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The Role of Conservation Agriculture for Soil Quality Improvement: A Review

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በኢትዮጵያ በሰብል መሬት ላይ ያለው የአፈር መከላት በዓመት ከ40-130 ቶን በሄክታር የሚደርስ ሲሆን፣ ከ1.0-1.5 ሚሊዮን ቶን እህል ምርትን እያሳጣት ይገኛል፡፡ የዕቀባ እርሻ በሶስት እርስ በእርስ በሚደጋገፉ መሰረታዊ መርሆዎች ላይ ተመስርቶ የአፈር መከላትን በመቀነስ፣ የአፈርን ጥራት በማሻሻል እና ዘላቂነት ላለው የግብርና ምርት አስተዋጽኦ እያደረገ ስለመሆኑ በሰፊው ይታወቃል፡፡ በኢትዮጵያ ውስጥ ከሶስት አስርት ዓመታት በላይ የምርምር እና የሰርቶ ማሳያ ጥረቶች ቢኖሩም የረጅም ጊዜ ጥናቶች ለአፈር ጥራት መጎልበት ያለዉን ጥቅሞች በበቂ ሁኔታ በማሳየት ላይ ውስንነት አለባቸው፡፡ በሀገር ውስጥም ሆነ በውጭ የረጅም ጊዜ የዕቀባ እርሻ ጥናቶችን መዳሰስ እና ያለውን እውቀት መቀመር የወደፊት የዕቀባ እርሻ አጠቃቀም ላይ ትክክለኛ ውሳኔዎችን ለመስጠት፤ እንዲሁም የምርምር እና የማስተዋወቅ ስራዎች ለመምራት ይረዳል፡፡ ይህ ጥናት ዓላማው የዕቀባ እርሻ ለአፈር ጥራት መሻሻል እና ተያያዥ ተግዳሮቶች ላይ የተሰሩ ጥናቶችን በመተንተን በኢትዮጵያ የወደፊት አቅጣጫን ለማሳየትና አርሶ አደሮች ተጠቃሚ የሚሆኑበትን መንገድ ለመጠቆም ነው፡፡ የዕቀባ እርሻ ከ3-5 ዓመታት ውስጥ የአፈር ጥራትን ሊያሻሽል እንደሚችል እና ዘላቂነት ላለው የግብርና ምርት አስተዋፅዖ እንደሚያበረክት የታዩት ጥናቶች ያመለክታሉ፡፡ በተጨማሪም ዝቅተኛ ርጥበት ባለባቸው አካባቢዎች የሰብል ምርት መሻሻልን በአጭር ጊዜ ውስጥ ማምጣት እንደሚችል ያሳያሉ፡፡ ሆኖም በኢትዮጵያ ውስጥ የዕቀባ እርሻ የመጠቀም ልምድ በአርሶ አደሩ ዘንድ እምብዛም አልሰፋም፡፡ ለዚህም ዋና ዋና ምክንያቶች የሰብል ተረፈ-ምርቶች ለተለያዩ ጠቀሜታዎች መዋልና የአቅርቦት እጥረት፣ ለዕቀባ እርሻ ተብለው የተመከሩ አሰራሮች እና ግብዓቶች ውስንነት፣ ለዕቀባ እርሻ ምቹና አቅም ያላቸው አካባቢዎችን ቅድሚያ ሰጥቶ አለመሥራት፣ የኤክስቴንሽን አገልግሎቶች ውስንነት እና ለዕቀባ እርሻ ትግበራ ምቹ ሁኔታዎች የማመቻቸትና የማስቀጠል ውስንነቶች ናቸው፡፡ በአጠቃላይ ከተለያዩ የሙያ ዘርፎች ባለሙያዎችን በማሳተፍ፣ አካባቢያዊ ማህበራዊና ኢኮኖሚያዊ ሁኔታዎችን ያማከለ የዕቀባ እርሻን በማጎልበት ለተጠቃሚው ማቅረብ እና ለሚኖሩት ተግዳሮቶች ቀድሞ ተገቢዉን አማራጭ መፍትሄዎችን በመተግበር ከዕቀባ እርሻ ሊገኝ የሚችለውን ጥቅም ለአርሶ አደሩ ማሳየትና ተጠቃሚ ማድረግ ያስፈልጋል፡፡ ለተመራማሪዎች፣ ለኤክስቴንሽን ሰራተኞች ለልማት ባለሙያዎች እና ለአርሶ አደሮች እንዲሁም ለወሳኝ ባለድርሻ አካላት የሚታዩትን ውስንነቶች የሚቀርፍ በቂ የአቅም ግንባታ ሥራም ወሳኝነት አለው፡፡

Abstract

Ethiopia experiences a very high soil loss of 40–130 t $ha^{-1}year^{-1}$ from croplands that costs the country about 1.0-1.5 million tons loss of grain production per year. Founded on its three interlinked principles, Conservation Agriculture (CA) is widely documented to reduce soil loss, improve soil quality and contribute to sustainable agricultural production. Despite more than three decades of research and promotion efforts on CA in Ethiopia, long-term comprehensive studies are scanty to sufficiently demonstrate its benefits for soil quality enhancement. Drawing lessons from long-term CA studies both within and outside the country would help to make informed decisions for wider use of CA and guide future research and promotion activities. Available pertinent CA literatures from peer-reviewed journals, research reports, dissertations, and proceedings were reviewed. This review was aimed to collate and analyse studies documented the effect of CA practices on soil quality improvement and associated challenges, and suggest the way forward for its application by smallholder farmers in Ethiopia. The review indicated that, when properly implemented, CA improves soil quality in 3-5 years and contributes to sustainable agricultural production. Besides, yield improvement is possible in early stages of CA application in the low moisture areas under sufficient crop residue retention. However, CA adoption in Ethiopia is generally low which is mainly attributed to limited availability and competing uses of *crop residue, limited availability and use of CA based recommendations, mis-location of CA promotions, limited participatory extension services and enabling conditions. Overall, the review suggested the need for a concerted multi and inter-disciplinary research effort to develop CA innovations suiting to the different biophysical environments and socioeconomic circumstances. Effectively demonstrating the power of CA on relieving soil problems, and providing alternative solutions for the challenges surrounding it are requisites to get its full benefits. Capacity building on innovative CA practices is crucial for researchers, extension workers, development practitioners and the smallholder farmers.*

Keywords: Conservation agriculture, soil quality, adoption, Ethiopia

Introduction

Conventional agriculture through intensive tillage and high input based production system has played a tremendous role to meet the global food, feed, fiber and bio-energy demands. Nevertheless, concomitant environmental (soil, water and associated ecosystem services) degradation was high in both high input intensive (Zhang *et al.*, 2018; Clark and Tilaman, 2017) and low input repeated tillage agricultural practices (Birhanu *et al.*, 2011; Stoorvogel and Smaling, 1998). This calls for transition towards sustainable agricultural production practices that help regenerating soil and land quality, and productivity (LaCanne and Lundgren, 2018; Clark and Tilman, 2017). In response, Conservation Agriculture (CA) has been considered one of the possible sustainable agriculture trajectories. It is founded on three pillars: maintaining permanent soil covers with crop residues or live mulches, no or minimum mechanical soil disturbance, and crop diversification through growing in sequences and/or associations. CA in conjunction with other complementary good agricultural practices is considered a major entry point for sustainable agriculture while concurrently protecting and enhancing the environment (FAO, 2012).

