WORKING PAPER

Conservation or Conventional Agriculture? A Soil's Perspective

Conservation or Conventional Agriculture ? A soils’ perspective

Highlights from the Sustainable

Intensification of Maize-Legume Cropping Systems for Food Security

in Eastern and Southern Africa (SIMLESA-II) project

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Abstract

Conservation agriculture, combined with other good agronomic management practices, is important to achieve sustainable intensification. In east and southern Africa where SIMLESA project focused scaling efforts, little evidence on changes in soils due to the practice of conservation agriculture is available. While yield effects of CA are moderately studied, mostly in the short-term, a good understanding of other perspectives of CA including ecosystem services such as soil water and greenhouse gases regulations, enhancement of life in soil and issues of nutrient cycling is needed. This report presents key findings by CIAT, with regard to soil-based effects of CA, a task undertaken during Phase II of the SIMLESA project. Key messages are:

1. CA presents a good opportunity to reduce potential chance of nitrogen leaching through temporary nitrogen lock-up in applied residues
2. Practicing CA has no effect on average, but moderates fluctuations of minimum and maximum soil temperature relative to CT system
3. Practicing CA enhances the abundance and activities of soil microbes, meso- and macro-fauna, involved in cycling of nutrient such as nitrogen and phosphorus vital for crop growth and yield
4. The effects of CA on soil organic carbon are variable and largely dependent on the actual management practice applied, period/length of time of the practice, climate and the soil type
5. Emissions of greenhouse gases such as nitrous oxide are driven by the source and amount of nitrogen application and not by tillage practice
6. From a long-term perspective, practicing CA result in legume yield benefits yet similar cereal yields compared to CT systems

Introduction

Conservation agriculture (CA) affects soils chemical, biological and physical properties. While some of the effects are realized in the short-term, others are only observed in the long-run. In East and Southern Africa where SIMLESA project focused its activities, there is little data on soil-based effects of CA especially with a long-term perspective. Since 2010, trials established in various SIMLESA project focus countries (Kenya, Malawi, Mozambique, and Tanzania) provided an opportunity to assess short-term effects of CA. CIAT-managed conservation agriculture trial established since 2003 provided a long-term perspective. Key results on different aspects assessed are provided below.

Conservation agriculture and soil structure

Practicing CA promotes aggregation of soil particles which improves overall soil structure. Good soil structure is important for aeration, soil water infiltration and protection of soil from erosion. Consistently, detailed analysis on two SIMLESA trials show that practicing CA improved soil structure (Table 1). Effects under a third trial of short-term duration (2 years) were less clear. Tilling soils as done under conventional systems is associated with macroaggregate breakdown and disruption of macropore continuity.

Table 1. Effects of conservation agriculture on soil aggregate mean weight diameter in trials of different durations.

Trial duration	Treatment	Mean weight diameter (topsoil)
15-yr trial	CT	1.03c
15-yr trial	CA	1.38b
15-yr trial	Minimum Tillage only (no residue)	1.32b
6-yr Trial	CT	1.41b
6-yr Trial	CA	1.60a

Effects on soil loss and water dynamics

Practicing CA minimizes water and soil loss compared to conventional tillage systems. Unlike the bare soil surfaces in CT systems, the residues in the CA systems provide surface cover that reduce direct rain-drop splash effects on the soil, thus minimizing runoff, soil erosion and associated water and nutrient losses. Surface residues in the CA systems cover and insulate soil from direct solar radiation thus minimizing evaporation and improve water infiltration often evident by enhanced soil moisture. Conventional tillage destroys soil structure resulting to very loose soils and water infiltration potential is highly variable across a season. Besides, there is a developing hard layer at the depth of the plough (Figure 1). Although not measured under SIMLESA, CA practices reduced runoff and soil loss by 53% and 79%, respectively, compared to conventional tillage in Ethiopia (Araya et al.,, 2011). Similarly, at least 60% reduction in soil losses due to CA is reported by Lanckriet et al., (2012) in Ethiopia and in Zimbabwe by Nyamadzawo et al., (2012).

