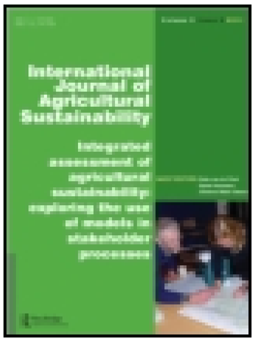

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Adoption by adaptation: moving from Conservation Agriculture to conservation practices

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ABSTRACT
Conservation Agriculture (CA) is a Sustainable Agricultural Intensification strategy based on minimum soil disturbance, permanent soil coverage by living or dead biomass, and diversification of crop rotations. We reviewed the literature on benefits, trade-offs, adoption and adaptation of CA in sub-Saharan Africa (SSA). While CA can improve soils and sustain crop yields, benefits are inconsistent and there are trade-offs with crop residue use, weeds and insect pests, labour demands and short-term yield penalties. Adoption rates by smallholders in sub-Saharan Africa are generally low. We hypothesize that underlying adoption constraints are 1) the magnitude of transformation of management practices required from farmers moving to CA, 2) the multiple inherent trade-offs associated with CA practices and 3) the incompatibility of CA practices to local conditions. We suggest CA adoption in SSA could be improved by focusing the promotion of CA to environments where it best fits, or by facilitating smallholders' adaptation of the practices of CA to respond to their conditions and constraints. We, therefore, propose to move from Conservation Agriculture to Conservation Practices by: (A) identifying and overcoming locally important CA trade-offs through adaptations and complementary practices, and (B) finding farm-specific optimal combinations of practices in terms of feasibility and benefits.

KEYWORDS
No-till; crop diversification; mulching; Africa; agroecology; smallholders; trade-offs

1. Introduction

Conservation agriculture has been defined as an integrated crop and soil management strategy that combines (1) minimum soil disturbance, (2) permanent soil coverage by crops, cover crops or crop residues and (3) diversification of crop rotations (FAO, 2008). Minimum soil disturbance is the most prominent and dominant component of this strategy, and both an enabling component as well as a precondition for crop residue mulching (CRM). Similarly, intensified and diversified cropping (e.g. cover and rotation crops) produces the additional biomass enabling CRM. The literature on CA in sub-Saharan Africa (SSA) distinguishes different crop establishment methods that allow minimum soil disturbance thereafter; (1) the basin system, where planting pits are established to concentrate water and fertilizer, (2) the ripping or rip-line seeding system, whereby seeding is done in furrows drawn by an animal traction chisel-tine opener, (3) direct seeding whereby seeding is done by a pointed stick, a dibble stick, or a jab-planter, and (4) no-till tied ridging, whereby permanent ridges and furrows are created and ridges are closed every 80–100 cm with perpendicular smaller ridges to conserve rainwater (Thierfelder, Rusinamhodzi, Ngwira, et al., 2015). Here we focus primarily on CA systems based on direct seeding, which is the most frequently studied system and most compatible with the other CA components i.e. crop residue mulching and crop diversification.

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Conservation agriculture has been developed as a putative sustainable way of crop production on degradable or degraded soils, expected to deliver multiple agricultural and environmental benefits (e.g. Kassam et al., 2009). The permanent coverage of the soil by living or dead plant biomass and the reduced soil disturbance minimizes topsoil displacement and may restore soil organic carbon content and benefit soil moisture content and water use efficiency (e.g. Pittelkow, Liang, et al., 2015; Thierfelder, Rusinamhodzi, Ngwira, et al., 2015). Crop diversification, including seasonal crop rotation and the use of legume fodder or food crops as cover crops, can have a range of beneficial effects on pest and disease regulation, soil health, food security and poverty alleviation (e.g. Iverson et al., 2014; Snapp et al., 2010). For the above reasons, CA has been supported and promoted by international donors and 'research for development' organizations as a Sustainable Agricultural Intensification (SAI) solution to smallholder farmers in SSA. The extent to which conservation agriculture is adapted to, and therefore feasible for, smallholder farming systems in sub-Saharan Africa (SSA) has however been debated (Andersson et al., 2014; Giller et al., 2009; Sumberg et al., 2013). The aim of this review is (1) to assess the current status regarding adoption of CA in SSA, (2) to investigate the role of CA trade-offs and the adaptations proposed to address these trade-offs, and based on that, (3) to propose a way forward regarding the promotion and adaptation of CA among smallholders in this region.

2. Literature review

The search terms 'conservation agriculture' and 'Africa' were used to generate a database of scientific papers. This resulted in 432 papers in Web of Science and 264 in Scopus, and 525 unique titles which have been reviewed individually for their relevance. Conference papers, papers only focussing on one of the CA practices and papers primarily focussing on the planting basin or the permanent raised bed system were not considered for this review. This resulted in a selection of 252 relevant papers, 64 of which were review or opinion papers and 188 research papers. Among the research papers, 84 were specifically focussing on adoption, trade-offs and/or adaptation on CA, which is the focus of the current paper. The remaining 104 were primarily dealing with the agroecological or socio-economic assessments of CA, which is summarized in the next section.

The vast majority of the selected studies on CA adoption, trade-offs and/or adaptation focus on East and Southern Africa (Figure 1). The most frequently studied staple crop was maize, followed by sorghum and rice, while cotton was the most important cash crop studied. The selected literature on conservation agriculture in sub-Saharan Africa expresses considerable concern about adoption, while agronomically it mostly focusses on the use of crop residues and methods to achieve minimum soil disturbance, and much less so on the crop diversification component (Figure 2).