Global literatures are well stocked with positive impacts of CA adoption on soil quality improvement (Naab *et al.*, 2017; Friedrich *et al.*, 2012; Wang *et al.*, 2010; Sombrero and de Benito, 2010; their felder and Wall, 2009; Fernandez-Ugalde *et al.*, 2009; Rockstrom *et al.*, 2009). The soil quality improvements are around enhancement of soil organic carbon (SOC) content, water infiltration capacity, water holding capacity and microbial activities, and thereby arresting decline in total factor productivity of applied inputs. Moreover, it was reported to have contributed to protection of the top fertile soil from wind and water erosion (Dumanski *et al.*, 2006; CTIC, 1999). Its contribution was indicated in build-up of effective nutrient recycling and enhancement of nutrient use efficiency by creating conducive rhizosphere for soil micro-flora and fauna (Sombrero and de Benito, 2010; Bessam and Mrabet, 2003). In addition to reducing the evaporation losses and non-point pollution of water bodies, CA contributed to reducing vulnerability against impacts of climate change on crop production and mitigation by reducing emissions and improving carbon sequestration in soils (Bessam and Mrabet, 2003; West and Post, 2002).

CA is practised worldwide in all the continents and agricultural ecologies on about 180 million hectares of cropland, corresponding to about 12.5% of the total global cropland (Kassam *et al.*, 2018). The annual rate of global expansion since 2008/2009 is about 10.5 million ha of CA cropland area. Its adoption is reported by 78 countries. However, adoption is shown mainly intense in North and South America, Australia, New Zealand, and only recently in Asia, Russia, Ukraine, Europe and few African countries.

Ethiopia experiences a severe soil resource base degradation where about 40-130 t ha^{-1} yr^{-1} soil is lost from croplands (Tamene and Vlek 2008; Berry, 2003; Girma, 2001; Kefeni, 1992). This rate is much higher than the world and African average of 17 Mg $ha^{–1}$ $yr^{–1}$ and 23 Mg $ha^{–1}$ $yr^{–1}$, respectively. The soil loss due to erosion was estimated to cost the country’s economy by 1.0-1.5 million tons of grain production per year (Hurni *et al.*, 2015; Girma, 2001). Degradation of soil productivity factors along with negative net soil nutrient balance in the farmlands (van Beek *et al.*, 2016; Amare *et al.*, 2006) have been challenging the country’s effort to ensure food security under sustainable production. Reduction in soil fertility and soil quality are among major factors contributing to low adaptability of agriculture to insufficient and erratic rainfall in many parts of the country (van Beek *et al.*, 2016; Gete *et al.*, 2010).

Quite intense natural resource conservation efforts have been made since the past several decades by the government and non-governmental organizations (NGOs) in the country. A number soil and water conservation practices including physical structures and a few biological measures (Grunder, 1988), and CA practices like minimum/zero tillage with/without mulching and with/without herbicides (Ito *et al.*, 2007; Assefa *et al.*, 2004) have been employed though with a little adoption by the farmers.

In Ethiopia, despite several researches and conservation tillage promotion endeavours for over three decades, only a few of initiatives and long-term studies were made to address the contributions of CA to soil health and demonstrate its benefits to smallholder farmers. Moreover, the results of the available scanty studies are not consistent and conclusive on soil, water and crop productivity improvement benefits obtained from practicing CA. The objectives of this review work is therefore to collate and synthesis available information within and outside the country in similar production environments, on CA contributions to soil health and crop productivity enhancement and associated challenges. By doing so, it aims to draw lessons and forward recommendations that help to inform policy makers, researchers, agricultural development practitioners and farmers in their CA application endeavors.

Principles of conservation agriculture

CA is an approach of managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. To this end, three interlinked CA principles; viz., no or minimum mechanical soil disturbance, permanent soil cover with crop residues and live mulches, and crop sequences and associations, applicable to all agricultural landscapes and land uses applied with locally tailored improved management practices are considered as the key road to increased system productivity, resilience and sustainability (FAO, 2012).

Zero or minimum mechanical disturbance of soils is aimed to minimize processes that contribute to degradation such as erosion, compaction, aggregate breakdown, loss of organic matter, leaching of nutrients and others (Kassam *et al*, 2015; Friedrich *et al.*, 2012). A suit of practices including direct sowing/broadcasting of crop seeds, direct placing of planting material in the soil or minimum soil disturbance from cultivation or farm traffic are used. In fact, the use of zero tillage without appropriate residue retention and suitable rotations is reported to be even more harmful to agro ecosystem productivity and resource quality than a continuation of conventional practices (Gebreyesus, 2012; Sayre, 2000).

The permanent soil cover both during crop growth phases as well as during fallow periods provides the soil surface a buffering effect from raindrops and radiation effects. It is recommended that at least 30% of the soil surface need to be covered with previous crop residue by the time of planting (CTIC, 1999; Erenstein, 2002). This threshold is thought to reduce soil erosion by 80% (Jat *et al.*, 2013). Overall, the practice reduces soil surface sealing, crusting and evaporative moisture loss and hence contributes to improved water infiltration, soil water use efficiency and increased insurance against in-season dry spells. Presence of high levels of lignin and phenolic acids that gives the residues a higher resistance to decomposition is used as criteria in residue cover selection to provide longer period soil protection.

Diversification of crops through sequences (rotations) and associations is done through practices like a balanced mix of legume and non-legume crops to offer a diverse “diet” to the diverse soil micro-organisms that in turn plays an important role in atmospheric N fixation and in the transformation of unavailable nutrients into plant available form. Furthermore, they can serve as biological pumps of nutrients as they possess different rooting depth in addition to their contributions to greater distribution of channels or bio pores created by diverse roots with various form, size and depths. The practices can also be used as a host break to harmful pests (insects, weeds and diseases) in the long-run that will result to reduced requirements for pesticide and herbicide chemicals (Dumanski *et al.*, 2006).

