



## Review

## Conservation agriculture and smallholder farming in Africa: The heretics' view

Ken E. Giller<sup>a,b,\*</sup>, Ernst Witter<sup>b,c</sup>, Marc Corbeels<sup>b,d</sup>, Pablo Tittonell<sup>a,d</sup><sup>a</sup> Plant Production Systems Group, Wageningen University, 6700 AK, Box 430, Wageningen, The Netherlands<sup>b</sup> Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT), P.O. Box MP 228, Mt. Pleasant, Harare, Zimbabwe<sup>c</sup> Department of Soil and Environment, SLU, P.O. Box 7014, SE-75007 Uppsala, Sweden<sup>d</sup> Systèmes de Culture Annuels, Département Persyst, Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Av Agropolis TA B-102/02 34398 Montpellier Cedex 5, France

## ARTICLE INFO

## Article history:

Received 9 April 2009

Received in revised form 26 June 2009

Accepted 27 June 2009

## Keywords:

Sub-Saharan Africa

No tillage

Zero-tillage

Soil conservation

Crop residue

Mulch

Soil carbon

Adoption

## ABSTRACT

Conservation agriculture is claimed to be a panacea for the problems of poor agricultural productivity and soil degradation in sub-Saharan Africa (SSA). It is actively promoted by international research and development organisations, with such strong advocacy that critical debate is stifled. Claims for the potential of CA in Africa are based on widespread adoption in the Americas, where the effects of tillage were replaced by heavy dependence on herbicides and fertilizers. CA is said to increase yields, to reduce labour requirements, improve soil fertility and reduce erosion. Yet empirical evidence is not clear and consistent on many of these points nor is it always clear which of the principles of CA contribute to the desired effects. Although cases can be found where such claims are supported there are equally convincing scientific reports that contradict these claims. Concerns include decreased yields often observed with CA, increased labour requirements when herbicides are not used, an important gender shift of the labour burden to women and a lack of mulch due to poor productivity and due to the priority given to feeding of livestock with crop residues. Despite the publicity claiming widespread adoption of CA, the available evidence suggests virtually no uptake of CA in most SSA countries, with only small groups of adopters in South Africa, Ghana and Zambia. We conclude that there is an urgent need for critical assessment under which ecological and socio-economic conditions CA is best suited for smallholder farming in SSA. Critical constraints to adoption appear to be competing uses for crop residues, increased labour demand for weeding, and lack of access to, and use of external inputs.

© 2009 Elsevier B.V. All rights reserved.

## Contents

1. Introduction . . . . .	24
2. Which principles of conservation agriculture contribute to the desired effects? . . . . .	24
3. The trade-offs of implementing CA. . . . .	25
3.1. Is mulching the most sensible, efficient or profitable use of crop residues? . . . . .	25
3.2. Is there a yield 'penalty' from employing CA practices in the short-term and a yield gain in the long run? . . . . .	25
3.3. Do CA practices result in saving of labour? . . . . .	26
3.4. Does CA result in increased soil organic matter contents and soil fertility? . . . . .	27
3.5. Is it necessary to apply more fertilizer when practicing CA? . . . . .	28
3.6. Can legume rotations be introduced on a large-scale? . . . . .	28
3.7. Does CA reduce soil erosion? . . . . .	29
3.8. Does CA enhance below-ground biological processes? . . . . .	29
4. Is there potential for adoption of CA by smallholder farmers in SSA? . . . . .	29
4.1. Evidence of 'adoption'. . . . .	29
4.2. Land-use rights . . . . .	30
4.3. The knowledge-intensive nature of CA . . . . .	30
4.4. A need for immediate returns to investment . . . . .	31

\* Corresponding author at: Plant Production Systems Group, Wageningen University, 6700 AK, Box 430, Wageningen, The Netherlands. Tel.: +31 317 485818; fax: +31 317 484892.

E-mail address: [ken.giller@wur.nl](mailto:ken.giller@wur.nl) (K.E. Giller).

5. Conclusions: defining a socio-ecological niche for CA in sub-Saharan Africa . . . . .	31
Acknowledgements . . . . .	31
References . . . . .	32

## 1. Introduction

Conservation agriculture (CA) is proposed as a panacea to agricultural problems in smallholder farming systems in the tropics (Hebblethwaite et al., 1996; Steiner et al., 1998; Fowler and Rockström, 2001; Derpsch, 2003; Hobbs, 2007; Hobbs et al., 2008). It specifically aims to address the problems of soil degradation resulting from agricultural practices that deplete the organic matter and nutrient content of the soil and, moreover, it purports to address the problem of intensive labour requirements in smallholder agriculture (African Conservation Tillage Network, 2008). Proponents of CA suggest that it offers a solution to these problems by providing “*the means that can prevent further destruction of precious soils, increase rainwater use efficiency and labour productivity, thereby ensuring higher and more stable yields while [...] reduc[ing] production costs*”. Given the continuing poor-productivity of smallholder agriculture in sub-Saharan Africa (SSA), and the alarming reports of soil degradation due to nutrient depletion and soil erosion (Stoorvogel and Smaling, 1998; Drechsel et al., 2001) CA appears to offer great potential to address these problems.

Zero-tillage was born out of a necessity to combat soil degradation and has been widely adopted by farmers of different scale in North and South America (Bolliger et al., 2006; Triplett and Warren, 2008). Brazil’s “Zero-tillage revolution”, in particular, is viewed as an attractive potential solution to reversing soil degradation and increasing land productivity in SSA (Fowler and Rockström, 2001; Hobbs, 2007). Zero-tillage, together with crop residue management (mulches) and crop rotation are the pillars of CA as it is now actively promoted by a growing number of research and extension programmes, supported by major international initiatives (e.g. FAO – Benites and Ashburner, 2003; FAO, 2008a; the Direct-sowing, Mulch-based, Conservation agriculture (DMC) – systems initiative under the Global Forum on Agricultural Research (GFAR), the European Conservation Agriculture Federation (ECAAF), etc.). Yet, apart from a few recent articles (Erenstein, 2002, 2003; Bolliger et al., 2006; Knowler and Bradshaw, 2007; Affholder et al., 2008; Lahmar, 2009), it appears that CA has escaped critical analysis. The more critical publications (Bolliger et al., 2006; Bolliger, 2007; Gowing and Palmer, 2008) address pertinent issues such as: (a) Which principles of CA, and under which conditions, actually contribute to the effects sought?; (b) What are the trade-offs of implementing CA?; (c) Does CA address a need identified by the farmer or one mainly identified by scientists and policymakers?; and (d) Do the preconditions for adoption by smallholder farmers exist in SSA?

In our work that addresses problems of soil fertility and productivity of smallholder farmers in SSA we often see that options for soil management that show great promise under controlled experimental conditions gain little foothold in practice (Tittonell et al., 2008). Most often this is not due to technical problems of the new options. More commonly the lack of uptake occurs because farmers are constrained in resources, such that investment in a new technology not only influences what must be done in one field, but involves trade-offs with other activities from which the farmers generate their livelihood (Benoit-Cattin et al., 1991; Scoones, 2001; Giller et al., 2006). Key resources that are constrained are land, labour at key periods during the cropping cycle, feed for livestock, manure for soil

amendment, money to invest in external inputs, and lack of markets for produce.

Conservation agriculture is commonly regarded as appropriate for a wide range of smallholder conditions (FAO, 2008a,b), but often this assumption goes without rigorous evaluation or detailed testing. The recent FAO (2008a) framework for action on CA states that “*The plough has become the symbol of agriculture and many, including farmers, extension agents, researchers, university professors and politicians have difficulty in accepting that agriculture is possible without tillage.*” We do not doubt that agriculture is possible without tillage, yet when we question whether CA is the best approach, or whether the suitability of CA in a given setting has been established, the reactions are often defensive. It seems as if we assume the role of the heretic – the heathen or unbeliever – who dares to question the doctrine of the established view.

In this article we first consider the diverse benefits and claims concerning CA to explore possible constraints that may assist us in understanding when and where CA is most likely to provide substantial benefits. Second we discuss the issue of which farmers, in which settings are likely to be able to make most use of CA approaches to assist in targeting of CA initiatives in African smallholder agriculture. In addressing these questions we aim to enrich the debate around CA and smallholder agriculture to assist in identification of ‘windows of opportunity’ in space *and* time to which efforts on CA could be focused.

## 2. Which principles of conservation agriculture contribute to the desired effects?

Conservation agriculture<sup>1</sup> was introduced by the FAO (2008b) as a concept for resource-efficient agricultural crop production based on an integrated management of soil, water and biological resources combined with external inputs. To achieve this, CA is based on three principles that are believed to enhance biological processes above and below the ground. These are: (1) minimum or no mechanical soil disturbance; (2) permanent organic soil cover (consisting of a growing crop or a dead mulch of crop residues); and (3) diversified crop rotations. This is in one sense revolutionary since over the centuries agriculture has traditionally emphasized the opposite, i.e. the need for a clean seedbed without crop residues. As such, CA is seen as an alternative to conventional agriculture that uses soil tillage (Erenstein, 2002; Hobbs, 2007; Gowing and Palmer, 2008). Proponents of CA perceive CA as an ‘indivisible’ concept for profitable and sustainable agriculture; therefore they see no need to identify the cause(s) of the effects of CA and summarize the benefits of CA “*without regard as to whether it is specifically related to minimal soil disturbance, permanent ground cover and rotation, since they all interact.*” Seeing CA as an ‘holistic’ package, which will only work when a number of agronomic management practices are applied simultaneously (e.g. the

<sup>1</sup> Although this definition of conservation agriculture appears to have gained wide acceptance, there is confusion as many different practices tend to be lumped under this general heading. If this definition is applied strictly, zero-tillage or reduced tillage applied alone do not constitute conservation agriculture. Further, use of permanent planting basins, or remaking of planting basins each year, is sometimes referred to under the general heading of CA, although use of planting basins does not necessarily imply use of all three CA principles. Others refer to planting basins as soil and water conservation practices. Other terms used to describe practices that fall within the general definition of CA are crop-residue mulching (CRM) and direct-seeding mulch-based cropping (DMC).