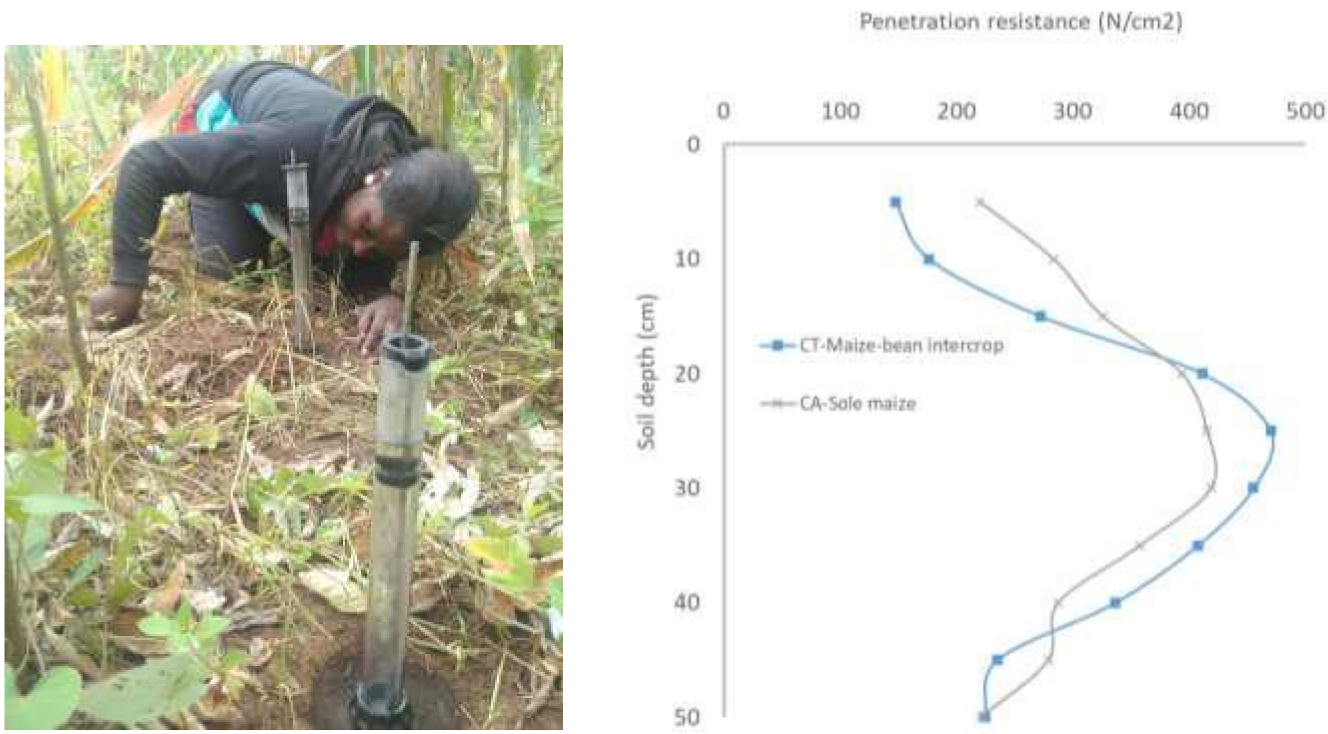

Figure 1. Measuring soil infiltration under a CA system in Tanzania (a) and penetration resistance example for CA and CT under a SIMLESA trial in Eastern Kenya

Effects of long-term and short-term CA practices on Soil Temperature

Soil temperature data at 30 minutes intervals for a period of one year were obtained in replicates, per each management system, in two conservation agriculture trials of different durations. Practicing CA moderates soil temperature relative to CT system. Although the average temperature was not always influenced by CA (all systems had average temperatures between 20.16 and 20.84 ^{o}C), practicing CT always resulted in significantly lower minimum and significantly higher maximum temperatures than CA treatments (Figure 2). In other words, minimum and maximum temperatures are more extreme under CT relative to CA, under our tropical environments where assessmentswere done. The regulation of soil temperatures increases with the amount of surface residue retention.