On implementing the three CA pillars, specific CA components (establishment methods, farm implement selection, crop residue and mulch management, crops in the rotation, soil fertility management, germplasm selection, pre-CA implementation management requirements, etc.) would appear to be different across different environments. Hence, adaptive research is needed to tailor specific components of CA principles to suit local conditions and constraints.

Soil quality parameters prone to CA management practices

Soil quality, as defined by Soil Science Society of America (SSSA) soil quality Ad Hoc committee, "is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen *et al.,* 1997). Soil quality being a function of both inherent and dynamic soil properties and processes can be viewed as a composite picture of measurable soils' physical, chemical and biological attributes. These attributes relate to functional soil processes that can be used as indicators to evaluate soil health as affected by management changes. Soil health is the continued capacities of soil to function as a vital living ecosystem that sustains plants, animals and humans (NRCS, 2012). CA recognizes soil as living entity essential to sustain quality of life and gives emphasize to the critical and highly active upper 20 cm layer soils (Dumanski *et al.*, 2006) to protect against erosion and degradation. This is a layer where human activities of land management have the most immediate, and potentially the greatest impact.

Soil physical quality

Soil physical qualities including infiltration, plant available water and aggregate stability are among major indices of productivity and are prone to changes in soil management practices. To this end, there are ranges of CA research results showing soil management change impacts on soil physical quality aspects.

Infiltration rate

Field experiment conducted on loamy sand ferric Lixisol receiving mean annual rainfall of 748 mm in Zambia, and on sandy soil of endostagnic dystric Luvisol receiving annual rainfall 884 mm in Zimbabwe showed significantly higher water infiltration for CA fields as compared to conventional shallow depth (10-15 cm) animal traction based mouldboard plough fields (Thierfelder and Wall, 2009). The report in Zimbabwe showed overall average infiltration rate of 25% and 39% higher for CA treatments as compared to conventional farmers practice in 2006 and 2007, respectively, while it was 42 and 100% in Zambia for CA treatments as compared to conventional farmers practices. The effect was higher on clay loams Lixisols of Zambia; three and five times greater for CA plots than for conventionally tilled fields (Thierfelder *et al.*, 2013). Similar improvement in total infiltration for long-term zero tillage was reported in India (Sikka *et al.*, 2005) and in semi-arid Morocco (Mrabet, 2004). On the contrary, in a deep and well drained sandy loam soil (Ultisol) with mean annual rainfall of 1600 mm at Nsukka, Nigeria, the conventional tillage under sole sorghum and the intercrop systems recorded significant enhancement of saturated conductivity than CA practices (Obalum and Obi, 2010). Higher rainfall can temporarily result in waterlogging for CA plots if macro-pores are not well developed in reduced tillage (Thierfelder and Wall, 2009), while ploughing which breaks up the blocky structure of the soil might have improved drainage in conventional tillage.

In Ethiopia, water infiltration measurement during 2015 and 2016 for CA plots established on silt loam of Andosols in 2010 at Melkassa Agricultural Research Center (MARC) was about 15% higher as compared to conventional practice, while the result on clay loam of Alfisols at Bako (CA plot established in 2015) was vice versa (Liben *et al.*, 2018). The cumulative rainfall was about 400 and 830 mm at Melkassa and 800 and 1300 mm at Bako in 2015 and 2016 seasons.

Soil moisture content

The higher water infiltration on CA plots during the growing season (Thierfelder and Wall, 2009; Mrabet, 2004) leads to a higher plant available soil moisture that generally enables crops to overcome in-season dry spells and reduce the risk of crop failure. Thierfelder and Wall (2009) and Olaoye (2002) reported that in CA plots available soil moisture above the permanent wilting point was constantly higher than that of the conventional farmers' practices. According to Mrabet (2004) in semi-arid Morocco, the non-tilled surface needed on average 32 days for soil moisture to reach a wilting point, while moldboard plow, chisel plow, rotavator and disking needed only 8, 21, 17 and 18 days, respectively. This in most cases resulted in improved rainfall-use efficiency mainly under lower rainfall seasons or in low-moisture stressed areas. Similarly, in a long-term field experiment, field water content was found significantly improved in no-tillage than in conventional tillage in the semiarid Mediterranean Ebro Valley of Spain during the driest months. The volume of equivalent diameter pores (0.2–9 mm) was reported 1.5 times higher under no-tillage (Fernandez-Ugalde *et al.*2009) contributing to increased plant available water content and improved production under no-tillage in a drier year.

As reported by Patil *et al.* (2016) and Rockstrom *et al.* (2009) a set of experiments conducted in semi-arid and dry sub-humid locations in East and Southern Africa demonstrated that minimum-tillage practices considerably increased water productivity and crop yields under even little mulch of crop residues. On the other hand, on clay soils of Nyabeda, western Kenya that receives annual rainfall of 1200 mm, in bimodal seasons showed lower crop water productivity (CWP) in reduced tillage plots than conventional plough plots though improvement was seen after four consecutive seasons (Kihara *et al.*, 2008). The authors documented the greatest CWP between 400 and 700 mm rainfall and a declining trend when rainfall exceeds 900 mm. The possible explanation for reduced CWP is that the macro-pores that act as water conduits in reduced tillage may not develop sufficiently in shorter period of time.

In Ethiopian studies, soil water content measured in the top 0-30 cm soil layer was reported remarkably high in CA plots established on sandy loam and loam soils of MARC and Wolenchity (Olanchiti) research sub-station than under conventional tillage during the main growing season (Worku *et al.*, 2006). Recent medium-term CA study in the semi-arid Central Rift Valley (CRV) also showed that stored soil water at 0 to 100 cm depth at physiological maturity of maize was 21% more with CA as compared to conventional ploughing (Liben *et al.*, 2017). Similarly, conservation tillage study on Vertisols in the drylands showed constantly higher soil-water storage (0–80 cm soil depth) during the growing season with DER+[1] followed by TER+ and conventional tillage, whereas the opposite trend was observed for runoff (Tesfay *et al.*, 2015). On a medium term CA study in the semiarid CRV of Ethiopia early emergence of maize planted under CA was reported compared to the conventional ploughing (Liben *et al.*, 2017). Crop emergence in the area is affected by surface soil crusting (Biazin *et al.*, 2015) especially when rainfall is not enough to moisten the soil for the period from planting to seedling emergence. Hence, the improved maize emergence in CA plots can be attributed to wetting effect by stored soil water (Liben *et al.*, 2017) that assists emerging seedlings by loosening surface crust. Furthermore, extended tasselling, silking or physiological maturity were reported for maize grown on CA plots mainly due to improved stored soil water. Overall, the studies showed that CA is effectively increasing green water in the root zone available for crops and thus good crop establishment, growth and crop productivity.

