Conservation Agriculture and Soil Fertility Improvements: Indications from Smallholder Farmers in Chafukuma, Solwezi, Zambia

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ABSTRACT

Introduction: This study assessed the effects of conservation agriculture (CA) practices on soil fertility of smallholder farmers' agricultural fields in Chafukuma, North-western Zambia.

Materials and Methods: A total of 34 paired soil samples from adjacent agricultural fields in which CA and conventional agriculture (CV) had been practised for at least five years were analysed for significant differences in plant-available phosphorus (P), exchangeable potassium (K), total nitrogen (N), soil organic carbon (SOC) and soil reaction (pH). Smallholder farmers' CA practices and their perceptions of CA's effects on soil fertility were investigated through 34 semi-structured interviews. Secondary data on CA were collected through desk analysis of CA publications.

Results: The study found out CA-associated improvements in soil fertility (T_{calc} = 4.520, p < 0.0001). This improvement was attributed to the consistent use of good agronomic practices in CA fields, whereas these practices were mostly absent from CV fields.

Conclusion: The study concluded that CA improved soil fertility in agricultural fields of smallholder farmers in Chafukuma could be promoted in CA systems in other high rainfall areas of Zambia provided all the important agronomic practices are utilised consistently. Most CA-associated agronomic practices could also be extended to CV fields successfully.

Keywords: *conventional agriculture, crop residue retention, crop rotations, Kansanshi Foundation, minimum tillage*

INTRODUCTION

Conservation agriculture (CA), comprising minimum soil disturbance, retention of crop residues and crop diversification, is widely promoted for reducing soil degradation and improving agricultural sustainability [1]. Although a substantial amount of research on CA practices in Sub-Saharan Africa (SSA) has been conducted in the last two decades [2, 3, 4, 5, 6, 7, 8, 9, 10], there are still knowledge gaps and debates on how different aspects of soil fertility are affected by CA practices under the region's highly diversified soil and agro-ecological conditions. Tittonell *et al.* [11] contended that little was known about CA's potential to increase productivity and reduce soil degradation within the smallholder farming systems of Southern Africa, where small and fragmented landholdings are common, and the farming systems are generally more complex [11, 12]. Govaerts *et al.* [4] noted that CA improved soil fertility, associated with the build-up of organic carbon in the soil, although the amount and the time needed to reach appreciable amounts of soil organic carbon vary significantly between sites and cropping systems. A recent review of CA advances in Southern Africa concluded that physical, chemical and biological soil parameters had been improved under CA in the medium to long term, and CA benefits could potentially reduce future soil fertility declines [11].

Conversely, in a global meta-analysis of the effects of CA on soil carbon contents, Luo *et al.* [13] found out that cultivation of natural soils for more than 5 years, on average, resulted in soil carbon loss of more than 20 tons/ ha, with no significant difference between conventional tillage and no-tillage. Furthermore, conversion from conventional tillage to no-tillage changed the distribution of carbon in the soil profile significantly but did not increase the total soil organic carbon except in double-cropping systems [13]. A meta-analysis of soil organic carbon stock changes in SSA revealed increases of between 0.28 and 0.96 Mg C ha^{-} yr^{-}, but with much greater variation and a significant number of cases with no measurable increase. Most reported soil organic carbon stock increases under CA were overestimated because of errors introduced by inappropriate soil sampling methodology [1].

Previous research done in Central, Southern and Eastern provinces of Zambia on the effects of CA on soil fertility of agricultural fields managed by smallholder farmers did not find any significant effects [9, 14, 15]. Notably, the studies were from low to medium rainfall areas of Zambia and from smallholder agricultural systems dominated by mixed crop-livestock systems, which precluded the retention of crop residues on agricultural fields.