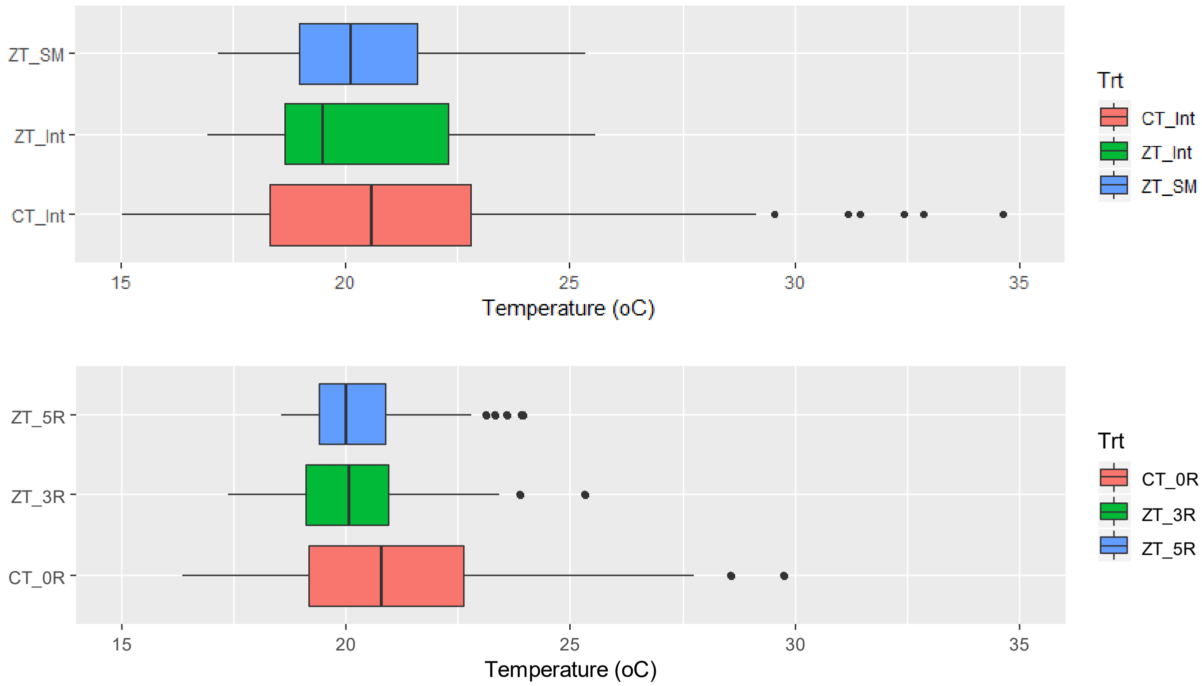

Figure 2. Effects of conservation agriculture and residue retention on temperature regulation in 6 year (top) and 2 year (bottom) trials in Embu, Eastern Kenya from 1st April 2016 to 31st July 2016 (main cropping season)

Effects of CA practices on nutrient cycling and soil biodiversity

Nutrient cycling under SIMLESA was assessed through microbe enzyme activities. Practicing CA improves enzyme activities of the two most important nutrients in crop production in east and southern Africa namely nitrogen and phosphorus. Under long term (13-yrs) experimentation in Western Kenya, practicing CA increased nitrogen mineralization rate by 74.5% and nitrification rate by 74.1% relative to CT systems in the first two months of crop growth. In addition,

CIAT team retrieving resin bags used to study nitrogen mineralization in a long-term conservation agriculture trials during its 13th year.

Photo credit: Peter Bolo

practicing CA increases phosphorus mineralization rate by 20% compared to CT. This is certainly aided by soil microbes. Practicing CA enhanced the abundance of phosphorus solubilizing microbes involving Aspergillus (64%), Penicillium (50%) and Trichorderma (37%) pointing to increased phosphorus solubilization in CA relative to CT systems. Overall, practicing CA enhances 10- 50% increment in microbial functional groups whose activities within the soil strata form an important component of soil fertility improvement.

The capacity of CA in enhancing soil life (microbial growth and activities) relative to conventional tillage systems is uncontested (see Figure 3). Microbial biomass is a common measure of soil microbes. In Kenyan trials, CA practices increased microbial biomass carbon (23.1%), microbial biomass phosphorus (73.1%) and microbial biomass nitrogen (12.1%) over conventional tillage In addition, microbial species abundance were elevated in CA than conventional tillage systems. For instance, practising CA increased the Glomeromycota (fungi) abundance by 11%. These increases are attributed to the conducive environments involving minimal disturbance, increased moisture and nutrient availability and microclimate that favour microbial species abundance in CA than CT.

Soil fauna are important soil engineers influencing soil aeration and water infiltration through burrows/tunnels in the soil. Practicing CA increased soil fauna population abundance and diversity in some sites and not others. These results are contained in a new SIMLESA publication

(see Ayuke et al., 2019, in press).

Photos. Collection of soil fauna in manure in a SIMLESA trial (a) and Berlese-Tullgren apparatus used for collection of mesofauna

