International Soil and Water Conservation Research 12 (2024) 828–843

Contents lists available at ScienceDirect

International Soil and Water Conservation Research

journal homepage: www.elsevier.com/locate/iswcr

Review Paper

Challenges and constraints of conservation agriculture adoption in smallholder farms in sub-Saharan Africa: A review

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A R T I C L E I N F O

Article history:
Received 17 July 2022
Received in revised form
14 March 2024
Accepted 18 March 2024
Available online 20 March 2024

Keywords:
Crop residue
Soil degradation
Climate change
Crop rotation
Minimal soil disturbance

A B S T R A C T

Common farming practices in sub-Saharan Africa (SSA) such as intensive and repeated tillage, complete crop residue removal, and biomass burning create risks of soil degradation. To reduce these risks, conservation agriculture (CA) uses minimal soil disturbance, crop residue retention, and crop rotation in order to reduce soil erosion, improve soil quality and crop production, and facilitate climate change mitigation and adaptation. Nevertheless, CA adoption in SSA is extremely low. This paper aims to review current practices, challenges, and constraints to the adoption of CA in SSA. Our analyses show that CA is practiced in only about 1.25% of the total cultivated area in SSA, despite two decades of efforts to promote CA adoption among smallholder farmers. Specific difficulties in CA adoption by smallholder farmers in SSA may be attributed to i) lack of locally adaptable CA systems, particularly those integrating the needs of livestock production; ii) lack of adequate crop residues for surface mulch; iii) inconsistent and low crop yields; iv) lack of smallholder CA equipment for direct sowing; v) limited availability, high cost, and inadequate knowledge associated with the use of appropriate fertilizer and herbicides; and vi) lack of CA knowledge and training. Other problems relate to the management of specific soil orders, e.g., CA implementation on steeply sloping land and poorly drained soils such as Vertisols. CA adoption by smallholder farmers is also obstructed by socio-economic factors due to smallholder farmers' focus on short term yield increases and their lack of access to markets, loans, and education. To facilitate wider adoption by smallholder farmers in SSA, CA approaches should be downscaled to fit the existing tillage tools and the specific agroecological and socio-economic farm settings.

Contents

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https://doi.org/10.1016/j.iswcr.2024.03.001
2095-6339/

1. Introduction

The UN projects Africa's population will double to 2.5 billion (UN, 2017) and that of sub-Saharan Africa (SSA) to 1.96 billion people in 2050 (Bongaarts & Casterline, 2013). This population growth will likely increase pressures on food supplies, and these pressures may be exacerbated by climate change and by soils that have already been degraded by unsustainable management and have poor inherent nutrient supply (Benites et al., 1998). According to the International Fertilizer Development Center (IFDC) (2006), about 95 million ha of arable land in Africa has already reached a state of degradation that requires significant investment to restore its productivity. Such investments will be difficult to achieve for smallholder farmers with limited income. Farms less than 2 ha in size account for more than 80% of all farms worldwide (UN FAO, 2014) and more than 11% of these small farms (51.3 million holdings) are found in SSA (Nagayets, 2005; UN FAO, 2014).

The majority of SSA small-holder farming systems, e.g., in Malawi, Tanzania, Zambia, Zimbabwe, Mozambique, and Ethiopia are cereal-based mixed crop/livestock systems (Araya et al., 2012; Dixon et al., 2001; Dowswell et al., 1996; Kassie et al., 2012). These systems are heavily affected by climate variability and change (Meze-Hausken, 2004; Thierfelder et al., 2017), and the effects are likely to become more severe in the next decades (Cairns et al., 2013; Lobell et al., 2008). These problems hit SSA farmers who are already operating at yield levels that are low compared with other countries (www.yieldgap.org). The low yields are related to insufficient and highly erratic rainfall (Falkenmark & Rockström, 2008; Nyssen et al., 2004) and to soil fertility depletion (Sanchez et al., 1997) due to loss of soil organic matter (SOM) and nutrients, soil structural degradation, soil erosion, and low pH values (Lobe et al., 2011; Lotter, 2015; Pimentel & Michael, 2013). This soil degradation can be accelerated by unsustainable management practices, such as intensive and repeated tillage at sites prone to erosion, monocropping, complete crop residue removal at harvest for animal feed or fuel or by post-harvest grazing (Araya et al., 2012; Six et al., 2004; Stroosnijder, 2009). Soil erosion is a particular threat contributing to both the long term decline and the seasonal reduction in food crop production in SSA (Drechsel et al., 2001; Lal, 2008). Drechsel et al. (2001) reported that complete crop residue removal at harvest and erosion constitute about 70% of all N losses, nearly 90% of all K losses, and 100% of the P losses in SSA.

To overcome soil degradation and potentially restore desirable soil properties, conservation agriculture (CA) has been increasingly recommended (Araya et al., 2016b; Islam & Reeder, 2014; Six et al., 2002). According to FAO (2022), “CA is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment”. CA is a key approach to addressing declining soil fertility and the adverse effects of climate change in SSA. Short term effects of CA systems included reduced runoff and soil loss and increased soil water availability due to the retention of crop residues (Araya et al., 2012; Biamah et al., 1993; Giller et al., 2009; Lal, 1986; Vogel, 1993). In the long term, CA may enhance soil fertility, soil organic carbon (SOC) sequestration, and crop yield. Nevertheless, crop yield responses to CA in the short term vary, and positive, neutral, or negative outcomes have been reported (Araya et al., 2015; Gill & Aulakh, 1990; Giller et al., 2009; Mbagwu, 1990). Govaerts et al. (2005) reported

Table 1
Conservation agriculture area coverage (‘000 ha) in Sub-Saharan Africa by country in 2008/2009, 2013/2014, 2015/2016, and 2018/2019.

No	Country	2008/2009	2013/2014	2015/2016	2018/2019
1	South Africa	368	368.00 [a]	439	1607.08
2	Zambia	40	200	316	552.67
3	Kenya	33.1	33.10 [a]	33.10 [b]	33.10 [c]
4	Zimbabwe	15	90	100	100.00 [c]
5	Sudan	10	10.00 [a]	10.00 [b]	10.00 [c]
6	Mozambique	9	152	289	289.00 [c]
7	Lesotho	0.13	2	2	2.00 [c]
8	Malawi	–	65	211	211.00 [c]
9	Ghana	–	30	30.00 [b]	235
10	Tanzania	–	25	32.6	32.60 [c]
11	Madagascar	–	6	9	9.00 [c]
12	Namibia	–	0.34	0.34 [b]	0.8
13	Uganda	- -		7.8	7.80 [c]
14	Swaziland	–	–	1.3	0.8
15	Burkina Faso	–	–	–	1
16	Cameroon	–	–	–	2
17	Rwanda	–	–	–	0.25
18	Burundi	–	–	–	0.2
19	Guinea	–	–	–	0.4
20	Ethiopia	–	–	–	7.5
21	DR Congo	–	–	–	2.06
22	Niger	–	–	–	5
	Total area				3109.26

Source: Conservation Agriculture Global website (https://www.ca-global.net/ca-stat, accessed February 7, 2023). The 2008/2009 and 2013/2014 data were estimated by FAO-AQUATSTAT; the estimated data from 2015/2016 and 2018/2019 were obtained from nationally published papers.
[a] estimates from 2008/2009;
[b] estimates from 2013/2014;
[c] estimates from 2015/2016.

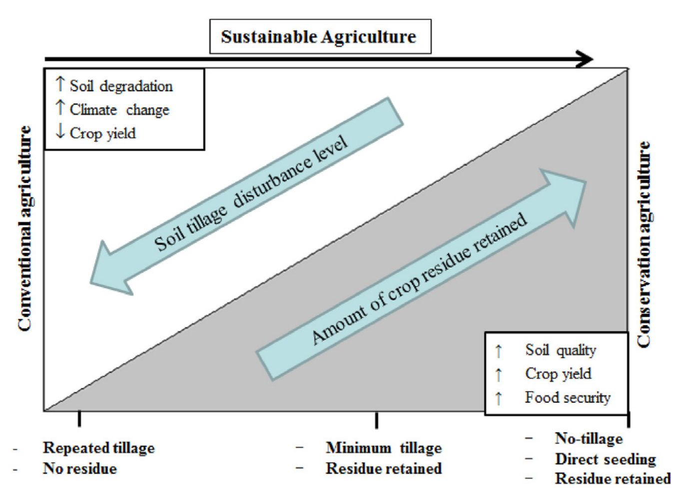


Fig. 1. Theoretical scheme representing the concept level of changing cropland management practices from conventional agriculture to conservation agriculture (Adapted from Araya, 2012).

Table 2
Different types of conservation agriculture and conservation agriculture-based systems in sub-Saharan African.

