Conservation Agriculture and Ecosystem Services

Theo Dillaha, Professor of Biological Systems Engineering; Cheryl Heatwole Shenk, Research Assistant; and Keith Moore, Associate Program Director, SANREM CRSP

Office of International Research, Education, and Development, Virginia Tech.

Abstract. Conservation agriculture has many agricultural and food security benefits. In addition, conservation agriculture has potential on- and off-site ecosystem service benefits that are the focus of this paper. Ecosystem services provided by conservation agriculture fall into three main categories: provisioning services such as increased food production; regulating services such as carbon sequestration and climate regulation, reducing losses of soil, pesticides, nutrients and other potential contaminants in surface and subsurface water flows, and water cycle improvements; and supporting services such as nutrient and storage and cycling. This paper focuses on the regulating service benefits of conservation agriculture: erosion control, reduced losses of pesticides and nutrients, and particularly water cycle benefits including increased water productivity (more crop per drop), infiltration, percolation, plant available water storage, groundwater recharge, plant available water, and stream baseflow and decreases in peak stream flows and downstream flooding.

Keywords: conservation agriculture, ecosystem services, hydrology, best management practices, developing countries

Introduction

Conservation agriculture production systems are an alternative to conventional agricultural production systems (conventional tillage) in which soil is tilled to varying extents to control weeds, pests, incorporate nutrients and other agricultural amendments, and control soil compaction problems. Conservation agriculture production systems are generally defined as production systems that:

- maintain, to the extent possible, a year-round soil cover provided by residues from previous crops and/or a cover crop intended to improve food production and soil quality;
- minimize soil disturbance by tillage; and
- utilize crop rotation systems that have been adapted to local socioeconomic and environmental conditions for the improvement of soil quality/health and control of agricultural pests.

Conservation agriculture is promoted as an alternative to conventional tillage because of problems associative with poor implementation of conventional tillage. These problems generally include long-term declines in soil quality/fertility due to soil erosion and declining soil carbon levels. Declines in soil carbon/organic matter also contribute to reduced soil moisture storage capacity, which decreases crop resilience to drought, and decreased utilization efficiency of applied nutrients. Lal (2009) indicates that a minimum soil carbon pool in the soil surface layer of about 1.2 percent is required for efficient nutrient uptake reasonable agronomic productivity.

Globally, there were an estimated 1.53 billion hectares of cropland (Thenkabail et al., 2009) in 2009, with the vast majority in conventional tillage. Global cropland in conservation agriculture in 2009 was estimated to be approximately 106 million hectares (Derpsch, R. and T. Friedrich 2009) where conservation tillage was defined as agricultural production systems in which seeds are planted into untilled soil by opening a narrow slot, trench or band only of sufficient width and depth to obtain proper seed coverage; however, they did not exclude rotational tillage, (e.g., tilling every third or fourth year). They did exclude cropland with no-till for one crop and regular plowing or tillage of the soil for the following crop.

Conservation agriculture is being adopted rapidly in both developed and developed countries, but adoption is most successful in countries with mechanized agriculture, as indicated in Tables 1 and 2. An estimated 45.5 million hectares of cropland were in conservation agriculture in 1998/1999 (Derpsch, 2001), which gives an average annual growth rate of approximately 22 percent. Adoption has been dominated by larger land holders with the exception of Brazil, where conservation agriculture has been adapted for and adopted by many smallholders. In general, perceived benefits of conservation agriculture, which are responsible for its rapid growth, include: more profitable and sustainable agricultural production, reduced fuel and machinery costs, reduced pesticide costs, improved opportunities for double and triple cropping, higher yields, improved soil quality/fertility, enhanced soil biodiversity, reduced erosion, improved soil water management, soil carbon sequestration (improved soil quality and carbon sequestration for climate change benefits), and water quality improvements due to possible reductions in losses of agrochemicals, sediment, and organic matter from cropland. It is important to recognize that these are potential benefits and that they are not universal. As with all agricultural production practices, the effectiveness of agricultural production practices/systems are site specific and a function of local crop, soil, climate, pest, and management conditions.