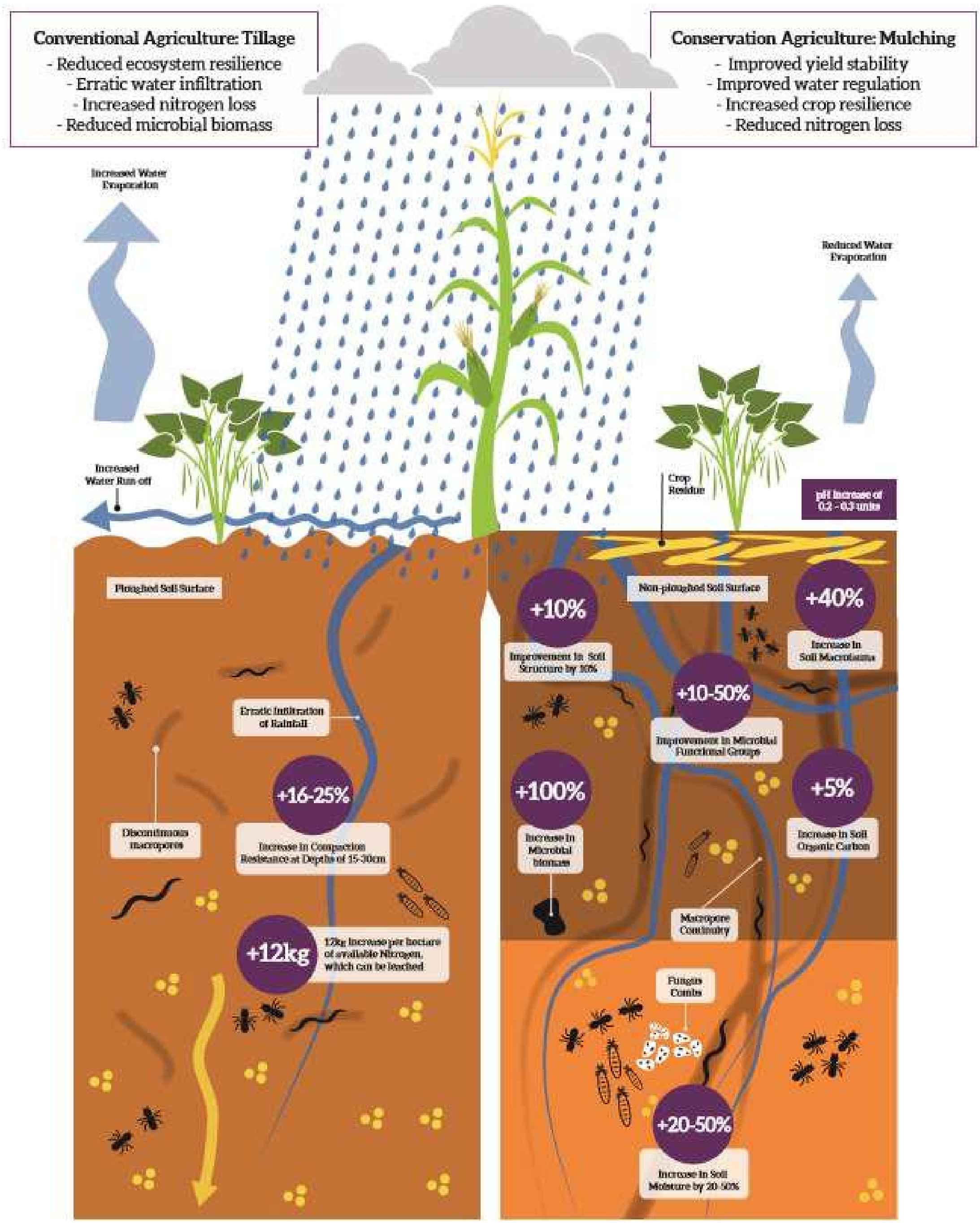

Figure 3. Pictorial representation of soil health benefits ofCA vs CT using data obtained from East Africa

CA and Soil Organic Carbon

The effects of CA on soil organic carbon are variable and largely depend on the actual management and length of time, the climate and also quite strongly on the soil type. For instance, in Malawi, practicing CA only increased (not significant) SOC in Kasungu (30%) and

Ntcheu (11 to 33%) relative to CT, with no observable effect in Mchinji, Lilongwe and Salima (Figure 4). The zero to modest effects on SOC are due to the short-term (4 years) CA implementation period. A similar observation was made in Tanzania (Karatu) where practicing CA only slightly increased SOC in the subsoil but did not improve soil total and active carbon status. Here, implementation of CA did not include residue application. From a long-term perspective (2003-2015), practicing CA (with 2 t/ha/season residue retention) resulted in somewhat elevated SOC levels in the topsoil relative to CT but over time, all the systems were losing carbon. The overall differences are still not large considering the period of CA implementation but this is because the associated soils are dominated by 1:1 kaolinitic Ferralsols that do not sequester more carbon like the 2:1 clay types, and there is high residue comminution by macrofauna (Kihara et al., 2015). As a result, SIMLESA introduced cover crops in areas of Mozambique as an alternative source of mulch (see picture).