Conservation agriculture practices	Description	Target areas (climate)	Topography	Mitigation		Risk	Reference
				CO_2	N_2O		
CA with no-tillage	Less than 50% soil disturbance level	Variable	Flat (0–0.2%) to level (0.2–0.5%)	‘[a]	Variable	– water logging on swelling and shrinking clayey soil – slower net mineralization and immobilization and requires higher level of N in degraded soils – higher chemical input for weed control – low crop emergence due to uneven distribution of straw	Derpsch et al., 2014;
CA with reduced tillage	Elimination of excess tillage	Variable	Flat (0–0.2%) to level (0.2–0.5%)	‘[a]	Variable	– reduction in yield in the absence of surface mulch – higher chemical input for weed control	Chivenge et al., 2007; Vanlauwe et al., 2014; Baudron et al. (2012)
CA with local *in situ* soil water conservation tillage practices using maresha ard plough. Different types of raised bed and furrow of planting systems	Raised bed/derdaro – have furrows and permanent raised beds with 35 cm wide – tillage was done once at sowing by refreshing furrows – no tillage on top of the raised bed	Humid and semiarid areas	Sloping lands (>5%)	‘[a]	‘[a]	– tendency to dry out more quickly	Nyssen et al., 2011; Araya et al., 2011; 2012; 2015; 2016a; Sayre (2004)
	Raised bed/derdaro – have furrows and raised beds with 35 cm wide made yearly - tillage was done once at sowing by refreshing furrows	Humid and semiarid areas	Sloping lands (>5%)	‘[a]	‘[a]		Nyssen et al., 2011; Araya et al., 2011; 2012; 2015; Sayre (2004)
	Raised bed/terwah – furrows made at 1.5 m intervals along the contour – tillage was done only once at sowing	Semiarid areas	Sloping lands (>5%)	‘[a]	‘[a]		Nyssen et al., 2011; Araya et al., 2012; 2015; 2016a; Sayre (2004)
CA with tie ridging	This is generally not considered a CA seeding system due to considerable soil movement during land preparation. In this system, farmers create ridges and furrows using hand-held hoes. Ridges are closed every 80–100 cm across the ridge direction to conserve rainfall water. The systems has proved to be an efficient water conserving technology but cannot be classified as CA in the strict sense.	Dryland, Arid and semiarid areas	<7%	‘[a]	Variable	Greater soil losses may result due to overtopping under highly variable rainfall	Thierfelder et al., 2015; Chivenge et al., 2007; Brhane et al., 2005.
CA with basin/zai planting	Basins are constructed during the winter season thereby spreading labor requirements during the off-season. manually dug planting basins of different sizes (15cm × 15 cm × 15 cm in Zimbabwe and 15cm × 30cm × 25 cm in Zambia).	Dryland areas	<5%	‘[a]	Variable	– Issue with labor shortage in peak period as the basins requires considerable labor – Poor rooting depth for shallow soil	Haggblade & Tembo, 2003; Thierfelder et al. (2015)
CA with two wheel tractor	Two wheel tractor with either a rotary strip-tillage seeders or tow-behind or toolbar-based seeders	Arid to semiarid area	<5%	‘[a]	Variable	– Non availability of spare parts for fixing tractor in case of breakdown	Baudron et al. (2015a) Haque et al. (2016)
CA with meresha vs marasha ard plough	Tool pulled with animal traction for setting up weed-free seedbeds	Humid and semiarid areas	>5%	‘[a]	Variable	– Possible surface runoff due to cross plowing into the unplowed strips	Temesgen et al., 2008; Nyssen et al., 2011;
CA with direct dibble stick (a pointed stick) planter	Seeding with a dibble stick (a pointed stick) where farmers make two holes and place seed and fertilizer	Variable	<5%	‘[a]	Variable	– Lost of interest because seeding is very time consuming when planting through mulch in no tillage and reduced tillage system	Thierfelder et al., 2015; Thierfelder et al. (2015)
CA with direct jab planter	A more mechanized version is the jab-planter (matraca) that supplies seed and fertilizer in planting holes created by the implement.	Variable	<5%	‘[a]	Variable	– Clogging in wet condition, irrigation or after rain especially for clay soils – Inconsistency in seed numbers dropped per station, failure to drop any seeds in some stations	Boahen et al., 2007; Famba et al., 2011; Thierfelder et al. (2015)
CA with direct animal traction		Variable	<5%	‘[a]	Variable		

Table 2 (*continued*)

Conservation agriculture practices	Description	Target areas (climate)	Topography	Mitigation		Risk	Reference
				CO_2	N_2O		
	Animal traction direct seeding systems using Brazilian and locally produced direct planters, where the implement creates a rip-line, supplies seed and fertilizer and covers the line in one operation.					– Residue accumulation in some parts of the seeders resulting in irregular spacing or total absence of seeds – No existence of seedings plates for some crops	Thierfelder et al., 2015; Chivenge et al., 2007; Brhane et al., 2005.
CA with hoe	Hand tool used for soil tillage, seed bed preparation etc.	Variable	Variable	‘[a]	Variable	Creation of hoe pan	Sims et al., 2012;
CA with ripping	Ripping and rip-line seeding practice developed in Southern Africa based on seeding with an animal traction chisel-tine opener (the Magoye ripper) that is mounted on a plough beam. Eg. Zimbabwe, Kenya, Tanzania. Sometimes opening wings are used on the ripper attachment (mainly for sandy soils). The implement creates a furrow of approximately 10–15 cm width and 10 cm depth.	Semi-arid	<5%	‘[a]	Variable	Residues and vegetation on the soil surface obstructs the implement; lifting stones and clods	Thierfelder et al., 2015; Mupangwa et al. (2017)
CA with physical soil and water conservation structures	Crop fields under high slope gradient. Soil and water conservation strategies: stone bunds, terraces, ridges, tied ridges, planting pits,	Humid to semi-arid	>5%	‘[a]	Variable		Gebreegziabher et al., 2009; Nicol et al., 2015; Hailu, 2017;

[a] Denotes reduced emissions or enhanced removal (positive mitigative effect).

that at least five years of cropping were required before the crop yield became significantly higher under CA systems as compared to conventional tillage systems, while Araya et al. (2011) reported at least three years in drier areas. Early CA success may be limited by increased weed infestation, lack of nutrient replenishment by fertilization, grazing of crop residue by livestock, and improper implementation of CA packages (Rockström & Barron, 2007). Therefore, complementary practices may be required to make CA systems more functional for smallholder farmers in the short term (Nyamangara et al., 2013; Thierfelder et al., 2018). CA is practiced on an estimated 205.4 million ha worldwide, with an increasing adoption rate of 10 million ha per year Since 2008/2009 (Kassam et al., 2022), thus comprising 14.7% of the 1.6 billion ha cropland on Earth. However, the CA area coverage in SSA is only 1.25% of the total cultivated area (Table 1, Kassam et al., 2022; Kassam et al., 2015). Therefore, the objectives of this article are to summarize the benefits, challenges, and constraints to adopting CA in smallholder agriculture in SSA, accounting for the region's unique agroecological and socio-economic settings.

2. Conservation agriculture principles

Fig. 1 shows the levels of soil tillage disturbance and crop residue retention under different CA systems. CA is defined as an agricultural system that simultaneously combines three principles, namely i) minimal soil disturbance, ii) retention of crop residues, and iii) crop rotations (FAO, 2022, Fig. 1; see Table 2 for details on CA in SSA). The first principle, minimizing soil disturbance, is critical because intensive tillage promotes aggregate break-down and SOM losses by oxidative degradation and erosion (e.g., Lobe et al., 2001, 2011; Prasad et al., 2016). In addition, there is the risk that repeated tillage promotes surface sealing and crusting after heavy rainfall, thus reducing subsequent infiltration and water use (Jakab et al., 2013). To avoid these risks, practices such as no-tillage farming have been developed. According to Phillips & Young (1973, p. 224), no-tillage is a conservation farming system, in which seeds are placed into otherwise untilled soil by opening a narrow slot, trench, or hole of only sufficient width and depth to obtain proper seed placement and coverage. This is also called direct seeding and may be performed with bare soil conditions or with partial soil cover with crop residues. If crop residue coverage is high, it may be necessary to cut or move the residues from the seeding zone to allow sufficient soil contact.

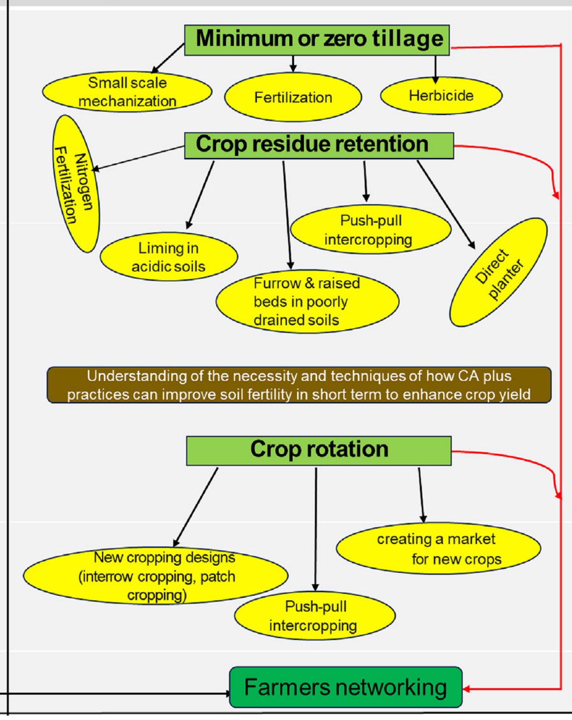
Systems that minimize soil disturbance have several advantages and disadvantages (Gattinger et al., 2011), with perhaps the most important advantage being the significant reduction of soil erosion by wind and water. Other advantages may include the reduction of SOM loss, improvement of soil structure and health, and reduced fuel and labor requirements. However, increased reliance may be placed on herbicides, especially when the crop residue soil surface cover is not ample. Optimal weed suppression requires at least 60% cover of surface mulch (Bilalis et al., 2003). The area under no-tillage management currently exceeds more than 100 million ha cropland worldwide (Derpsch & Friedrich, 2009), but there has been little adoption in SSA. These no-till systems often require a specialized planter, however, smallholder farmers in SSA rarely have access to such mechanized small-scale implements. No-till systems are not synonymous with CA unless they adhere to all three CA principles.

