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Conservation Agriculture in Zambia: Effects on Selected Soil Properties and Biological Nitrogen Fixation in Soya Beans (*Glycine max* (L.) Merr)

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Abstract

Conservation agriculture has been promoted in Zambia as a strategy to mitigate some of the negative effects arising from conventional tillage practices. Conservation agriculture offers several potential benefits on soil properties. However, these benefits and impacts vary across agro ecological regions and management practices. This study investigated changes, over time, associated with the practice of conservation agriculture in selected soil chemical, physical and biological properties, including an assessment of the effects on soil respiration, nodulation and biological nitrogen fixation in soya beans (*Glycine max* (L.) Merr). Six paired soil samples were collected from conservation agriculture and conventional tillage fields. Fields under conservation agriculture were 4, 7 and 16 years old while those under conventional tillage had been cultivated for over 18 years. Changes in soil properties due to conservation agriculture practice were determined using published laboratory procedures and compared using the paired t-test at 95% confidence level. The results indicated significantly higher soil pH, soil organic carbon, nodulation and biological nitrogen fixation under conservation agriculture than conventional tillage after seven years of practice. The study also showed significantly higher total porosity, soil microbial biomass, soil respiration and lower soil bulk density after sixteen years of practice. Based on these results, the practice of conservation agriculture has potential to improve crop productivity by improving the different aspects of soil fertility, the length of time before this is realized notwithstanding. Further studies that compare several conservation agriculture systems are recommended in other agro-ecological zones of the country to validate these findings.

Keywords: biological nitrogen fixation, conservation agriculture, soil microbial biomass, soil respiration, soya beans, Zambia

1. Introduction

Agricultural farming systems involving extensive tillage and removal or on site burning of crop residues have hastened, by as much as 2.6 times, the rate of soil erosion and degradation (Verhulst et al., 2010). This depletion of soil fertility has now been associated with low productivity and subsequent decline in food security in Africa (Giller, Witter, Corbeels, & Tittonell, 2009). Even with interventions such as the introduction of high yielding improved varieties, the poor management of the soil has still resulted in persistently low productivity (Hobbs, 2007); in response to this challenge, conservation agriculture (CA) has been promoted in Zambia (Giller et al., 2009).

Conservation agriculture is a farming system based on three principles: 1) minimum soil disturbance, 2) permanent soil cover with crop residues and/ or cover crops; and 3) crop rotations with different plant species which include legumes (Food and Agriculture Organisation [FAO], 2010). In Zambia, the practice of CA by smallholder farmers is characterised by the three principles including minimum tillage (ripping or permanent planting basins), crop residue retention by mulch or incorporation, legume crop rotation and input application in fixed planting stations (Haggblade & Tembo, 2003). Crop residue retention is usually a challenge due to competitive usage as livestock feed. Conservation agriculture fields are usually cropped alongside conventional tillage (CT) fields by some of the farmers.

Already, the practice of conservation agriculture has been reported to bring about positive effects such as improved soil structure, soil water retention and subsequent crop yields (Haggblade & Tembo, 2003; Thierfelder & Wall, 2009; Verhulst et al., 2010). The derived positive benefits of CA practices have, however, been linked to several factors including management, environmental and soil conditions prevailing in different agro ecological regions, type of crop grown and the length of period of practice (Haggblade & Tembo, 2003; Thierfelder & Wall, 2012). The effects of CA on soil biology, a major determinant of soil fertility and productivity in CA farming systems, have not yet been reported in Zambia. The study therefore, evaluated the effect of CA practices on selected chemical, physical and biological soil properties over time. The study determined the effect of CA practices on soil pH, soil organic carbon, total nitrogen, total sulphur and available phosphorus. The study also evaluated the effect of CA practices on soil bulk density and total porosity. The effects on soil biology were determined by measuring soil microbial biomass, soil respiration, and nodulation and biological nitrogen fixation of a soya bean crop. More insight into the effects of CA practices on soil properties could provide fundamental information on the effectiveness of CA in Zambia.