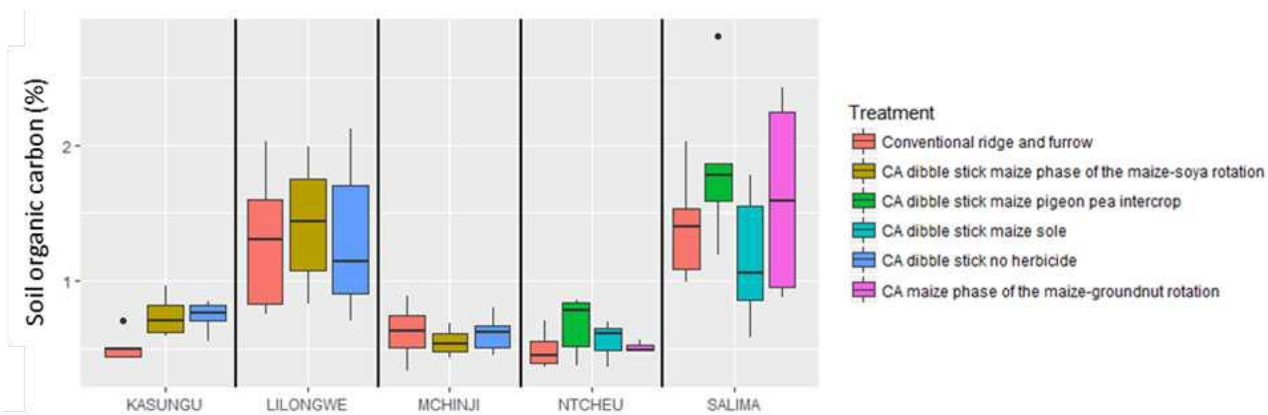

Figure 4. Comparison of conservation agriculture (CA) and conventional tillage systems on total soil organic carbon (SOC) stocks in different sites in Malawi


Photo. Cover crops introduced in SIMLESA trials in Mozambique. Foreground shows high termite comminution of residues while the live cover crops provide good ground coverage besides serving as a good alternative during drought season. Photo courtesy of Dias Domingos.

Conservation agriculture and greenhouse gas fluxes

Nitrous oxide emissions are essentially the same in CA (zero tillage system with residue application) and CT systems (purple and blue lines in Figure 5). These data show, under our systems, emissions of nitrous oxides are driven by the source and amount of nitrogen application and not by tillage practice. Thus although CA can promote denitrification and release of nitrous oxide (Sommer et al., 2015) due to microbial activity in anaerobic sites of aggregates, there are no notable differences relative to CT. Besides, the emissions are generally very low, overall less than 0.7 kg N_2O-N/ha/season, hence, under the prevailing low-input systems in smallholder systems, in-situ N_2O emissions from soils are not of major concern and we cannot make conclusion for or against CA based on these nitrous oxide data. With regard to CO2, emissions and consequently the global warming potential are even higher in CT relative to CA (Robertson et al., 2000) due to tillage effects.

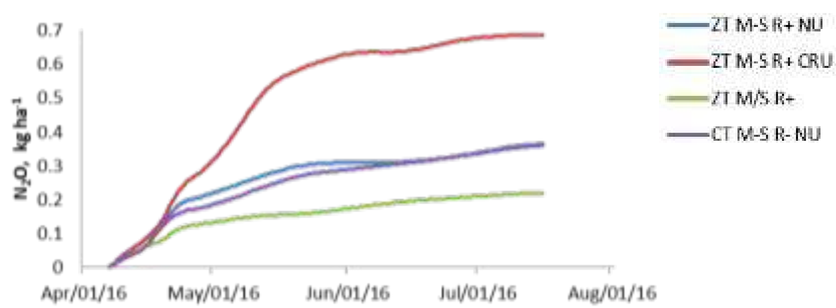

Figure 5. Cumulative nitrous oxide emissions during a long rains season in 2016.

Long-term trends in yield stability

Under long term perspectives, practicing CA often results to similar yields with CT and this is the case with cereals (maize) in our study. Interestingly, practicing CA result in the highest yields of legumes (soybean) compared to CT systems. Besides, practicing CA improves yield stability compared to CT (Govaerts et al., 2005), although this varies by the particular CA practice and sites (Nyagumbo et al., 2016; Mupangwa et al., 2017). In our long-term study in Western Kenya, 4 treatments under CA and 3 treatments under CT have either constant or improving yields over time, and these also perform well across different environments (i.e., regression against environmental mean).

The importance of rainfall distributions in influencing productivity and potential for targeting irrigation interventions is revealed using the 30 seasons of assessment. Rainfall amount (for dekads 6 to 8) and distribution (i.e. number of rainy days from dekad 7 to 10) explain 46 to 56% of the season to season variations in production (Figure 6). In contrast, total seasonal rainfall explain no more than 19% of variations in grain yield. Although the least variance accounted for by the fitted variables is of CT system, there is little difference with the CA treatments. Interventions such as supplemental irrigation under limited water supplies and labour may have greatest benefits when targeted to dekads 6 to 10 which coincide with late May to early July and late November-early January for long rains and short rains, respectively. Positive relationships between crop productivity and growing season precipitation as observed also in Ghana (Ndamani and Watanabe 2014) and in Ethiopia (Bewket, 2009) are expected only under conditions of moisture shortage (rather than excess; Huang et al., 2015) i.e., in our case, rainfall is relatively high during the first two months.