Small-scale tillage implements for CA in SSA are diverse and adaptable to the needs and resources of local farmers. Farmers can implement CA practices effectively by selecting appropriate soil tillage implements with low to moderate soil disturbance levels (Fig. 1 and Box 1). Some small-scale tillage implements commonly used in CA practices in SSA include ripper tines, chisel plows, handheld motorized tillers, no-till planters, mulch spreaders, seed drills, and manual conservation tillage tools. The soil disturbance levels depend on the type of tillage implements used. For example, the soil disturbance levels with no-till planters are minimal or zero while there is a moderate soil disturbance levels with rippers tines (Figs. 1 and 4).

Adoption and spread of CA practices under the small-scale farmers' condition in SSA may be improved by providing appropriate tillage tools and equipment that can improve soil health, increase crop yields, and enhance resilience to climate change in the region.

Box 1

Examples of key challenges and good agronomic practices that can be combined with CA depending on the soil and climatic resources, implement tools, and availability of farmers networking for knowledge exchange group and decision making in order to facilitate its wider adoption and spread among smallholder farmers in Sub-Saharan Africa.

Challenges for proper implementation of the principal components of CA by small-scale farmers in SSA	Examples of CA plus practices that could help SSA small-scale farmers implement CA
1. Minimum or zero tillage - Provide knowledge how to cope with additional weed infestation and additional pest risks - Provide knowledge on the need to preserve soil rather than performing shifting cultivation - Provide access to machinery and possibly herbicide and means to fertilizer **2. Crop residue retention** - Provide solutions to crop residue tradeoffs between CA and livestock - Provide understanding to manage high C: N ratio crops (recommended at early phases of CA but risk of additional fertilizer needs) - Provide technical means for crop residue management and planting - Understand specific risks of crop residue management (yield loss in poorly drained soils, snails) - Motivate for and combine with, if possible, with nitrogen fertilizer - Provide shoes, access to health systems (e.g., for snake bites) and infrastructure for kids to facilitate school attendance (more time to help) **3. Crop rotation** - Soil and climate factors limit crop choice: provide help and market access needed to diversify the cropping system - Combine with traditional management of niche products **4. Overall** - CA is knowledge- and time intensive, demonstration trials needed	

Crop residue retention is the second principle of CA, aiming at covering at least 30% of the soil surface of the crop field at all times. This recommendation is based on studies on soil erosion, where 30% of ground cover reduces soil erosion by approximately 80% (Wall, 2007). However, higher or lower levels of residue may be appropriate depending on the management goals and the risks of erosion. In all CA systems, the ultimate goal is the same: to retain a sufficient amount of residue on the soil surface in order to protect the soil from erosion and to enhance long term sustainable production (Araya, 2012; Govaerts et al., 2006). The amount of crop residues that can be retained depends on the climate, the types of crops grown, and the level of soil disturbance (Table 2). Apart from the protective role against erosion, crop residues also protect soil from raindrops, wind, and radiation, and thus from surface crust formation. Crop residues may also increase water infiltration, reduce evaporation, and promote SOM accrual and biological activity (Araya et al., 2015; Vanlauwe, 2004). However, for smallholder farmers, retaining high amounts of crop residue may be problematic: it interferes with planting and may require cutting into smaller pieces, which is difficult without mechanized equipment. Standing stubble additionally increases the risk of foot injuries for workers lacking suitable shoes and may provide cover for snakes. Also, snake bites are a major health risk for agricultural workers in SSA (Halilu et al., 2019). Bouwman et al. (2021) reported that CA increased mice populations and burning by mice hunters completely removed crop residue retained in Malawi. Yet, cutting the standing stubble crop residue into smaller pieces can also increase the soil surface area coverage.

The third main principle of CA is crop rotation as a biological means to enhance soil health and suppress weeds and soil pathogens (Pittelkow et al., 2015). Well balanced rotations frequently involve cereals and legumes (e.g. maize and legumes; Mupangwa et al., 2017), with the additional advantage that legumes in rotation may contribute to biological N fixation and to the improvement of soil fertility. In SSA as in other regions, properly designing the sequence and profitable crop rotation practices can avoid pest transmission to the next crop from the crop residues of the previous season, while also helping to diversify food crops.

3. Challenges of conservation agriculture adoption

Despite decades of investment in development and dissemination, uptake of CA is persistently low in SSA (Box 1; Corbeels et al., 2015, pp. 443–476; Araya et al., 2012; Baudron et al., 2012; Giller et al., 2009). Local adaptation requires tailoring CA to the local farming systems, tillage tools, soil, and climatic resources. CA practices implemented in combination with other good local agricultural practices provide greater short term benefits. In part, CA measures are also soil group specific (Amelung et al., 2020; Driessen et al., 2000). For instance, integrating furrow and raised beds may be needed as elements of CA in Vertisols to avoid waterlogging, increase soil water storage and reduce runoff (Araya

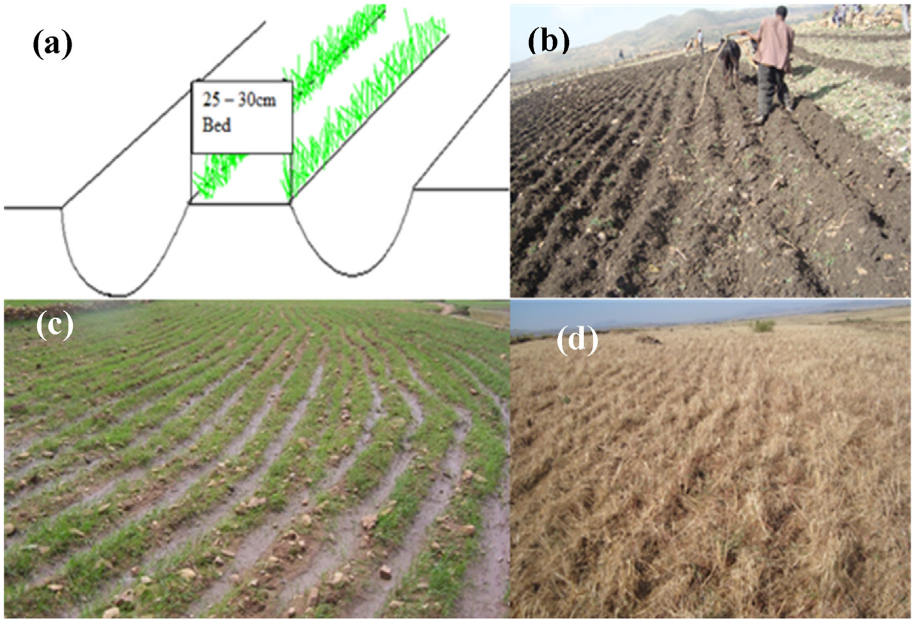


Fig. 2. Section view of the raised beds made using oxen ard plough *maresha* with (a) diagrammatical representation, (b) at planting, (c) after crop emergence, and (d) after harvest with crop residue retained in Ethiopia.

et al., 2016b), whereas incorporating lime is needed for CA in acidic soils, such as Nitisols and Acrisols. The integration of furrows and raised beds with CA using the oxen ard plough or *maresha* has increased CA adoption and spread in Ethiopia (Table 1; Araya et al., 2012; Lanckriet et al., 2014). Araya et al. (2012) reported that CA-based systems that incorporate furrows and raised beds have encouraged row planting although the seeds were sown by broadcasting because the seeds that fell in the furrow were moved to the bed during refreshing the furrow at planting (Table 2; Fig. 2).

In a basin CA planting system, nutrient sources (e.g. manure, compost and/or fertilizers) are often used in greater quantity than conventional practices, and added to the planting basin, where they can be better utilized by the crops (Haggblade & Tembo, 2003; Thierfelder et al., 2015). Contour ridges, sometimes planted with perennials, can be integrated into CA systems as an important erosion control method in hilly landscapes (Box1; Gebreegziabher et al., 2009; Nicol et al., 2015; Araya et al., 2016; Hailu, 2017, Table 2). Leguminous trees can be planted with annual crops in an agroforestry system as food, mulch, or nitrogen fixers (Table 2; Franzel et al., 2014; Bayala et al., 2011; Akinnifesi et al., 2011). “Push-pull” intercropping can also be integrated with CA to control pests (the ‘push') while also growing plants (trap crops) that are attractive to pests around sorghum (Sorghum bicolor L.) (the ‘pull') (Khan et al., 2012; Vanlauwe & Dobermann, 2020). CA practices thus sometimes enable other good practices. Reduced tillage and soil cooling with mulch may allow farmers to plant early in the planting season and spread labor across the off-season, improving yields.