CA promotion efforts since the early 1990s have increasingly also included the high rainfall areas of the northern part of Zambia. The literature review during the current study did not reveal any previous soil fertility and CA research from these high rainfall areas. Despite this dearth of empirical evidence, many organisations have continued promoting CA as a strategy for improving the soil fertility of agricultural fields in Zambia's high rainfall areas. This is problematic for several reasons; it could potentially result in a misallocation of scarce resources if the CA practices cannot mitigate poor soil fertility. By focusing on CA, which is essentially an untested intervention, research into other (more effective) solutions for the challenge of soil fertility is not prioritised. Given the differences in the biophysical setting, the high rainfall areas may present opportunities for mitigating challenges that have characterised CA practice in the low rainfall areas. These include the low biomass production from crops and the concomitant shortages of crop residues needed as a soil cover [14, 15]. CA promotion in high rainfall areas could also present new challenges such as waterlogging of fields, increased weed pressure [16] and nutrient leaching. To address this knowledge gap, this study assessed the effects of CA practices on soil fertility of smallholder farmers' agricultural fields by analysing and comparing soil samples for plant-available P, exchangeable K, total N, SOC and soil reaction (pH) in CA and CV managed agriculture systems in Chafukuma in North-western Zambia. The hypothesis tested was that there are statistically significant differences in the mean levels of plant-available phosphorus (P), exchangeable potassium (K), total nitrogen (N), soil organic carbon (SOC), and pH between the soil in CA and CV managed agriculture fields.

MATERIALS AND METHODS

Site description

Soil samples analysed in this study were collected from fields of smallholder farmers in Chafukuma located 50km north-east of Solwezi district in the North-Western province of Zambia (Figure 1). Chafukuma experiences three seasons, namely, the cold-dry season, which is from April to August; the hot-dry season from September to October and the hot-wet season from November to March. The area receives a mean annual rainfall of 1400mm with temperatures ranging from 23ºC to 32ºC [17]. Chafukuma has the Oxisol red clays type of soils, which are highly leached, strongly acidic (pH 4.2) with low nutrient reserves, low nutrient retention capacity and severe aluminium and iron toxicity [18] due to high rainfall conditions [19].

Owing to these conditions, the soil is generally infertile for crop production and requires liming [20]. The crop growing period is between 120 and 150 days [20]. The area is characterised by woodlands type of vegetation dominated by *Brachystegia* species such as *Brachystegia spiciformis L, Brachystegia boehmii L, Burkea Africana L, Parinari curatellifolia L, Uapaca kirkiana L, Afzelia quanzensis L, Pericopsis angolensis L, Pterocarpus angolensis L,* to name but a few [22, 23].