3. What are the impacts of Conservation Agriculture?

3.1. Environmental impact

Improvement of soil quality has been observed following residue retention and legume cultivation in maize-based no-till systems in semi-arid and sub-humid environments (e.g. Muzangwa et al., 2019) but such improvement is usually a long-term process (Corbeels et al., 2014; Sithole et al., 2019; Thierfelder, Mwila, et al., 2013; Thierfelder & Wall, 2012). More specifically, CA practices have been reported to positively affect soil microbial biomass nitrogen, mineralizable nitrogen and extractable phosphorus (Njaimwe et al., 2018), soil organic carbon, mineralizable carbon and microbial biomass carbon levels (Ngwira et al., 2012; Sithole et al., 2019), as well as the biological activity of soil beneficial and detrimental microfauna (Brevault et al., 2007). The crop residue management seems to be the most important practice as Okeyo et al. (2016) show that when crop residue was incorporated with tillage, the soil improvement benefits were greater than crop residue mulching with minimum soil disturbance. Minimum soil disturbance alone, on the other hand, resulted in a smaller SOC increase than when CA practices were combined. Another potential environmental benefit of CA practices is that they can increase infiltration (Sithole et al., 2019) and water use efficiency and decrease soil and water losses in agricultural production processes (Nyamadzawo et al., 2012). Under CA practices, soil water storage was (21%) higher than under conventional practices (Liben et al., 2017) and mulching of the soils with crop residues contributes to a large extent to such increases (Mupangwa et al., 2007).

The common claim regarding the potential contributions of CA to climate change mitigation is more debatable. A large-scale assessment on farms in

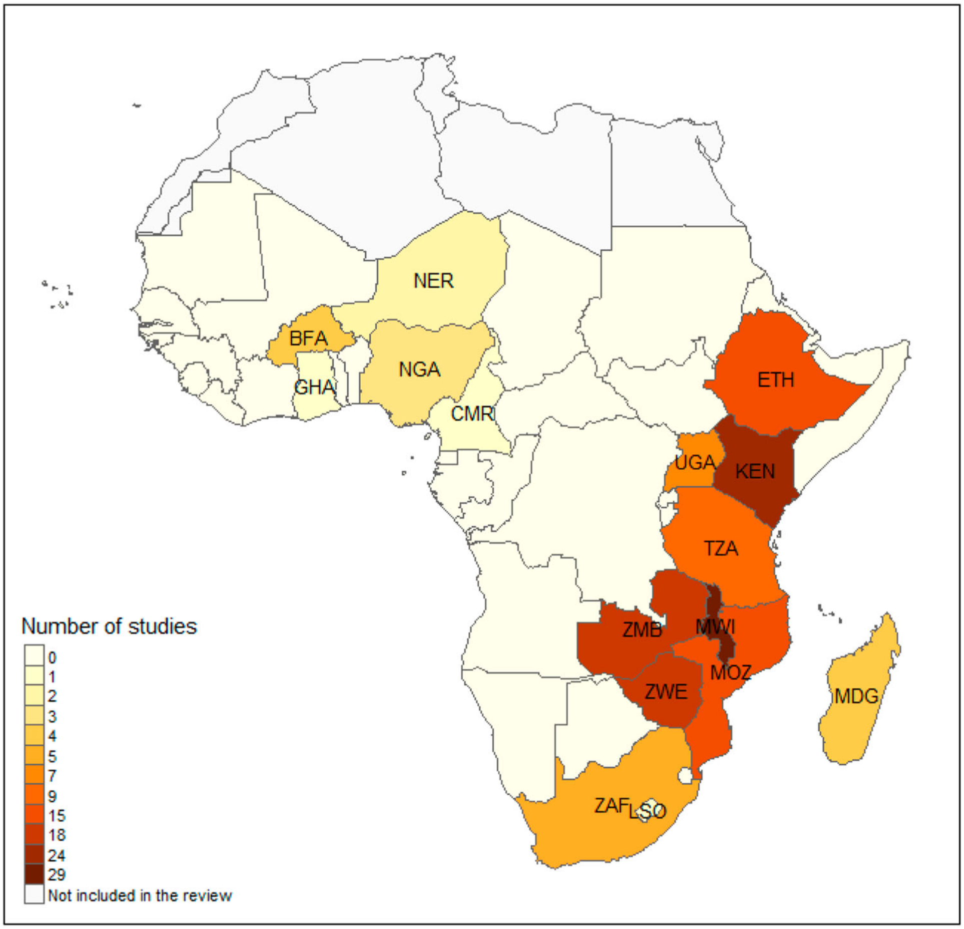

Figure 1. Geographic distribution of the 84 studies on trade-offs, adaptation and adoption of Conservation Agriculture in sub-Saharan Africa.

southern Africa showed that the potential for CA to enhance the carbon stocks in the soil was limited (Cheesman et al., 2016), but a recent meta-analysis on data from sub-Saharan Africa showed that CA can contribute significantly to soil carbon sequestration (Gonzalez-Sanchez et al., 2019), although only when all three CA principles are applied (Corbeels et al., 2019). When compared per unit of grain produced, GHG emissions under CA decreased by a third compared to conventional practices (Kimaro et al., 2016). In fact, the effects of CA on soil carbon sequestration and reduction in GHG emissions are variable because they depend on agroecological environments and the availability of crop residue biomass (Thierfelder et al., 2017).

3.2. Agronomic impact

A global meta-analyses of the impact of the most prominent components of CA (no-till and crop residue mulching) on yield was conducted by Pittelkow, Linquist, et al. (2015), based on 5,463 paired observations, from 610 studies, 48 crops and 63 countries. This analysis showed that crop yields, while variable across locations and conditions, are generally lower in no-till systems, but when combined with crop residue mulching it may benefit yield in rainfed crop production systems in dry environments. The studies on CA yield effects from sub-Saharan Africa present a similarly variable pattern, both regarding the performance of individual and integrated components. A review of case studies from SSA showed that mulch alone, in both CA and no-till systems, did not contribute to maize yield increases (Mupangwa et al., 2019), while experiments conducted on four discrete sites in the Central Rift Valley in Ethiopia, showed that conventional tillage resulted in higher maize yields than minimum soil disturbance techniques (Sime et al., 2015).