Sasakawa Global 2000 package – Ito et al., 2007), makes it hard to assess CA practices. Trials designed to test CA or to compare it with other practices often meet with the criticism from proponents of CA that essential aspects were omitted from experiments, so that what was tested was not ‘real’ CA. It is not unusual for demonstration programmes to compare a full CA package, including additions of external inputs such as fertilizers, herbicides and/or improved seeds with a ‘farmer’s practice’ control plot that lacks these inputs (Hagbladh and Tembo, 2003; Kaumbutho and Kienzle, 2007, p. 41; Shetto and Owenya, 2007, pp. 89 and 134). This means that the effects of CA *per se* or zero-tillage in particular, are impossible to segregate from the stimulation of crop growth due to the fertilizers, retention of crop residues in the field, use of herbicides or improved seed.

In practice farmers have been found to not adopt all principles of CA due to various reasons such as limited access to inputs (herbicides, cover crop seeds), labour constraints, or insufficient resources to grow cash crops (see e.g. Baudron et al., 2007; Shetto and Owenya, 2007; Kaumbutho and Kienzle, 2007). What farmers practice may therefore be quite different from the “ideal” CA developed in on-station trials so that it is less certain what benefits are actually realised by the CA practiced by farmers (Bolliger et al., 2006, p. 92). The constraints for farmers to adopt all principles of CA as a package make it imperative that the benefit of each principle is properly evaluated. In the following section we review questions associated with the trade-offs experience when implementing the principles of CA, including factors influencing the likelihood of adoption of CA by smallholder farmers.

### 3. The trade-offs of implementing CA

#### 3.1. Is mulching the most sensible, efficient or profitable use of crop residues?

While benefits of CA are most directly attributed to the mulch of crop residues retained in the field, limited availability of crop residues is under many farming conditions an important constraint for adoption of CA practices. The retention of mulch is the defining aspect of CA in (sub-)tropical countries where tillage is traditionally much less intensive than in temperate countries (Erenstein, 2003). Whereas the US Conservation Technology Information Center (CTIC, 1999) defined conservation tillage as “any tillage and planting system that covers at least 30 percent of the soil surface with crop residue.” (CTIC, 1999), the CA definition by FAO does not indicate the extent of soil cover required. The 30% threshold for soil cover (Allmaras and Dowdy, 1985), is thought to reduce soil erosion by 80%, but undoubtedly greater soil cover would suppress erosion even further (Erenstein, 2002). Mulching has other beneficial effects such as reducing soil evaporation, improving water infiltration, reducing maximum temperatures in the soil surface layers, increasing aggregate stability and soil porosity, etc. Less seems to be known of how much, or if any, mulch is needed to achieve the other effects.

In semi-arid regions mulching has been shown to be effective in reducing the risk of crop failure at field level due to better capture and use of rainfall (Kronen, 1994; Scopel et al., 2004; Bationo et al., 2007). Across a set of experiments in semi-arid and dry sub-humid locations in East and Southern Africa, Rockström et al. (2008), however, demonstrated that minimum-tillage practices increased water productivity and crop yields, even when little or no mulch through crop residues was achieved. Instead, the yield improvements were attributed to the water-harvesting effects of minimum-tillage practices and improved fertilizer use from concentrated application along the ripped and sub-soiled planting lines. This study clearly illustrates the need to assess the

contribution of each principle of CA, rather than seeing it as an indivisible concept.

Mulching with crop residues profoundly alters the flow of resources at farm scale, where several competing uses for crop residues exist (e.g. fodder, fuel or construction material). Crop residues, and in particular cereal stover, provide highly valued fodder for livestock in smallholder farming systems in SSA. Indeed feed is often in critically short supply, given typical small farm sizes, and limited common lands for grazing. Given the cultural and economic value of livestock (Dugue et al., 2004) – as an investment and insurance against risk (e.g. Dercon, 1998), for traction (e.g. Tulema et al., 2008), for the manure produced (Powell et al., 2004; Rufino et al., 2007) and for milk and meat – livestock feeding takes precedence. As a result mulching materials are often in critically low supply, which makes the application rates of 0.5–2 t ha<sup>-1</sup> reported to be needed to increase yield unrealistic (Wezel and Rath, 2002). In many mixed farming systems of SSA not feeding crop residues to livestock would probably create too great a trade-off in livestock production.

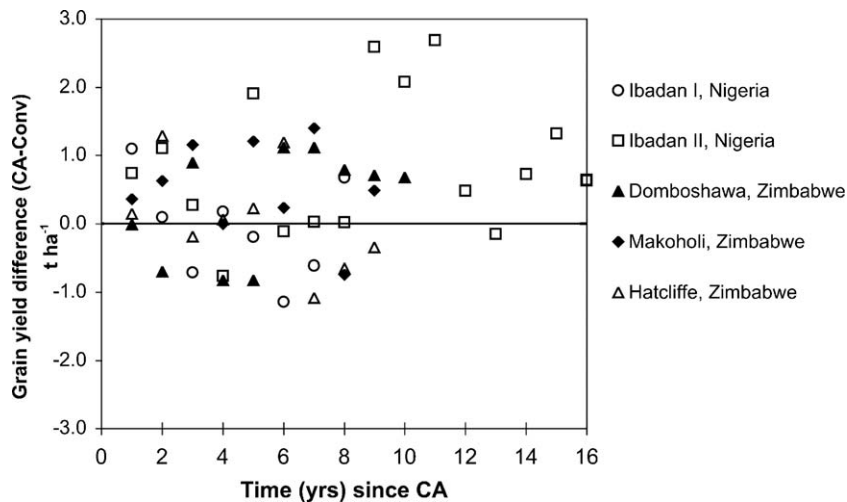
Further intensification of livestock production in order to improve household income means an increased demand for feed, posing a new claim on the crop residues produced. In the highlands of Kenya, smallholder milk production by stall-fed cows (under zero-grazing) has expanded rapidly in the past decades (Bebe et al., 2002). This has been accompanied by development of a market for maize stover as a valuable feed resource, again providing competition for potential residues for mulch (Tittonell et al., 2007b).

In regions where farmers own few livestock, such as southern Malawi, parts of Zambia and Central Mozambique, and rely on hand hoes for tillage, crop residues are traditionally not retained as mulch but burned as a fast way to clear agricultural fields and thus facilitate further land preparation and planting. Although the need to clear land does not arise in CA, other important reasons for burning include fertility enhancement, weed/pest management to control rodent populations that increase when crop residues are retained, or hunting (Asefa et al., 2004; Kanmegne, 2004). Such difficult to quantify trade-offs need also to be taken into account when assessing the benefits of retaining crop residues as a mulch. Moreover, retention of mulch is not always feasible. In Mozambique we have observed that the mulch is often removed in a matter of weeks by termites. Although the mulch improves infiltration initially, the soil cover is lost too quickly to provide effective protection against rain splash erosion or surface runoff, suppress weeds or to reduce evaporation. If the latter factors are important then the benefits of mulching will clearly be diminished.

Overall, the points raised above suggest that in many African mixed farming systems, particularly in the semi-arid areas where livestock are of great importance, the costs of retaining crop residues as a mulch may be too great in relation to the potential benefits that are often difficult to quantify.

#### 3.2. Is there a yield ‘penalty’ from employing CA practices in the short-term and a yield gain in the long run?

Proponents of CA claim that it results in higher and more stable crop yields (African Conservation Tillage Network, 2008), although there also are numerous examples of no yield benefits and even yield reductions. Short-term yield effects have been found to be variable (positive, neutral or negative yield responses, Fig. 1) (see e.g. Lal, 1986; Mbagwu, 1990; Gill and Aulakh, 1990). Short-term benefits are important, because they determine to a large extent the attractiveness of CA to farmers, and some of the negative effects presented in Table 1 discourage their adoption of CA. The variability in short-term crop responses to CA is principally the result of the interacting effects of crop requirements, soil



**Fig. 1.** Maize grain yields ( $\text{t ha}^{-1}$ ) under conservation agriculture practice compared with conventional tillage over time. Data are from Lal (1991) for sites Ibadan I and II, Nigeria; Vogel (1993b) and Nyagumbo (2002) for Domboshawa, Zimbabwe; Moyo (2002) for Makoholi, Zimbabwe; Nyagumbo (2002) and Munyati (2000, unpublished) for Hatcliffe, Zimbabwe.

**Table 1**

Factors determining potentially positive or negative crop yield responses to implementation of conservation agriculture.

Response	Short-term	Long-term
Positive	Increased soil water availability (reduced soil evaporation; reduced water run-off; increased water infiltration)	Reduced soil erosion
	Reduced soil temperature oscillations	Increased soil organic matter
Negative	Soil nutrient immobilization	Increased soil N mineralization
	Poor germination	Increased soil aggregation
	Increased weed competition	Soil compaction (coarse-textured soils)
	Occurrence of residue-borne diseases	Soil acidity
	Stimulation of crop pests	Aluminum toxicity
Waterlogging (poorly drained soils)	Reduced mixing of organic matter into the soil	

characteristics and climate (Table 1). For example, one of the beneficial effects of CA is improved rainwater use efficiency through improved infiltration and reduced evaporative water losses. Under conditions where moisture is limiting crop yields this may improve yields in the short-term (Lal, 1986; Vogel, 1993a), although the full yield benefits of improved water availability are not realised unless nutrient deficiencies, common in the soils of the semi-arid regions of SSA, are also addressed (Rockström and Barron, 2007). But under more humid conditions and on poorly drained soils the same effect can cause waterlogging resulting in yield depression.