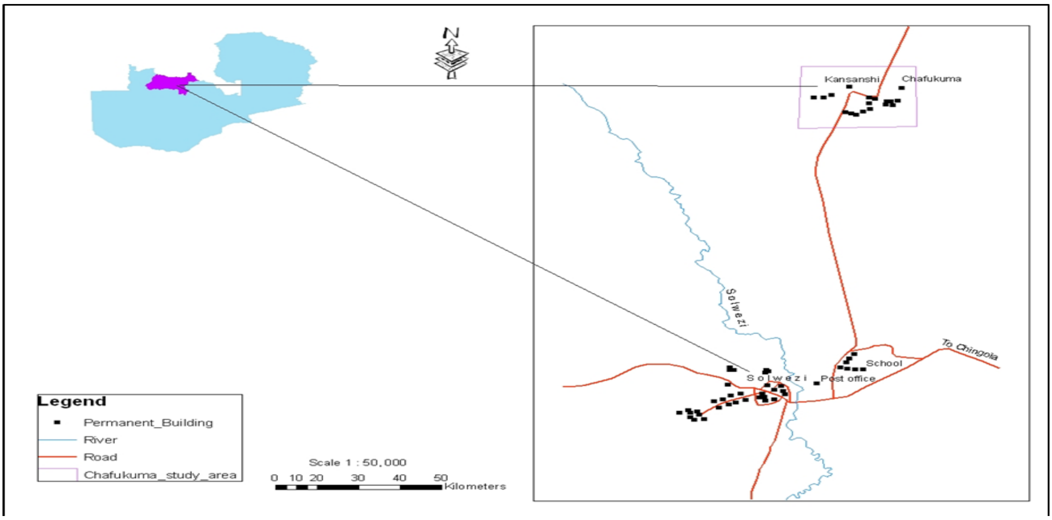

Figure 1: Location of Chafukuma of Solwezi in Zambia

The two major economic activities in the area are smallholder agriculture and copper mining. The major crops grown are maize (*Zea mays L*), groundnuts (*Arachis hypogaea L*), sorghum (*Sorghum bicolor L*), cassava (*Manihot esculenta L*), common beans (*Phaseolus vulgaris L*), finger millet (*Eleusine corocana L*), bulrush millet (*Pennisetum typoides L*) and sugarcane (*Saccharum spp.*). Smallholder farming households sell beans, sugar cane and maize. Chafukuma is home to Kansanshi Mine, Zambia's largest mine, where some of the locals are employed in low skill positions such as machine operators, cleaners, spotters, labourers and drivers.

Sampling Technique

Fieldwork for this study was conducted between December 2015 and April 2016. Soil samples were collected from fields that had been cultivated for at least five years using CA practices and adjacent fields cultivated using conventional agriculture (CV) practices. This was to minimise the effects of natural soil variation in fields located far away from one another. Views of smallholder farmers and agricultural development officials on the soil fertility improving benefits of CA were collected using questionnaires and interview guides, respectively. Interview guides consisted of questions on soil fertility management and CA. These questions were asked to experts from the Ministry of Agriculture and Chafukuma Development Trust. The use of interview guides aided the collection of information from key informants that had worked in the agricultural sector in the area and had comprehensive knowledge of CA. Field observations were made on tillage types, crops grown and crop residue management. A desk study of publications on soil fertility and CA was also conducted. A *Google Scholar* search of publications on CA in the past ten years was conducted, and the results were analysed. Publications related to soil fertility management under CA were reviewed. A post-test only control group research design was employed in this study. In this design, the chemical soil fertility of two groups, the experimental and comparison groups, were compared. The CA fields that had been cultivated for at least five years were the experimental group, while the adjacent CV fields were the comparison group. CV fields are those tilled using conventional tillage methods such as ridging, ploughing or flat culture, which involve complete soil inversion using a hand hoe, mouldboard plough or tractor. Soil samples were only collected from basins in CA fields and CV fields that had been tilled using hand-hoes. Soil samples were taken from inside the basins (and not the inter-basin spaces) because inputs are placed inside basins. Thus, any effect of CA practices on soil fertility would be evident there.

Conventional agriculture (CV) in the Zambian context is any farming method that involves complete soil inversion using a hand hoe or the mouldboard plough [14]. CA involves two subsystems distinguished by tillage implements: basin digging and ripping. Ripping involves using either ox or tractor drawn ripper to make rip furrows across the prevailing slope at 90cm to 100cm spacing. Crop residue retention, nitrogen-fixing crop rotations and cover cropping, dry-season land preparation and precise input application are other practices under this system. These are the conceptualisations of CV and CA adopted in this study.

Soil sampling

A total of 34 smallholder farmers out of the target population of 180 that had been involved in CA with Kansanshi Foundation in the area since 2010 were randomly selected and soil samples were obtained from their CA and CV fields. These farmers engaged in both CA and CV. This sample size was arrived at using *a priori* power analysis with the aid of the software G Power 3.1.9 [21]. The sample size of 34 provided statistical power of 0.81 for detecting moderate effect size at the (two-tailed) 0.05 level of significance [22]. A paired sample was obtained from the fields of each of the 34 smallholder farmers sampled. They all had fields under CA and CV. Soil samples were taken from 0cm to 20cm depth from each of the 34 paired samples of CA and CV fields using a soil auger. Ten soil sub-samples were taken at 10m intervals (determined by measuring tape) starting with a randomly selected point across the traverse from each sampled field and were thoroughly mixed to obtain a composite sample. The soil samples were air-dried and finely ground before being stored in polythene bags. Soil sample collection from the field was done in the first week of April 2016, a transition period from the wet to the dry season, when the soil in the fields was still soft. The soil samples were tested for soil organic carbon (SOC) [23], pH [24], total nitrogen [25], exchangeable potassium [26] and plant available phosphorus [27]. These parameters are essential in determining the fertility of the soil.