2. Method

The study was conducted in two stages; the first stage involved the collection and characterization of soil samples from fields under conservation agriculture and adjacent conventional fields. Stage two was a greenhouse experiment to assess the nitrogen fixation capabilities of soya beans in response to CA practice over time.

2.1 Study Area Description

Soils used in the study were collected from Kafue District, about 45 km from Lusaka, Zambia. The area receives an average annual rainfall of 800-1000 mm with temperatures ranging from 23-32 ºC. The soil type was classified as a chromi-haplic Luvisol (Soil Survey Section Research Branch, 1991).

2.2 Soil Sampling and Characterization

Soils were only collected from CA fields that were adjacent to conventional fields. This was in order to minimize the effects of natural soil variation in fields located far away from one another. A composite sample of 12 sub-samples was collected. Paired soil samples in replicates of six (6) were collected from three sites at a depth of 0-20 cm. A pair consisted of one sample from a CA field and another from a conventional field. Samples from CA fields were of 4, 7 and 16 years age categories while those from conventional fields had been cultivated for over 18 years. Soil samples in replicates of six (6) were then subjected to chemical, physical and biological characterization. The soil samples were analysed for soil pH (Mclean, 1982), total nitrogen (Bremner & Mulvaney, 1982), available phosphorus (Olsen & Sommers, 1982), total sulphur, soil organic carbon (Rhodes, 1982) and exchangeable bases (K^+, Na^+, Ca^{2+} and Mg^{2+}) (Thomas, 1982). The samples were also characterized for soil bulk density (Core Ring method), total porosity, microbial biomass (Kassem & Nannipieri, 1995) and texture (Day, 1965).

2.3 Greenhouse Experiment

The greenhouse experiment arranged in a Completely Randomized Design was set up with the following treatments: 4 years, 7 years and 16 years replicated six (6) times. A promiscuous soya beans variety (Magoye) and a reference, pearl millet crop (Lubasi) were planted in pots with six kilograms of soil. At ten days from germination, the crops were thinned to one plant per pot. The crops were allowed to grow for eight weeks after which they were uprooted and nodulation per plant determined by physical counting of nodules on the soya beans crop. Tissue nitrogen from both soya beans and pearl millet crops was determined from the harvested plant biomass followed by determination of total nitrogen fixed using the Nitrogen Difference Method (Unkovich et al., 2008).

2.4 Statistical Analysis

The results of the soil characterization, nodulation and tissue nitrogen were analyzed using a paired t-test to compare CA and CT at 95% confidence level. Statistical analysis was done using SAS Package Version 9.1.

3. Results

3.1 Effect of Conservation Agriculture on Soil Chemical Properties

3.1.1 Soil pH

Soil pH ranged from 5.86 to 6.54 and 5.57 to 5.69 in CA and CT soils, respectively. Results indicated significant differences in soil reaction between conventional tillage and conservation agriculture at $P \leq 0.05$ at 7 and 16 years (Table 1). The soils from CA plots had a higher pH average 6.18 than the CT (5.62). The results also suggested an increase in pH over the years.

Table 1. Soil pH in conservation agriculture and conventional tillage systems

Age CA Site	CA	CT	*p*-value
4 years	5.86	5.57	0.0728
7 years	6.14	5.60	0.0095
16 years	6.54	5.69	0.0001

3.1.2 Soil Organic Carbon (SOC) and Total Nitrogen (N)

The amounts of SOC followed a similar trend as the soil pH (Table 2); there were significant differences in the SOC contents between CA and CT soils at 7 and 16 years, but not at 4 years. Across the years, SOC under CA was higher than in CT ranging from 1.54 to 1.87%. There was a general increase in SOC under CA over time, while the reverse was true for CT (1.57 to 1.38).