Likewise, smallholder tillage implements vary across SSA countries (Corbeels et al., 2014), and thus, the distribution of small-scale equipment may be needed to foster CA as described in section 2 (Box 1). For example, in Mozambique, some farmers do not even have steel tillage tools but rather “plough” their sandy soils manually with wooden sticks. While this limitation is not unique to CA, adequate equipment is a prerequisite also for appropriate nutrient and pest management necessary to close yield gaps. Thierfelder et al. (2018) reported 11 complementary practices from southern Africa that can substantially enhance the functioning of CA systems, and each must be tailored to the local farmer contexts.

Frequently, in the short term, the benefits of CA practices do not adequately outweigh their immediate costs (Giller et al., 2009; Vanlauwe et al., 2014). Resource-poor farmers need immediate returns from their investments in CA to be able to feed their families. Much of the literature introducing CA did so for soil and agroecological conditions much different from those of SSA farming systems. In SSA, benefits like snow and thus water harvesting by stubble (Tanaka et al., 2010) are lacking, while other problems like inadequate residue production due to low crop productivity, lack of herbicides and spraying equipment, and insufficient farmer training are substantial barriers to CA adoption in SSA.

Several authors (Akinnifesi et al., 2011; Araya et al., 2015; Bayala et al., 2011; Corbeels et al., 2014; Thierfelder et al., 2018; Vanlauwe et al., 2014) reported that CA management is successful when all the three principles are fulfilled simultaneously. However, additional complementary practices may be important to improve the performance of CA systems in SSA. Vanlauwe et al. (2014) thus redefined CA specifically to the smallholder farmers' context in SSA and added “appropriate use of fertilizer” as a fourth principle of CA. Others state that other specific elements should be added to CA, such as small-scale mechanization of planters in SSA (Sims et al., 2012), raised bed and furrow tillage structures in poorly drained Vertisols (Araya et al., 2015), or agroforestry (Akinnifesi et al., 2011; Bayala et al., 2011). Specific practices of CA in SSA are diverse and vary according to local farming conditions (Corbeels et al., 2015, pp. 443–476). However, standardization of the principal components of CA is crucial to achieve better results (Derpsch et al., 2014). The following sub-sections discuss specific challenges to CA adoption in the SSA context.

3.1. Small-scale mechanization for conservation agriculture

Mechanization has played a significant role in implementing CA in large commercial farms using heavy tractors and large-scale machinery (especially seeders). The limited adoption of CA in developing countries, particularly by small-scale farmers, is thus mainly associated with the absence of small-scale appropriate equipment at an affordable price (Sims & Kienzle, 2006, 2015). Even when mechanized equipment is available, smallholder farmers

Fig. 3. Examples of smallholder tillage implements in SSA (a) ripper for direct seeding in Zambia (b) animal-drawn direct seeder and fertilizer distributor in Tanzania, and (c) mechanical jab planters for manual direct seeding and fertilizer application.

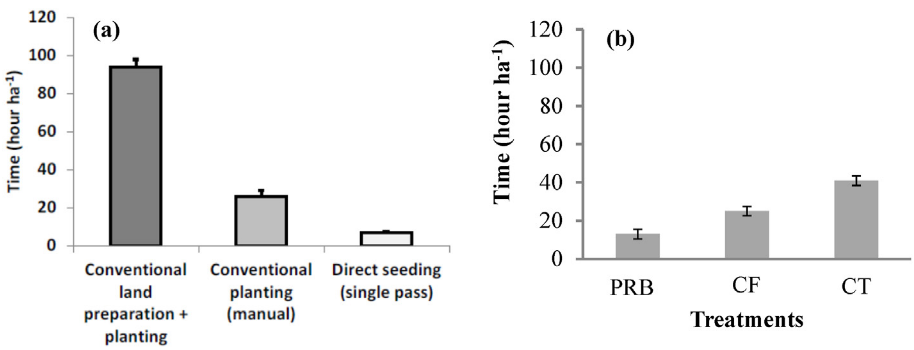


Fig. 4. Comparison of the average time required (a) for conventional land preparation and conventional planting of maize (land preparation using an animal-drawn *maresha* and planting by hand), for conventional planting of maize only (following conventional land preparation), and for direct seeding of maize using a 2BFT-100 seeder powered by a 15 HP two-wheel tractor in an untilled land in Hawassa Ethiopia (adopted from Baudron et al., 2015b) and (b) for conventional tillage (CT) and two CA-based systems (permanent raised bed (PRB) and contour furrowing (CF) using oxen-drawn *maresha* (Araya et al., 2012).

often have difficulties in making the necessary investments (Sims & Kienzle, 2015). According to Johansen et al. (2012), smallholder farmers in SSA adopting no-tillage or minimum tillage systems mostly rely on manual or animal draft power, with few using mechanized direct seeders. Consequently, mechanization of the smallholder farm sector can crucially facilitate the adoption of CA.

Appropriate tillage tools for CA differ depending on the soil type, climate, and socio-economic factors. According to Derpsch et al. (2014), the level of the soil surface disturbance by tillage (Fig. 1) should be less than 50% to be considered as a CA system. The final level of soil disturbance, as well as the planting method and fertilizer placement, are different among CA systems. In recent decades, there have been several small-scale tillage implements adopted in SSA that are useful for wider adoption and spread of CA. These include ripper tines, chisel plows, handheld motorized tillers, no-till planters mulch layers, seed drills, and manual conservation tillage tools. No-till planters have minimal to none soil disturbance levels while low soil disturbance levels are related to hand hoes and manual tillage tools. Seed drills with minimum tillage features and cultivators with surface mulching capability have low to moderate soil disturbance levels. However, the soil disturbance levels by chisel plows and ripper tines are moderate. By selecting appropriate soil tillage implements with low to moderate soil disturbance levels, farmers can implement CA practices effectively while preserving soil health, enhancing crop productivity, and mitigating environmental degradation.

Manual systems include planting with a pointed stick, hoe, and mechanical jab planters (*matracas*). The hand jab planter, a simple and cheap implement for penetrating surface mulch and depositing seed and fertilizer at the required depth in the soil, is a key tool for smallholder farmers using hand labor. With animal-drawn traction, *maresha* ard plows are used, e.g., in Ethiopia (Fig. 2), rippers (Fig. 3(a)) and other direct seeders (Fig. 3(b)) are sometimes employed in SSA. The pointed stick remains the main planting tool in Ghana (West Africa) (Diop, 2016). The openings in jab planters (Fig. 3(c)) at planting are clogged with mud in fine and sticky soils such as Vertisols. Therefore, further research in the evaluation, development, and modification of different small-scale seeders for CA is of interest in SSA to adapt the benefits from the zero tillage or minimum tillage practice to site-specific settings. One promising recent development that should be further investigated is the mechanized hand planter developed at Oklahoma State University (Dhillon et al., 2018).

Ripper tines are narrow, curved metal tools designed to penetrate the soil without turning it over and they create narrow slits or furrows in the soil, which helps to break up compacted layers, improve water infiltration, and enhance root penetration (Fig. 3). Ripper tines are often attached to hand tools or animal-drawn cultivators for small-scale operations. Chisel plows are similar to ripper tines but feature multiple shanks arranged in a row and they are used to loosen compacted soil layers and break up hardpans without completely inverting the soil. Chisel plows are suitable for small-scale farmers who have access to animal traction or small tractors. Handheld motorized tillers or mini-tillers are compact, lightweight machines powered by engines. They are suitable for small-scale farmers who need mechanized assistance for soil preparation but cannot afford larger machinery. Handheld tillers can be equipped with various attachments such as cultivators or rippers for CA practices. No-till planters are specialized seeding machines designed to plant crops directly into untilled soil with minimal disturbance. They feature coulters or disc openers that create small furrows for seed placement without fully overturning the soil. No-till planters are particularly beneficial for small-scale farmers practicing CA as they help retain soil moisture, reduce erosion, and preserve soil structure. Mulch layers are implements used to apply mulch (such as crop residues or plastic film) to the soil surface after planting. Manual or animal-drawn mulch layers are suitable for small-scale farmers practicing CA. Seed drills are implements used to sow seeds directly into untilled soil at precise depths and spacing such as the jab planter. They can be adapted for CA by incorporating features such as no-till coulters or seed tubes to minimize soil disturbance. Seed drills enable small-scale farmers to plant crops efficiently while conserving soil moisture and reducing erosion. Traditional hand tools such as hand hoes, mattocks, and dibbers can also be used in CA practices on a small scale which allows farmers to perform minimal soil disturbance while preparing their lands.