Table 1: Conservation agriculture/no-tillage in 2008 (Derpsch, R. and T. Friedrich. 2009)

Country	No-tillage (ha)
USA	26,593,000
Brazil	25,502,000
Argentina	19,719,000
Canada	13,481,000
Australia	12,000,000
Paraguay	2,400,000
China	1,330,000
Kazakhstan	1,200,000
Bolivia	706,000
Uruguay	672,000
Spain	650,000
South Africa	368,000
Venezuela	300,000
France	200,000
Finland	200,000
Chile	180,000
New Zealand	162,000
Colombia	100,000
Ukraine	100,000
Others (estimate)	1,000,000
Total	**105,863,000**

Table 2: Conservation agriculture/no-till by continent (Derpsch, R. and T. Friedrich. 2009)

Continent	Area (ha)	Percent of total
South America	49,579,000	46.8
North America	40,074,000	37.8
Australia & New Zealand	12,162,000	11.5
Asia	2,530,000	2.3
Europe	1,150,000	1.1
Africa	368,000	0.3
World total	**105,863,000**	**100%**

There are many potential ecosystem services associated with the benefits of conservation agriculture. Ecosystem services are natural processes through which the environment produces natural resources that we and other species require for life. Ecosystem services were classified into the following categories of services by the Millennium Ecosystem Assessment (2005). Ecosystem services to which conservation agriculture may make positive contributions are indicated with an upward arrow (↑) in the list below.

Provisioning services

- food (including seafood and game), crops, wild foods, and spices ↑
- water ↑
- pharmaceuticals, biochemicals, and industrial products
- energy (hydropower, biomass fuels)

Regulating services

- carbon sequestration and climate regulation ↑
- soil moisture storage ↑
- regulation of stream flows and groundwater levels ↑
- waste decomposition and detoxification ↑
- purification of water and air ↑
- crop pollination

- pest and disease control ↑
- erosion control ↑

Supporting services

- nutrient dispersal and cycling ↑
- seed dispersal
- primary production ↑

Cultural services

- cultural, intellectual and spiritual inspiration
- recreational experiences (including ecotourism)
- scientific discovery

This rest of this paper reviews the regulating service benefits of conservation agriculture: erosion control, reduced losses of pesticides and nutrients, and particularly water cycle benefits including increased water productivity (more crop per drop), infiltration, percolation, plant available water storage, groundwater recharge, plant available water, and stream baseflow and decreases in peak stream flows and downstream flooding. Concerns that increases in conservation agriculture and resulting water productivity in upland areas will decrease downstream water flows and interfere with existing downstream water rights are also addressed briefly. There is more focus on the potential ecosystem services of conservation agriculture for small-scale farmers in developing countries because the authors have initiated a five-year, $15 million program, the Sustainable Agriculture and Natural Resource Management Collaborative Research Support Program (SANREM CRSP) to research and adapt conservation agriculture production systems for small holders in developing countries. The SANREM CRSP is supported by the U.S. Agency for International Development. More information on SANREM CRSP is available at: http://www.oired.vt.edu/sanremcrsp.

Potential Ecosystem Service Benefits of Conservation Agriculture

Carbon Sequestration and Climate Regulation

One of the most beneficial aspects of conservation agriculture is its ability to increase soil carbon compared with traditional tillage-based agricultural production systems. One of the best studies of the benefits of increasing soil carbon on its potential for carbon sequestration for climate regulation was conducted by Lal (2004), who reported that the carbon sink capacity of the world's agricultural and degraded soils is 50 percent to 66 percent of the global historic carbon loss of 42 to 78 gigatons of carbon and that improved land management practices on the world's agricultural and degraded soils could sequester 50 percent to 66 percent of the historic soil carbon loss. This is equivalent to 0.4 to 1.2 Gt C/year, or 5 percent to 15 percent of global carbon emissions. Lal noted that the rate of increase in the SOC stock, through recommended management practices, follows a sigmoid curve, attains the maximum 5 to 20 years after adoption of recommended management practices, and continues until SOC attains a final equilibrium. Hillel and Rosenzweig (2009) also reported that the conversion to no-till farming increased soil organic carbon by rates varying from 0.1 to 0.7 Mg/ha-yr and, like Lal, indicated that such positive increments cannot be expected to continue indefinitely as well managed carbon depleted soils will tend to approach their natural equilibrium (or C saturation) state within a few decades. Lal (2004) reported similar rates of soil organic carbon sequestration in agricultural and restored ecosystems depending on soil texture, profile characteristics, and climate, which ranged from 0 to 0.15 Mg/ha-year in dry and warm regions, and 0.1 to 1.0 Mg/ha-yr in humid and cool climates.