Field Observations and Interviews

Field observations were conducted on tillage practices, crop residue retention, crops planted under CA and CV tillage systems during fieldwork. This information was also captured from two study visits to smallholder farmers' fields during farmer field days. Data on perceptions of smallholder farmers were collected through interviews. A total number of 34 structured interviews were conducted with the smallholder farmers from whose fields the soil samples had been collected. The 34 smallholder farmers were individually interviewed in their local languages (*KiiKaonde, Luvale and Lunda*). Three key informant interviews with purposefully selected Kansanshi Foundation and Ministry of Agriculture field officers were also conducted. The key informant interviews were employed to get local experts' opinions on CA from the CA promoters and the Ministry of Agriculture.

Data Analyses

Paired T-Test was used to compare the chemical soil fertility statuses of CA and CV fields at (two-tailed) 95 per cent confidence level using the Statistical Package for Social Sciences (SPSS) Version 20 software (IBM Corporation, 2010). The quantitative data from the farmer interview results were analysed using simple descriptive statistics such as the mean and standard deviation using the same statistical software. The qualitative data from key informant interviews and farmer interviews were analysed for common themes. Responses belonging to one theme were grouped, and their frequency of occurrence was noted and reported as percentages. This indicated how particular prevalent views were among the respondents.

RESULTS

Soil analysis of conservation agriculture and conventional agriculture fields

The soil analyses results for the sampled CA and CV fields are presented in Table 1. The levels of nutrients were higher in CA than CV managed fields, as was the pH.

Field observations

Minimum tillage, crop residue retention, crop rotations and no burning of crop residues were observed in all the CA fields but were absent in 60 per cent of the CV fields. This was despite the fact that every farmer interviewed had fields under CA and CV. The farmers focused on retaining crop residues in their CA fields more than their conventionally farmed fields.

All the CA fields observed had manually dug potholes instead of the prescribed basins. "Potholes" are smaller than basins. The "potholes" were 30cm wide and 20cm deep interspaced in a 60cm by 75cm matrix resulting in 22, 222 "potholes" per hectare. They covered a total area of 1, 555.5m^2 per hectare resulting in 16 per cent of the area being mechanically disturbed due to tillage. Prescribed basins should have dimensions 30cm length, 20cm depth, and 15cm width interspaced in a 70cm x 90cm matrix. This results in 15, 850 basins per hectare and mechanical soil disturbance of 7 per cent. Most of the CA fields that were observed had

Table 1: Soil Analyses Results from CA and CV Fields in Chafukuma in Zambia

Nutrient	**CA Field** Mean (n=34)	**Status**	**CV Field** Mean(n=34)	**Status**	**Paired T-Test** (95% CI) results
Total N (%)	0.96	High	0.23	Low	t =19.878 p= 0.0001*
SOC (mg/ha)	0.93	High	0.43	Low	t= 28.59 p = 0.0001*
P (mg/kg)	*26.09*	High	21.29	High	t= 4. 720 p= 0.0001*
K (cmol/kg)	11.97	High	8. 74	High	t= 8. 787 p=0.0001*
pH(1-14)	5. 49	Slightly acidic	5. 19	Slightly acidic	t= 4.520 p= 0.0001*

** Statistically significant at $p \leq 0.05$. The statuses were guided by average figures for the Tropics (Landon, 1984; Aune & Lal, 1997)* substantial crop residues retained by the farmers (Figure 2). The farmers explained that they retained crop residues in their CA fields because this is what they had been trained to do by CA promoters. Crop residue retention is one of the three principles of CA and is thus emphasised in CA promotional messages.

Maize was the major crop grown in most of the CA and CV systems observed. Soya beans were also grown on smaller portions of the same field (Figure 3). Over 60 per cent of the CV fields were dominantly maize fields. Urea fertilizer (46% N) and agricultural lime were applied to both CA and CV fields at the rates of 100 kg/ha and 200 kg/ha, respectively. Most of the fields observed had good maize, and soya bean stands (Figure 3).