Soil aggregate stability

Several research findings have indicated a higher proportion of stable aggregates in the soil surface in no-tillage than conventional tillage (Wang *et al.*, 2010; Roldan *et al.*, 2003; Lahlou and Mrabet, 2001; Bossuyt *et al.*, 2001). Long-term on-farm experiment by Fernandez-Ugalde *et al.* (2009) on silt loam Haplic Calcisol of semiarid Mediterranean Ebro Valley of Spain also depicted

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[1] -DER+ is '*dirdaro'* plus crop straw where beds and furrows are made along the contour at intervals of 0.6 m while TER+ is '*terwah'* plus crop straw where furrows are made along the contour at regular intervals of 1.5 m (Tesfay *et al.*, 2011). In both cases only one tillage operation refreshing the furrows at planting was made and 30% of the crop straw standing stubble was left on the field.

improvement in soil physical quality for no tillage treatment plots. In this study, aggregate dry mean weight diameter (MWD) and stability in water were 1.2 and 2.2 times greater, respectively, for no-tillage as compared to conventional tillage. This is attributable to reduced mechanical disturbance and increased SOC content. Stable soil aggregate formation contributes to the conservation and protection of SOC that allows its function as a reservoir of plant nutrients and energy. The physical disturbance due to repeated ploughing exacerbates the turnover of aggregates and rapid loss of soil organic matter (SOM) in conventional tillage (Zheng *et al.*, 2018; Murage *et al.*, 2007).

Penetration resistance

Penetration resistance is an indicator for the degree of compaction of soil. Soil compaction limits root growth and the availability of air and water to the roots. Research results on effects of no-tillage and crop residue retention on soil penetration resistance are generally inconclusive resulting in conflicting reports. For instance, increasing penetration resistance from the good to the poor fields was reported due to minimum tillage (Liben *et al.*, 2018; Guto *et al.*, 2011). Sufficient quantity of residue retention on the other hand was reported to considerably reduce the penetration resistance in the medium class fields (Liben *et al.*, 2018; Baudron *et al.*, 2012; Guto *et al.*, 2011), while neither tillage nor crop residue practice did significantly affect penetration resistance of the good class fields. On the other hand, zero tillage with residue retention increased soil penetration resistance in surface soil layer (Choudhary *et al.*, 2018).

Soil Chemical quality

Soil organic carbon accumulation

SOC accumulation is the most reported soil chemical attribute from tillage experiments as it is the key soil quality indicator well linked to other soil properties. Field experiment on sandy loam Andosols at Ajuno experimental site in the central Mexico depicted significant increase in total SOC with crop residue additions (Roldan *et al.*, 2003) over conventional tillage. Another evidence of total SOC improvement was reported from two long-term (4 and 11 years) experiments conducted on deep clay vertic Calcixeroll soil receiving mean annual precipitation of 358 mm in semiarid Morocco. The result indicated that carbon sequestration under no-tillage was found 3.5 t ha^{-1} and 3.4 t ha^{-1} higher than conventional tillage in the 0-20 cm layer after 4 and 11 years, respectively (Bessam and Mrabet, 2003). Similarly, about 11.0 and 25.0 % SOC improvement was reported in CA plots over conventional tillage (CT) after 3 and 10 years, respectively in a semi-arid area of Castile-Leon, Spain (Sombrero and de Benito, 2010). As can be seen from Figure 1, under no-/minimum-tillage system, the initially higher SOC in the upper soil layer showed a declining trend with increasing depth (Sombrero and de Benito, 2010).

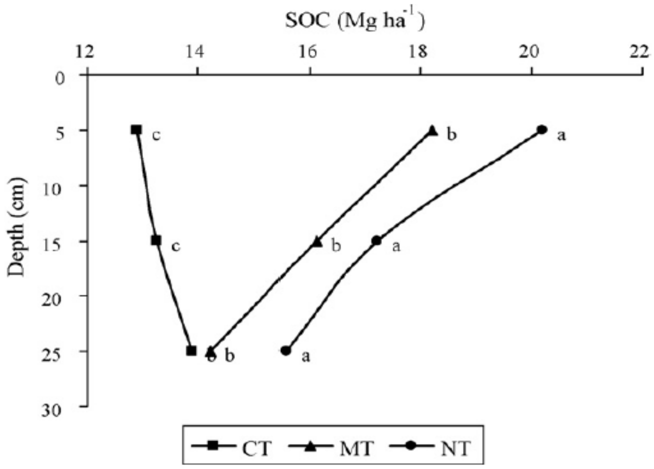

Figure 1. Vertical distribution of the SOC content in 2004 by tillage system
Lettered values mark significant differences at $p < 0.05$ (Duncan's test). CT, conventional tillage; MT, minimum tillage; NT, no tillage.
Source: Sombrero and de Benito (2010)

Labile (water soluble) carbon fractions mainly used by the soil microbial community as an energy source for metabolic activity were reported to have direct relationship with the rate of crop residue addition (Mrabet *et al.*, 2004). Saber and Mrabet (2002) also reported an increase in the labile fraction of SOC under no-tillage as compared to conventional tillage. In this respect, growing legumes as cover crop had significant contribution to increase the water soluble carbon fractions (Roldan *et al.*, 2003). Overall, according to West and Post (2002) the global database of 67 long-term experiments depicted significantly higher SOC levels under zero tillage as compared to the conventional and reduced tillage, and concluded that a move from conventional tillage systems to zero tillage plus residue retention can sequester on average 48 ± 13 g C m^{-2} yr^{-1}.

Increase in soil organic matter under no-tillage may be attributed to reduced contact of crop residues with soil (Gosai *et al.*, 2010). The majority of SOC increase under no-tillage has been found to be in the top 10 to 25 cm with insignificant changes relative to conventional tillage at higher depth (Sanderman *et al.*, 2012). Surface residues tend to decompose more slowly than soil-incorporated residues, because of greater fluctuations in surface temperature, moisture and reduced availability of nutrients to microbes colonizing the surface residue (Olaoye, 2002). Hence, the newly sequestered C is accumulating where it is most vulnerable to environmental and management pressures that actually made it arguable about the permanence of the increase.