Figure 2. Cloud of words appearing more than 25 times in the abstracts of the 84 studies on trade-offs, adaptation and adoption of conservation agriculture in sub-Saharan Africa.

Conservation Agriculture may increase maize yields in SSA, as observed in Zambia (Thierfelder, Mwila, et al., 2013), Malawi (Ngwira, Thierfelder, & Lambert, 2013; Ngwira, Thierfelder, Eash, et al., 2013) and Tanzania (Kimaro et al., 2016). The latter study, by Kimaro et al. (2016), showed that such yield improvement was associated with an increased rainfall use efficiency. A large-scale assessment from four countries in southern Africa reports yield increases by CA in 80% of the cases, compared to conventional practices (Thierfelder, Matemba-Mutasa, et al., 2015). Yield increases from CA are usually observed over the long-term (e.g. Ngwira, Thierfelder, & Lambert, 2013; Thierfelder, Chisui, et al., 2013) and under semi-arid or erratic rainfall conditions (Corbeels et al., 2014; Ngwira, Thierfelder, Eash, et al., 2013). However, there are also studies that show limited yield effects (e.g. Kitonyo et al., 2018; Rodenburg et al., 2020) or yield declines (Corbeels et al., 2014; Mupangwa et al., 2016; Rosenstock et al., 2014) following CA, or studies that only show yield increases from an integrated approach when it was combined with additional weed control and fertilizers application (e.g. Ngwira et al., 2014).

3.3. Household economic impact

Relatively few studies have reported on economic impact of CA in sub-Saharan Africa. A number of studies have shown no-till cropping systems to be more profitable than conventional tillage systems (Naab et al., 2017; Thierfelder, Bunderson, et al., 2016). On 22 farms in eastern Kenya, monitored during four seasons, Micheni et al. (2016) observed an average of 12% increase in farm incomes, due to reduced labour costs and increased yields following CA practices. In Zambia, Manda et al. (2016) observed that farmers can improve maize yields and incomes by combining maize-legume rotation with crop residue retention compared to a monoculture of maize with crop residue removal. However, a study from Zimbabwe showed that the economic viability of CA for smallholders is highly dependent on the application of fertilizers and therefore on subsidized fertilizer prices (Tui et al., 2015).

4. What is the adoption status of Conservation Agriculture and what are the drivers and constraints?

The adoption rate of CA by smallholder farmers in SSA is low. A recent estimate of the adoption of CA in SSA is provided by Tambo and Mockshell (2018); based on a survey of 3,155 randomly selected maize farmers across 100 selected villages from nine SSA countries (2 in West, 4 in East and 3 in Southern Africa). They found that 8% of farmers had adopted the complete package of CA. Often CA adoption is only partial, i.e. some but not all of the practices are taken up by farmers (e.g. Holden et al., 2018; Penot et al., 2015). Farmers that are exposed to CA have been observed to develop cropping systems that are intermediates

Table 1. Factors enabling or constraining adoption of Conservation Agriculture among smallholders in sub-Saharan Africa, the number of times these are mentioned in the literature (#), whether they positively (+) or negatively (−) impact on adoption and the supporting literature sources.

Factors	# (+/−)	Details
Access to information	12 (+)	Education (Tambo & Mockshell, 2018), extension and education (Brown, Nuberg, et al. 2018a; Kaweesa et al., 2018; Khataza et al., 2018; Kunzekweguta et al., 2017; Ntshangase et al., 2018; Marenya et al., 2017; Tsegaye et al., 2017), access to information (Thierfelder, Mutenje, et al., 2015; Fisher et al., 2018), farmer-to-farmer extension (Bell et al., 2018), information and knowledge (Brown, Llewellyn, et al. 2018b; Thierfelder, Mutenje, et al., 2015)
Market access and institutions	6 (+), 1 (−)*	Institutional support and land tenure (Tambo & Mockshell, 2018), distance to markets (Kunzekweguta et al., 2017), access to markets (Corbeels et al., 2014; Thierfelder, Mutenje, et al., 2015), loans (Dube et al., 2018; Senyolo et al., 2018) and subsidies (Abro et al., 2018; Marenya et al., 2017); * Subsidies may disincentivize adoption (Muzangwa et al., 2017)
Productivity and economic benefits	4 (+), 1 (−)*	Economic benefits (Brown, Llewellyn, et al. 2018a), total crop productivity (Baudron, Tittonell, et al., 2012) determining biomass (Dugue & Bassala, 2015; Pannell et al., 2014); *Local crop preferences may negatively impact adoption (Tsegaye et al., 2017; Umar et al., 2012)
Labour requirements	4 (−)	Labour requirements and management intensity (Dube et al., 2018; Nana et al., 2015; Pannell et al., 2014; Senyolo et al., 2018)
Farm size	4, 2(−), 2(+/−)	Farm size may have mixed effects on adoption (Kunzekweguta et al., 2017; Lalani et al., 2016, 2017; Ntshangase et al., 2018)
Access to production factors	3 (+)	Crop land and farm inputs (Corbeels et al., 2014; Kunzekweguta et al., 2017), multipurpose grain legumes, fertilizer and locally adapted water-conserving tillage methods (Droppelmann et al., 2017).
Experience and experimentation with CA	2 (+), 1 (−)*	(Kunzekweguta et al., 2017; Van Hulst & Posthumus, 2016); *Negatively affects adoption if risks are experienced (Thierfelder, Mutenje, et al., 2015)
Investments in social and human capital	2 (+)	(Marenya et al., 2017; Schaafsma et al., 2018)
Risks and uncertainties	2 (−)	(Pannell et al., 2014; Thierfelder, Mutenje, et al., 2015)
High initial costs	2 (−)	(Dube et al., 2018; Senyolo et al., 2018)
Lack of adaptation or local relevance	1 (−)	(Brown, Nuberg, et al. 2018b)
Livestock availability	1 (+)	(Senyolo et al., 2018)
Ownership of ox-drawn plough	1 (−)	(Kunzekweguta et al., 2017)
Drought	1 (+)	(Khataza et al., 2018)

between CA and conventional systems (Penot et al., 2015), including practices that address their specific production constraints (Penot et al., 2018). CA uptake by farmers in Africa is not only partial in terms of the adopted practices but also in terms of the share of farm area under CA practices. In Zambia for instance, minimum soil disturbance techniques were only implemented on 8% of the land of adopters (Ngoma, 2018) while in Malawi, Ngwira et al. (2014) reported 30% of land of adopters to be under CA.