CA practices were widely adopted during the 1990s in the commercial farming sector in Zimbabwe and a meta-analysis of maize (*Zea mays* L.) yields indicated that yields were equal or improved with respect to conventional production systems in 'normal' or dry years, but tended to be depressed during seasons with above-average rainfall (P. Grant, personal communication, 2001). The improved water use under CA in 'normal' or dry years is largely due to the presence of a mulch of crop residues (Biamah et al., 1993), whereas absence of tillage in itself can result in the opposite effect: higher run-off and lower infiltration leading to lower yields (e.g. Tadesse et al., 1996; Akinyemi et al., 2003; Alabi and Akintunde, 2004; Abdalla and Mohamed, 2007). Indeed, the

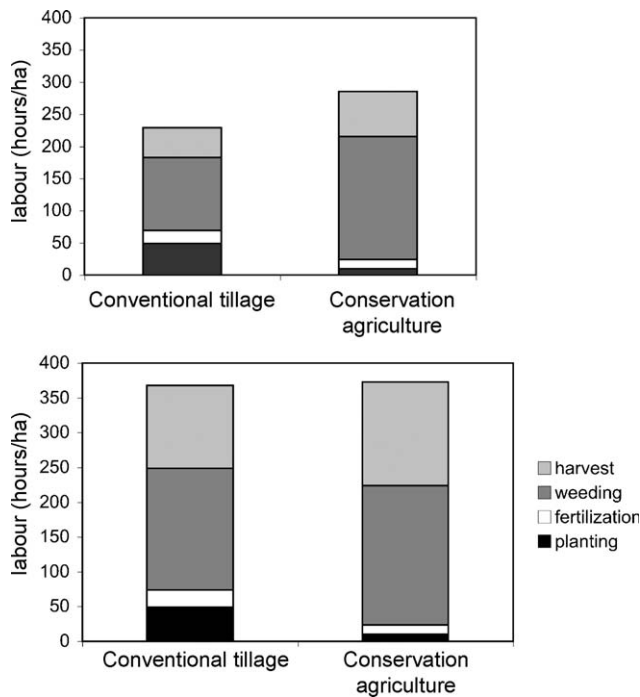
reason given by farmers for the traditional tillage practices in the Ethiopian highlands involving repeated ploughing is precisely to improve infiltration, minimize run-off and to reduce evaporation (Temesgen et al., 2008). The negative effects of no tillage occur especially on the clay-poor, structurally weak soils of the (semi-) arid areas which are widespread throughout SSA (Aina et al., 1991). On such soils the beneficial effects of mulching may not always be sufficient to offset the negative effects of no tillage resulting in lower yields during the first years under no-till when compared with ploughing even if a mulch of crop residues is applied (Nicou et al., 1993; Ikpe et al., 1999).

Even though the short-term yield effect of CA is variable over space and time productive benefits accumulate over time as mulching arrests soil degradation and gradually improves the soil in biological, chemical and physical terms (e.g. Erenstein, 2002). Therefore, yield responses to CA over a longer time period tend to be neutral to positive (Fig. 1). For example, 6 years of zero-tillage with application of herbicides gave no or marginal improvement in yield of t'ef (*Eragrostis tef* [Zucc.] Trotter), wheat (*Triticum aestivum* L.) and lentils (*Lens culinaris* Medikus) in Ethiopia (Erkossa et al., 2006). Similarly, in Burkina Faso no effect of tillage on crop yields was observed after 10 years (Mando et al., 2005). On the other hand, Lal (1991) reported from two studies of 8 years or more that larger maize grain yields were maintained with a mulch-based no-tillage system than with a plough-based system.

We conclude therefore that although introduction of CA can result in yield benefits in the long-term, in the short-term (and this may be up to nearly 10 years! – see Fig. 1) yield losses or no yield benefits are just as likely. Further work is needed to identify the causes of the often-observed short-term yield reductions and how they can be avoided.

### 3.3. Do CA practices result in saving of labour?

It is recognized within the CA community that weeds are the 'Achilles heel' of CA as weed control is often laborious and costly in the first years, with a greater requirement for herbicides than with conventional tillage at least in the first years (Wall, 2007). On the other hand, some proponents of CA argue that with good ground cover resulting from mulching or cover crops, there is less weed pressure with CA. Apart from anecdotal reports there appears to be little published evidence to back this claim. Especially in manual cropping systems, land preparation and weeding are very labour intensive. Not tilling the soil and planting directly into a mulch of



**Fig. 2.** Labour use for conventional tillage using an ox-drawn mouldboard plough (with no residues returned) and conservation agriculture practices using an ox-drawn direct seeder (with mulching) at two experimental sites in Zimbabwe: (a) a low production potential site (Zimuto) and (b) a high production potential site (Shamva). Data from Siziba (2008).

crop residues can reduce labour requirements at a critical time in the agricultural calendar, particularly in mechanized systems when a direct-seeding machine is used. Moreover, shortage of animal traction may severely limit the land area that can be ploughed within the short window at the start of the growing season when the first rains fall and the soil is wet enough to be tilled. This can lead to strong delays in the time of planting which results in strong yield penalties (Tittonell et al., 2007a). CA can provide a major benefit by removing the need for tillage and thus allowing a larger proportion of the land to be cropped.

But not tilling the soil commonly results in increased weed pressure (Vogel, 1994, 1995; Kayode and Ademiluyi, 2004). The increased amount of labour required for weeding with CA may outweigh the labour-saving gained by not ploughing, unless herbicides are used to control weeds. A case study in Zimbabwe (Siziba, 2008; Fig. 2) clearly shows the change in labour use profiles from planting to weeding with the adoption of the CA practice. If CA results in a strong shift of labour required from tasks normally performed by men, such as hand tillage or ox-drawn ploughing, to hand weeding that is performed mainly by women. Without a reallocation of the gender-division of these roles in agricultural production this may lead to an unacceptable increase in the burden of labour on women.

In one of the few long-term assessments of conservation tillage practices in SSA, Vogel (1995) found that CA systems subjected to continuous maize production led to unacceptable infestation with perennial weeds within 6 years. This reflects experience in North America, where perennial broad-leaved and grass weeds became increasingly problematic with reduced tillage despite the use of herbicides (Locke et al., 2002). Vogel (1995) concluded that traditional hoe weeding proved unable to control the rapid build-up of perennial weeds, and that acceptable weed control was only possible with herbicides. Although it may be argued that absence of an adequate mulch of crop residues may have exacerbated weed problems in these trials, it is clear that restricted access to

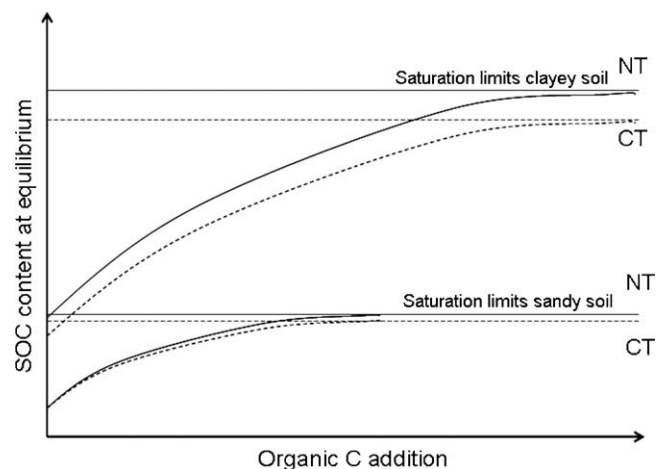
agricultural inputs such as herbicides due to the expense and the lack of effective input supply chains represents a major limitation to the implementation of CA, and to the implementation of other technologies designed to increase productivity in smallholder systems of SSA.

We therefore conclude that in the short-term and without the use of herbicides, which will be the case for most smallholder farmers, CA is unlikely to result in significant net savings in total labour requirements while it may increase the labour burden for women. In the long-term, and with the use of herbicides net savings appear to be possible.

### 3.4. Does CA result in increased soil organic matter contents and soil fertility?

Rates of decline in soil organic matter (SOM) when land is converted from forest or grassland to agriculture are rapid, with up to 50% of the SOM being lost within 10–15 years (e.g. Diels et al., 2004; Zingore et al., 2007). A common claim by the proponents of CA is that no-tillage with residue mulching will halt this decline and leads to accumulation of SOM.

Although it is often difficult to separate the effects, it appears that reported increases in SOM are mainly due to increased biomass production and retention in CA systems rather than reduced or no-tillage (Corbeels et al., 2006). Under dryland conditions on the sandy soils of West-Africa, simulation model predictions using the CENTURY and RothC models suggest that conversion to no-tillage will result in small increases in soil C contents ( $0.1\text{--}0.2\text{ t ha}^{-1}\text{ year}^{-1}$ ) (Farage et al., 2007). Only practices that entailed an increased input of organic matter, for example through agroforestry or manure, were predicted to result in large increases in soil C. Chivenge et al. (2007) demonstrated that reduced tillage is only likely to have a strong positive effect on SOM in finer-textured soils. This is due to the lack of physical and structural protection of SOM in sandy soils, in which the organic matter contents depend strongly on amounts of crop residue added regularly to the soil. Thus the effect of not tilling the soil is likely to be larger on heavier-textured soils that have a larger equilibrium



**Fig. 3.** Theoretical relationship between organic C addition and soil organic contents at equilibrium and the potential effect of no-tillage for a sandy and clayey soil that have different C saturation potential (Stewart et al., 2007). Soil organic matter stabilization does not increase linearly with increasing rates of organic C input (at steady state) but has an asymptotic relationship. No-tillage reduces the rate of decomposition of C, resulting in increased soil C storage (at steady state). The soil C saturation limit is higher in clayey soil than sandy soil, due to higher capacity to protect soil organic matter from decomposition in clayey soils. No-tillage increases the soil C saturation limit for a given soil because of better soil aggregation and associated protection of soil organic matter. Solid line: no-tillage (NT); broken line: tillage (T).

content of soil organic matter for a given C input (Feller and Beare, 1997; Fig. 3).

Although reduced soil erosion under CA is likely to play a role in the long-term (Lal, 1998a; Scopel et al., 2005), the body of evidence supports the conclusion that SOM content of any given soil is determined largely by the amounts of organic matter returned to the soil, independent of whether it is incorporated or used as a mulch. Thus, the corollary is whether SOM contents can be increased in tropical soils subject to conventional tillage. Comparison of changes in SOM with length of cultivation showed equilibrium soil C contents to be almost three times as large ( $34 \text{ t C ha}^{-1}$ ) on large commercial farms than on nearby smallholder farms in Zimbabwe ( $20 \text{ t C ha}^{-1}$ ) (Zingore et al., 2005). In both cases the soil was ploughed annually (by tractor on the large commercial farms and ox traction on the smallholder farms). The differences in SOM contents on this red clay soil were explained by the greater agricultural productivity ( $\sim 8 \text{ t ha}^{-1}$  maize grain vs.  $\sim 1 \text{ t ha}^{-1}$ ) and because the crop residues were left in the fields on the commercial farms whereas they were grazed by livestock in the dry season on the smallholder farms. In general, availability of organic matter inputs is critical for productivity on farms in sub-humid and semi-arid Africa; and fields that receive large inputs of organic matter in the form of crop residues, manure or compost (fields that are generally close to the homestead), are generally rich in C, while fields that receive no or little organic matter (the outfields further away from the homestead) have small soil C contents (Tittonell et al., 2005; Samaké et al., 2005; Zingore et al., 2007).