Similarly, studies in Ethiopian confirmed SOC improvement with CA. On a conservational tillage experiment established on sandy loam and loam soils in the dry land areas of the CRV, soil organic matter on weight basis at a depth of 0-15 cm was higher under conservation tillage (1.6%) as compared to conventional tillage (1.2%) (Worku *et al.*, 2006). Another experiment conducted on smectite rich clay mineral vertisol at Chefe Donsa in the central high lands showed a trend of increase in SOM content in reduced tillage (Teklu, 2011). Similarly, a higher level of SOC 16 g kg^{-1} was reported in CA fields as compared to 12 g kg^{-1} in conventional ploughed fields at 0-0.05m surface soil depth at Melkassa (Liben *et al.,* 2018). Thirty years crop growth simulation study in seven different agro-ecologies of Ethiopia showed 33% maize grain yield advantage by combined use of N fertilizer, crop rotation and conservation tillage (Liben *et al.,* 2020). It further showed to slow down the rate of SOC and N decline over time as compared to combined use of conventional tillage and recommenced N rate only.

Nutrient cycling

Retention of crop residues and diversification of crop species grown in sequence or associations under no-tillage affects nutrient cycling and availability. It has been found that no-tillage helped to conserve more nitrogen (Bessam and Mrabet, 2003), and resulted in increased extractable phosphorus and exchangeable potassium concentrations in the upper root-zone similar to the finding by Tesfa *et al.* (2003) from Ethiopia (Fig. 2). Total nitrogen content increased from low to medium level (0.13%) in conservation tillage while it remained under low category (0.07%) in conventional tillage (Worku *et al.*, 2006).

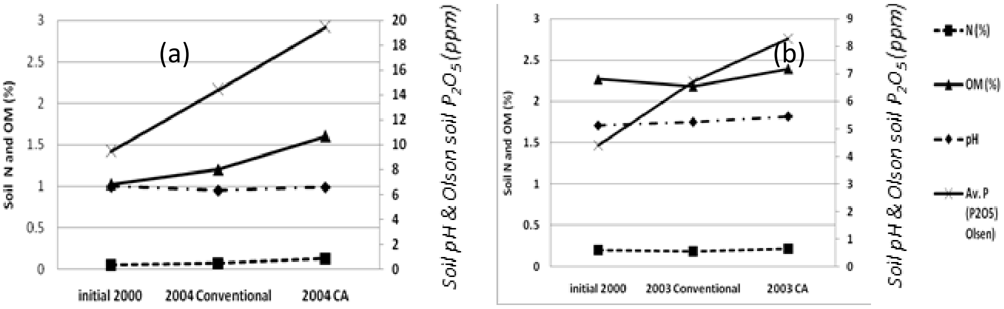

Figure 2. Chemical properties of soils in conventional and CA systems at (a) MARC and (b) Jimma
The secondary vertical axis shows the soil pH and Olson soil P_2O_5 (ppm). Computed from Worku *et al.* (2006) and Tesfa *et al.* (2003)

A study conducted at Bako in Ethiopia on clay loam soils reported appreciable improvement of soil organic C and total N content as well as extractable P and exchangeable K for zero-tillage with five years residue retention (Tolessa *et al.*, 2007). The larger total N values under no-tillage than conventional tillage imply N immobilization in microbial biomass near the soil surface, leaving less N available for mineralization or leaching that is slow release overtime.

Soil Biological quality

Biological activities in soils are considered important indicators of soils capacity to support biological productivity. Macro faunal activity and microbial biomass responds quickly to changes in soil management and are among adequate indicators of soil quality and hence soil health.

Macro fauna population and activity

Significant increase in mean density of earthworm casts in no-tillage than in conventional tillage plots was shown in Nigeria by Obalum and Obi (2010). Other research works (Brevault *et al.*, 2007; Johnson-Maynard *et al.*, 2007) have also demonstrated higher number of earthworms to thrive under no-tillage. These findings suggested a close linkage of the higher water infiltration measured on CA fields to increased biological activity and pore continuity. A study conducted in Zimbabwe on two soil types: Vertisol receiving low and erratic rainfall of 450 mm year^{-1} and Luvisol receiving moderate rainfall of 650 to 800 mm year^{-1} but still prone to severe mid-season dry spells showed higher macro fauna population in CA systems. The macro fauna population was found increasing with increasing amount of crop residues retained as soil cover than conventional practice (Mutema *et al.*, 2013). Conventional tillage on the other hand is associated with reduction in soil macro fauna including earthworm population (Reedler *et al.*, 2006; Obalum and Obi, 2010; Mutema *et al.*, 2013) probably due to mechanical soil disturbance deleterious effects such as drying the soil, burying the plant residue they feed on, destroying their vertical burrows, and cutting up and killing the worms themselves.

However, macro fauna diversity was shown somewhat different under different residue types. According to Mutema *et al.*, (2013) higher diversity was found in CA plots with maize residue while that was not confirmed where sorghum residues were used. This is in agreement with Verhulst *et al.* (2010) who reported increased species diversity on reduced tillage used in combination with maize residue retention. This suggests that species diversity may depend on the quality of organic material retained on the soil surface.

Microbial biomass

Soil microbial biomass increased in surface soils under no-tillage (Choudhary *et al.*, 2018; Gosai *et al.*, 2010; Teklu *et al.*, 2007) as compared to the tilled plots. Likewise, Gonzalez-Chavez *et al.* (2010) experiment result revealed that microbial biomass C and N nearly doubled under no-tillage as compared to conventional tillage treatments. The same work showed decreased microbial biomass C, N and P from low to high tillage disturbance regime and also from surface to sub-surface soil layers.

In general, from the above CA literature review it is possible to deduce that CA offers improvement to soil quality parameters and hence soil functions such as biomass production; storing, filtering and transforming nutrients and water; biodiversity pool, and serve as carbon pool that in one way or another benefits ecosystem functioning in general and sustainable agricultural production in particular. By avoiding or reducing the frequency of tillage, farmers can timely plant right after rainfall onset that help them adapt to climate change, save labour and energy requirements for land preparation. In addition, soil erosion is arrested, soil productivity functions improved and yields stabilized by adopting and implementing CA effectively. These benefits may have contributed to the high rate of CA adoption in countries such as North and South America, Australia, New Zealand, Asian and few Southern African countries.