A wide variety of factors have been suggested as drivers or constraints of adoption of Conservation Agriculture (Table 1). Interestingly, the most frequently mentioned are associated with access to information, markets and enabling institutions. The role of adequate agricultural extension services is perceived as critically important in this respect. Farmers' concerns with respect to increased labour requirements with CA practices also emerges as an important point of concern.

Adoption of CA is however hampered by high demands for labour and fertilizer inputs (Grabowski & Kerr, 2014; Ndlovu et al., 2014). Thus smallholder adoption constraints regarding CA practices, both at farm (i.e. access to markets, social capital) and country level (i.e. agrochemical input subsidies, quantity/quality of extension services), are no different from those of any other agricultural technology (Marenya et al., 2017). Subsidies may make fertilizer inputs more affordable and thereby contribute to increased adoption, but such solutions are unlikely to be sustainable in the longer term (Ward et al., 2016) and may also indirectly de-incentivize the use of organic soil amendments (Khataza et al., 2017). A high reliance on government grants, rather than direct farm revenues as an income source, may also demotivate smallholders to adopt innovations like CA (Muzangwa et al., 2017).

The effect of farm size and input subsidies on CA adoption seem ambiguous. A study from South Africa showed that farmer adoption of CA is negatively correlated to farm size (Ntshangase et al., 2018), while a study from Zimbabwe showed farm size had a positive effect on CA adoption (Kunzekweguta et al., 2017). Lalani et al. (2017, 2016) found no evidence of an adoption bias towards the better-off and larger scale farms in Mozambique; they actually observed CA to be beneficial for extreme risk-aversive poor farmers. This seems to be confirmed by Brussow et al. (2017) who observed strongest crop income effects from mulching in the group of marginalized farmers and a decrease in this effect with increasing levels of farm output.

Conservation agriculture does not necessarily respond to common biophysical and socio-economic constraints of smallholders in SSA, such as high input prices vs low commodity prices, labour constraints, uncertain land tenure, resource limitations and high overall risks (Baudron, Andersson, et al., 2012; Giller et al., 2009; Pannell et al., 2014; Rosenstock et al., 2014). In addition, the above-mentioned benefits of CA do not necessarily motivate smallholders. First, the gains from CA may not be sufficient to compensate for the required additional costs for herbicides and labour for weed control and land preparation (Ngoma, 2018). Second, individual smallholders need to bear the costs of implementation of CA, whereas some of the benefits (such as improved ecosystem services, carbon sequestration) accrue to higher levels of society (Dallimer et al., 2018). Climate change coping measures are primarily selected by farmers based on their short-term benefits and then only when they are also compatible with local ecological, social, institutional and customary settings (Callo-Concha, 2018). A study by Brown et al. (2017) shows that an important constraint towards adoption of CA practices concerns farmers' perceived low feasibility in combination with uncertainty regarding the relevance and benefits of these practices. An example is the management of crop residues. Farmers have firm convictions about the usefulness of burning crop residues in some areas in SSA (Ngwira, Thierfelder, & Lambert, 2013), for pest control and soil fertility reasons, and it would require an important shift in farmer's mindset to change that to favour longer-term and higher-level benefits such as carbon sequestration.

5. What are the trade-offs and challenges of Conservation Agriculture and how can they be addressed?

The major challenge associated with the need for integration of multiple practices, as suggested by the Conservation Agriculture paradigm and supported by recent literature, is that it necessitates a major transformation of the established farming practices, which is not always a realistic requirement for smallholder farmers (Giller et al., 2009). Such changes embody uncertainties, which in the absence of production surpluses or safety-nets increase the risk for farmers' livelihoods in the short-term. In addition, constraints to implementation and hence uptake of CA are imposed by trade-offs, as identified by Giller et al. (2009). Subsequent research has improved our understanding around four of these trade-offs: (1) crop residue use, (2) pest management, subdivided in weed and insect pests, (3) labour, and (4) short term yield penalties. While the number of studies confirming these trade-offs outnumber the ones that propose solutions to them (Table 2), there seems to be a growing awareness that trade-offs need to be addressed, through cropping strategy adaptations, in order to increase the likelihood of uptake of CA.

5.1. Crop residue use

The main trade-off concerns the use of crop residue biomass, which can either be used for mulching, as proposed under CA guidelines or fodder for livestock (Baudron, Delmotte, et al., 2015; Corbeels et al., 2014; Dugue et al., 2015; Naudin et al., 2015; Ndah et al., 2014; Rodriguez et al., 2017; Rusinamhodzi et al., 2015; Valbuena et al., 2012) or other uses, such as fuel (Valbuena et al., 2012) or fencing (Hove & Gweme, 2018).

For farmers that keep livestock, it is not feasible to retain all crop residues as mulch in their field

Table 2. Studies from SSA confirming or addressing the main trade-offs identified.