In one of the few long-term studies on changes in soil quality under different tillage management treatments in Africa, Lal (1998b) reported soil C contents in the 0–10 topsoil layer of fields cropped with maize in Nigeria showed a decrease in soil C in all treatments. The rate of decline was more with conventional tillage compared with the no-tillage treatment ( $-0.86 \text{ g kg}^{-1} \text{ year}^{-1}$  vs.  $-0.46 \text{ g kg}^{-1} \text{ year}^{-1}$ ). However, such data must be interpreted with caution, since the lack of soil mixing under CA may lead to increased stratification with accumulation of SOM in the topsoil. Although stratification of SOM may lead to improved soil surface properties, and enhanced infiltration, it may lead to overestimation of the benefits of CA in increasing overall SOM contents.

Despite the widespread belief to the contrary, we conclude that there is little evidence that reduced tillage *per se* leads to increased SOM contents and increased soil fertility. This conclusion is reinforced by a recent meta-analysis of soil C storage under CA drawing largely on experience from North America. C contents were increased by CA compared with conventional tillage in roughly half of the cases, showed no change in 40%, and a reduction in soil C in 10% of the experiments (Govaerts et al., 2009). Benefits of enhanced SOM and soil fertility with CA are more a function of increased inputs of organic matter as mulch.

### 3.5. Is it necessary to apply more fertilizer when practicing CA?

Large amounts of cereal residues with a high C:N ratio that are left on the soil surface temporarily result in a net immobilization of mineral N in the soil, although it is expected that N immobilization will be less than when residues are incorporated (Abiven and Recous, 2007). Farmers without access to mineral fertilizer cannot compensate for such N deficiencies and will suffer yield reductions as a direct result.

If soil N availability decreases under CA with a mulch of crop residues – and some studies indicate that this does not always occur (Lal, 1979; Mbagwu, 1990) – a larger amount of N fertilizer will be needed to achieve equivalent yields as compared without crop residues. The amount of fertilizer required will depend on the rates of crop residue added and their quality. If repeated additions

of large amounts of crop residues lead to a greater soil C content in time this may lead to a greater net N mineralization once a new equilibrium is achieved (Erenstein, 2002). If residues are ploughed into the soil this happens more quickly. The length of time required to achieve net N mineralization depends on rates of residue addition, rates of N fertilizer added and the environmental conditions – particularly on the length and ‘dryness’ of the dry season. Evidence from temperate North America (e.g. Logan et al., 1991) indicates cereal yields are larger under conventional than zero-tillage during the initial years with or without moderate rates of mineral N fertilizer, but larger yield responses under zero-tillage as N fertilizer rates increase.

An attractive research topic around CA is to explore, across agroecological conditions of Africa, the existence of ‘cross-over points’ beyond which investments in N fertilizer to counteract N immobilization by crop residues becomes profitable. It is evident that strong interactions exist between the amounts and quality of the crop residues and the soil characteristics, which determine the degree of N immobilization due to the surface mulching and hence in turn the need for additional N fertilizer.

This remains an open question, as there is insufficient evidence to conclude whether or not more fertilizer is needed with CA in smallholder farming, which will depend on the quality and quantity of the mulch applied in each case.

### 3.6. Can legume rotations be introduced on a large-scale?

Crop rotation forms a central pillar of CA, and many approaches highlight the use of cereal–legume rotations. The most widely grown legumes in the farming systems of SSA are the grain legumes; groundnut (*Arachis hypogaea* L.), cowpea (*Vigna unguiculata* (L.) Walp.) and common bean (*Phaseolus vulgaris* L.). These crops have the advantage over other legumes in that they provide a direct economic yield for food or for sale. Yet unless there is a ready market for the grain, farmers tend to grow grain legumes on only a small proportion of their land, and certainly not sufficient to provide a rotation across the farm. Analyses in Zimbabwe, where farmers indicated their normal rotation is groundnut/maize/maize, showed that the actual area sown to groundnut was less than 5% of the farm area (Mapfumo et al., 2001). Further investigation indicated that crop rotations tended to be practiced more on the fertile ‘homefields’ than on the poorer outfields (Zingore et al., 2007). Only where a ready cash market is available for surplus produce has the production of grain legumes achieved a more central role in terms of cropped area, for example with soyabean (*Glycine max* (L.) Merrill) (Mpeperekwi et al., 2000). The rotational soil fertility benefits of grain legumes to subsequent crops can be substantial, giving double the yield of subsequent cereal crops in some cases (Kasasa et al., 1999; Giller, 2001). But often the crop residues are removed from the field at harvest so they do not provide the mulch cover wanted for CA.

Green manure legumes have often been recommended for CA systems, particularly in the DMC systems, as they fix substantial amounts of N and can provide large amounts of N-rich biomass. Although large benefits in cereal yields can be seen after only one season of a green manure crop, this is an insufficient incentive for smallholder farmers. One approach that has proved to be inherently attractive to farmers and is standard practice in much of southern Malawi is intercropping maize with the grain legume pigeonpea (*Cajanus cajan* (L.) Millsp.). If pigeonpea is sown between planting stations on maize rows, the plant population and yield of maize can be maintained, whilst reaping the advantage of yield from the pigeonpea harvest (Sakala, 1998). Pigeonpea is an ideal legume for intercropping with cereals. Its slow initial growth affords little competition with the cereal for light or water, and it continues growing into the dry season after the maize crop has

been harvested. The leaves that fall from pigeonpea before harvest provide a mulch and can add as much as  $90 \text{ kg N ha}^{-1}$  to the soil that then mineralizes relatively slowly during the subsequent season, releasing N for the next maize crop (Adu-Gyamfi et al., 2007; Sakala et al., 2000). Thus a substantial rotational benefit, although not a perfect soil cover, can be achieved for the next season. Maize–pigeonpea intercropping is predominant in southern Malawi and in parts of central and southern Tanzania, but only in areas with small livestock densities as otherwise the crop is grazed after maize harvest before it can reach maturity.

Comparisons of a range of soil fertility improving technologies, including grain legumes, green manures, fodder legumes and legume tree fallows have indicated smallholder farmers invariably choose grain legumes due to the immediate provision of food (Chikowo et al., 2004; Adjei-Nsiah et al., 2007; Kerr et al., 2007; Ojiem et al., 2007). Although green manures and agroforestry legumes are much more efficient in provision of N and mulch for subsequent crops (Giller and Cadisch, 1995), they do not provide the immediate benefits sought by farmers. Multipurpose varieties of soyabean and cowpea have been developed that produce prolific biomass that can be used as fodder or to enhance soil fertility and yet give good yields of grain (Giller, 2001; Sanginga et al., 2001).

Future emphasis on cereal–legume rotations for CA should focus on multipurpose grain and fodder legumes, although expansion of their cultivation will depend on the availability of ready markets for the quantities of grain produced beyond the direct needs of the farming households.

### 3.7. Does CA reduce soil erosion?

Soil erosion control is perhaps the clearest benefit of CA. There is a clear relationship between retention of mulch and reduction of runoff and soil losses by erosion (Lal, 1998a; Erenstein, 2002; Fig. 4). Given that erosion rates are greatest under high rainfall intensity, on steep slopes and on more erodible soils, it seems likely that these are precisely the conditions where CA can have the greatest benefits (Lal, 1998a; Roose and Barthes, 2001). However, on very steep slopes, mulch retention alone will be insufficient to control erosion and other physical control measures such as contour bunds are needed to reduce the slope length (Roose and Barthes, 2001). Reduced erosion can lead to regional benefits such as a reduced rate of siltation of water courses and increased recharge of aquifers (Jarecki and Lal, 2003; Lal et al., 2007).

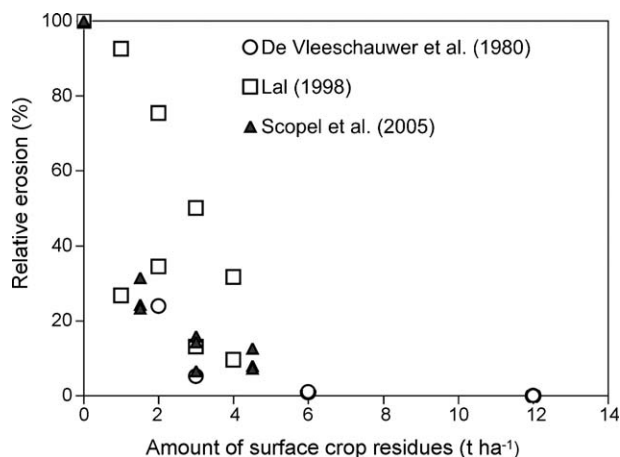


Fig. 4. Effect of the amount of surface crop residues (mulch) on soil erosion. Data are from on-station experiments in Nigeria (De Vleeschauwer et al., 1980; Lal, 1998a) and Mexico (Scopel et al., 2005).

There is little doubt that CA can substantially reduce erosion although the benefits will mainly be reaped in the long-term rather than the short-term.

### 3.8. Does CA enhance below-ground biological processes?

Hobbs et al. (2008) write that under CA the soil biota “take over the tillage function and soil nutrient balancing” and that “mechanical tillage disturbs this process”. Whilst the role of soil macrofauna in mixing organic matter into the soil, and in creating macropores in soil is widely accepted (Lavelle et al., 1999), the role of soil biota in “nutrient balancing” is obscure. There seems to be a simple belief in some articles on CA that more soil life, activity and diversity are bound to be beneficial (e.g. Christoffoleti et al., 2007).

Nhamo (2007) clearly shows that there is more abundance and activity of soil biota under maize-based CA cropping systems than with conventional practice in the sandy soils of Zimbabwe. But it is unclear what this means in terms of biological processes. Research on decomposition processes clearly shows that rates of decomposition and N mineralization from organic residues are largely under the control of the (chemical and physical) quality of the organic residues and the environmental conditions (e.g. temperature, moisture, pH) (Swift et al., 1979; Heal et al., 1997; Palm et al., 2001). Only minor effects on the rate of organic matter decomposition can be observed by manipulating the abundance and activity of the soil biota experimentally (Swift et al., 1979; Heal et al., 1997).