Conservation agriculture in Ethiopia

Research on conservation tillage in Ethiopia began early in 1980s (Kidane and WoldeYesus, 1993, Tanner *et al.*, 1991, Asefa *et al.*, 1991) with the focus of reducing heavy disturbance from frequent tillage operations by the traditional tillage implement, *Maresha plow* (Melesse, 2007). Reports on crop performance and soil productivity improvements in most trials of zero and minimum tillage showed varying results in different soils and rainfall conditions (Tanner *et al.*, 1991; Asefa *et al.*, 1991). Soil hindrance to germination, and weed infestation were among the challenges accounted for the inconsistent performance of the crops in early stages of the no or minimum tillage practices.

Later on, the research focus changed into stubble management and different tillage practices along with cropping sequences (Assefa *et al.*, 2004). Wheat based field experiment on tillage systems conducted from 1993-2000 at Kulumsa clay soil (an intergrade between eutric Nitisol and luvic Phaoezem) and Asasa clay loam (calcic Chernozem) in Arsi revealed that there was no improvement in productivity. Both sites receiving mean annual precipitation ranging from 600 to 900 mm in bimodal distribution rather showed consistently higher severity of *Bromus pectinatus* weed under zero and minimum tillage (Assefa *et al.*, 2004) that was attributed to the decreased grain yield throughout the experimental period despite glyphosate application during the “short rain” season. Over years the same study showed a wheat grain yield increase and *B. pectinatus* severity decrease for conventional tillage in contrast to minimum and zero tillage. However, crop rotation with faba bean under reduced tillage systems showed reduction on severity of *B. pectinatus* infestation.

CA with its full components was introduced to Ethiopia in 1998 by Sasakawa Global 2000 (SG-2000) (Matsumoto *et al.*, 2004), which demonstrated CA with 30% residue retention for maize, wheat and tef between 1999 and 2003. The overall results showed a biological yield improvement and hence profitability of the practice (Ito *et al.,* 2007). Similar experiments were conducted from 2000-2004 on maize by Jimma, Bako and Melkassa Agricultural Research Centers in collaboration with Sasakawa Global 2000 to determine and compare the advantages of conservation tillage over the conventional practice. The on-farm researcher managed conservation tillage at Mana and Omonada districts in Jimma zone showed significant improvement in SOC content and maize grain yield in CA plots as compared to the conventional tillage (Tesfa *et al.,* 2003). Similar trend of SOC and grain yield improvement was reported on sandy loam and loam soils in Melkassa area (Worku *et al.,* 2006).The result from Bako on station and on farm fields at Shoboko, Tibe, Ijaji and Gudar indicated the need to wait at least three years to see the benefit of CA on grain yields (Tolessa *et al.,* 2007).

On the other hand, lower grain yield of sorghum in general was experienced from zero-tillage at MARC research plot (Tewodrose *et al.,* 2005) where 70% grain yield increase was recorded from conventional tillage to which 3t ha^{-1} of tef straw applied as soil surface mulch, and only 46% for same level of straw application under zero tillage. Such results were often experienced during the early stage of CA implementation (Tesfay *et al.,* 2010; Tolessa *et al.,* 2007) while the result also clearly indicated that permanent cover of the field with organic material is the most important component to be combined with the minimum or no tillage practice. On another study, lower average grain yield of sorghum was reported on zero tillage treatment without residue retention on water and nutrient constrained Typic Pellustert soil of Abergelle area, Tigray (Gebreyesus, 2012). The author suggested the need for pre-soil amendment to improve the infiltration and water holding capacity of the soil before zero tillage implementation, and a further long-term study. CA experiment by Tesfay *et al.,* (2010) on Calcic Vertisol at Gumselasa (Adigudom), Tigray showed 53 to 61% soil loss reduction in no-tilled 60 cm wide permanent beds with 30% residue retention as compared to traditional tillage. Considerably low to comparable grain yields were reported for conservation tillage from different studies suggesting the need for weed control while growing tef (Tesfay *et al.,* 2010; Tigist *et al.,* 2010) and wheat (Asefa *et al.,* 2004). In another research, Tesfay *et al. (*2015) documented increased grain and straw yield of wheat, 1.6 and 3.7 t ha^{-1} with conventional tillage and 2.6 and 5.2 t ha^{-1} due to DER+.

Comprehensive on-station and on-farm CA experiments and demonstrations were conducted across wider agro-ecologies by six research centers: Melkassa, Hawassa and Jigjiga (representing mid-altitude dry land low potential maize growing areas), and Bako, Adet and Pawe (representing mid-altitude sub-humid high potential maize growing areas) under the Sustainable Intensification of Maize-Legume cropping systems for food security in Eastern and Southern Africa (SIMLESA) project during 2010 to 2018 cropping seasons. Results of the first year CA trials showed reduction in grain yield as compared to conventional practice in both maize and common bean yields (Dagne *et al.*, 2012) mainly attributed to lack of appropriate residue management and weed control as inferred by the authors. Later on, Liben *et al.* (2017) from the same experiment in the semiarid CRV (2011–2014 on-farm and 2010–2014 on-station trials) indicated maize bean rotation and intercropping under CA had 28 and 19% maize grain and 29 and 17% more stover yield advantages compared with maize monoculture under conventional practice, respectively. The same study revealed that 21% higher stored soil water in 1 to 100 cm soil depth for CA plots compared with conventional tillage practice. Consequently, rainfall use efficiency was on average 20% higher with no-till maize-bean intercropping compared to treatments with conventional practices. However, the same on-farm study indicated 23 and 47% less maize grain and stover yield under maize bean rotation under CA compared to maize monoculture under CA practice.

Adoption and adoption constraints of CA by smallholder farmers in Ethiopia

Conservation agriculture, introduced with its full components in 1998 by SG-2000, was first demonstrated on 77 farmers' plots on maize in Central Ethiopia (Matsumoto *et al.*, 2004). According to Wondwossen *et al.* (2016), the technology demonstrations reached more than 16 districts in 2008 and recently over 35 districts. The authors also indicated at least 3000 farmers started using CA in 2011 from 262 farmers in 2006. SIMLESA project had worked with over 100,000 farming households to help them apply 'conservation agriculture' based practices. Recently, the public agricultural extension system has taken up CA as one of the sustainable soil management technology packages. In addition to CA based programs' and projects' researches and demonstration initiatives, there are a number of NGOs promoting CA in Ethiopia. Among others, the Canadian Food Grains Bank working with Food for the Hunger Ethiopia in Beneshengul-Gumuz, Migbare Senay Children and Family Support Organization in Amhara, and Terepeza Development Association in Wolaita are currently supporting the promotion of CA in different parts of the country.