Main trade-offs	Confirmation	Solution
Crop residue use	(Corbeels et al., 2014; Dugue & Bassala, 2015; Hove & Gweme, 2018; Ndah et al., 2014; Rodriguez et al., 2017; Valbuena et al., 2012)	(Baudron et al., 2014; Jaleta et al., 2013; Lahmar et al., 2012; Naudin et al., 2015)
Weeds	(Camara et al., 2018; Mashingaidze et al., 2012; Thierfelder, Bunderson, et al., 2016)	(Muoni et al., 2013; Odhiambo et al., 2015)
Insect pests	(Mutsamba et al., 2016; Nyagumbo et al., 2015; Rafarasoa et al., 2016)	
Labour	(Hove & Gweme, 2018; Nana et al., 2015; Umar et al., 2012)	(Morrison, 2006; Sims et al., 2012)
Short-term yield penalty	(Bruelle et al., 2015; Droppelmann et al., 2017; Masvaya et al., 2017; Thierfelder, Matemba-Mutasa, et al., 2015)	

(Baudron, Delmotte, et al., 2015) and this trade-off is reflected in CA adoption estimates (e.g. Ndah et al., 2014). At least in the short term, it is economically more attractive to use crop residues for livestock feeding than for soil management purposes (Rusinamhodzi et al., 2015).

CA is however also considered by some to be an opportunity for mixed farms as it promotes the production of fodder crops (Mupangwa & Thierfelder, 2014), but it obviously still depends on the amount of biomass that can be produced. The level of biomass production depends highly on the productivity potential set by the local environment and the input levels that a particular farmer can apply. A study from Zimbabwe showed that the trade-off between crop residue for feed or mulch can be reduced by using a prolific biomass producing species, in this case mucuna, as a rotation crop (Tui et al., 2015). Stylosanthes spp. could be an alternative cover crop that produces high amounts of biomass (Rodenburg et al., 2020). Other solutions to reduce this trade-off are identifying alternative feed stocks (Jaleta et al., 2013; Valbuena et al., 2012), producing more maize biomass as feed, and introducing small-scale mechanization to further reduce the dependency on animals for traction (Baudron et al., 2014). The critical level of crop residue retention to secure the benefits and minimize the negative trade-offs thus needs to be studied for each soil and climatic environment (Paul et al., 2013).

5.2. Pest management

The most important pest management trade-off of CA is weed infestation (e.g. Camara et al., 2018; Giller et al., 2009; Lee & Thierfelder, 2017). Soils that are not tilled seasonally are prone to higher infestations of weeds, in particular perennials (Vogel, 1994). The reduced pre-season weed control of no-till systems necessitates complementary weeding during the growing season and this imposes an additional burden on available family labour in smallholder systems (Giller et al., 2009; Mashingaidze et al., 2012). Reports on changes in weed infestation between conventional tillage and minimum soil disturbance practices are however contradicting. For instance, a study from Zimbabwe observed little or no difference in weed abundance between conventional and no-till/mulch systems (Mandumbu et al., 2012). The reduced weed control resulting from minimum soil disturbance may be compensated by mulching (Sime et al., 2015), provided the mulch sufficiently covers the soil (Giller et al., 2009; Ranaivoson et al., 2019; Randrianjafizanaka et al., 2018). An alternative is the use of herbicides (Odhiambo et al., 2015) or the combined use of mulching and herbicides. This combination has been shown to contribute to a decline in some of the dominant weed species (Odhiambo et al., 2015), overall weed density (Muoni et al., 2013) or the weed seed bank (Muoni et al., 2014). While the use of agrochemicals may counter CA-related pest problems, this may trade-off with environmental and human health (Ifejika Speranza, 2013) as well as with biodiversity. The dysfunctional pesticide markets and agricultural advisory systems in rural parts of SSA (Rodenburg et al., 2019) do also not currently provide the necessary enabling environment for safe use of agrochemicals.

Other pest management trade-offs are associated with reduced tillage and crop residue mulching attracting detrimental insects. Mulching may benefit common crop pests such as black beetles (Heteronychus spp. Coleoptera: Dynastidae) (Rafarasoa et al., 2016) and increase termite prevalence, that subsequently damage crops (Mutsamba et al., 2016). Some of these limitations may be addressed by pest management measures or the use of resistant crop varieties.

5.3. Labour

A proposed benefit of CA is that labour demand may be decreased by shifting from conventional, seasonal tillage to practices that aim for minimum soil disturbance (e.g. Baudron, Thierfelder, et al., 2015). However, for smallholders in SSA this is often not true (Chinseu et al., 2019; Ndlovu et al., 2014; Umar et al., 2012). The labour savings obtained from not tilling the soil prior to crop establishment are often cancelled out by increased demands during later stages in the cropping season. Crop establishment may be complicated by the lack of a seedbed and the presence of crop residues, while harvesting a crop may become more laborious due to the presence of a companion crop. A modelling study focussing on farming systems in Burkina Faso, conducted to investigate the scope for CA, indeed showed that benefits of CA (e.g. diversified food, fodder and income sources) trade-off with increased labour inputs for sowing, weeding and harvesting (Nana et al., 2015). Hove and Gweme (2018) observed that such labour trade-offs can be an important reason for farmers in Zimbabwe not to adopt CA.

5.4. Short-term yield penalty

One important trade-off that potentially hampers adoption is the likelihood of a short-term yield penalty (Bruelle et al., 2015; Droppelmann et al., 2017; Masvaya et al., 2017; Thierfelder, Matemba-Mutasa, et al., 2015). While immediate benefits from CA practices, such as soil conservation, are evident (Rodenburg et al., 2020), consistent yield benefits are often only obtained after several years of implementation (Giller et al., 2009). Smallholders who need to decide whether a change of cropping practice would be a beneficial and wise decision to take may be discouraged by reduced yields in the first years following a change from conventional to conservation agriculture. Again, the production environment and agroecological conditions determine the performance of CA practices (Thierfelder, Matemba-Mutasa, et al., 2016) and the extent and direction of trade-offs around production, profits and soils (Rodriguez et al., 2017; Snapp et al., 2018).