Figure 3: Soya Beans grown in rotation with Maise in CA field in Chafukuma, Zambia

Results from interviews with farmers and key informants

The interviewed smallholder farmers, Kansanshi Foundation and Ministry of Agriculture field officers all claimed that

Figure 2: Crop Residue Retention in CA Maize Field in Chafukuma in Zambia

CA improved the soil fertility of fields in Chafukuma. All the smallholder farmers claimed that average maize yields of around 8 tonnes/ha were achieved under the CA system compared to only about 1.6 tonnes/ha from CV systems. All the farmers claimed that the colour of leaves, state of stems and roots of their crops were better in CA compared to CV fields.

When the farmers were asked to give their perceptions of the soil fertility of their CV fields, 11.8 per cent claimed it was high, 8.8 per cent claimed it was medium, while 79.4 per cent claimed it was low. When the same farmers were asked to mention the practices they had been using on their CV fields in the last two years, 26.5 per cent claimed they had stopped burning crop residues, 65.5 per cent mentioned burning crop residues, and liming 8.0 per cent did not use any lime. When the smallholder farmers were asked to suggest what they felt could be done to improve the soil fertility of their CV fields, all of them mentioned that they needed to adopt CA practices such as crop rotation, minimum tillage and crop residue retention on these fields too. Field observations found evidence of some of the farmers (about 11.0 %) retaining crop residues in their CV fields.

DISCUSSION

The observed statistical differences in the amount of the analysed selected chemical soil fertility variables between CA and CV fields (Table 1) suggest that CA practices can improve the chemical soil fertility as well as reduce soil acidity in high rainfall areas of Zambia. The soil analysis results suggest that all the soils sampled were slightly acidic pH (5.49 to 5.19). This slight increase in pH in CA fields could not be attributed to liming but the buffering effect of accumulated soil organic matter under CA. The use of agricultural lime was a common practice in both the CA and CV systems because the soil in the study area, being a high rainfall area, was inherently strongly acidic with an average pH of 4.2 [19].

The differences in the SOC content between CA and CV soils (0.5Mg C per hectare) were statistically significant (Table 1). A meta-analysis of SOC stock changes under CA practices conducted in Sub-Saharan Africa (SSA) found annual increases in SOC stock of between 0mg and 1.8mg C per hectare per year [3]. While appreciating debates suggesting longer periods of over five years for sufficient SOC to accumulate in CA fields [14]. The results of this study suggest that even in five years, sufficient accumulation of SOC can still be achieved provided farmers correctly and consistently apply the recommended CA agronomic practices. Previous research from low rainfall areas [14, 28] did not find significant improvements in soil fertility after four to five years of CA practice. The low levels of SOC in CV fields could be attributed to the burning and removal of crop residues from the fields [14], while the high levels of SOC in CA fields could be attributed to crop residue retention [29, 30]. Incorporating crop residues in CV fields speeds up decomposition and mineralisation of soil organic matter leading to carbon loss, while the retention of crop residues in CA promotes organic carbon stabilisation [4].

For nitrogen (N), the soil analyses results indicate that the CA fields had sufficient nitrogen; all samples from the CA fields were above the critical levels (0.25%) needed for plant growth and crop production [31, 32, 33]. Retention of crop residues, a characteristic of CA systems, is associated with increased total soil N. The results of this study are contrary to those by Umar *et al.* [14], who did not find any significant differences in the amounts of total N between CA and CV fields after five years of CA practice; but are consistent with the results by Muchabi *et al.* [29], who found out significant differences in the N amounts between CA and CV fields.

This increase in N content reported in the current study can be attributed to crop rotation and crop residue retention in the CA fields. Nitrogen is essential in plant nutrition and is required in large amounts [34]. Its levels in the soil provide a good indication of soil fertility [33]. Being the second most limiting single nutrient after nitrogen, available P deficiency is very common in acidic regions such as the high rainfall areas of Zambia [33]. In this study, the values from the fields indicate high levels of plant-available P (26.09 to 21.29 mg/kg) from both the CA and the CV fields [33, 35], although they were statistically significantly higher ($p=0.0001$) in soils from CA fields (Table 1). This result was consistent with the report by Muchabi *et al.* [29], who found similar observations after four and seven years of CA practice in a low rainfall area. As high levels of P were also observed in CV fields, the P levels could be attributed to factors other than agricultural practice. It is possible that the soils had high levels of naturally occurring P. For exchangeable K, both CA and CV fields had sufficient quantities for good crop production [33].