Provision of Food

Increasing soil carbon has significant positive impacts on soil quality, fertility, and productivity. This is particularly appealing for smallholders in developing countries who have essentially been mining their soils of carbon and nutrients for centuries and millennia in some circumstances and who cannot afford or lack access to agrochemicals and other soil amendments required to help compensate for declining soil quality. Giller et al. (2009) did a critical review of the ability of conservation agriculture to improve agricultural productivity and reduce soil degradation in sub-Saharan Africa. They identified potential short- and long-term positive and negative consequences of conservation tillage on agricultural productivity in sub-Saharan Africa (Table 3) and concluded that available research data on the effectiveness of conservation agriculture in improving agricultural productivity in sub-Saharan Africa is not clear and consistent and that there is an urgent need to identify the ecological and socioeconomic conditions for which conservation is best suited for smallholder farming in sub-Saharan Africa. Critical constraints to increasing agricultural productivity through implementation of conservation agriculture in sub-Saharan Africa include competing uses for crop residues, increased labor demand for weeding, and lack of access to, and use of external inputs (Giller et al., 2009).

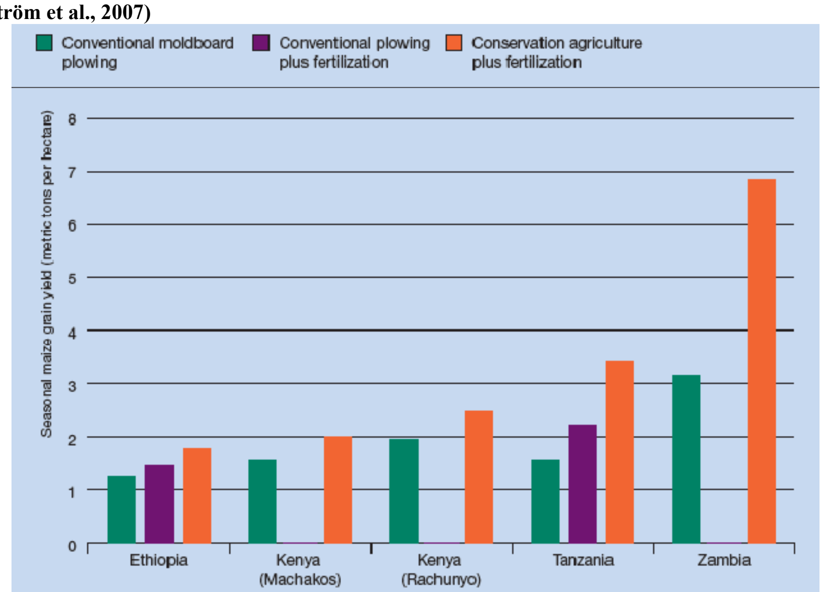
Table 3. Factors determining crop yield responses to conservation agriculture (Giller et al., 2009).

Response	Short-term	Long-term
Positive	Increased soil water availability Reduced soil evaporation Reduced water run-off Increased infiltration Reduced soil temperature oscillations	Reduced soil evaporation Increased soil organic matter Increased soil N mineralization Increased soil aggregation
Negative	Soil nutrient immobilization Poor germination Increased weed competition Occurrence of residue-borne diseases Reduced mixing of organic matter into the soil Stimulation of crop pests	Soil compaction (coarse-textured soils) Soil acidity Aluminum toxicity Waterlogging (poorly drained soils)

Other key findings concerning the potential of conservation agriculture to enhance food production include the following:

- Soil organic carbon levels in many tropical countries have declined to levels of 0.1 percent to 0.2 percent, a level at which soils are so degraded that they cannot effectively utilize applied nutrients or available precipitation (Lal, 2004).
- The critical limit of soil organic carbon concentration for most tropical soils of the tropics is 1.1 percent, where the critical limit is defined as the soil organic carbon concentration required for effective utilization of precipitation and applied fertilizers. See Aune and Lal (1997) for additional details.
- An increase of 1 ton of soil carbon pool of degraded cropland soils may increase crop yield by 20 to 40 kilograms per hectare (kg/ha) for wheat, 10 to 20 kg/ha for maize, and 0.5 to 1 kg/ha for cowpeas (Lal, 2004).
- Rockström et al. (2007) reported that conversion from conventional tillage to conservation agriculture resulted in major improvements in yield and water productivity in parts of semiarid to dry sub-humid East Africa, with a doubling of yields in good years due to increased capture of rainwater (Figure 1).