Use of crop rotations is a well-recognized approach to reducing the risk of building up pest and disease problems, which may be exacerbated when crop residues are retained in the field. But addition of large amounts of decomposable organic matter, as with grain legumes, legume green manures, forage legumes or improved tree fallows can also have negative effects such as the stimulation of white grubs or cutworms that cut roots of cereals and can eliminate cereal growth – resulting in complete loss of the crop stand if incidence is severe. This phenomenon is not uncommon. In Zimbabwe severe incidence of grubs of *Agrotis* spp. was stimulated by large inputs of readily decomposable litter from legume tree fallows in no-till systems (Chikowo et al., 2004). In Mozambique and Madagascar the grubs of the black maize beetle (*Heteronychus* spp. – a scarab beetle) are recognized as a major problem where large amounts of decomposable organic matter from legumes or maize straw are incorporated.

We therefore conclude that it is important to realise that enhancement of biological activity in the soil as a result of CA may not always be beneficial, but can result in effects detrimental to crop production.

## 4. Is there potential for adoption of CA by smallholder farmers in SSA?

### 4.1. Evidence of ‘adoption’

Confusion abounds in the literature as to what constitutes ‘adoption’ by farmers. There are many experiences where adoption claimed during the course of active promotion of technologies by NGOs and research later transpired to be due to the temporary influence of the project, rather than a sustained change in agricultural practice. For example, the apparent success of Sasakawa Global 2000 in promoting CA (Ito et al., 2007) appears largely to have been due to its promotion within a technology package including inputs of fertilizers, pesticides and herbicides. When the project support stops farmers quickly revert to their former crop management practices. The widespread adoption of CA that was claimed through promotion programmes appears to have suffered the same fate in South Africa (Bolliger, 2007) and in

Zambia (F. Baudron, personal communication, 2008). In a detailed study of uptake of zero-tillage practices in South Africa, Bolliger (2007) found sporadic pockets of small numbers of farmers who embraced and practiced CA, but little adoption of CA across most of the areas he surveyed, despite earlier claims of spectacular success. Gowing and Palmer (2008) concluded that there has been virtually no uptake of CA in most SSA countries, with only small groups of adopters in Ghana, Zambia and Tanzania. Haggblade and Tembo (2003) suggest that 75,000 Zambian smallholder farmers practiced conservation farming in 2002/03, from about 20,000 in the 2001/02 season because of the 60,000 starter packs issued as a drought-relief measure by a consortium of donors. They estimated that some 15,000 were spontaneous adopters, while the remaining 60,000 practiced conservation farming as a condition for receiving their input. Shetto and Owenya (2007) reported that approximately 5000 farmers had taken on at least one or two elements of CA promoted by the FAO CA-SARD project. Whether this constitutes 'true' adoption remains to be demonstrated. In a review of NGO efforts to promote CA in Zimbabwe, Mashingaidze et al. (2006) concluded that there has been limited adoption despite nearly two decades of development and promotion by the national extension programme and numerous other projects. The constraints identified included: a low degree of mechanization within the smallholder system; lack of appropriate implements; lack of appropriate soil fertility management options; problems of weed control under no-till systems; access to credit; lack of appropriate technical information; blanket recommendations that ignore the resource status of rural households; competition for crop residues in mixed crop-livestock systems and limited availability of household labour.

In many ways the problems that smallholder farmers face with adoption of CA are analogous to the problems experienced with adoption of green manures or 'improved fallows' of fast-growing shrubby legumes. There are few windows of opportunity in terms of out-of-season rainfall to relay cover crops into cereals without sacrificing a main crop. Although many success stories of farmer uptake of green manures and improved legume tree fallows (sometimes referred to as fertilizer trees), few of these have outlasted the lifetime of the promotion project. Where successes have been claimed there have been distortions of 'adoption' or 'farmer uptake'. In the late 1990s in Malawi during an intensive campaign promotion intercropped green manures led by research scientists and NGOs, seed of the fish bean (*Tephrosia vogelii* Hook. f.) was worth three times as much in the local markets as the main staple legume, common bean, and farmers responded by producing and selling tephrosia seed (Giller, 2001). The same story holds for the 'green gold' of mucuna (*Mucuna pruriens* [L.] DC. var. *utilis*) in Benin which was claimed as a success story but has largely disappeared from farmers fields since project support withdrew. Although widespread farmer adoption of improved legume tree fallows was claimed in western Kenya, these have vanished from the fields of smallholder farmers, together with the seed market for the legume trees, when the intensive promotion campaigns stopped (Ojiem et al., 2006).

It is clear from the above discussion that it cannot be automatically assumed that CA will bring benefits to the farming system and rural livelihood as a whole simply because benefits are shown at the plot level. A farming system consists of many interacting components and is subject to a range of bio-physical, socio-economic as well as cultural constraints. A technology can only be considered a successful 'innovation' that is likely to spread spontaneously when fully embedded within the local social, economic and cultural context (Leeuwis, 2004). Thus the suitability and adoption of a new technology in one place as, for example, observed for CA in South America does not imply that the conditions for adoption necessarily exist in SSA (Bolliger, 2007; Gowing and Palmer, 2008).

#### 4.2. Land-use rights

Limited availability of crop residues is under many mixed farming conditions an important constraint for adoption of CA practices. Apart from the trade-off for the individual farmer between using crop residues as feed or as a mulch land-use rights can be an obstacle to mulching. In many mixed farming systems cattle and goats are often herded or tethered during the main cropping seasons, and released to graze freely after harvest. The free grazing systems rely on communal use of land and traditional grazing patterns. Livestock tend to prefer to graze in crop fields due to the relative abundance of feed and the better feed quality in comparison with open grazing areas. Individual farmers cannot restrict grazing even on their own land without challenging the traditional rights of others in the community. If farmers who do not own livestock were to opt to keep their residues as mulch they would need to fence their fields. This would require re-negotiation of the traditional rules or local by-laws governing free-grazing outside the cropping season (Martin et al., 2004; Mashingaidze et al., 2006).

#### 4.3. The knowledge-intensive nature of CA

The integrated nature of CA when considered as a holistic package is at the same time one of its weaknesses. The number of practices that are required to be changed at the same time necessitates a major transformation in crop and soil management practices (Erenstein, 2002). At the same time, extension programmes relating to complex technologies can also result in indirect benefits. Mutekwa and Kusangaya (2006), for example, stressed that intensive participatory research on water-harvesting technologies in Chivi district, Zimbabwe yielded not only benefits in terms of improved crop yields and livelihoods but was also important in building the capacity of farmers. The social benefits were expressed in the words of one farmer: '*These technologies have taught us to work together. We learn from each other, share labour and tools. We have already formed permanent labour clubs. Otherwise as individual households, we would not manage.*'

Given the complexity of the CA management packages, and the need to tailor the practices to local conditions (see below), there is a need for strong capacity in problem-solving around CA practices among development agents (NGO and extension workers) as well as in local research capacity (Rockström et al., 2001; Mazvimavi et al., 2008; Lahmar and Triomphe, 2008). It is therefore important that a non-linear, flexible approach is used when disseminating CA, with emphasis on capacity building and with room for adaptations to local conditions. Failures of extension in SSA are often due to a combination of a lack of relevant technology, failure by research and extension to understand and involve farmers in problem definition and solving, and weak linkages between extension, research, and farmers (Davis, 2008). Restrictive definitions of what constitutes CA rather than flexibility with consideration to the local conditions are therefore in the long run more likely to hamper rather than promote adoption of complex technologies such as CA (Baudron et al., 2007).

As with other complex crop management technologies, adoption is unlikely to be immediate, but will be incremental, with farmers experimenting on small areas and only adopting on a large-scale when they are fully convinced of the benefits of the new practices. In the Conservation Agriculture in Africa Case Study Project (Triomphe et al., 2007) it is recognized that there cannot be a linear transfer of CA technologies. There are many adoption pathways and what farmers realistically can achieve at a given time and in a given farm context depends on the environmental, socio-economic, institutional and political circumstances and constraints. Aspects that need to be considered in tailoring CA



systems to the local circumstances include: farmers' production objectives, factors limiting production, expected relative costs (requirements in terms of inputs, equipment but also knowledge, labour, etc.) and benefits (to the farmer, the community and/or the region) of CA approaches in the specific socio-ecological setting and institutions present who can assist with input supply, technical advice, marketing, etc. Clearly the job of an extension officer is challenging, requiring a broad knowledge of agriculture and of the effects of CA under different environments, access to support (e.g. information), social skills to communicate and work with the farmers and above all commitment. Given the parlous funding situation of many agricultural extension services in SSA, support to farmers for implementation of CA is often weak.

#### 4.4. A need for immediate returns to investment

The number of changes in farming practice required to implement CA can be substantial, whereas the benefits of the changes are likely to be household specific (Erenstein, 1999). Consequently, the private returns to adopting CA are likely to vary between farm households. Farmers in SSA often attribute a substantially higher value to immediate costs and benefits than those incurred or realised in the future due to the constraints of production and food security that they face. Yet, while farmers seek substantial, visible and immediate benefits when considering adoption of CA practices (FAO, 2008b), many of the benefits of employing CA are only realised in the longer term.

In many agricultural systems of SSA, traditional land preparation and weeding are labour intensive and farmers may find the use of herbicides attractive – but often lack the cash to invest in them. Indeed there is a general lack of support for smallholder agriculture in much of SSA, such that there are actually economic disincentives to investment in agriculture (Ehui and Pender, 2005). Institutional elements required for all successful strategies for agricultural intensification include a stable macroeconomic environment, provision of incentives through markets where markets function, development of market institutions where they do not, and public and private investment in an appropriate mix of physical, human, natural, and social capital (Ehui and Pender, 2005). Although these constraints are common to other strategies for improvement of productivity, unless they are addressed there is little point in pushing CA as one more “silver bullet”.

### 5. Conclusions: defining a socio-ecological niche for CA in sub-Saharan Africa

Knowler and Bradshaw (2007) concluded on the basis of a world-wide study that there was a lack of universal variables that explain the adoption of conservation agriculture and that efforts to promote conservation agriculture need to be tailored to local conditions. This resonates with the conclusions of Erenstein (2002) and Kronen (1994) that the potential of CA and soil conservation technologies in general, is site-specific and depends on the local bio-physical and socio-economic environments.