6. What is the way forward for Conservation Agriculture?

6.1. Recognizing and capitalizing the concept of partial and stepwise adoption

Recognizing that CA adoption is often partial, Thierfelder, Mombeyarara, et al. (2013) proposed a gradually expanding area under CA practices, as a realistic out-scaling strategy for smallholder maize farmers in SSA. As farmers adopt strategies like CA most often through a process of adaptation of the techniques to their specific needs and (resource) constraints (Dugue et al., 2015), adoption and adaptation are intertwined processes. Adoption of one CA principle can be viewed as an entry point to full adoption (Ndah et al., 2018), as part of a stepwise process. Such a pathway to adoption is schematically represented in Figure 3. The choices farmers make with respect to adoption of individual elements of innovation are based on various criteria and represent a putative compromise between (perceived) feasibility and profitability. Therefore, such partial adoption should be regarded as adaptation of CA to local conditions, needs and challenges. Ikazaki et al. (2018) showed that not all three main CA principles are always needed to achieve a certain outcome (for instance soil conservation) and a reduced number of CA practices could be equally or more beneficial to smallholder farmers as the complete package. Therefore, in SSA, CA adoption, should not be considered in terms of a fixed technology package (Droppelmann et al., 2017; Ndah et al., 2018) but as a set of optional practices that can be adopted and adapted according to the local smallholder farming context (e.g. Descheemaeker et al., 2019; Droppelmann et al., 2017; Tessema et al., 2015; Thierfelder, Mutenje, et al., 2015; Thierfelder, Rusinamhodzi, et al., 2015).

6.2. Focusing the promotion of CA to environments where it best fits

It has been shown that in some cases the local conditions may limit the expected benefits of CA (Masvaya et al., 2017), and under such conditions CA may not be the most appropriate practice. Indeed, there is increased awareness among scholars working on Conservation Agriculture that the relevance of this crop production and soil management system depends on the local conditions and constraints (e.g. Liben et al., 2018; Mupangwa et al., 2017). Ideally CA promotion should be targeted to areas with conditions likely to be suitable for adoption (Tessema et al., 2015). Attempts have been made to profile and identify potentially suitable areas for CA in sub-Saharan Africa, for better targeted promotion (Tesfaye et al., 2015). While it is difficult to make generalizations regarding pedoclimatic conditions, some studies have indicated under which conditions CA would likely not result in benefits compared to conventional practices.

The soil texture is an important determinant with respect to CA effects on soil organic carbon. CA carbon sequestration was shown to be higher on clay than on sandy soils (Swanepoel et al., 2018). Chivenge et al. (2007) found that on clay/loam soils, SOC decomposition rate could be decreased by minimum soil disturbance practices (i.e. mulch-, clean- or tied-ripping), whereas on sandy soils, the crop residue retention (mulch) was a crucially important factor for improving SOC. Soil fertility determines the outcome of CA as well. A study in central Kenya found that only on soils of intermediate fertility minimum soil disturbance and crop residue retention increase maize yields; on the richer and poorer soils conventional practices (i.e. regular tillage and crop residue removal) were superior (Guto et al., 2012). Climate factors also have an effect. A meta-analysis showed that CA increase crop yields in drier climate zones (Pittelkow, Liang, et al., 2015). The complication is that the

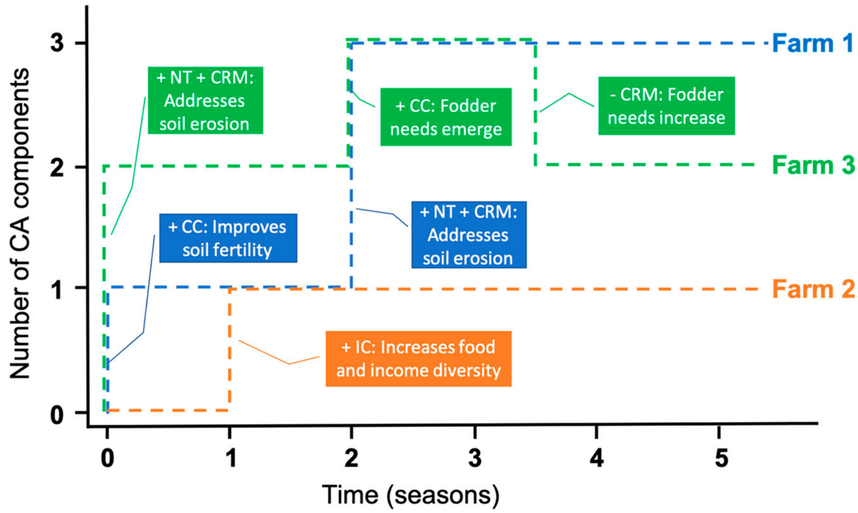

Figure 3. Examples of stepwise and farm-specific adoption and disadoption scenarios of Conservation Agriculture (CA) by smallholders in sub-Saharan Africa over time. Farm 1 (blue line): starts growing cover crops (CC) to improve soil fertility, and two seasons later add no-till (NT) and crop residue mulching (CRM) for soil conservation purposes; Farm 2 (orange line): just adopts one component, e.g. intercropping (IC) to increase food and income diversity; Farm 3 (green line): adopts two components, e.g. no-till (NT) and crop residue mulching (CRM), to reduce soil erosion and add cover crops as a third component two seasons later when fodder needs emerge because of the purchase of cattle, and later decide to drop the practice of crop residue mulching when fodder needs further increase.

above edaphic and climatic factors interact. For instance, other meta-analyses have shown that on soils with a high clay content combined with high rainfall regimes, the risks of waterlogging may be increased by no-till and mulching practices, resulting in lower yields (Steward et al., 2018), whereas on sandy soils under semi-arid conditions, these practices may not provide better crop performance than conventional practices due to the low water storage capacity (Rusinamhodzi et al., 2011).