Figure 1. Maize yield improvements from conservation agriculture in on-farm trials in East Africa (Rockström et al., 2007)



Soil Moisture Storage

Enhanced soil moisture storage has both water resources and agronomic benefits. In a study of gray cracking clay and sandy loam soils in n southeastern Australia (semi-arid Mediterranean-type environment) over 8 to 10 years zero tillage provided an 8-fold and 2-fold increase in surface layer saturated hydraulic conductivity over conventional tillage for clay and sandy loam soils, respectively (Bissett and O'Leary, 1996). Conventionally tilled clay had lower surface layer saturated hydraulic conductivity (K_s) values than conventionally tilled sandy loam soil, but zero-till clay had much higher K_s values than the zero-till loam, suggesting that conservation tillage methods may be more effective for soils that are generally considered to have poor infiltration rates (such as soils with high clay content). In semi-arid and arid regions, rainfall variability and scarcity are significant constraints to agricultural productivity and conservation agriculture would be expected to increase infiltration, soil moisture storage and utilization, and consequently water use efficiency. Unfortunately, in many low rainfall regions with significant dry seasons, it is difficult to maintain an effective soil organic matter cover because of competing uses for cover (livestock forage, fuel, etc.). In these cases, conservation agriculture may not work because removal of the organic cover, even with no-till, results in bare soil and the formation of a soil crust, which decreases the potential for water infiltration. Rockström et al. (2009) evaluated conservation farming strategies for arid and semi-arid agriculture in East and Southern Africa. Yields were higher with conservation agriculture than conventional tillage during drier rainy seasons but there was not much difference in yields during wetter rainy seasons suggesting that conservation farming in savannah agro-ecosystems may foremost function as a water harvesting system, which enhances the ability of crops to bridge dry spells.

Fabrizzi et al. (2005) studied soil water dynamics, physical properties and corn and wheat responses to minimum and no-till systems without fertilization in the southern Pampas of Argentina. They observed greater soil water storage and soil water content with no-till than minimum tillage, with less soil evaporation the reported likely cause of greater soil water content with no-till. Thierfelder and Wall (2009) studied the effects of conservation agriculture compared to conventional tillage on infiltration and soil moisture in Zimbabwe (sandy soil) and Zambia (finer-textured soil) from 2005-2007. The conservation agriculture plots had significantly higher water infiltration than conventional for two seasons in Zimbabwe (49 percent and 45 percent higher), and Zambia (57 percent and 87 percent higher). Most conservation agriculture plots had higher average soil moisture throughout the season. There were no drought years during the study period, but results suggest improved water use efficiency, which would reduce risk of crop failure in low-rainfall years.

Numerous researchers have reported increased soil aggregation, which improves infiltration and soil moisture storage, with conservation agriculture. A field study in Kansas (Mikha and Rice, 2004) assessed the impacts of conventional versus no-till on soil aggregate size and the associated soil carbon and nitrogen. No-till increased soil aggregate size, the proportion of macroaggregates, and had significantly more total carbon, and soil nitrogen. Macroaggregates were found to be more significant in nutrient cycling than microaggregates. In a study of soil aggregation in a clayey Brazilian soil under no tillage or conventional tillage (Madari et al., 2005), significant differences were seen between no-till and conventional tillage in the surface 5 cm of soil. No-till had higher aggregate stability, a larger proportion of macroaggregates, greater soil organic carbon, and more soil organic carbon in macroaggregates. The results suggest that soil carbon contributes to large macroaggregate formation.