Ojiem et al. (2006) introduced the concept of the socio-ecological niche and applied it to matching legume technologies to smallholder farming systems in western Kenya. The concept of the socio-ecological niche (Ojiem et al., 2006) could assist in providing a framework for ‘ideotyping’ the contexts within which CA has most to offer. Farmers' requirements to be able to adopt CA are many (access to inputs, equipment, knowledge, immediate returns, constraints of labour, constraints of cash). There are many different types of CA, each with their specific requirements for labour, equipment, fertilizer, etc. Direct seeders have a high equipment cost, although there are cheaper alternative such as the jab planter. Perhaps CA can offer most on erodible soils on steep

slopes, where there is no strong competition for crop residues for livestock feeding, where herbicides are readily available and where good markets exist for farm produce so that farmers can afford to use herbicides and other inputs. It seems likely that CA will be most rapidly adopted by smallholder farmers with adequate resources of land, cash and labour, and not by the most resource-constrained groups. A challenge for the CA research community is to assess where particular CA practices may best fit, and which farmers in any given community are likely to benefit the most. Although we focus on the potential of CA for smallholder farmers in SSA, the arguments presented here apply to resource-constrained farmers in many regions of the (sub)tropics.

In his review, Bolliger (2007) highlighted that nobody is questioning *if* CA should be adopted by farmers when analysing the reasons for the lack of uptake of CA in South Africa. He refers to the lack of consideration of the potential mismatch between the technology and the target users, a point raised by Sumberg (2005) in a more general context. As discussed in the previous sections, CA may not always be able to satisfy key conditions such as increases in crop production and soil quality, capacity to control weeds and reduce production costs, alternatives to free-roaming livestock and time saving that farmers seek from CA (FAO, 2008b). If CA cannot be expected to satisfy these conditions then CA and its principles may not be appropriate. We hope that our critical review can contribute to the discussion of *if, when and for whom* CA is a useful and appropriate technology in a constructive way. The response of many CA proponents to such questions is simply to raise their hands and say “*but what are the alternatives to CA?*”, as if agriculture has no future if all farmers do not adopt CA *en masse*. Perhaps one possibility is the plough – and it may be worth evaluating with farmers how a technology relatively new in a historical sense in SSA has become so widely a central part of farming practice.

Given the concerns we have raised, it is hard to understand why scientists working for international scientific organisations appear to have undertaken the promotion of conservation agriculture as a personal mission. Wall (2007) proposes that successful adoption of conservation agriculture depends on “awareness raising” in the community to the problems of soil degradation. But in the face of immediate problems of poverty, food insecurity and poor agricultural productivity, soil degradation may be readily relegated down their list of priorities. How can resource-constrained farmers be expected to adopt practices that in the long-term may improve production, but in the short-term realise no net benefits, or even net losses?

Perhaps a simpler conclusion is that under present circumstances CA is inappropriate for the vast majority of resource-constrained smallholder farmers and farming systems. We do not doubt that CA is one approach that can offer substantial benefits for certain (types of) farmers in certain locations at certain times. Identification of the situations when CA can offer major benefits is a challenge that demands active research.

A large body of development agencies active in many parts of SSA seeks advice on how best to assist smallholder farmers in agricultural development. They reach out to the international research community for help, and yet we are often not in a position to offer realistic and practical options for farmers. Knowledge on where and when CA works best, for whom, and how CA should be configured in different settings is urgently required. We conclude that CA is but one of the options in the ‘basket’ for addressing the critical problem of raising agricultural productivity in SSA and that there is no case for promoting CA as a panacea.

#### Acknowledgements

We thank six anonymous referees for their careful reading, critical reviews and useful suggestions on an earlier manuscript.

## References

- Abdalla, M.A., Mohamed, A.E., 2007. The response of two-sorghum cultivars to conventional and conservation tillage systems in central Sudan. *AMA – Agric. Mech. Asia, Afr. Lat. Am.* 38, 67–71.
- Abiven, S., Recous, S., 2007. Mineralisation of crop residues on the soil surface or incorporated in the soil under controlled conditions. *Biol. Fertil. Soils* 43, 849–852.
- Adjei-Nsiah, S., Kuyper, T.W., Leeuwis, C., Abekoe, M.K., Giller, K.E., 2007. Evaluating sustainable and profitable cropping sequences with cassava and four legume crops: effects on soil fertility and maize yields in the forest/savannah transitional agro-ecological zone of Ghana. *Field Crop Res.* 103, 87–97.
- Adu-Gyamfi, J.J., Myaka, F.A., Sakala, W.D., Odgaard, R., Vesterager, J.M., Høgh-Jensen, H., 2007. Biological nitrogen fixation and nitrogen and phosphorus budgets in farmer-managed intercrops of maize–pigeonpea in semi-arid southern and eastern Africa. *Plant Soil* 295, 127–136.
- Affholder, F., Jourdain, D., Morize, M., Dan Dinh, Q., Ricome, A., 2008. Eco-intensification dans les montagnes du Vietnam. Contraintes à l'adoption de la culture sur couvertures végétales. *Cahiers Agricultures* 17, 289–296.
- African Conservation Tillage Network, 2008. 2009-06-26 [www.act-africa.org/](http://www.act-africa.org/).
- Aina, P.O., Lal, R., Roose, E.J., 1991. Tillage methods and soil and water conservation in West Africa. *Soil Till. Res.* 20, 165–186.
- Akinyemi, J.O., Akinpelu, O.E., Olaleye, A.O., 2003. Performance of cowpea under three tillage systems on an Oxic Paleustalf in southwestern Nigeria. *Soil Till. Res.* 72, 75–83.
- Alabi, S., Akintunde, O., 2004. Effect of tillage method on soil properties and performance of groundnut (*Arachis hypogaea* L.) in Southwestern Nigeria. *J. Sust. Agric. Environ.* 6, 22–29.
- Allmaras, R.R., Dowdy, R.H., 1985. Conservation tillage systems and their adoption in the United States. *Soil Till. Res.* 5, 197–222.
- Asefa, T., Tanner, D., Bennie, A., 2004. Effects of stubble management, tillage and cropping sequence on wheat production in the south-eastern highlands of Ethiopia. *Soil Till. Res.* 76, 69–82.
- Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. *Agric. Syst.* 94, 13–25.
- Baudron, F., Mwanza, H.M., Triomphe, B., Bwalya, M., 2007. Conservation Agriculture in Zambia: A Case Study of Southern Province. African Conservation Tillage Network, Centre de Coopération Internationale de Recherche Agronomique pour le Développement, Food and Agricultural Organization of the United Nations, Nairobi, Kenya.
- Bebe, B.O., Udo, H.M.J., Thorpe, W., 2002. Development of smallholder dairy systems in the Kenya highlands. *Outlook Agric.* 31, 113–120.
- Benites, J.R., Ashburner, J.E., 2003. FAO's role in promoting conservation agriculture. *Conserv. Agric.: Environ. Farmers Exp. Innov. Socio-Econ. Policy* 139–153.
- Benoit-Cattin, M., Calkins, P., Kebe, D., Sabatier, J.-L., 1991. Perspectives de la modélisation des systèmes agraires cotonnières du Mali: l'exemple des régions cotonnières du Mali. *Cahiers de la Recherches Développement* 29, 14–29.
- Biamah, E.K., Gichuki, F.N., Kaumbutho, P.G., 1993. Tillage methods and soil and water conservation in eastern Africa. *Soil Till. Res.* 27, 105–123.
- Bolliger, A., 2007. Is Zero-till an appropriate agricultural alternative for disadvantaged smallholders of South Africa? A study of surrogate systems and strategies, smallholder sensitivities and soil glycoproteins. PhD Thesis. University of Copenhagen, Copenhagen, p. 67.
- Bolliger, A., Magid, J., Amado, T.J.C., Neto, F.S., Ribeiro, M.D.D., Calegari, A., Ralisch, R., de Neergaard, A., 2006. Taking stock of the Brazilian “zero-till revolution”: a review of landmark research and farmers' practice. *Adv. Agron.* 91, 47–110.
- Chikowo, R., Mapfumo, P., Nyamugafata, P., Giller, K.E., 2004. Woody legume fallow productivity, biological N<sub>2</sub>-fixation and residual benefits to two successive maize crops in Zimbabwe. *Plant Soil* 262, 303–315.
- Chivenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P., Six, J., 2007. Long-term impact of reduced tillage and residue management on soil carbon stabilization: implications for conservation agriculture on contrasting soils. *Soil Till. Res.* 94, 328–337.
- Christoffoleti, P.J., de Carvalho, S.J.P., Lopez-Ovejero, R.F., Nicolai, M., Hidalgo, E., da Silva, J.E., 2007. Conservation of natural resources in Brazilian agriculture: implications on weed biology and management. *Crop Prot.* 26, 383–389.
- Corbeels, M., Scopel, E., Cardoso, A., Bernoux, M., Douzet, J.M., Neto, M.S., 2006. Soil carbon storage potential of direct seeding mulch-based cropping systems in the Cerrados of Brazil. *Global Change Biol.* 12, 1773–1787.
- Conservation Technology Information Center (CTIC), 1999. What's Conservation Tillage? CTIC, Core 4 Program, Lafayette, IN, USA.
- Davis, K.E., 2008. Extension in sub-Saharan Africa: overview and assessment of past and current models, and future prospects. *J. Int. Agric. Ext. Educ.* 15, 15–28.
- Dercon, S., 1998. Wealth, risk and activity choice: cattle in western Tanzania. *J. Dev. Econ.* 55, 1–42.
- Derpsch, R., 2003. Conservation tillage, no-tillage and related technologies. *Conserv. Agric. Environ. Farm. Exp. Innov. Socio-Econ. Policy* 181–190.
- Diels, J., Vanlauwe, B., Van der Meersch, M.K., Sanginga, N., Merckx, R., 2004. Long-term soil organic carbon dynamics in a subhumid tropical climate: C-13 data in mixed C-3/C-4 cropping and modeling with RothC. *Soil Biol. Biochem.* 36, 1739–1750.
- Drechsel, P., Gyiele, L., Kunze, D., Cofie, O., 2001. Population density, soil nutrient depletion, and economic growth in sub-Saharan Africa: a Malthusian nexus? *Ecol. Econ.* 38, 251–258.
- Dugue, P., Vall, E., Lecomte, P., Klein, H., Rollin, D., 2004. Evolution of relationships between agriculture and livestock in the savannas of West and Central Africa. A new framework for analysis and intervention for improving modes of intervention and favouring innovation. *Oleagineux* 11, 268–276.
- Ehui, S., Pender, J., 2005. Resource degradation, low agricultural productivity, and poverty in sub-Saharan Africa: pathways out of the spiral. *Agric. Econ.* 32, 225–242.
- Erenstein, O., 1999. The economics of soil conservation in developing countries: the case of crop residue mulching. PhD Thesis. Wageningen Agricultural University, Wageningen, Netherlands.
- Erenstein, O., 2002. Crop residue mulching in tropical and semi-tropical countries: an evaluation of residue availability and other technological implications. *Soil Till. Res.* 67, 115–133.
- Erenstein, O., 2003. Smallholder conservation farming in the tropics and sub-tropics: a guide to the development and dissemination of mulching with crop residues and cover crops. *Agric. Ecosyst. Environ.* 100, 17–37.
- Erkossa, T., Stahr, K., Gaiser, T., 2006. Soil tillage and crop productivity on a Vertisol in Ethiopian highlands. *Soil Till. Res.* 85, 200–211.
- FAO, 2008a. Investing in Sustainable Agricultural Intensification. The Role of Conservation Agriculture. A Framework for Action. Food and Agriculture Organization of the United Nations, Rome.
- FAO, 2008b. Conservation Agriculture. 2008-07-08 <http://www.fao.org/ag/ca/index.html>.
- Farage, P.K., Ardo, J., Olsson, L., Rienzi, E.A., Ball, A.S., Pretty, J.N., 2007. The potential for soil carbon sequestration in three tropical dryland farming systems of Africa and Latin America: a modelling approach. *Soil Till. Res.* 94, 457–472.
- Feller, C., Beare, M.H., 1997. Physical control of soil organic matter dynamics in the tropics. *Geoderma* 79, 69–116.
- Fowler, R., Rockström, J., 2001. Conservation tillage for sustainable agriculture—an agrarian revolution gathers momentum in Africa. *Soil Till. Res.* 61, 93–107.
- Gill, K.S., Aulakh, B.S., 1990. Wheat yield and soil bulk-density response to some tillage systems on an Oxisol. *Soil Till. Res.* 18, 37–45.
- Giller, K.E., 2001. Nitrogen Fixation in Tropical Cropping Systems. CAB International, Wallingford, UK.
- Giller, K.E., Cadisch, G., 1995. Future benefits from biological nitrogen-fixation—an ecological approach to agriculture. *Plant Soil* 174, 255–277.
- Giller, K.E., Rowe, E.C., de Ridder, N., van Keulen, H., 2006. Resource use dynamics and interactions in the tropics: scaling up in space and time. *Agric. Syst.* 88, 8–27.
- Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K.D., Dixon, J., Dendooven, L., 2009. Conservation agriculture and soil carbon sequestration: between myth and farmer reality. *Crit. Rev. Plant Sci.* 28, 97–122.
- Gowing, J.W., Palmer, M., 2008. Sustainable agricultural development in sub-Saharan Africa: the case for a paradigm shift in land husbandry. *Soil Use Manage.* 24, 92–99.
- Hagblade, S., Tembo, G., 2003. Conservation farming in Zambia. EPTD Discussion Paper. Environment and Production Technology Division, International Food Policy Research Institute.
- Heal, O.W., Anderson, J.W., Swift, M.J., 1997. Plant litter quality and decomposition: an historical overview. In: Cadisch, G., Giller, K.E. (Eds.), *Driven by Nature: Plant Litter Quality and Decomposition*. CAB International, Wallingford, UK, pp. 3–30.
- Hebblethwaite, J., Soza, R., Faye, A., Hutchinson, N., 1996. No-till and reduced tillage for improved crop production in sub-Saharan Africa. Achieving greater impact from research investments in Africa. In: *Proceedings of the Workshop Developing African Agriculture: Achieving Greater Impact from Research Investments*, Addis Ababa, Ethiopia, September 26–30, 1995, pp. 195–199.
- Hobbs, P.R., 2007. Conservation agriculture: what is it and why is it important for future sustainable food production? *J. Agric. Sci.* 145, 127–137.
- Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. *Philos. Trans. Roy. Soc. B* 363, 543–555.
- Ikpe, F.N., Powell, J.M., Isirimah, N.O., Wahua, T.A.T., Ngodigha, E.M., 1999. Effects of primary tillage and soil amendment practices on pearl millet yield and nutrient uptake in the Sahel of West Africa. *Exp. Agric.* 35, 437–448.
- Ito, M., Matsumoto, T., Quinones, M.A., 2007. Conservation tillage practice in sub-Saharan Africa: the experience of Sasakawa Global 2000. *Crop Prot.* 26, 417–423.
- Jarecki, M.K., Lal, R., 2003. Crop management for soil carbon sequestration. *Crit. Rev. Plant Sci.* 22, 471–502.
- Kanmegne, J., 2004. Slash and burn agriculture in the humid forest zone of Southern Cameroon: soil quality dynamics, improved fallow management and farmers' perceptions. *Tropenbos-Cameroon Series* xii.
- Kasasa, P., Mpepereki, S., Musiyiwa, K., Makonene, F., Giller, K., 1999. Residual nitrogen benefits of promiscuous soybeans to maize under field conditions. *Afr. Crop Sci. J.* 7, 375–382.
- Kaumbutho, P., Kienzle, J., 2007. Conservation Agriculture As Practised in Kenya: Two Case Studies. African Conservation Tillage Network, Centre de Coopération Internationale de Recherche Agronomique pour le Développement, Food and Agriculture Organization of the United Nations, Nairobi, Kenya.
- Kayode, J., Ademiluyi, B., 2004. Effect of tillage methods on weed control and maize performance in southwestern Nigeria. *J. Sust. Agric.* 23, 39–45.
- Kerr, R.B., Snapp, S., Chirwa, M., Shumba, L., Msachi, R., 2007. Participatory research on legume diversification with Malawian smallholder farmers for improved human nutrition and soil fertility. *Exp. Agric.* 43, 437–453.
- Knowler, D., Bradshaw, B., 2007. Farmers' adoption of conservation agriculture: a review and synthesis of recent research. *Food Pol.* 32, 25–48.