Because of the locally specific interactions between soil, climate and management, adapting the promotion of CA to the niche environments where it best fits or where positive outcomes are most likely to appear may be a laudable but complicated approach. On top of the pedoclimatic conditions, an 'enabling environment' for CA is shaped by conducive institutions and innovation systems (e.g. Brown, Llewellyn, et al., 2018a; Orr, 2018; Thierfelder et al., 2018). Local capacity building and access to affordable and effective machinery and implements are seen as important enablers of CA in Africa (Thornton et al., 2018). The adoption potential of CA in sub-Saharan Africa is estimated to be substantial, but this can only be fulfilled when output and input markets improve (Corbeels et al., 2014), adapted CA technologies like machinery and seeds are developed and made available and when CA is supported by motivated service providers (Ndah et al., 2015).

6.3. Facilitating smallholders' adaptation of CA practices to respond to local circumstances

A complementary approach would be to adapt CA practices themselves to the locally prevailing biophysical, socio-economic, cultural and institutional conditions. Following earlier suggestions (e.g. Descheemaeker et al., 2019; Giller et al., 2015; Ndah et al., 2018), for effective adaptation we propose to move from Conservation Agriculture being a fixed set of three components to Conservation Practices, as a basket of options inspired by CA. The would be implemented by: (A) identifying locally important trade-offs associated with CA and adaptations or complementary practices that help overcoming them, and then (B) identifying which combination of practices comprises a farm-specific optimal solution in terms of their complexity and feasibility and of their agroecosystem benefits.

A. Identifying Conservation Agriculture adaptations and complementary practices

It is often observed that farmers only adopt just one or two of the CA components and their choices and adaptations are not consistent among farmers (Andersson & D'Souza, 2014; Pedzisa et al., 2015). Presumably, every additional component implies an added adoption threshold for the farmer and also the more components a farmer needs to adopt, the more trade-offs they may encounter. This may discourage the adoption of multiple components. On the other hand, CA adoption decisions are interrelated. For example, the use of crop residue mulching benefits from the additional biomass produced by a legume crop and introduces an incentive for the adoption of minimum soil disturbance practices (Ward et al., 2018). In the reality of smallholder agriculture, farmers may judge that sometimes different practices complement each other and sometimes they counteract each other (Ward et al., 2016). The preference for individual CA components and combinations of components differ across locations. For instance, in Malawi (Holden et al., 2018) and Madagascar (Penot et al., 2015), the highest adoption potential was observed for crop rotation, as farmers often continued to till their soils. In Zimbabwe, mulching seems to be the least popular of the CA practices (Cheesman et al., 2017; Kunzekweguta et al., 2017), while in Tanzania mulching was the most popular (Brussow et al., 2017).

Conservation Agriculture practices themselves could also be adapted and redesigned to match local conditions both in terms of the bio-physical and the socio-economic and cultural environment (e.g. Corbeels et al., 2014; Serraj & Siddique, 2012; Thierfelder et al., 2018), and this requires a thorough understanding of the local constraints and opportunities as well as the strengths and weaknesses of CA (Ndah et al., 2014). As shown before, the benefits of CA are highly context-specific and therefore CA practices need to be matched to the contextual reality of farmers (Brown et al., 2019; Thierfelder, Matemba-Mutasa, et al., 2015). It would require farmer participation in research and extension systems to permit a flexible and transitional promotion of CA by enabling farmers to test and adapt its components. Such adaptive management through the participation of farmers, researchers or extension services has been recommended for other complex cropping systems with long-term outcomes such as agroforestry (Brown et al., 2019; Haggar et al., 2001) and the System of Rice Intensification (Krupnik et al., 2012). A concrete example of CA adaptation is the move from no-till to different techniques of reduced tillage, such as shallow tillage or strip tillage. Other adaptations may be to add components, such as the judicious use of mineral fertilizers and other agrochemical inputs, improved varieties and small-scale mechanization, but also the use of planting pits and the integration of livestock or farm trees, may be introduced.

Appropriately scaled mechanization, for instance, to slash and roll crop residues or for ripping the soil to allow sowing, could make CA feasible on a larger-scale or entire farms rather than parts of the farm only (Thierfelder et al., 2018). However, many (smallholder) farmers are still facing limited access to such technologies (Baudron et al., 2019). Increasing adoption of CA would require the development of minimum tillage technologies that match a broader range of farmer types (Grabowski et al., 2016). Mechanization within CA systems would offer farmers flexibility regarding planting times (Nyagumbo et al., 2017). Small power sources such as two-wheel tractors are deemed to be compatible for CA systems (Morrison, 2006; Sims et al., 2012) and involvement of the private sector in the combined promotion of CA and adapted mechanization to smallholder farmers is proposed as a viable model in East and Southern Africa (Baudron, Sims, et al., 2015). The use of complementary agrochemicals, such as fertilizers and herbicides, is already observed among smallholders practising CA in Zambia (Westengen et al., 2018) and Kenya (Odhiambo et al., 2015). Mineral fertilizers and herbicides have been seen as important enablers of CA in Africa as they alleviate some of the important aforementioned trade-offs and challenges. Fertilizers can be a pivotal input to make CA viable, as shown by Tui et al. (2015) in Zimbabwe and further supported by Vanlauwe et al. (2014). However, the costs of these inputs form adoption barriers to farmers, while non-chemical alternatives seem to be suboptimal or not yet well adapted to CA (Thierfelder et al., 2018). Masvaya et al. (2018) investigated the best combination of sowing time, tillage, fertilizer and mulch practices for maize under semi-arid conditions in southern Africa. They found that for early planting a combination of reduced tillage, mulch and N-fertilizer reduced the risk of crop failure. CA combined with drought-tolerant varieties can constitute an effective climate change adaptation strategy in terms of crop yield (Setimela et al., 2018; Thierfelder, Rusinamhodzi, et al., 2016). Randrianjafizanaka et al. (2018), showed synergies between CA and Striga-resistant rice varieties in the control of *Striga asiatica*. When trees are integrated in CA, farm output can be further diversified and more biomass could be produced, although this may come at the expense of annual crop yields under certain conditions. Where

