaw *et al.*, 2001). In the areas where crop residues have other uses, solutions have to be found to increase the overall productivity of the system in order to meet the farmer and soil needs (Hobbs and Govaerts, 2010). Improved fodder sources should also be part of the improved management package (Govaerts *et al.*, 2005; Verhulstetal., 2010). Alternatively, for enhanced biomass supply suitable cover crops with high biomass production capacity should be identified for different types of production systems under various agro-climatic conditions. Introduction of cover crops can however, be very challenging in some environments, depending on the climate conditions and the difficulty in convincing a farmer to grow a crop that will not give any immediate economic return (Hobbs and Govaerts, 2010). Rotations with forage crops, ley-arable systems, integration with legume fodder trees, agroforestry and live-fences might help increase residue availability for both fodder and mulching (Wall, 2009; Giller *et al.*, 2011). Intercropping systems growing cover crops with the main crops may be another feasible way of producing sufficient biomass for CA (Baudron *et al.*, 2009). Grain legumes and cover crops like cowpea (*Vigna unguiculata* (L.) Walp.), velvet bean (*Mucuna pruriens*), Indian bean (*Dolichos lablab)* (L.) D.C.), sunnhemp (*Crotalaria juncea* L.) and jackbean (*Canavalia ensiformis* (L.) D.C.) could be used as intercrops as per their suitability in different agro-climatic conditions (Golden Valley Agricultural Research Trust 2004).

As the introduction of CA is shown to work best if it is farmer driven, on-farm demonstrations and training events such as workshops, field visits, overseas study tours, and training courses should be given higher priority (Mousques and Friedrich, 2007). It may also be pointed out that suitable agro-ecological and socio-economic niches should be identified for scaling up CA in SAT as also stressed by Guto *et al.* (2011) and Carter (1994). Governments wishing to support the spread of sustainable agriculture can provide incentives to encourage natural resource conservation or penalize those degrading the environment, or do both (FAO, 2001).

9. Concluding Remarks

The SAT is characterized by highly variable and low rainfall, poorly developed infrastructure, degraded soils, and low socio-economic condition of the farmers. The crop productivity is very low with no or very low surplus produce. CA has been reported by numerous workers as sustainable and eco-friendly crop production technique in the fragile eco-systems of SAT. But concerns have been raised about slight yield decline mainly during the initial years of adoption of CA. But at the same time reduction in cost of cultivation due to omission of tillage practice and higher input use efficiency may not have overall effect on economic returns to farmers even during initial years. However, in the long-term CA has been found to render several benefits including soil conservation with improved soil health, higher rain water use efficiency, climate change mitigation and adaptation, improved biodiversity, resilience to climate shocks, higher economic returns, and more leisure time to farmers. However, before recommending CA under given set of agro-climatic and socio-economic conditions, it is essential to undertake medium to long-term studies on CA to better guide the farmers for successful adoption. The use of decision support systems such as DSSAT and APSIM may be successfully employed after proper calibration and validation to predict the long-term effects of

CA on yield and soil quality, which will save time and resources to undertake the long-term studies in the field.

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