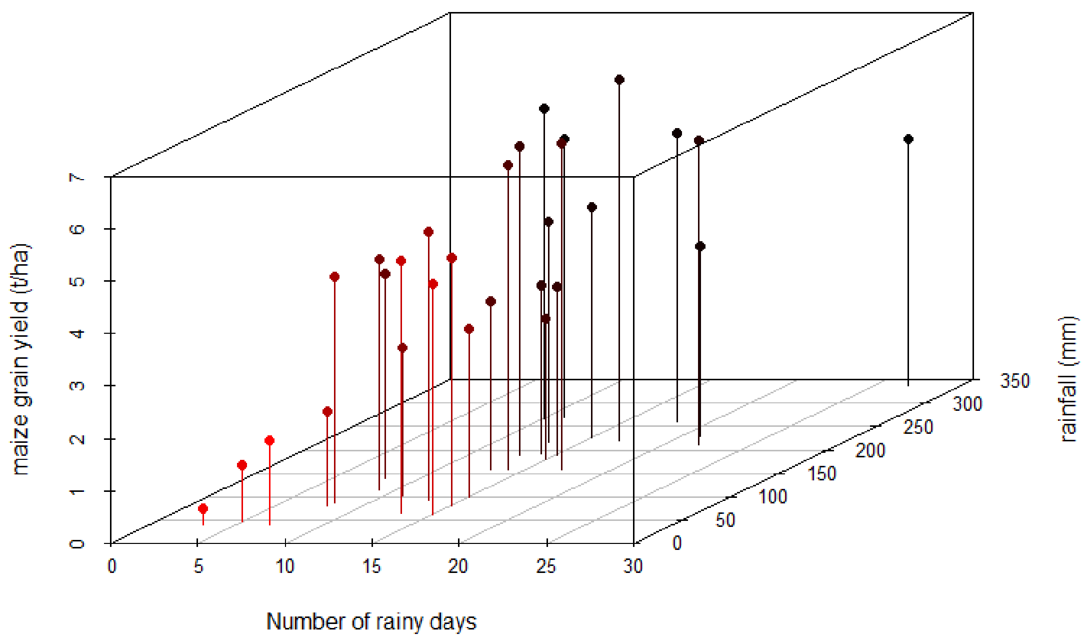

Figure 6. Influence of rainfall amount and number of rainy days of targeted period on maize yield of a conservation tillage treatment over 30 seasons

Nitrogen management

Nitrogen is a mobile nutrients with strong dynamics across the growing season influenced by timing of application, amount of nitrogen applied, soil moisture, sampling depth and crop growth stage among others. At the SIMLESA trials of KALRO Kakamega, mineral-N in soil was by 58-72% higher in CT than in CA all through from planting time to late season even though both treatments had similar nitrogen application rate of 75 kg N ha^{-1}. Similar results are observed at KARLO Embu site especially during the early growth stages. Higher mineral N especially the ammonium form is susceptible to volatilization and leaching losses. Contrary to CA, CT systems without residue retention present large levels of mineral N in the soil which are prone to losses especially if high rainfall is experienced as is often for both Western and Eastern Kenya SIMLESA sites.

Increasing rates of residue application under CA beyond 2 t ha^{-1} depressed mineral N only at certain periods, e.g., the 2nd and 5th samplings. Such effect, called N lock-up, is expected and is the main premise behind investigating nutrient management regimes for CA systems. Conservation agriculture practices can enhance nitrogen lock-up compared to CT, but this may vary under different agronomic managements. For Kakamega, 4 t ha^{-1} crop residue retention is a good bet. The nitrogen locked-up essentially subverts leaching and the nitrogen is subsequently released to support crop nutrient demand later on.

Photo. Scientists from CIAT Training a group of students and field staff on use of lysimeters to monitor nutrient leaching at KALRO Embu, Eastern Kenya

Under long-term (30 seasons) assessments of full CA (no-till+residue+ maize-soybean rotation), practicing the CA resulted in higher mineral N relative to CT without residues mostly at the topsoil. It seems, as expected, that nitrogen immobilization is no longer an issue after the long-term application of organic resources under CA in this environment. On the other hand, aggregated agronomic data over the 30 seasons suggest requirement of a greater amount of nitrogen fertilizer application of 60 kg N ha^{-1} under CA unlike 30 kg N ha^{-1} under CT. In CA systems, higher rates of N application increase plant nitrogen status (chlorophyll readings) while increasing residue has a slight depressive effect.

