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Article

Where to Target Conservation Agriculture for African Smallholders? How to Overcome Challenges Associated with its Implementation? Experience from Eastern and Southern Africa

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Abstract: Since the paper by Giller *et al.* (2009), the debate surrounding the suitability of conservation agriculture (CA) for African smallholders has remained polarized between proponents and opponents. The debate also gave rise to a few studies that attempted to identify the "niche" where CA would fit in the region, but the insight offered by these studies has been limited. In this paper, we first analyze the rationale of adoption where it occurred globally to define "drivers" of adoption. Our analysis suggests that CA has first and foremost been adopted under the premises of being energy-saving (time and/or power), erosion-controlling, and water-use efficient, but rarely to increase yield. We then define the niche where CA fits, based on these drivers of adoption, as systems where (1) the energy available for crop establishment is limited and/or costly (including labor and draft power); (2) delayed planting results in a significant yield decline; (3) yield is limited or co-limited by water; and/or (4) severe erosion problems threaten the short- to medium-term productivity of farmland. In Eastern and Southern Africa, this niche appears rather large and likely to expand in the near future. When implemented within this niche, CA may still be limited by "performance challenges" that do not constitute drivers or barriers to adoption, but limitations to the performance of CA. We argue that most of these performance challenges can (and should) be addressed by agronomic and socio-economic research, and provide four examples where the International Maize and Wheat Improvement Center (CIMMYT) and its partners have been successfully alleviating four very different challenges through research and development (R&D) in Eastern and Southern Africa. Finally, we describe an iterative and multi-scale R&D approach currently used by CIMMYT in Eastern and Southern Africa to overcome challenges associated with the implementation of CA by African smallholders. This approach could also be useful for other complex combinations of technologies aiming at sustainable intensification.

Keywords: niche; reduced tillage; no tillage; energy-saving technology; erosion, water use efficiency; residue trade-off; innovation platform

1. Introduction

Conservation agriculture (CA) is defined as the simultaneous application of minimal soil disturbance, permanent soil cover through a surface mulch of crop residues or living plants, and crop rotations [1]. In Eastern and Southern Africa, CA has been intensively promoted for more than a decade as a means to increase crop productivity while conserving soil and water. However, since the paper by Giller and colleagues [2], the debate surrounding the suitability of CA for African smallholders has remained polarized between proponents and opponents [3].

The debate also gave rise to few studies that attempted to identify the "niche" where CA would fit in the region. Tesfaye and colleagues [4] delineated recommendation domains in Ethiopia, Kenya and Malawi where CA investment should be prioritized. They used three biophysical variables—soil texture, surface slope, and rainfall—and three socioeconomic variables—market access, human density (as a proxy of market demand) and livestock population densities—in their work. These variables, however, were selected on the assumption that CA is first and foremost a yield-increasing set of principles: the three biophysical variables were selected based on a literature search on yield response to CA in Africa, and two of the socioeconomic variables were selected assuming that CA would lead to an increase in farm production (market access and human density as a proxy of market demand). However, CA seldom increases yield in the short term and yield increase is rarely a motivation to adopt CA (see Section 2).

Andersson and N'Souza [5], adapting a framework from Sumberg [6], made another attempt to understand the barriers to CA adoption. They distinguished adoption constraints (*i.e.*, "goodness-of-fit" between the innovation and the potential users) from prerequisite conditions (*i.e.*, contextual factors that cannot be influenced by the innovation-development process). Prerequisites refer mainly to (1) the accessibility by the target group of potential users of the inputs necessary to implement a particular innovation; (2) the existence of demand for the output of the innovation; and (3) the conduciveness of the environment for the particular innovation [6]. Therefore, the notion of a prerequisite for the particular case of CA implicitly assumes that the innovation will lead to an increase in input use and in output production, *i.e.*, intensification. As already mentioned, CA may not primarily be a yield-increasing set of principles in the short-term. Moreover, this framework is only useful for well-defined, homogeneous technologies, but not for the very polymorphous basket of technologies promoted as CA in Africa (ranging from dibble stick planting, to manual planting basins, to semi-permanent raised beds shaped with a local plough, to the use of chisel-tine rippers and imported Brazilian implements pulled by draft animals [7–9]). These different seeding technologies have very different input requirements and need very different supporting environments, making generalization difficult. Finally, focusing on barriers to adoption is very much a technology-centered approach (even though the authors ironically call for less technology-centered approaches when it comes to CA research and development (R&D) and more consideration for the context): it looks at the specifications of the technologies and lists all the possible factors that could lead to poor performance.