Water Productivity

The key principles for improving agricultural water productivity are to infiltrate as much precipitation/irrigation as possible while simultaneously reducing all soil water outflows (e.g. drainage, seepage, percolation, and soil evaporation) and increasing the proportion of crop stomatal transpiration. Conservation agriculture supports this by enhancing infiltration, reducing soil evaporation, and increasing soil water holding capacity for subsequent stomatal transpiration. For conservation agriculture in arid and semi-arid East and Southern Africa, crop yields improved 20 percent to 120 percent, and water productivity increased by 10 percent to 40 percent percent (Rockström et al., 2007).

Soil Erosion

There is no question that conservation agriculture and other forms of conservation tillage drastically reduce soil erosion as this has been documented in hundreds of studies. An interesting question is whether continuous conservation agriculture is necessary to control soil erosion and whether conservation agriculture provides residual protection against soil erosion if tillage is reintroduced. In a study in Mississippi (Dabney et al., 2004), on a silt loam soil comparing no-till and chisel/disc till under corn cultivation, no-till decreased soil erosion significantly while the land was in no-till for 5 to 10 years and for the first year after no-till ended, but a year no-till was abandoned and tillage was reinstituted, the protective effects of the previous no-till were no longer significant.

Nutrient Dispersal and Cycling

Lal (1997) assessed the effects of slope length (10-60m) and tillage method (conventional versus no-till) on soil chemical properties and nutrient loss in runoff in Nigeria. No-till improved soil chemical properties compared to conventional tillage (higher soil organic carbon, total soil N, CEC, Ca, Mg, Bray-I P). Following deforestation, soil under conventional tillage saw steady declines with time in soil chemical properties; however, no-till soils did not experience statistically significant changes. There was significantly less (24 percent to 74 percent) nutrient loss in runoff with no-till than conventional tillage. Powers et al. (2001) reported greater water infiltration with no-till and increased water movement caused more nitrate movement to deeper soil depths. Large inputs of organic matter to soils increased especially the microbial biomass and mineralizable N pools, thereby increasing the N supplying power of soils without greatly increasing inorganic N pools and subsequent N leaching potential. Effects such as these are expected. With respect to surface runoff, conservation tillage should reduce surface runoff and will reduce erosion, which should decrease nutrient losses in surface runoff, with one cravat. If fertilizers and/or manure are surface broadcast, there may be a tendency for nutrients and particularly phosphorus to concentrate at the surface and be more available for transport with what erosion and runoff there is. As a consequence, it may be worthwhile to consider injecting fertilizers below the soil surface.

Conclusion

Experience with conservation agriculture indicates that the short-term interests of the farmers often differ from the long-term interests of society and that the financial benefits that accrue from changes in cultural practices often take a long time to materialize (FAO, 2003). For conservation agriculture, the agronomic benefits may take 3 to five years to materialize. For large mechanized farms, conservation agriculture is an accepted technology that increases agricultural productivity and profitability in many situations and as a consequence its use is rapidly expanding worldwide. Mechanisms are currently under-development to capture carbon sequestration payments from the world carbon market for large farmers but the situation is much more challenging for small holders because of the small land holdings and consequently small quantities of potential carbon sequestration per person, which would result in very high transaction costs per unit of carbon sequestered. The SANREM CRSP and others are working to develop payment mechanisms that are appropriate for small holders and will provide them with incentives to adopt conservation agriculture, particularly during the first few years after adoption when there may not be significant production benefits. It should also be remembered that soil carbon sequestration through conservation agriculture can make significant contributions to short-term carbon sequestration and climate change efforts but it is not a long-term solution to climate change as soil carbon in carbon depleted soils will only be sequestered until soils approach their natural equilibrium soil carbon levels. With good soil management (e.g., conservation agriculture), this equilibrium soil carbon level will be reached within a few decades. In addition to carbon sequestration and improved agricultural productivity, conservation agriculture offer opportunities to enhance many other ecosystems services including erosion control, reduced losses of pesticides and nutrients, and water cycle benefits including increased water productivity (more crop per drop), infiltration, percolation, plant available water storage, groundwater recharge, plant available water, and stream baseflow and decreases in peak stream flows and downstream flooding.

References

Aune, J.B. and R. Lal. 1997. Agricultural productivity in the tropics and critical limits of properties of Oxisols, Ultisols, and Alfisols. Tropical Agriculture 74(2):96-103.