- Kronen, M., 1994. Water harvesting and conservation techniques for smallholder crop production systems. *Soil Till. Res.* 32, 71–86.
- Lahmar, R., 2009. Adoption of conservation agriculture in Europe: lessons of the KASSA project. *Land Use Policy*, doi:10.1016/j.landusepol.2008.02.001.
- Lahmar, R., Triomphe, B., 2008. Key lessons from international experiences about conservation agriculture and considerations for its implementation in dry areas. In: Stewart, B.L., Asfary, A.F., Belloum, A., Steiner, K., Friedrich, T. (Eds.), *Conservation Agriculture for Sustainable Land Management to Improve the Livelihood of People in Dry Areas*. ACSAD & GTZ, pp. 123–140.
- Lal, R., 1979. Influence of 6 years of no-tillage and conventional plowing on fertilizer response of maize (*Zea mays* L.) on an Alfisol in the tropics. *Soil Sci. Soc. Am. J.* 43, 399–403.
- Lal, R., 1986. Soil surface management in the tropics for intensive land use and high and sustained production. *Adv. Soil Sci.* 5, 1–109.
- Lal, R., 1991. Tillage and agricultural sustainability. *Soil Till. Res.* 20, 133–146.
- Lal, R., 1998a. Soil erosion impact on agronomic productivity and environment quality. *Crit. Rev. Plant Sci.* 17, 319–464.
- Lal, R., 1998b. Soil quality changes under continuous cropping for seventeen seasons of an Alfisol in western Nigeria. *Land Degrad. Dev.* 9, 259–274.
- Lal, R., Follett, F., Stewart, B.A., Kimble, J.M., 2007. Soil carbon sequestration to mitigate climate change and advance food security. *Soil Sci.* 172, 943–956.
- Lavelle, P., Brussaard, L., Hendrix, P. (Eds.), 1999. *Earthworm Management in Tropical Agroecosystems*. CAB International, Wallingford.
- Leeuwis, C., 2004. Communication for Rural Innovation. Rethinking Agricultural Extension (with contributions by A. Van den Ban) Blackwell Science, Oxford.
- Locke, M.A., Reddy, K.N., Zabolotowicz, R.M., 2002. Weed management in conservation crop production systems. *Weed Biol. Manage.* 2, 123–132.
- Logan, T.J., Lal, R., Dick, W.A., 1991. Tillage systems and soil properties in North America. *Soil Till. Res.* 20, 241–270.
- Mando, A., Ouattara, B., Sedogo, M., Stroosnijder, L., Ouattara, K., Brussaard, L., Vanlauwe, B., 2005. Long-term effect of tillage and manure application on soil organic fractions and crop performance under Sudano-Sahelian conditions. *Soil Till. Res.* 80, 95–101.
- Mapfumo, P., Chikowo, R., Giller, K.E., Mugendi, D.N., Kimetu, J.M., Palm, C.A., Mutuo, P., 2001. Closing the Loop: Identifying N sources and minimizing N losses in leguminous cropping systems. Final Project Report to the Rockefeller Foundation. University of Zimbabwe, Harare.
- Martin, C., Castella, J.C., Hoang Lan, A., Eguienta, Y., Tran Trong, H., 2004. A participatory simulation to facilitate farmers' adoption of livestock feeding systems based on conservation agriculture in the uplands of northern Vietnam. *Int. J. Agric. Sust.* 2, 118–132.
- Mashingaidze, A.B., Govere, I., Rohrbach, D., Hove, L., Twomlow, K., Mazvimavi, K., 2006. Review of NGO Efforts to Promote Conservation Agriculture in Zimbabwe, 2005/2006 Season (unpublished, pre-edited draft).
- Mazvimavi, K., Twomlow, S., Belder, P., Hove, L., 2008. An Assessment of the Sustainable Uptake of Conservation Farming in Zimbabwe. Global Theme on Agroecosystems Report no. xx.
- Mbagwu, J., 1990. Mulch and tillage effects on water transmission characteristics of an Ultisol and maize grain yield in SE Nigeria. *Pedologie* 40, 155–168.
- Moyo, A., 2002. Assessment of the effect of soil erosion on nutrient loss from granite-derived sandy soils under different tillage systems in Zimbabwe. PhD Thesis University of Zimbabwe, Harare, Zimbabwe.
- Mpepereki, S., Javaheri, F., Davis, P., Giller, K.E., 2000. Soybeans and sustainable agriculture—promiscuous soybeans in southern Africa. *Field Crops Res.* 65, 137–149.
- Munyati, M., 2000. Conservation tillage for sustainable crop production. Results from on-station research in Natural Region II of Zimbabwe (unpublished).
- Mutekwa, V., Kusangaya, S., 2006. Contribution of rainwater harvesting technologies to rural livelihoods in Zimbabwe: the case of Ngundu ward in Chivi District. *Water SA* 32, 437–444.
- Nhamo, N., 2007. The contribution of different fauna communities to improved soil health: a case of Zimbabwean soils under conservation agriculture. PhD Thesis. Rheinischen Friedrich-Wilhelms-Universität, Bonn, Germany, p. 128.
- Nicou, R., Charreau, C., Chopart, J.L., 1993. Tillage and soil physical properties in semiarid West Africa. *Soil Till. Res.* 27, 125–147.
- Nyagumbo, I., 2002. The effects of three tillage systems on seasonal water budgets and drainage of two Zimbabwean soils under maize. PhD Thesis, University of Zimbabwe, Harare, Zimbabwe.
- Ojiem, J., Ridder, N., Vanlauwe, B., Giller, K.E., 2006. Socio-ecological niche: a conceptual framework for integration of legumes in smallholder farming systems. *Int. J. Agric. Sust.* 4, 79–93.
- Ojiem, J.O., Vanlauwe, B., de Ridder, N., Giller, K.E., 2007. Niche-based assessment of contributions of legumes to the nitrogen economy of Western Kenya smallholder farms. *Plant Soil* 292, 119–135.
- Palm, C.A., Giller, K.E., Mafongoya, P.L., Swift, M.J., 2001. Management of organic matter in the tropics: translating theory into practice. *Nutr. Cycl. Agroecosyst.* 61, 63–75.
- Powell, J.M., Pearson, R.A., Hiernaux, P.H., 2004. Crop-livestock interactions in the west African drylands. *Agron. J.* 96, 469–483.
- Rockström, J., Barron, J., 2007. Water productivity in rainfed systems: overview of challenges and analysis of opportunities in water scarcity prone savannahs. *Irrig. Sci.* 25, 299–311.
- Rockström, J., Kaumbutho, P., Mwalley, P., Temesgen, M., 2001. Conservation farming among small-holder farmers in E. Africa: adapting and adopting innovative land management options. Conservation agriculture, a worldwide challenge. In: *Proceedings of the First World Congress on Conservation Agriculture*, vol. 1: *Keynote Contributions*, Madrid, Spain, October 1–5, 2001, pp. 363–374.
- Rockström, J., Kaumbutho, P., Mwalley, P., Nzabi, A.W., Temesgen, M., Mawenyi, L., Barron, J., Mutua, J., Damgaard-Larsen, S., 2008. Conservation farming strategies in East and Southern Africa: yields and rain water productivity from on-farm action research. *Soil Till. Res.* 103, 23–32.
- Roose, E., Barthes, B., 2001. Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. *Nutr. Cycl. Agroecosyst.* 61, 159–170.
- Rufino, M.C., Tittonell, P., van Wijk, M.T., Castellanos-Navarrete, A., Delve, R.J., de Ridder, N., Giller, K.E., 2007. Manure as a key resource within smallholder farming systems: analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. *Livestock Sci.* 112, 273–287.
- Sakala, W.D., 1998. Nitrogen dynamics in maize/pigeonpea intercropping in Malawi. 1998. PhD Thesis. Wye College, University of London.
- Sakala, W.D., Cadisch, G., Giller, K.E., 2000. Interactions between residues of maize and pigeonpea and mineral N fertilizers during decomposition and N mineralization. *Soil Biol. Biochem.* 32, 679–688.
- Samaké, O., Smaling, E.M.A., Kropff, M.J., Stomph, T.J., Kodio, A., 2005. Effects of cultivation practices on spatial variation of soil fertility and millet yields in the Sahel of Mali. *Agric. Ecosyst. Environ.* 109, 335–345.
- Sanginga, N., Okogun, J.A., Vanlauwe, B., Diels, J., Dashiell, K., 2001. Contribution of nitrogen fixation to the maintenance of soil fertility with emphasis on promiscuous soybean maize-based cropping systems in the moist savanna of West Africa. In: Tian, G., Ishida, F., Keatinge, J.D.H. (Eds.), *Sustaining Soil Fertility in West Africa*. ASA, Wisconsin, pp. 157–178.
- Scoones, I. (Ed.), 2001. *Dynamics & Diversity: Soil Fertility Management and Farming Livelihoods in Africa: Case Studies from Ethiopia, Mali and Zimbabwe*. Earthscan Publications Ltd., London.
- Scopel, E., Macena, F., Corbeels, M., Affholder, F., Maraux, F., 2004. Modelling crop residue mulching effects on water use and production of maize under semi-arid and humid tropical conditions. *Agronomie* 24, 1–13.
- Scopel, E., Findeling, A., Guerra, E.C., Corbeels, M., 2005. Impact of direct sowing mulch-based cropping systems on soil carbon, soil erosion and maize yield. *Agron. Sust. Dev.* 25, 425–432.
- Shetto, R., Owenya, M., 2007. Conservation Agriculture As Practised In Tanzania: Three Case Studies. African Conservation Tillage Network, Centre de Coopération Internationale de Recherche Agronomique pour le Développement, Food and Agriculture Organization of the United Nations, Nairobi, Kenya.
- Siziba, S., 2008. Assessing the adoption of conservation agriculture in Zimbabwe's smallholder sector. PhD Thesis. University of Hohenheim, Germany.
- Steiner, K., Derpsch, R., Koller, K., 1998. Sustainable management of soil resources through zero tillage. *Agric. Rural Dev.* 5, 64–66.
- Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., 2007. Soil carbon saturation: concept, evidence and evaluation. *Biogeochemistry* 86, 19–31.
- Stoorvogel, J.J., Smaling, E.A., 1998. Research on soil fertility decline in tropical environments: integration of spatial scales. *Nutr. Cycl. Agroecosyst.* 50, 151–158.
- Sumberg, J., 2005. Constraints to the adoption of agricultural innovations—is it time for a re-think? *Outlook Agric.* 34, 7–10.
- Swift, M.J., Heal, O.W., Anderson, J.M., 1979. *Decomposition in Terrestrial Ecosystems*. Blackwell Scientific Publications, Oxford, UK.
- Tadesse, N., Ahmed, S., Hulluka, M., 1996. The effects of minimum tillage weeds and yield of durum wheat in central Ethiopia. *Trop. Agric.* 73, 242–244.
- Temesgen, M., Rockström, J., Savenije, H.H.G., Hoogmoed, W.B., Alemu, D., 2008. Determinants of tillage frequency among smallholder farmers in two semi-arid areas in Ethiopia. *Phys. Chem. Earth* 33, 183–191.
- Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya. I. Heterogeneity at region and farm scale. *Agric. Ecosyst. Environ.* 110, 149–165.
- Tittonell, P., Vanlauwe, B., de Ridder, N., Giller, K.E., 2007a. Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients? *Agric. Syst.* 94, 376–390.
- Tittonell, P., van Wijk, M.T., Rufino, M.C., Vrugt, J.A., Giller, K.E., 2007b. Analysing trade-offs in resource and labour allocation by smallholder farmers using inverse modelling techniques: a case-study from Kakamega district, western Kenya. *Agric. Syst.* 95, 76–95.
- Tittonell, P., Vanlauwe, B., Corbeels, M., Giller, K.E., 2008. Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. *Plant Soil* 313, 19–37.
- Triomphe, B.J., Kienzie, S., Bwalya, M., Damgaard-Larsen, S., 2007. Case study project background and method. In: Baudron, F., Mwanza, H.M., Triomphe, B., Bwalya, M. (Eds.), *Conservation Agriculture in Zambia: A Case Study of Southern Province*. Conservation Agriculture in Africa Series. African Conservation Tillage Network, Centre de Coopération Internationale de Recherche Agronomique pour le Développement, Food and Agriculture Organization of the United Nations, Nairobi, Kenya, pp. IX–XX.
- Triplett, G.B., Warren, A.D., 2008. No-tillage crop production: a revolution in agriculture! *Agron. J.* 100, S-153–S-165.
- Tulema, B., Aune, J.B., Johnsen, F.H., Vanlauwe, B., 2008. The prospects of reduced tillage in tef (*Eragrostis tef* Zucca) in Gare Arera, West Shawa Zone of Oromiya, Ethiopia. *Soil Till. Res.* 99, 58–65.