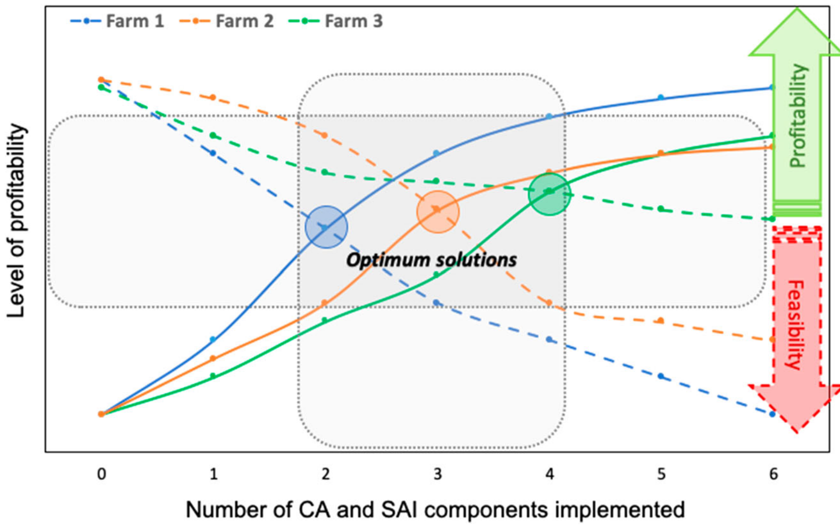

Figure 4. A theoretical representation of increasing profitability and decreasing feasibility with implementation of an increasing number of CA and other SAI components for different farms (colours blue, orange, green). Profitability is expressed in terms of agroecosystem outputs (continuous lines) and feasibility in terms of implementation by farmers (dashed lines). The overlap in shaded areas indicates the optimum profitability within feasible reach of the smallholder farmer.

and how trees may benefit smallholder farmers practicing CA, needs to be investigated (Ndoli et al., 2018).

B. Identifying and using farm-specific optimal solutions

The best number and composition of the above-mentioned Conservation Practices may vary according to the local requirements, and practices may be further adjusted to meet local conditions or overcome trade-offs. As previously shown with SRI in Senegal (Krupnik et al., 2012), such a redesign of CA would follow farmer-participatory identification of feasible solutions to smallholder farming constraints, operationalizing farm household diversity (Descheemaeker et al., 2019; Michalscheck et al., 2018), as well as determining acceptable degrees of cropping system complexity. The aim is to improve agronomic, economic, ecological and environmental returns or services (i.e. *agroecosystem outputs*) of smallholders' production systems in the most feasible and profitable way, given their social-, economic-, ecological- and physical- production environment. This may involve long-term and iterative experiments, resulting in farm-specific strategies whereby an optimal solution is found between the input required (or the number of components adopted) and the benefits reaped from them, hence between the feasibility and the profitability. A theoretical representation of this idea is provided in Figure 4, where the overlap between the shaded areas comprises the number of component technologies representing the best compromise between feasibility and profitability.

When components of CA are combined, they tend to generate higher positive effects than when they are adopted alone (e.g. Tambo & Mockshell, 2018) and the additional combination of breeding and natural resource management technologies may create further synergies (Wainaina et al., 2018). To reach such synergies would necessitate the encouragement of farmers to test multiple components in an integrated way, with the farmer as the ultimate decision-maker in deciding which components works best in their environment. One major complication when it comes to promotion and adoption of CA in general and the above approach in particular is that many of the benefits may only become apparent on the long-term, while there is a lack of immediate income gains from CA (Corbeels et al., 2014). But we believe that this complication can also be addressed by the above stepwise approach, provided that involved stakeholders, including governments and donor agencies, embrace a long-term investment plan.

7. Conclusions

Conservation Agriculture (CA) is one of the Sustainable Agricultural Intensification (SAI) strategies that is widely supported by international 'research for development' organizations and donor agencies to achieve sustainable agricultural development in sub-Saharan Africa. CA practices are interrelated and mutually enabling one another but also have specific trade-offs. Conservation Agriculture as a fixed package is often not adapted to the biophysical and socio-economic, cultural and institutional conditions of smallholder farms in SSA. Adoption rates of CA among smallholder farmers across SSA are therefore low, in particular when only adoption of the 'complete package' of CA is considered. Improving adoption rates would require for CA *promotion* to be better targeted, i.e. to the environments where these practices likely fit best and deliver most. Simultaneously or alternatively, it would require CA *practices* to be adapted in order to overcome trade-offs and to adjust CA to locally prevailing conditions, through a farmer-participatory process. This requires moving from Conservation Agriculture, as a fixed package of three components, to *Conservation Practices*, encompassing a basket of options for sustainable agricultural intensification.

The leading rationale of this is that, rather than promoting CA as a fixed and therefore rigid package, farmers should be exposed to a wider range of practices to enable them to consider and test them individually or combined on their own farm. Stepwise, on-farm experimentation should provide farmers with the required experiences and insights to develop the best production strategy within their own farming system. Future research and development endeavours should focus on CA adaptations that help overcoming trade-offs and adjusting the strategy to locally prevailing conditions. We believe that this will contribute to realizing the potential CA and other SAI strategies hold to sustainably intensify agriculture and improve livelihoods of smallholders in sub-Saharan Africa.

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