Photo. Obtaining soil samples from SIMLESA trial (photo credit: Job Kihara).

Nitrogen use efficiency is hampered by non-application of highly deficient yet little-studied secondary and micronutrients. That productivity of major crops is increased by 25% due to these nutrients over what is achieved with macronutrients application is the key message of the SIMLESA publication (Figure 7). Titled "Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa" published in Agronomy for sustainable development journal, the publication (Kihara et al., 2017) has re-energized debate on these important nutrients (high attention score and thousands of downloads already and in the top 5% of all research outputs scored by Altmetric). Interventions in soil fertility and agronomy must include appropriate fertilization to achieve maximum benefits.

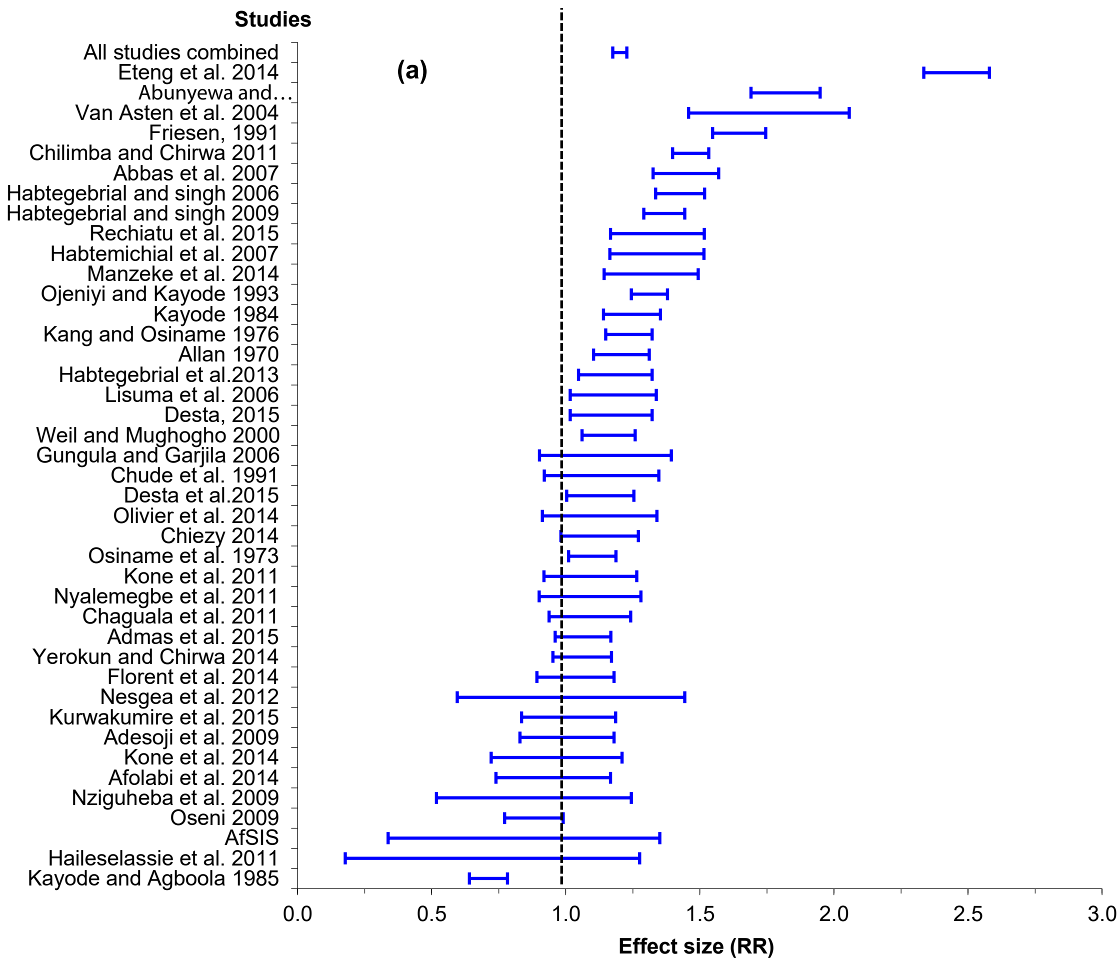

Figure 7. Forest plot of response ratios to micronutrient applications observed under different studies in SSA.