To make CA techniques more accessible to smallholder farmers, there is a need for technical and business management training of entrepreneurs focused on developing and delivering locally adapted agricultural equipment. Such training must recognize that 70% of smallholder farms in SSA rely exclusively on manual labor, and only about 10% uses engine powered sources (Corbeels et al., 2014). Draught animals contribute to the remaining 20–25 % of farm power supply (Kienzle et al., 2013). In this context, a key benefit of CA is that it dramatically reduces the time needed to establish a crop as compared to conventional tillage (CT) because the number of operations required to prepare the land (and the intensity of these operations) is reduced (Baudron et al., 2015b, Fig. 4). Fig. 4(b) shows the average time required to plough per ha using oxen-drawn *maresha* ard plough at planting time in CT and in two CA-based systems (permanent raised bed PRB and contour furrowing CF). Araya et al. (2012) reported that the tillage at sowing was 3 times faster in raised bed (PRB) system (16 h ha^{-1}) than in the CT system (41 h ha^{-1}), thus fostering acceptance for farmers as an elements of CA principles.

There are several commercially available CA seeders for two-wheel tractors from countries such as China, India and Brazil. The two-wheel tractors can be used to seed most large seeded crops such as maize and cotton and small grain crops such as wheat and rice (Baudron et al., 2015a). According to Baudron et al. (2015a), rotary strip-tillage seeders and tow-behind or toolbar-based CA seeder technologies can be used for seed placement. However, the sustainability of mechanization includes financial and social, as well as environmental factors. Local manufacturing should be supported, as was the case in Brazil, but this is a slow development process, especially in SSA. A more immediate solution is to equip and train CA service provision entrepreneurs. Local manufacturers should be supported where feasible as they can provide implements and machines adapted to local conditions and better technical service and replacement part supply (Rai et al., 2011; Sims & Kienzle, 2006).

3.2. Management of crop residues

The second principle of CA, crop residue retention, is challenging in the SSA context. The amount of crop residue produced is often inadequate for effective CA due to low crop biomass yields, and the cereal residues also represent a major source of feed for livestock. Therefore, following CA guidelines strictly creates hard tradeoffs between soil conservation, livestock production, and food security in these smallholder farming systems. Implementing CA may not be feasible when feeding livestock depends on crop residues, particularly in cases where farm size is shrinking, soil fertility is declining, and costs for maintaining livestock are becoming prohibitive (Tegebu et al., 2012). Besides, there is the need to build paddocks to collect the animals overnight for dung collection, and the dung has to be transported to and spread on the fields, which are not necessarily nearby or lack easy access via roads. Some options for increased ground cover in such cases may be intercropping, cover crops, or agroforestry practices. Integrating CA implementation with the planting of fodder trees and forage grass production might thus facilitate CA acceptance in such farming environments (Franzel et al., 2014). Leguminous nitrogen-fixing tree species in combination with CA may help to improve crop yield (Akinnifesi et al., 2011; Bayala et al., 2011) and increase fodder availability to livestock. Trees are pruned once a year and their branches spread over the field adding organic matter to the soil and serve as fodder; yet with risks of increased water usage (Wallace, 2000). Intercropping maize, millet, or sorghum with *Faidherbia albida*, *Gliricidia sepium* or *Tephrosia candida* has been promoted to farmers in Malawi, Zambia, Burkina Faso, and Niger (Garrity et al., 2010).

Another problem with retaining the crop residues on the soil surface is that they might be eaten up rapidly by termites. The use of pesticides to control termites is thus recommended though not necessarily successful if these termites inhabit deep soil niches in significant amounts even without nest formation (Bignell & Eggleton, 2000). However, mulch induced termite can even be crucial for the restoration of crusted soils in semi-arid areas of West Africa (Lahmar et al., 2012; Mando & Miedema, 1997; Nyagumbo et al., 2015). Nyagumbo et al. (2015) reported that the application of crop residues in CA leads to increased termite activity and termite numbers but reduces termite-induced crop lodging of maize plants in Mozambique. They found a commercial insecticide fipronil (phenylpyrazole) to be effective in reducing crop lodging and termite activity in CA systems. On the contrary, at other sites, termite activity in mulched crusted soils in northern Burkina Faso resulted in greater infiltration along with soil water storage and deep drainage (Mando, 1997). Besides, many termite nests are enriched with carbon and other nutrients such as P (Rückamp et al., 2010), thus rendering them a yet underexplored fertilizer source (Batalha et al., 1995; Black & Okwakol, 1997). The examples again show that successful implementation of CA is site-specific, thus calling for guidelines to disentangle the complex interplay of positive and partly negative feedbacks of CA for crop yield.

In acidic soils, liming may be essential to avoid yield losses. However, pure liming to minimize crop yield losses on acidic soils (Table 2) may also accelerate crop residue decomposition when placed at the surface soil (Bot & Benites, 2005). Depending on rainfall intensity, however, the crop residue may also promote the transport of calcium carbonate (lime) to deeper soil layers after surface application (Bot & Benites, 2005).

Crop residue mulching is beneficial to control weed (Mtambanengwe et al., 2015). Crop residue can be successfully retained in countries where livestock is not requiring straw (e.g. Malawi) so that residue is available to control weeds (Andersson and D'Souza, 2014; Thierfelder et al., 2018). In the absence of tillage, however, weed control by crop residue management requires much more knowledge and, frequently, a more intense use of herbicides and particularly insecticides (Bolliger et al., 2006). Adoption of CA in Brazil occurred particularly when herbicides such as glyphosate were available and affordable (Bolliger et al., 2006). Also in Malawi, use of herbicides were a major entry point for CA adoption when NGOs gave it out on loan basis (Thierfelder et al., 2018; Andersson and D'Souza, 2014). Nevertheless, to prevent health risks, appropriate use and dosing of the herbicide is of utmost importance. Many smallholder farmers, however, lack experience with herbicide application, in addition, they usually lack safety equipment for spraying as well as knowledge on how to use it. Besides, there are elevated costs for herbicide acquisition and labor, which finally add to the barrier of adapting CA (Erenstein, 2002).

3.3. Implementation of crop rotation

The third principle in CA, crop rotation practices, is important

Table 3
Pros and cons of implementing conservation agriculture in terms of soil physical, soil chemical, soil biological, ecological, biomass productivity and profitability.

Response	Physical quality	Chemical quality	Biological quality	Mechanical quality	Agronomic & economic productivity	Ecological quality
Positive	Green water availability (reduced soil evaporation and runoff; and increased soil infiltration and water holding capacity)	Cation exchange capacity increased	Enhanced soil biodiversity	Penetration resistance	Crop yield (straw and grain yield)	Reduced soil degradation and improve soil regeneration
	Reduced salinity	Enhanced nutrient retention and availability	Food and habitat for soil biota	Soil strength/ erodibility	Reduction in labor and cost of production	Reduce water and wind erosion
	Resistance to surface sealing and crusting formation	Altered buffer capacity (against pH)			Increased profit	Deep drainage and recharge aquifers
	Improved aeration and microporosity	Increased soil N mineralization			Reduce oxygen for draught power and straw demand	Use efficiency of input
	Improved soil aggregation and structural stability	Increased soil organic matter				Nutrient cycling & biogeochemical transformations
	Reduced soil temperature oscillations					Diversification of crops Reduce CO_2 emission & Carbon sequestration Adaptation and mitigation to climate change
Negative	Soil compaction, particularly in subsoil (coarse-textured soils)	Soil nutrient immobilization (in short-term)	Prone to weeds and pathogenic organisms		Increased weed competition at the beginning of CA implementation	Risk of enhanced N_2O release at needs for elevated use of N fertilizer
	Water-logging (poorly drained soils) (in short-term)	Acidification and aluminum toxicity	Difficulties in controlling larger soil fauna (like snails)		Occurrence of residue-borne diseases at the beginning of CA implementation	
		Requires large amounts of herbicides and insecticides		Stimulation of crop pests at the beginning of CA implementation	Health risks from stubble injuries and snake bites hiding below the mulch	
	Reduced mixing of lime and organic matter into the soil	pH control in subsoil difficult				

for the success in pest and weed control. When successful, yields and related crop residue input and intention will rise, thus increasing C sequestration as a result of increased C input (Amelung et al., 2020). Particularly high amounts of crop residues can be retained upon cereal cropping, whereas legume intercrops help to improve N inputs and thus crop residue return in the following season (Araya et al., 2016a). According to FAO (2022), a minimum of three different crop species is recommended. However, many smallholder farmers in SSA have limited choice of crop to grow, partly due to climate and soil restrictions, but largely due to personal needs and restricted market access. When implementing CA, priority in the first and second year should be given to crops that provide high crop residue biomass with a high C:N ratio preventing its rapid decomposition, especially in drylands areas where soil moisture stress is a determinant factor for crop yield. Particularly in such regions the residues can help to improve water storage by reducing evaporation and enhancing infiltration rate. Yet, to prevent lock-up of N by elevated C/N ratios in the residues, adapted N fertilization will be needed. When feasible, the inclusion of legumes (low C:N ratio) should be planned at least starting from the third year to maintain soil fertility (Araya et al., 2016b; Mandiringana et al., 2005; Mupangwa et al., 2017), the final crop sequence options depend again on the agroecological setting. Crops with a higher distance between row spacing, such as sorghum and maize, facilitate erosion and evaporation relative to crops with less distance between rows, as common, e.g., for cowpea and grass pea, which, however, enhance transpiration (productive water loss). The best choice of crops thus depends, among others, largely on the rainfall regime adaptability. In bimodal rainfall areas with two cropping seasons per year, it may even be important not to accumulate too many residues to avoid interference of crop residue during double cropping; in these cases, even Azoter bacteria biofertilizers have been recommended to increase the decomposition rate and plant nutrient availability (https://www.azoter.sk/?lang=en).