Bissett, M.J. and G.J. O'Leary. 1996. Effects of conservation tillage on water infiltration in two soils in south-eastern Australia. Australian Journal of Soil Research 34(2): 299–308. DOI: 10.1071/SR9960299

Dabney, S.M., G.V. Wilson, K.C. McGregor and G.R. Foster. 2004. History, residue, and tillage effects on erosion of loessial soil. Transactions of the ASAE 47(3): 767-775.

Derpsch, R. 2001. Frontiers in Conservation Tillage and Advances in Conservation Practice. In: D.E.Stott, R.H.Mohtar and G.C.Steinhardt (eds). Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24 -29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory, p 248-254. http://www.tucson.ars.ag.gov/isco/isco10/SustainingTheGlobalFarm/K008-Derpsch.pdf. Accessed 10 January 2010.

Derpsch, R. and T. Friedrich. 2009. Global Overview of Conservation Agriculture Adoption. Paper presented to IV World Congress on Conservation Agriculture New Delhi, India, February 2009. http://www.fao.org/ag/ca/doc/Derpsch-Friedrich-Global-overview-CA-adoption3.pdf. Accessed 10 January 2010.

Fabrizzi, K.P., F.O. Garcia, J.L. Costa and L.I. Picone. 2005. Soil water dynamics, physical properties and corn and wheat responses to minimum and no-tillage systems in the southern Pampas of Argentina. Soil and Tillage Research 81(1): 57–69.

FAO. 2003. Unlocking the Water Potential of Agriculture. Food and Agricultural Organization of the United Nations, Rome. http://www.fao.org/docrep/006/y4525e/y4525e00.htm. Accessed 10 January 2010.

Giller, K.E., E. Witter, M. Corbeels, and P. Tittonell.2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. Field Crops Res. 114 (2009) 23–34.

Hillel, D. and C. Rosenzweig. 2009 Soil carbon and climate change. CSA News 54(6):4-11.

Lal, R. 1997. Soil degradative effects of slope length and tillage method on alfisols in western Nigeria II. Soil chemical properties, plant nutrient loss and water quality. Land degradation and Development 8(3): 221-244.

Lal, R. 2004. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science 11(304): 1623 - 1627. DOI: 10.1126/science.1097396.

Madari, B., P.L.O.A. Machado, E. Torres, A.G. de Andrade and L.I.O. Valencia. 2005. No tillage and crop rotation effects on soil aggregation and organic carbon in a Rhodic Ferralsol from southern Brazil. Soil and Tillage Research 80(1-2): 185-200

Mikha, M.M. and C.W. Rice. 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Science Society of America Journal 68(3): 809-816

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC. http://www.millenniumassessment.org/documents/document.356.aspx.pdf. Accessed 10 January 2010.

Power, J.F., R. Wiese and D. Flowerday. 2001. Managing farming systems for nitrate control: A research review from Management Systems Evaluation Areas. Journal of Environmental Quality 30(6): 1866-1880.

R. Lal. 2009. Enhancing Crop Yield in Developing Countries through Restoration of Soil Organic Carbon Pool in Agricultural Lands. Land Degradation and Development 17: 197–209.

Rockström, J., N. Hatibu, T.Y. Oweis, and S. Wani. 2007. Managing water in rainfed agriculture in Water for Food Water for Life: A Comprehensive Assessment of Water Management in Agriculture. Ed. David Molden. Earthscan, London and International Water Management Institute, Colombo, Sri Lanka. pp. 315-352. http://www.iwmi.cgiar.org/assessment/Publications/books.htm. Accessed 10 January 2010.

Rockström, J., P. Kaumbutho, J. Mwalley, A.W. Nzabi, M. Temesgen, L. Mawenya, J. Barron, J. Mutua and S. Damgaard-Larsen. 2009. Conservation farming strategies in East and Southern Africa: Yields and rain water productivity from on-farm action research. Soil & Tillage Research 103(1):23-32.

Thenkabail, P.S., G.J. Lyon, H. Turral, and C.M Biradar. 2009. Remote Sensing of Global Croplands for Food Security; CRC Press-Taylor and Francis Group: Boca Raton, London, UK, p. 556.

Thierfelder, C. and P.C. Wall. 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil and Tillage Research 105(2): 217-227.