Conclusions and suggestions for the future

Conservation agriculture practices involving zero tillage and surface residue retention have higher potentials in promoting ecosystem health and productivity through increased soil faunal biodiversity compared to conventional tillage. The long term perspectives have shown CA to produce similar maize grain and higher soybean yields than CT. Besides, CA enhances yield stability relative to that of CT. Residue application in CA systems provide surface cover that minimize surface runoff, soil erosion and the associated water and nutrient losses. In addition, ensuring at least 30% of surface cover regulates soil temperature hence minimizing evaporation and improving water infiltration. Practicing zero tillage without residue application is not a good practice because it leads to reduction in soil faunal abundance, and thus compromising the realization of their beneficial roles i.e., soil aggregation, organic matter decomposition, nutrient transformations and cycling. It is important to ensure that appropriate rates of residue and inorganic N are applied in CA to moderate N lock-up effect which may implicate on crop production.

The following are suggestion for future research:

1. Broaden understanding of residue by nitrogen interactions across a range of soils and agro-ecological conditions
2. Increased understanding of the greenhouse gases effects of tillage and residue application
3. Studies on green manure cover crops as alternatives of residues with also a long-term perspective
4. Understanding of the biological implications of herbicide use under CA and potentially the nutritional effects
5. Response of CA systems after amendment by secondary and micro-nutrients (S&M) in tropical systems. Utilizing S&M may help in unlocking N use efficiency and increase crop yields.
6. Research on multiple perspectives of CA such as role on provision of ecosystem services of soil management/health is not widespread and more studies are needed across different soil types and agro-ecological zones
7. Opportunities for unlocking adoption including role of mechanization

References

Ayuke F.O., Kihara, J., Ayaga, G., & Micheni A.N. (2019). Conservation agriculture enhances soil fauna richness and abundance in low input systems: examples from Kenya. Frontiers in Environmental Science

Kihara, J., Martius, C., & Bationo, A. (2015). Crop residue disappearance and macrofauna activity in sub-humid western Kenya. Nutrient cycling in agroecosystems, 102(1), 101-111.

Kihara, J., Sileshi, G. W., Nziguheba, G., Kinyua, M., Zingore, S., & Sommer, R. (2017). Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. Agronomy for Sustainable Development, 37(4), 25.

Bewket, W. (2009). Rainfall variability and crop production in Ethiopia: Case study in the Amhara region. In Proceedings of the 16th International Conference of Ethiopian Studies (Vol. 3, pp. 823-836). Trondheim, Norway: Norwegian University of Science and Technology.

Sommer, R., Mukalama, J., Kihara, J., Koala, S., Winowiecki, L., & Bossio, D. (2015). Nitrogen dynamics and nitrous oxide emissions in a long-term trial on integrated soil fertility management in Western Kenya. Nutrient cycling in agroecosystems, 105(3), 229-248.

Robertson, G. P., Paul, E. A., & Harwood, R. R. (2000). Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science, 289(5486), 1922-1925.

Araya, T., Cornelis, W. M., Nyssen, J., Govaerts, B., Bauer, H., Gebreegziabher, T., Oicha, T., Raes, D., Sayre, K.D., Haile, M., & Deckers, J. (2011). Effects of conservation agriculture on runoff, soil loss and crop yield under rainfed conditions in Tigray, Northern Ethiopia. Soil Use and Management, 27(3), 404-414.

Ndamanl, F., & Watanabe, T. (2014). Rainfall variability and crop production in Northern Ghana: The case of Lawra District. Society for Social Management Systems Internet Journal

Govaerts, B., Sayre, K.D., & Deckers, J. (2005). Stable high yields with zero tillage and permanent bed planting? Field Crops Research, 94, 33-42.

Nyagumbo, I., Mkuhlani, S., Pisa, C., Kamalongo, D., Dias, D., & Mekuria, M. (2016). Maize yield effects of conservation agriculture based maize-legume cropping systems in contrasting agro-ecologies of Malawi and Mozambique. Nutrient cycling in agroecosystems, 105, 275-290.

Mupangwa, W., Mutenje, M., Thierfelder, C., & Nyagumbo, I. (2017). Are conservation agriculture (CA) systems productive and profitable options for smallholder farmers in different agro-ecoregions of Zimbabwe? Renewable Agriculture and Food Systems, 32, 87-103.

Lanckriet, S., Araya, T., Cornelis, W., Verfaillie, E., Poesen, J., Govaerts, B., Bauer, H., Deckers, J., Haile, M., & Nyssen, J. (2012). Impact of conservation agriculture on catchment runoff and soil loss under changing climate conditions in May Zeg-zeg (Ethiopia). Journal of Hydrology, 475, 336-349.

Nyamadzawo, G., Nyamugafata, P., Wuta, M., Nyamangara, J., & Chikowo, R. (2012). Infiltration and runoff losses under fallowing and conservation agriculture practices on contrasting soils, Zimbabwe. Water SA, 38(2), 233-240.