Cover crops such as Pigeon pea (Mwila et al., 2021) may also be part of the crop rotation in SSA. Many cover crops such as black oat (*Avena strigosa* Schreb.) have been successfully integrated into CA systems in temperate regions (Fageria et al., 2005). Cover crops offer opportunities for smallholders by addressing soil fertility, livestock feed, soil erosion, and weed management constraints. However, as cover crops may also increase transpiration (Meyer et al., 2019), the potential of using cover crops is restrained again to the (sub) humid zones and to instances, where the opportunity cost of using land to grow cover crops, is low (Erenstein, 2003). Many cover crops are not grown for market purposes (Fageria et al., 2005), particularly for smallholder farmers it is thus not profitable to grow them during the main rainy season.

3.4. Conservation agriculture and crop yield response

In general, the goal is to meet the demand of the growing population. CA might have a disadvantage that crop responses can be highly variable, and not always higher than the conventional tillage practices (Araya et al., 2012, 2015; Gill & Aulakh, 1990; Mbagwu, 1990). Without clear short term benefits, however, the acceptance of CA by smallholder farmers may be low, and some of the negative effects presented in Table 3 and Box 1 discouraged its adoption by smallholder farmers in SSA.

Corbeels et al. (2014) reported that CA had positive overall effects on crop yields relative to no-till without mulch and conventional practices in SSA. Yet, improvements in crop yield in CA systems required a period of 5 years of cropping before they became significant (Govaerts et al., 2005), depending on agroecological and topographical (slope) conditions. CA can improve yields in short term in dryland areas where moisture is limited (Lal, 1986; Vogel, 1993), although the full yield benefits of improved water availability are realized only after improvements in soil fertility (Rockström & Barron, 2007). Also, the effects of CA on soil biochemical properties are dependent on certain biophysical factors, which include soil type, amount and quality of residue retained and climate. Chivenge et al. (2007) reported that SOM loss because of tillage was much larger for sandy than for fine-textured soils due to the lack of physical protection of the SOM under sandy soils. In a similar manner, also crop yield response to CA can vary with soil texture. Yield responses would likely be positive overall when CA is combined with organic fertilization.

For drylands of some West African countries (Burkina Faso, Mali, Niger and Senegal), Bayala et al. (2011) reported more positive effects of CA on crop yields (76%) than negative (24%) cases. On the contrary, CA partly performed worse in terms of crop yield than conventional tillage under high rainfall and poor soil drainage conditions, which has often been attributed to aeration problems resulting from waterlogging (Anazodo et al., 1991). Hence, the success of CA for yield improvement depends on climate. According to Falkenmark & Rockström (2008), the relationship at which CA enhances grain yields of cereal crops by water harvesting is exponential in SSA for crop yields below 4 t ha^{-1}, whereas, at yield levels above 4 t ha^{-1}, the relationship between water productivity and CA practice is a linear mode, i.e., each new ton of food requires a proportional gain in water. Thierfelder & Wall (2009) reported that improving infiltration rate and soil moisture availability under CA systems enhanced maize yields in Zimbabwe and Zambia especially when these effects manifested during critical crop developmental stages.

Crop yield in CA systems can be reduced due to a low mineralization rate in the absence of tillage. The most commonly retained crop residues for soil cover in CA systems are cereal derived, and thus have, unlike leguminous residues, a high C:N ratio that reduces crop yield (Gentile et al., 2009). Gentile et al. (2011) reported a high C:N ratio crop residue retention can increase nitrogen immobilization (also called N lock-up) in the short term, which calls for a different fertilization strategy to enhance crop yield under CA. Consequently, N fertilization is needed to increase grain yields in CA (Corbeels et al., 2014), despite the risk of greenhouse gas formation and boosting microbial growth for residue decomposition. Targeting non-excessive but adapted use of N fertilizer rate is necessary as a fourth principal components of CA (see above sections 3 and 3.3). Also, Thierfelder et al. (2018) reported that fertilization is essential in nutrient-limited conditions in southern Africa, especially with nitrogen for CA systems to produce sufficient crop residues for surface mulching. Although farmers in SSA widely acknowledged the benefits of mineral fertilization, its use has remained very low (Sommer et al., 2013; Thierfelder et al., 2018). Thierfelder et al. (2018) reported the average mineral NPK fertilizer used by smallholder farmers in Africa in 2012 was only 17 kg ha^{-1} which was the lowest rate of all continents. However, high mechanization and good access and use of mineral fertilizer were reported to be associated with wider adoption of CA systems (Bolliger et al., 2006; Kassam et al., 2009). An example for success might be the Farmer Input Support Program of Zambia, where the government supports efficient soil fertilization by farmers via an E-voucher system, which increases crop residue return and may thereby increase SOC, even at small-holder farm level (http://www.pmrczambia.com/wp-content/uploads/2015/09/Farmer-Input-Support-Programme-Infographic.pdf). Such programs may also help to improve nutrient status in soils with elements other than N. Particularly the Acrisols widely found in SSA are, for instance, usually also limited in P, basic cations, or Zn (Margenot et al., 2016).

Baudron et al. (2015b) and Vanlauwe et al. (2014) reported maize grown under CA systems in southern Zimbabwe have lower chlorophyll content in its early growth stage because of N immobilization and thus insufficient availability of N for the crop, which is later reverted, providing sufficient N for the plant. Although green manure and leguminous crops with low C:N ratios favor both decomposition and short term increase in the labile nitrogen pool during the growing season, they have little benefit in terms of biomass accumulation during their own growing season. Yet, due to the formation of deeper biopores, legumes may help to access water from the subsoil when the surface soil dries out (Kautz et al., 2013).

As many of the soils in SSA are poor in SOM, adding organic fertilizers with CA practice will accelerate its success. This also applies to biochar, aiming at both sequestering persistent C and improving yields (e.g., Woolf et al., 2010). Yet, mere biochar additions showed variable effects on the yields of some productive soils in humid climates (Borchard et al., 2014; Jeffery et al., 2011). Biochar amendments have positive effects on soils when applied in combination with inorganic fertilizers and organic manures irrespective of climate (Ye et al., 2019) and improved aggregate formation in sandy and clayey soils (Liu et al., 2013; Omondi et al., 2016). Such amendments can also improve soil fertility with pronounced effects on anion exchange capacity due to the additional cation exchange surface area by oxidized biochar surfaces (e.g., Ferralsols, Acrisols; Kätterer et al., 2019). However, the on-site production of biochar may include forest cutting and collection of dead wood, which then can go along with forest ecosystem degradation that clearly has to be avoided.

3.4.1. Meta-analysis on crop responses to conservation agriculture

Crop responses to CA in SSA have been meta-analyzed (Corbeels et al. 2014, 2020; Rusinamhodzi et al., 2011). The effects of long term tillage and residue retention on crop yield can be determined by meta-analysis of long term studies on soil texture, crop rotation, nitrogen input, climate, herbicide use, and soil disturbance levels. In a meta-analysis of 933 observations from 16 SSA countries, Corbeels et al. (2020) found that CA yields are only slightly higher than CT yields. Mulching and crop rotations/intercropping increase maize yields. Maize yield rises 8.4% when CA principles are implemented simultaneously. A meta-analysis by Corbeels et al. (2020) revealed that CA outperformed CT on all soil types below seasonal rainfall of 800 mm but only on coarse-textured soils under 800–1200 mm in SSA. The negative effects of CA on medium-textured soils were significantly lower than on medium- and fine-textured soils, probably due to the higher risk of waterlogging on these soil types.

Corbeels et al. (2014) and Rusinamhodzi et al. (2011) found that waterlogging reduced yields in 92% of high-rainfall areas with mulch cover. This study found that well-drained soils yield more and that soil texture affects CA effects in 85% of cases. Additionally, 73% of data showed that CA practices increase yield with high inputs, especially nitrogen. Many calculations ignore seasonal rainfall differences, but rotation increased yields in 63% of the data. In 56% of semi-arid regions, reduced tillage without mulch lowers yields. Farmers need crop residues and herbicides to control weeds to succeed. The study emphasizes crop intensification and reduced tillage in SSA to boost food production. Mulching can waterlog soil under continuous rainfall due to reduced evaporation and soil aeration. However, mulch is less effective in low-rainfall areas, so crop residues may be better as livestock feed. CA may increase maize yield below 600 mm and decrease above 1000 mm due to poor drainage in high-rainfall areas and CA in low-rainfall areas.