Despite the different initiatives and the potential contribution of CA to the agricultural development and Climate Resilient Green Economy strategy of the country, and its recognition by the government, several factors as identified by different studies are constraining the adoption of CA by smallholder farmers. They are briefly discussed as below:

Limited availability and competing use of crop residue in mixed crop-livestock production systems

Mixed crop-livestock production is the dominant production system in Ethiopia. In this areas, limited availability and competing demand for crop residues such as for livestock feed, mulch, and fuel has been repeatedly reported as one of the key constraints affecting CA adoption by smallholder farmers (Liben *et al.*, 2017; Moti *et al.*, 2015; Baudron *et al.*, 2014; Moti *et al.*, 2013; Kindu *et al.*, 2011). In areas where livestock are kept in stalls (zero-grazing), crop residues are often harvested and kept to feed animals during the dry season. The situation is worse in areas where livestock are released to graze freely on crop aftermaths (Moti *et al.*, 2013; Kindu *et al.*, 2011). A survey conducted at Kobo and Nekemte areas revealed a declining trend of mulching practices in crop fields (Kindu *et al.*, 2011). In hot dry areas of the country, biomass production and residue availability is generally low making crop residue retention for permanent organic mulch very difficult.

Nevertheless, the competing demand for crop residues in mixed crop-livestock systems should not be a barrier to the adoption of CA as it can be solved through appropriate interventions (Duncan *et al.*, 2016; Baudron *et al.*, 2015; 2014; Moti *et al.*, 2013). Hence, promotion of CA must take into consideration introduction of alternative means to increase biomass production, and alternative sources to alleviate the opportunity costs of leaving crop residues as mulch (Kindu *et al.*, 2011; Valbuena *et al.*, 2012). Cereal-legume intensification, quality based sharing of crop residue between livestock feed and mulching, and introduction of high biomass cover crops that can provide fodder for animals may help in meeting the subsequent year crop residue requirements of CA. Promoting CA aligning with the integrated watershed management practices may also help to retain crop residues by reducing competition with animals since free grazing is not allowed in managed watershed areas. Furthermore, the public agricultural extension agency must create enabling environment to reduce free grazing practices in selected CA promotion strategic geographic areas.

Limited availability and use of CA adapted recommendations

Using CA adapted technology packages including improved fertilizer, seed/variety and moisture management of the CA promotion locations can also improve biomass production for livestock feed and minimal initial soil cover required for initiating CA.

Insufficient nitrogen fertilization

Implementation of CA can modify N dynamics in the soils compared with conventional practices (Vanlauwe *et al.*, 2014; Giller *et al.*, 2009; Erenstein, 2002) since reducing soil disturbance leads to lower N release from the mineralization of soil organic matter at least for some years compared to repeated tillage (Zheng *et al.*, 2018; Murage *et al.*, 2007). Retention of wider C:N ratio crop residues, a preferred organic soils cover in CA, may also lead to temporary N immobilization (Vanlauwe *et al.*, 2014; Abiven and Recous, 2007). Under Ethiopian smallholder farmers' condition where fertilizer application is sub-optimal, this might be one reason for N stress commonly observed early in the season in CA systems leading to depressed plant vigor and growth (Verhulst and Govaerts. 2010). Hence, nitrogen fertilizer recommendation rate and timing for the conventional production may need adjustment by understanding the ‘cross-over points’ beyond which investments in N fertilizer to counteract N immobilization by crop residues becomes profitable across agro-ecological conditions (Baudron *et al.*, 2015; Giller *et al.*, 2009). Nitrogen fertilization is generally challenging in crop production due to its mobile nature in soil. Therefore, alternative method that can enable in-season crop N requirements prediction such as hand-held sensors measuring the Normalized Difference Vegetation Index of the crop canopy (Verhulst and Govaerts. 2010) need to be calibrated and adapted.

Lack of adaptation of soil water balance situation of an area to CA

CA often shows improvement in crop production in areas where low moisture is a major limiting factor. There are also situations where results are neutral or even negative for crop production by causing waterlogging (Thierfelder and Wall, 2009) depending on the amount of rainfall received and infiltration capacity of the soils of the specific location. On the other hand, no or retention of insufficient quantities of crop residues as surface mulch hardly improved the rainwater infiltration properties of the soil and crop yield, particularly on soils that are prone to crusting and compaction (Baudron *et al.*, 2012; Guto *et al.*, 2011). The soil physical properties improvement can take several years. Hence, CA system in such situations has to be adapted to the water balance situations of the study location soils at least to avoid the adverse effects on short-term crop productivity. For instance, formation of semi-permanent raised beds were found to reduce water runoff (Tesfay *et al.*, 2015) and opening rip-lines in CA system increased water infiltration compared with conventional practices and has led to higher maize and wheat yields (Liben *et al.*, 2017; Tesfay *et al.*, 2015).

Lack of suitable CA farm implements

Availability of soil- and crop-specific adequate implements that can sow in an unploughed soil under crop residue mulch is among vital components contributing to CA adoption. Besides, cover crop management implements/tools to flatten and kill cover crops and leave the plant residues on the soil surface are also essential. In Ethiopia, a number of CA implements, modifications to the local *Maresha* plough that cause minimal soil disturbance, have been developed to make the conservation tillage implements affordable, light and easy to be used by smallholder farmers (Rockstrom *et al.*, 2009; Melesse *et al.*, 2009; Melesse, 2007). Also, locally made *Berken Maresha*[2] with reduced draft power requirement was indicated promising which helps ripping at the center to break the hardpan, improving infiltration, and creating invisible barriers (*Siwur Erken*) to retard water movement (Feed The Future, 2017; Muche *et al.*, 2017). Some modern CA implements like hand Jab-planters and rippers were also demonstrated. However, the effectiveness of existing local tillage implements for planting under residue is yet a challenge making CA practice less attractive.

Therefore, prior to promoting CA as a good alternative practice, limiting factors that counteract its benefits need be well understood and given solutions. For instance, to address the problem of hard soil pan common with the traditional tillage, soil sub soiling is a requisite to improve the poor water infiltration and thus crop yields (Muche *et al.*, 2017; McHugh *et al.*, 2007; Melesse, 2007). A sub-soiling (25─30 cm depth, 75 cm intervals) experiment in compacted soils in a dry sub-humid environment showed an increase in plant available soil water and sorghum yield (McHugh *et al.*, 2007). Leaving the soil undisturbed without cover crops or sufficient crop residues can result in high surface runoff (Muche *et al.*, 2017; Gebreyesus, 2012). Hence, opening the soil to allow infiltration, while minimizing the adverse effects of tillage, would be a good strategy.