For total N, significant differences were observed at 4 and 16 years (Table 2). Soils under CA had more total nitrogen than those under CT. There was no observable trend over time in the accumulation of total nitrogen under CA, but there was a reduction in N under CT with age.

Table 2. Soil organic carbon and total nitrogen in conservation agriculture and conventional tillage systems

Age CA Site	CA	CT	*p*-value	CA	CT	*p*-value
		SOC (%)			Total N (%)	
4 years	1.54	1.57	0.784	0.23	0.19	0.0163
7 years	1.56	1.39	0.0371	0.18	0.15	0.1447
16 years	1.87	1.38	0.0001	0.25	0.13	0.0001

3.1.3 Available Phosphorus (P) and Total Sulphur (S)

Levels of available P ranged from 5.65 to 15.59, and 3.35 to 3.84 mg/kg in CA and CT soils, respectively. Available P was higher in CA than CT but these differences were only significant at 4 and 7 years. P levels in soils under CA reduced with age such that the 16 year old site had the lowest available P; no relationship between soil pH and available P level was observable. No statistical differences were observed in total S between the CA and CT systems at the different years; however, across the years, CA had higher total S than CT. The levels of total S ranged from 16.20 to 26.09 and 11.92 to 20.10 mg/ kg, in CA and CT soils, respectively.

Table 3. Available phosphorus and total sulphur in conservation agriculture and conventional tillage systems

Age CA Site	CA	CT	*p*-value	CA	CT	*p*-value
	Available P (mg/kg)				Total S (mg/kg)	
4 years	15.59	3.38	0.0209	26.09	20.10	0.3401
7 years	11.39	3.35	0.0361	17.57	11.92	0.0573
16 years	5.65	3.84	0.0973	16.20	17.26	0.7982

3.2 Effect of CA Practice on Soil Physical Properties

3.2.1 Soil Bulk Density and Total Porosity

Table 4 shows the results of soil physical characterization. Soil bulk densities ranged from 1.14 to 1.38 and 1.32 to 1.42 g/cm^3 in CA and CT soils, respectively; even if CA soils had lower bulk densities than CT significant differences were only at 16 years. Bulk density also reduced with the age of the CA plot with the 16 years site having the lowest.

Results show that the differences in porosity between the CA and CT soils were only significant at 16 years (Table 4) even if CA soils had consistently higher porosities at all ages.

Table 4. Soil bulk density and total porosity in conservation agriculture and conventional tillage systems

Age CA Site	CA	CT	*p*-value	CA	CT	*p*-value
		Bulk Density (g/cm^3)			Porosity (%)	
4 years	1.38	1.42	0.1001	47.50	45.75	0.0556
7 years	1.27	1.32	0.1423	51.38	49.50	0.1863
16 years	1.14	1.36	0.0001	57.88	48.00	0.0001

3.3 Effect of CA Practice on Biological Properties of Soils

3.3.1 Soil Microbial Biomass-C and Soil Respiration

Soil microbial biomass-C ranged from 0.65 to 3.47 and 0.50 to 0.58 mg/ g in CA and CT soils, respectively. Soil microbial-C was higher in CA than CT soils but differences were only significant at 16 years (Table 5).

Table 5. Soil microbial biomass and respiration in conservation agriculture and conventional tillage systems

Age CA Site	CA	CT	*p*-value	CA	CT	*p*-value
		Microbial biomass-C (mg/g)			Total Soil respiration-CO_2	
4 years	0.65	0.50	0.3425	4.66	4.43	0.2463
7 years	0.80	0.58	0.3046	5.38	5.15	0.4024
16 years	3.47	0.58	0.0005	10.76	4.77	0.0001

A similar trend to what was observed in microbial biomass was observed for soil respiration (Table 5); soil respiration was higher in CA than in CT soils. Statistically significant differences at $P \leq 0.05$ were observed only at 16 years between the two farming systems. In general, both soil microbial biomass-C and respiration-CO_2 increased with number of years under CA.