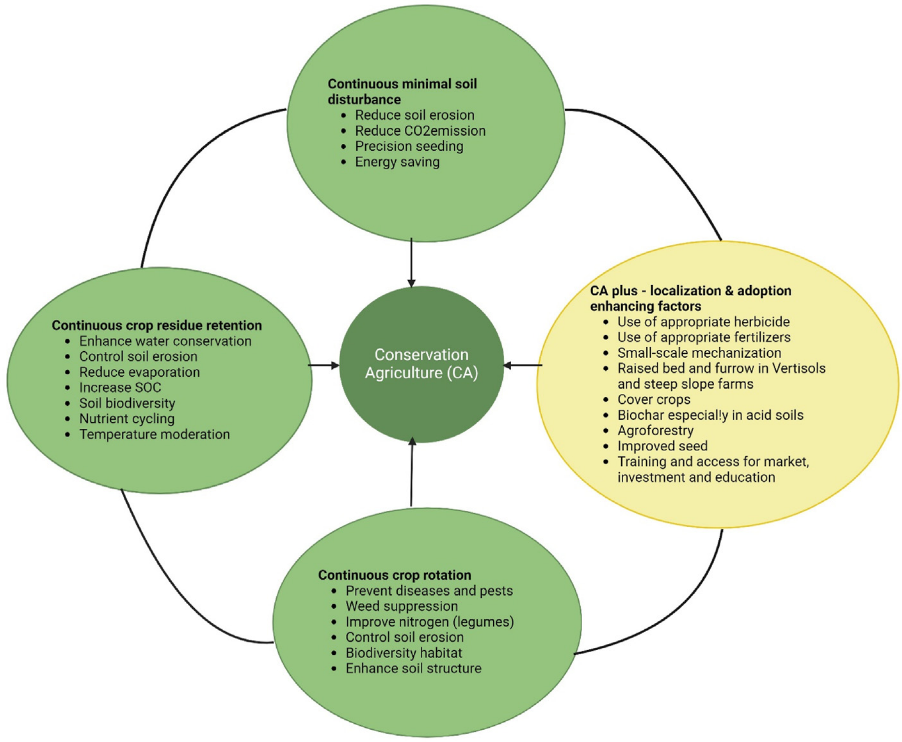


Fig. 5. Diagram representing the different components of conservation agriculture and potential practices that can be integrated with CA to adapt to the local conditions by smallholder farmers in Sub-Saharan Africa.

However, the authors did not include in their meta-analysis study the role of some good agronomic practices, for example, practices that minimize the effects of waterlogging on crop yield such as furrow and raised bed tillage structures and biochar applications.

Over time, CA reduced southern African rain-fed maize grain yield by 5–20% in wet years and increased it by 10–100% in dry years. Yield variability is most affected by precipitation.

Due to soil texture and experiment duration, weighted mean differences were mostly negative in clay soils but positive in loam and sandy soils. CA and CT had no effect on maize yield on silt clay loams. Corn grain yield increased on loamy and sandy soils (Corbeels et al., 2014).

Arslan et al. (2022) found in their meta-analysis that adapting CA practices to local conditions, needs, and challenges is crucial because local conditions may limit CA benefits. Farmers should identify locally important CA trade-offs and adapts or complementary practices to overcome them. Understanding local constraints, opportunities, and CA strengths and weaknesses is essential for successful implementation.

3.5. Partial adoption of conservation agriculture principles

Fig. 5 and Box 1 indicate the components of CA and its potential complementary practices that can be integrated with CA in different agroecological and socio-economic settings. Smallholder farmers in SSA usually undertake one or two CA principles in an isolated fashion without applying all of the three (or even four, when including N fertilization) principles together (Ito et al., 2007). Minimizing tillage and maintenance of soil cover are the least adopted CA principle(s) by many smallholder farmers in several countries in SSA, thus preventing the realization of the full benefits of CA. In contrast, minimum soil disturbance is partly well adopted when conducting CA by smallholder farmers, like in Zambia, Zimbabwe and Mozambique (Fig. 5 and Box 1; Thierfelder et al., 2018; Brouder & Gomez-Macpherson, 2014; Andersson and D'Souza, 2014). Reasons may vary, including governmental incentives in Zambia but lacking ploughing equipment at some poorer farms, e.g. in Mozambique. In this regard, there may be specific socio-economic constraints that determine to what degree specific principles of CA are adopted or not. However, given the fact that smallholder farmers tend to adopt CA partially in bits and pieces only (Fig. 5; Giller et al., 2009), the essential benefits of practicing the main principles of CA in combination are hardly seen. As a result, an incomplete adaptation of CA means by neighbors might be even a key hindering rather than a key entry point for potential adoption by the farmer (Araya et al., 2016b; Thierfelder et al., 2013; Valbuena et al., 2012). Also, scientific trials designed to test CA often do not meet the minimum requirements needed to demonstrate CA (Fig. 5; Giller et al., 2009; Ito et al., 2007). Particularly when farmers do not retain crop residues to cover at least 30% of the soil surface every year, the absence of tillage aggravates infestation of pre-emergent weeds such as *Digitaria* species (Araya et al., 2016a), which prevents adaptation by their neighbors. We suggest that CA in different socio-ecological settings should be supplemented with alternative complementary practices of sustainable agriculture, such as integrated pest management, planting of perennial legume trees, liming of acidic soils, and the use of cover crops or even agroforestry (Fig. 5).

In summary, to make CA a success story, we must keep in mind that there is no unique CA strategy across the globe. Different soils, climatic regions, topography and socio-economic settings require specific means to restore fertility as complements to adapt CA for more sustainable management. For instance, CA is less effective in crop fields with steep slope gradients, especially in poorly drained soils without other complementary *in situ* soil and water conservation measures (Araya et al., 2016a). In the latter case, soil-specific management practices should likely accompany CA, such as the augmentation of bed and furrow tillage structures in poorly drained Vertisols, with the outcome that they may hold rainfall, drain excess rainwater to the furrow, and therewith avoid waterlogging to crops grown on the ridge (Araya et al., 2016b). Bed planting, for instance, has the advantage over flat planting in terms of improved water use efficiency (Sayre, 2004) and easier control of weeds, which primarily spread in the furrows but not on the beds (Sayre, 1998; see also Fig. 2). Also, for other soils worldwide, farmers frequently have developed *in situ* soil and water management options based on local experiences over generations that can increase the soil's ability to store water for plant use, reduce vulnerability to drought as well as help halting soil erosion and degradation (Sayre, 2004). More innovations are likely to come also from deeper insights into traditional management practices that are commonly shown to correlate with improved soil fertility at the farms (Vanlauwe et al., 2014).

4. Effects on climate-resilient agriculture

Smallholder farmers farms in SSA are less resilient to the effects of climate changes due to lack of adaptive agronomic practices (Brown & Funk, 2008), declining in soil fertility (Sanchez, 2002), increased and severe soil degradation (Nkonya et al., 2016) and a rapidly increasing population (Godfray et al., 2010). SSA is predicted to be affected by global warming because it already experiences high temperatures and low and highly variable precipitation (Bryan et al., 2009; Kurukulasuriya et al., 2006; Liu et al., 2008; Twomlow et al., 2008). According to Bryan et al. (2009), more than two thirds of farmers in SSA perceived that temperature has been increasing and rainfall has been decreasing over time. Cairns et al. (2012) predicted that there will be more frequent dry spells and an increase in temperature by an average of 2.6 °C in the Central to Southern Africa. In fact, climate change increased evaporation in dry areas with an increased risk of crop failure in SSA (Cooper et al., 2008; Twomlow et al., 2008; UNDP, 2006; UNEP, 2003). The area suitable for maize production in SSA is projected to decrease by 30–50% due to climate change (Ramírez Villegas & Thornton, 2015). Rowhani et al. (2011) predicted maize yield reduction by 13% in Tanzania because of a 2 °C increase in temperature, while a 4.2% yield reduction was due to 20% increase in intra-seasonal precipitation variability. Twomlow et al. (2008) reported increased fungal outbreaks and insect infestations due to changes in temperature and humidity. In some mid-highlands areas of Ethiopia, for instance, farmers have already switched from long-cycle crops such as maize and sorghum to short-cycle crops such as wheat and barley (Meze-Hausken, 2004). Yet, crops such as wheat may be significantly affected by elevated surface temperatures while other crops, such as millet, might rather benefit from this climate change impact in SSA (Liu et al., 2008; Ortiz et al., 2008). Several researchers reported on CA under the smallholder context in SSA showed that it has a positive effect on adaptation and productivity, while its mitigation potential is below expectation. CA with adequate mulching can thus help to improve soil moisture and soil fertility and thus minimize the effects of declining rainfall and seasonal dry spells (Fig. 2; Thierfelder et al., 2018; Araya et al., 2016b) and high soil surface temperature (Giller et al., 2009) on crop yields. Maize is the principal food security crop across much of Africa (Dowswell et al., 1996) and its production in Southern Africa is estimated to decrease up to 70% of current production levels by 2030 (Lobell et al., 2008). Over 40% rain-fed maize yield loss has been reported by recurrent droughts in areas of Northeast South Africa, Southern Africa and northern Botswana (Cairns et al., 2013; Thierfelder et al., 2017). Overall, climate change may thus promote the establishment of CA also at smallholder agricultural farms; yet, the related benefits in terms of an adaptation strategy likely depends on the selection of crops grown in rotation. Therefore, climate resilient systems such as CA are crucial to adapt climate change and variability in SSA. However, crop residue retention in poorly drained soils and high rainfall areas might also increase the emission of greenhouse gases (GHG) (particularly N_2O) by both nitrification and denitrification, possibly even by abiotic N_2O release, which may aggravate N losses (N_2, NO and N_2O) (Lal, 2010; Wei et al., 2017).