Pest problems

In practicing minimum and no-tillage weeds appears a serious challenge at the early crop growth stage (Tesfay *et al.*, 2010; Tigist *et al.*, 2010; Giller *et al.*, 2009; Assefa *et al.*, 2004). Therefore, uses of herbicides are recommended at early stage of CA establishment to control weeds though not a desirable option for a healthy environment. On the other hand, repeated use of glyphosate herbicide need to be monitored to avoid any undesirable effect like weed resistant development, human and environmental hazards. Although it might be costly, the environmentally safe investment of hand weeding is mandatory in CA early implementation years (Brown *et al.*, 2018; Baudron *et al.*, 2015; Giller *et al.*, 2009). Furthermore, pre-emergence and post emergence weed control herbicides availability by type, time and location as well as farmers' skill of application need to be considered in CA promotion.

Untargeted promotion of CA to meet its primary purpose

The biophysical and socioeconomic environments are among major factors influencing CA performance and its adoption by farmers (Wondwossen *et al.*, 2016; Baudron *et al.*, 2015; Kindie *et al.*, 2015; Guto *et al.*, 2011; Giller *et al.*,

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[2] *Berken Maresha also known as Silet Deger is a modification of local Maresha. Wooden Deger in local Maresha is replaced with metal Deger.*

2009). For instance, minimum tillage and crop residue retention in low soil fertility classes (Guto *et al.*, 2011) and in areas receiving high amount of rain fall in low infiltration capacity soils were not found promising for crop production (Thierfelder and Wall, 2009). CA has been promoted in the country with no beforehand knowledge about the biophysical and socioeconomic potential of the area. Cognizant of such limitations, a study in Ethiopia identified CA recommendation domains from the perspectives of biophysical (soil texture, surface slope and rainfall) and socioeconomic potentials (market access, human density, livestock population densities) where conventional crop-livestock mixed farming is a common practice (Kindie *et al.*, 2015). Accordingly, about 4.6% (821,006 ha) of the cultivated land in Ethiopia is identified as high potential for CA recommendation domain and about 42.4% as medium or higher potential for CA recommendation domain. Therefore, the country's CA promotion need to be targeted based on recommendation domains.

On the other hand, some research findings indicate that CA has first and foremost been adopted in USA and Brazil primarily for energy-saving (time and/or power), erosion-control, and improving water use efficiency (Baudron *et al.*, 2015; Lal *et al.*, 2015; Giller *et al.*, 2009). They argue that the primary motivation of CA adopters has rarely been for immediate yield increase, except perhaps where low-moisture is a major limiting factor. The yield increases in CA plots, in most cases, have been occurring after several years of gradual physical, chemical and biological improvement of soils. Hence, the purpose of adopting CA can be linked with rainwater use efficiency, energy use efficiency, protection of soil from erosion and sustainable optimum yield during poor seasons as target variables in addition to sustainable yield improvement in the long-term.

Limited extension services

Access to strong extension services, frequency of extension visit, and human capital (years of formal education and farming experience) are *inter alia* factors found to positively influence adoption decision of improved practices in general and CA in particular (Woldegebrial *et al.*, 2017; Wondwossen *et al.*, 2016; Marenya *et al.*, 2015; Moti *et al.*, 2015; Moti *et al.*, 2013). On the other hand, availability of high quality information enables farmers to learn, experiment, evaluate and allocate resources to new practices and hence likely to positively influence adoption of new technology/practice.

Participatory methods and innovative responsiveness of the extension service is crucial to satisfy farmers' dynamic needs which is changing with the emerging market, customer demand and varying biophysical environment (Brown *et al.*, 2018; Gerba. 2018; Davis *et al.*, 2010; Erenstein, 2002). Studies indicated that inadequate technical and innovation capabilities, and mind-sets developed over the years are constraining the success of public agricultural extension system of the country (Brown *et al.,* 2018; Brown *et al.,* 2017; Gerba, 2018; Lanckriet *et al.,* 2014; Davis *et al.,* 2010). For instance, the repetitively ploughed and clean farms that are considered to be an attribute of a good farmer, and the dominance of "technology supply-push" mind-set than farmer-driven and market-pull technology are challenging the implementation, promotion and adoption of conservation agriculture. Despite the considerably large number of development agents (Davis *et al.,* 2010), lack of adequate skills and multiple tasks they are in charge of limited their effectiveness in providing proper extension services and winning the farmers' trust (Brown *et al.,* 2018). The adverse effect of such limitations particularly in CA implementation, promotion and hence its adoption by farmers is considerable (Wondwossen *et al.,* 2016; Feed The Future, 2017). Hence, shifting from conventional practice to conservation farming requires strong capacity building for the extension workers, farmers and other development practitioners to build the required capability and bring about a mind-set change.

On the other hand, extension approaches for CA should suit the varying biophysical factors (soil types, agro ecologies, crops) and socio-economic factors such as indigenous practices of local farmers. As stated by Erenstein (2002), a blueprint package is no panacea to be successfully fit in widely varying production systems. Hence, flexible and dynamic extension service that considers the existing biophysical and socioeconomic factors of selected strategic geographic areas of CA promotion is required to facilitate its adoption (Marenya *et al.,* 2015; FAO, 2006).

Furthermore, CA as a complex system requires multi and inter-disciplinary approaches involving experts from crop, natural resources, mechanization, livestock, agroforestry, energy, economics, and technology extension and communication. Hence, a concerted and coordinated research and extension efforts are needed for effective testing and evaluation of appropriate tools and machinery, crop management, etc. and successful adoption of CA (Baudron *et al.,* 2015; Hengxin and Xuemin, 2006). Then, long term strategic investment in agricultural extension and improved access to farm inputs are key policy issues to be considered (Marenya *et al.,* 2015; Melesse, 2007) supported by a new knowledge base and strong technical backstopping at the field level (Milder *et al.,* 2011; Davis *et al.,* 2010). Limited financing of operation costs of agricultural extension services for effective execution, supervision and sharing experiences are also constraints that need to be addressed

Furthermore, limited access to affordable financial services, the challenge for actual investment requirements and use of CA adapted recommendations in general (Brown *et al.,* 2018; Marenya *et al.,* 2015), necessitate concerted effort to create enabling environment.

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