3.4 Nodulation and Biological Nitrogen Fixation (BNF)

Results showed significant differences in the number of nodules per plant (Table 6) among all the paired samples and the number of nodules increased with age of the CA site. It was also observed that the nodules per plant were bigger in CA than in CT soils (Figure 1).

Table 6. Nodulation and biologically fixed nitrogen (BNF) in conservation agriculture and conventional tillage systems

Age CA Site	CA	CT	*p*-value	CA	CT	*p*-value
		Nodules /plant		Total Biologically Fixed N (%)		
4 years	23	11	0.0001	0.80	0.85	0.8054
7 years	24	10	0.0001	1.22	0.42	0.0002
16 years	49	9	0.0001	1.64	0.72	0.0007

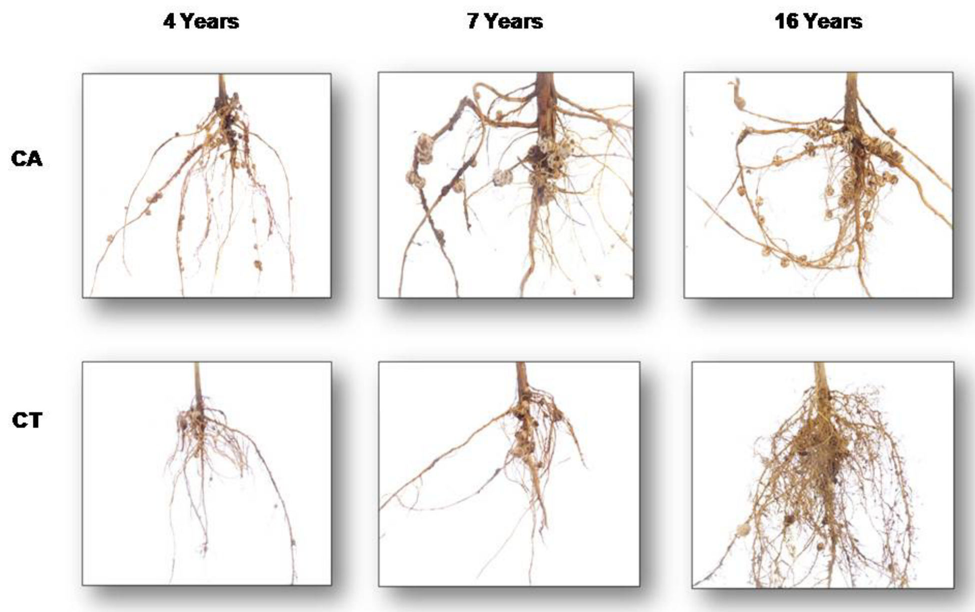

Figure 1. Nodules on soya beans roots in 4, 7 and 16 years CA and CT soils at 8 weeks after planting

The amount of biologically fixation nitrogen ranged from 0.80 to 1.64 and 0.42 to 0.85% in soya beans grown in CA and CT soils, respectively. At 7 and 16 years, the amount of fixed N was significantly higher in CA than in CT (Table 6). The biologically fixed N was higher by 190 and 127% in CA compared to CT in 7 and 16 year old CA soils, respectively.

4. Discussion

The observed differences between CA and CT at 7 and 16 years and the increase in soil pH in CA soils over time show that CA practices can reduce soil acidification. The differences between CA and CT soils in pH and organic carbon followed a similar trend, suggesting a possible relationship between the two soil properties. Earlier findings by Umar, Aune, Johnsen and Lungu (2011) and Duiker and Beegle (2006) attributed the upward changes in pH to the buffering effect of accumulated soil organic matter under CA.