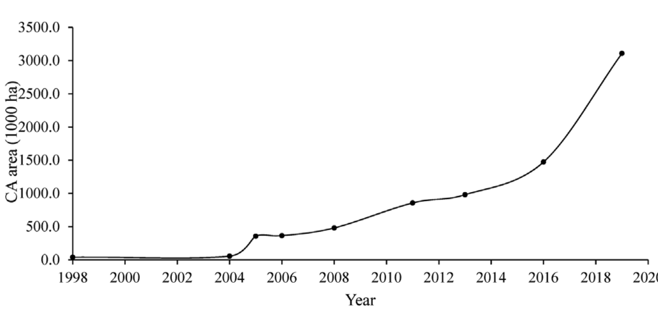


Fig. 6. Estimated conservation agriculture area and adoption rate in Sub-Saharan Africa (data from FAO, 2022).

5. Adoption implementation policy

Fig. 6 indicates CA area coverage and adoption rate from 1998 to 2016 in SSA. Lack of relevant policies that support wider and faster adoption of CA is one of the main constraints in smallholder farmers conditions in SSA. Policy in SSA should favor crop residue management and proper grazing management systems to protect the crop residue cover of at least 30% on the soil surface and to avoid over-trampling in the crop fields by livestock to facilitate the adoption of CA. In order to circumvent such problems when implementing CA in mixed crop-livestock farming systems, CA strategies likely have to be targeted at the community rather than at the individual farmer level. To overcome feed shortage, only community-based decisions can likely manage to introduce alternative feed resources and/or to rotate among different crop and livestock systems in a holistic manner. And, likely, there must be an insurance system supported by governments in order to reduce social risks for farmers to invest in less short term profit oriented, but possibly more sustainable CA farming options.

Rainfed agriculture is the norm in 80% of cultivated hectares worldwide, but irrigated land is below 4% in SSA (Sims et al., 2012). Climate change makes rain-fed agriculture risky and causes food shortages in SSA. Rainfed land technology must improve to feed a growing population in SSA. SSA smallholder farmers can increase crop yields dramatically and sustainably with CA practices by avoiding hand hoes and plows that degrade the soil. Similar to southern Brazil's smallholder farmer-focused manufacturing sector (Sims et al., 2012), SSA should encourage local manufacturing of CA-appropriate small equipment. CA equipment includes no-till planters, sprayers for phytosanitary and herbicide applications, and chisel-pointed tines. Many CA farmers prefer planting into shallow rip lines produced by chisel-pointed tines, which are a cheaper alternative to no-till planters and have greater potential for local manufacture (Sims et al., 2012). Most CA equipment for smallholder farmers has been introduced into SSA by development projects bringing in equipment from, e.g., Brazil (Sims et al., 2012). Local manufacturing involves farmers, machinery repair and hire services, finance institutions, extension and training services, R&D institutions, and policymakers. CA equipment manufacturing and supply chain stakeholders work together to succeed. Mechanization can help smallholder farmers gain productivity and income while conserving natural resources. Supporting the private sector in providing localized mechanization, machines, implements, and tools can enhance CA adoption. Smart subsidies, which lower acquisition costs without undermining private sector initiative and profitability, can help the public sector create demand. This will facilitate the stakeholders to increasingly support CA adoption and generate knowledge for better performance. The expansion of CA is primarily farmer-driven and involves various stakeholders at national and international levels. Farmers CA networking groups that include smallholders can further enhance CA adoption and spread in SSA.

Keeping animals in paddocks overnight helps to collect organic debris as essential fertilizer supplement that is otherwise lost when spread into the savannah. However, it is important to understand that there is a substantial variation in the demand level of crop residues for livestock feed in different farming systems. This demand level depends on the livestock density level and availability of other alternative feed sources such as grazing land. Valbuena et al. (2012) divided the level of livestock densities in Africa in to three categories (low, medium and high) to characterize the demand level of crop residue for feed. They reported all farmers used crop residues for feed in high livestock density areas where the share of grazing is relatively negligible. Farmers in medium-density and low-density areas in West Africa reported the most prolonged shortages of feed resources over the course of the year. However, the duration of feed shortages in low-density areas in Southern Africa is intermediate. One of the low-density areas in Malawi, stood out for its limited duration of residue scarcity to feed livestock, linked to relatively limited livestock numbers. Therefore, the policy formulations on crop residue management should consider the actual competition of crop residue for livestock feed and CA systems.

The smallholder farmers might additionally need help in getting access to specific minimum tillage equipment as well as to non-selective herbicides such as glyphosate for weed control. Farmers should be encouraged to use integrated weed management control systems to minimize their dependence on herbicides. The same applies for the additional need of fertilizers as part of the CA implementation (Vanlauwe et al., 2014). Help also applies to health issues that are little if at all discussed in the literature – the increased risk of injuries for farmers and kids when running without shoes over partly buried stubbles in the field, particularly in areas with only a few medical services, but also increased health risk from non-adapted use of pesticides without following the rules of their application.

6. Conclusions

This study examines SSA smallholder farm CA adoption barriers and proposes several solutions for regional CA adoption. Key issues include lack of locally adaptable CA systems, insufficient crop residues for mulching, inconsistent crop yields, limited equipment and inputs, and lack of CA knowledge and training. Socioeconomic factors like farmers' focus on short term yield increases and limited markets, loans, and education hinder CA adoption. Technical impediments (lack of suitable equipment, fertilizer, and herbicides), environmental impediments (climate - too wet, topography - steep slope farms), and socio-economic impediments limit smallholder farmers' CA adoption in SSA. This paper stresses the need to adapt CA methods to SSA smallholder farms' agroecological and socio-economic conditions. One farm may use one agronomic approach one year but not another due to soil type, topography, climate, equipment, and human variables. Because of this, researchers and farmers reported CA's crop yield effects inconsistently. This study suggests farmers should be encouraged to experiment and adapt CA methods to their local conditions. CA is often used as an integrated system with other local agronomic practices, making it hard to determine which causes which results. Farmers must compare CA styles that use feasible agronomic practices to CT and consider how different farming methods interact. Generally, SSA faces numerous agricultural challenges, including soil degradation, water scarcity, and climate change impacts, making CA particularly relevant in this region. However, adoption of CA in SSA is very low although more than two decades of research and development investments. In part, this can be attributed to the fact that the three principles of CA alone (reduced tillage, crop residues retained on field, crop rotation) may not be achieved in all farms, especially not in those under smallholder ownership. The latter struggle largely with lacking tools for direct seeding or other reduced soil management, as well as with other needs to use crop residues, e.g., for dairy cattle or for heating purposes. Also, the crop rotations most beneficial for soil fertility might not match those most needed for market and subsidence purposes, such as legumes in the absence of market. In SSA, there is certainly a need to adapt the CA practices to the local environmental site conditions and socio-economic smallholder farmers' farming context.

The anticipated benefits of CA by smallholder farmers in SSA is to improve crop yields in short term compared with conventional practices. However, immediate crop yield benefits from CA are highly variable and not always positive, particularly after immediately implementing CA. Crop yields are most likely to be positive in dry areas where mulching minimizes water loss in the form of evaporation, as well as in hot areas, where surface soil cooling by the mulch allows to extend the cropping period. Improvements in SOM storage are expected to increase over time, however, results related to soil fertility and crop yields from long term experiments are inconsistent. They indicate that grain yields are higher in CA mainly with increased use of plant protection agents and additional nitrogen fertilizers. In order to avoid the latter practice exacerbating the positive benefits of CA for soil, there is an urgent need to establish localized optimization in CA practice to fit the diverse ecological and socio-ecological settings of SSA, including climate, farming systems, soil group, slope gradient of the farm and crop requirements, as well as the need to tailor CA for integration with other agricultural practices to adapt to an overall climate-smart land-use across the area, and to cope with the challenges of specific soils like poorly drained Vertisols. Moreover, local implementation of adapted CA systems to smallholder farmers also requires increasing local and scientific knowledge of the agroecological and socio-economic challenges that are specific to the type of land use when intensive tillage is abandoned.

In summary, there is still huge potential to promote CA by smallholder farmers in SSA for sustainable land management and thus to prevent poverty traps when technical means are lacking to cultivate soils in an efficient manner. Yet, incentives are needed to convince farmers to adopt CA, and more positive examples of long term success. Global agribusiness players and the international community should thus help to establish and particularly also maintain respective long term agricultural experiment trials. And it likely should seek benefits from combining such soil restoration programs with other programs for protecting biodiversity or mitigating climate change. Restoring degraded soils via CA would acknowledge that these tasks and thus also their success are usually interlinked.

Conflicts of interest statement

The authors declare no conflict of interest with any person and institution.

CRediT authorship contribution statement

Tesfay Araya: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Tyson E. Ochsner:** Writing – review & editing. **Pearson N.S. Mnkeni:** Writing – review & editing, Funding acquisition. **K.O.L. Hounkpatin:** Writing – review & editing. **Wulf Amelung:** Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest with any person and institution.

Acknowledgments

This research was funded by TWAS-DFG Cooperation Visits Programme in Germany. Wulf Amelung additionally acknowledges support from the Deutsche Forschungsgemeinschaft under Germany's Excellence Strategy, EXC-2070–390732324–PhenoRob.

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