These soil analysis results suggest that the differences observed in soil fertility in CA and CV fields could not be due to chance but are due to the practice of CA. A study on chemical characteristics of ten representative benchmark soils of Zambia showed pH (4.2), P (16mg/kg) and SOC (1.6 %) levels in uncultivated soils in Chafukuma [19]. The pH, P and SOC were lower in the uncultivated soils than those observed in CA fields during this study. This is consistent with the literature on CA, in which scholars have noted that soil organic matter in minimally tilled fields increases due to reduced erosion, increased yields resulting in more crop residue added to the soil surface, which is eventually converted to stable organic matter [36].

All the farmers whose fields were sampled during this study had consistently practised CA on the same fields for at least five years. That is, they had adhered to the CA principles of minimum tillage, crop residues retention, and cereal-legumes crop rotations. They had also received agricultural extension support from Kansanshi Foundation, an organisation that actively promotes CA in the area. On the other hand, these agronomic practices and the agricultural extension support were either absent or minimal for the CV fields. The CA practices of residue retention, crop rotation, minimum tillage found in this study were consistent with those reported in most publications on CA [15, 29, 37]. However, the practice of minimum tillage was found to be outside the threshold for the definition of minimum tillage, which stipulates that less than or equal to 10 per cent of the area of land is tilled [15]. The higher tillage levels found in this study are due to the higher number of potholes per unit area in the CA fields. In low and medium rainfall areas, emphasis is on moisture conservation, and basins are ideal for this purpose. This is not the case for high rainfall areas, such as the one studied. The other CA practices used in the study area are similar to those recommended for low and medium rainfall areas of Zambia [37, 38].

The farmers and key informants' perceptions that CA improved soil fertility in the study area were consistent with the empirical evidence from soil analysis results. Smallholder farmers' perceptions of greener maize plant leaves, stronger healthy stalks, better roots formation and darker brown crumble soils in their CA than CV fields suggested higher levels of total N, available pant P, exchangeable P and SOC in CA than CV fields. This was consistent with the soil analysis results.

Noteworthy from the results is that all the farmers had both CA and CV fields, that is, they continued to practice conventional agriculture despite being fully aware of the soil fertility improving benefits of CA. This paradox has been reported earlier by Umar *et al.* [14, 15]

Limitations of the study

The study was limited to one study site. Thus the results could merely reflect the unique biophysical and socio-economic attributes of the study sites and may not apply to different contexts. That being said, the results have contributed to the empirical evidence on CA under diverse farming conditions. The results apply to other regions characterised by smallholder farming in high rainfall regions. The study recommends further research focused on the physical and biological characteristics of soils maintained under CA and in mixed crop-livestock systems of high rainfall regions across Sub-Saharan Africa.

Conclusion

The main objective of this study was to determine whether the practice of CA improved soil fertility in smallholder farmers' agricultural fields. The study found higher amounts of plant-available P (26.09 to 21.29mg/kg), exchangeable K (11.97 to 8. 74 cmol/kg), Total N (0.96% to 0.23%), SOC (0.93 to 0.43mg/ha), as well as pH (5.49 to 5.19) in CA fields. Minimum tillage; using hand hoes to make potholes, crops residue retention; in which maize stalks were mainly retained after harvest and crop rotation involving maize and soya beans in their fields were the main CA practices the farmers employed in their fields. These practices were probably responsible for the soil fertility improvements observed in the CA fields. All the 34 smallholder farmers, Kansanshi foundation officers, and Ministry of Agriculture extension officers interviewed asserted that the practice of CA improved soil fertility. Inferring from these results, it is concluded that CA improved soil fertility of agricultural fields in the study area and could be scaled up in the other high rainfall areas of Zambia provided all the important agronomic practices are utilised consistently and adaptations made to suit the local context better. Adaptations could include the use of small-sized potholes instead of basins that are more suited for low to medium rainfall areas and cause waterlogging problems in high rainfall areas. Agricultural policymakers could use the results to redesign agricultural extension messages to include CA as a soil fertility management strategy.

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