In this study, all the CA soils had SOC amounts above the critical limit of 1.5% for crop productivity (Fairhurst, 2012), while only one CT soil was above that limit. However, differences between SOC contents in CA and CT soils were only significant at 7 and 16 years and not at 4 years. Studies by Umar et al. (2011) also showed that soils from 5 year old CA trials in Eastern, Southern and Central provinces of Zambia did not accumulate significantly higher amounts of SOC compared to CT soils. Both of these observations suggest the existence of a minimum length of time for sufficient SOC to accumulate. Higher SOC in CA than CT can be attributed to crop residue retention and non-incorporation of residues into the soil (Dolan, Clapp, Allmaras, Baker, & Molina, 2006). Incorporation of crop residues in CT systems hastens decomposition and mineralization of soil organic matter leading to carbon loss, while the practice of CA promotes organic carbon stabilization (Umar et al., 2011).

Addition of crop residues, a characteristic of CA systems, is associated with increased total soil N (Govaerts, Sayre, Lichter, Dendooven, & Deckers, 2007). The results in this study are contrary to the report by Umar et al. (2011) who did not find any significant differences in the amounts of total N between CA and CT after five years of CA practice. In this study, CA soils had higher total N levels compared to CT but the levels of N were lower than the optimal amount (0.25%) needed for plant growth (Tisdale, Nelson, & Beaton, 1985). Nitrogen is essential in plant nutrition and is required in large amounts. Its levels in the soil provides a good indication of soil fertility.

The results show that available P was more in CA than CT soils at 4 and 7 years and that P levels declined over time. This decline in P resulted in levels far below the optimum level (10 mg/kg) for plant growth (Shitumbanuma & Banda, 2004) at 16 years. The results of this study show non-significant differences for total S. Previously, Tsuji et al. (2005) reported that total sulphur in soil is primarily regulated by the amount of organic carbon because 95% of total sulphur in arable soils is in organic form. Such a relationship between the amount of organic carbon in CA and total sulphur could not been found in this study, if anything, while the SOC content increased over time, the amount of total S declined. The study by Tsuji et al. (2005) also showed that Zambian soils have relatively low levels of total S from 110 to 150 mg/kg. The levels obtained in this study were far much lower than this. Sulphur like any other nutrient is important for plant growth. It is a structural component of proteins, peptides and various enzymes. Sulphur deficiency, therefore, negatively affects the quality and yield of crops.

Results from this study show that the practice of CA can influence soil pH, SOC, total N, total S and available P positively. The effects of CA on selected chemical properties are evident generally after 7 years of practice, even if total N and available P levels are higher in CA even at 4 years. Although total N improved with time of CA practice, the levels remained far below the critical limits for crop production, an indication that perhaps either longer periods of CA are necessary before the levels increase to meet crop requirements or that accumulated amounts are taken up by plants and that cumulative levels do not go beyond the critical limits.

Conservation agriculture not only influences the chemical and biological properties of the soil, but also affects the physical properties such as bulk density and porosity (Verhulst et al., 2010). In this study, bulk density was lower in CA than in CT soils at 16 years and across age. These results mirror those of Li, Wu, Li, Wang and He (2007) who found lower bulk densities in the 0-20 cm soil depth in a study in northern China. Conservation agriculture practices of residue retention/cover crops promote soil organic carbon accumulation in the upper layers of the soil profile (Hobbs, 2007). Separate studies conducted by Shaver et al. (2002) and Blanco-Canqui and Lal (2007) found that cropping systems that returned more crop residues were less compacted and more porous. Soil organic carbon plays an important role in maintaining a good soil physical structure through increased soil particle aggregation which ultimately results in lower bulk density. Bulk density measurements are an indicator of soil compaction; it is an indicator of problems of root penetration and soil aeration. Values above 1.45 g/cm^3 are quoted by Brady (1990) as causing hindrance to root penetration. Nevertheless, soils from both CA and CT had bulk densities in this study were below 1.45 g/cm^3, suggesting that there was no plant root growth impairment at the time of soil sampling. Apart from promoting a good plant root soil relationship, lower bulk densities in the CA systems may promote aeration and water movements which ultimately enhance crop productivity. In this study, total porosity for all the soils was within the desirable range of 40-60% for soil water percolation and easy penetration of plant roots.