- De Vleeschauwer, D., Lal, R., Malafa, R., 1980. Effects of amounts of surface mulch on physical and chemical properties of an Alfisol from Nigeria. *J. Sci. Food Agric.* 31, 730–738.
- Vogel, H., 1993a. Tillage effects on maize yield, rooting depth and soil–water content on sandy soils in Zimbabwe. *Field Crops Res.* 33, 367–384.
- Vogel, H., 1993b. An evaluation of five tillage systems for smallholder agriculture in Zimbabwe. *Der Tropenlandwirt* 94, 21–36.
- Vogel, H., 1994. Weeds in single-crop conservation farming in Zimbabwe. *Soil Till. Res.* 31, 169–185.
- Vogel, H., 1995. The need for integrated weed management–systems in smallholder conservation farming in Zimbabwe. *Der Tropenlandwirt* 96, 35–56.
- Wall, P., 2007. Tailoring conservation agriculture to the needs of small farmers in developing countries: an analysis of issues. *J. Crop Improv.* 19, 137–155.
- Wezel, A., Rath, T., 2002. Resource conservation strategies in agro-ecosystems of semi-arid West Africa. *J. Arid Environ.* 51, 383–400.
- Zingore, S., Manyame, C., Nyamugafata, P., Giller, K.E., 2005. Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. *Eur. J. Soil Sci.* 56, 727–736.
- Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agric. Ecosyst. Environ.* 119, 112–126.