While changes in some of chemical properties were observable at as early as 4 years of CA practice, measured physical characteristics were only significantly different at 16 years. This might suggest that physical properties do take longer to change as a result of soil management when compared to chemical properties.

Soil microbial biomass represents about 2-7% of the organic matter in the soil. Soil organisms are dynamic and sensitive to soil management practices such as tillage, residue retention, crop rotation, fertilizer and pesticides application. In this study, soil microbial biomass-C was measured as an indicator of the changes in soil biology due to soil management; results indicated higher microbial biomass-C in CA soils than the CT although significant differences were only at 16 years. Alvear et al. (2005) reported higher microbial biomass under reduced tillage compared to conventional tillage in southern Chile. Results were attributed to higher levels of C substrates, better soil physical conditions and moisture needed for microbial growth. Substrate (organic C) availability from plant biomass is generally considered the dominant factor controlling the amount of microbial biomass in the soil (Campbell, Janzen, & Juma, 1997). Franzluebbers, Haney, Hons and Zuberer (1999) demonstrated that as the amount of organic C increases or reduces due to changes in C input to the soil, the microbial pool also expands or contracts. The results from this study confirmed the findings of Franzluebbers et al. (1999); microbial biomass was higher in the 16 year CA soil that had the highest organic C of 1.87%. Therefore, the long term CA practices of residue retention/cover crops and reduced tillage that promote organic matter (organic C) accumulation are beneficial to soil microbes and the processes they mediate.

Soil respiration followed a similar trend as microbial biomass. The rate of soil respiration under optimum temperature, aeration, moisture and available nitrogen is generally limited by the supply of organic matter (Araujo, Leita, Santos, & Carneiro, 2009). CA practices, such as residue retention, legume crop rotation and/or cover crops, reduced tillage or any other practices that promote organic matter accumulation in the soil will increase soil respiration holding other factors optimum. These practices provide a more stable system by balancing losses with organic matter additions (United States Department of Agriculture [USDA], 1998). Soil respiration is also an important indicator of soil fertility; it reflects the level of microbial activity, soil organic matter content and its decomposition (USDA, 1998). Higher respiration rates in CA system entail increased availability of nutrients to plants, therefore, offers a potential for improved crop productivity compared to the conventional system.

The higher number of nodules per plant and subsequently higher biologically fixed nitrogen in soya beans grown in 7 and 16 year old CA than CT soils could be attributed to improved soil conditions that provide a conducive environment for both the host plant and rhizobia for a symbiotic relationship. Improved soil properties such as increased soil porosity, higher carbon content, increased pH and better chemical fertility status observed in this study could be contributing factors to the better nitrogen fixation capabilities observed in soya beans. These results agree with findings by Laudicina et al. (2011) who showed higher BNF in soya beans grown under CA than under conventional practice in southern Brazil. In addition to other soil properties, the results were attributed to a relatively cooler rhizosphere environment leading to enhanced activity of rhizobia.

While changes in soil respiration and microbial biomass-C were observable only at 16 years, the response of the crop (with respect to nitrogen fixation) to CA practice was observed as early as 7 years. This suggests that changes to soil properties take place over a long period but crop response to CA maybe faster.

It can be concluded that the practices of conservation agriculture of residue retention/cover crops, reduced tillage and legume crop rotation have positive effects on the investigated soil properties. These practices increase soil pH, soil organic carbon, total nitrogen, and total porosity, and reduce soil bulk density compared to conventional tillage. The study also shows that conservation agriculture practices ultimately promote soil microbial population and activity as evidenced through increased microbial biomass, soil respiration, nodulation and biological nitrogen fixation. However, the soil improvement benefits of conservation agriculture practices become evident after at least 7 years of practice and for some, it can take as long as 16 years. Further field studies that compare several conservation agriculture systems are recommended in other agro-ecological zones of the country to validate these findings.

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