In this paper, we favor an approach that emphasizes the rationale of adoption where it occurred (rather than the hypothetical causes for non-adoption everywhere else) and learn from these successful examples with the aim to define "drivers" of adoption. In addition to these factors that condition whether adoption takes place or not, we identify "performance challenges" that do not constitute drivers or barriers to adoption, but limitations to the performance of CA. We argue that most of these performance challenges can (and should) be addressed by agronomic and socio-economic research.

Below, we first look at drivers of adoption globally (*i.e.*, what motivates farmers to adopt CA). Landscapes or farms where at least one of these drivers is found could be defined as part of the niche where CA fits. Outside of these landscapes or farms, CA may not be a priority under the current context. In a second section, we look at performance challenges, which are often confused with barriers to adoption. Agronomy can propose solutions to alleviate these challenges. We strongly feel that it is the role of research to not only document these challenges, but to turn them into research questions that lead to the development of innovations (technical or institutional) to overcoming them. Our opinion thus points to the need for more research efforts and resources to be channeled towards development of appropriate solutions to identified challenges and less towards simply pointing at these challenges. Various cases from the experience of the International Maize and Wheat Improvement Center (CIMMYT, www.cimmyt.org) and its partners in Eastern and Southern Africa are used to illustrate this section. In a third section, we describe an R&D approach—iterative and multi-scale—used by CIMMYT and its partners in Eastern and Southern Africa to overcome challenges associated with the implementation of CA by African smallholders.

2. What Drives CA Adoption? A Simple Approach to Target CA

The vast majority of CA adoption (more than 95% of the area under no tillage) has occurred in the Americas, Australia, Russia and China, where it is practiced on large-scale mechanized farms [10]. In these farming systems, the reduction in fuel (and machinery cost) has been a major incentive to adopt CA [11]. Indeed, although this depends on site-specific soil properties (e.g., texture, soil moisture), reduced or no tillage cuts energy requirements by about half compared to moldboard or disc ploughing [12]. Therefore, it appears that CA has mostly been adopted in the world as an energy saving technology, and that adoption has been driven by the need to establish crops with as little energy as possible.

Energy is the product of power by time. A lower energy demand could thus enable the use of smaller and cheaper power sources [13]. It could also reduce the time needed for land preparation and seeding, a major benefit in agroecologies characterized by a short optimum planting window (*i.e.*, where the yield potential declines dramatically with delayed planting). In the Indo-Gangetic Plains, early planting has been a major driver of adoption of no-tillage for wheat [14]. Indeed, delayed planting of wheat after mid-November in this agroecology results in a loss of potential yield of 1% to 1.5% day^{-1}, while no-tillage allows for wheat to be planted one to three weeks earlier than conventional crop establishment methods [14]. Early planting also reduces the risk of terminal heat stress [15]. Interestingly, in this rice-wheat farming system, no-tillage has mostly been adopted for wheat, but rarely for rice, for which similar incentives do not seem to exist [10].

In addition to energy savings for crop establishment, a major driver for CA adoption in the US and Brazil—the first and second country in the world, respectively, in terms of area managed under CA—has undoubtedly been erosion control. In the US, adoption of less intensive tillage practices started in the Great Plains region, following severe wind erosion problems during the mid-1930s "Dust Bowl" [16]. In Brazil, CA adoption started in the State of Paraná (Southern part of Brazil) in the 1970s, primarily as a response to severe erosion problems [17,18]. Similarly, lower cost of crop establishment is evidently part of what drove CA adoption in Australia—the fourth country in the world in terms of area managed under CA—but the primary driver of adoption in part of the country appears to be soil moisture management, at least in the regions of New South Wales and Queensland [19].

This brief analysis suggests that CA has first and foremost been adopted globally under the premises of being energy-saving (time and/or power), erosion-controlling, and water use efficient. The primary motivation of CA adopters has rarely been to increase yield, except perhaps where water is a major limiting factor or where delayed planting leads to severe yield penalties. In most situations, yield increase has been a side effect of CA, occurring after several years of gradual physical, chemical and biological improvement of soils. Thus, it is not surprising that global analyses of large data sets (as the one conducted recently by Pittelkow and colleagues [20]) find that CA tends not to increase yield: yield increase may simply not be the primary purpose of adopting CA. Such analysis would be more enlightening if they included e.g., energy use efficiency or rainwater use efficiency as target variables, and e.g., planting date as independent variables.

Although adoption in still low in the region, Eastern and Southern Africa does not appear to be an exception to this global trend: CA has been found to equally be energy-saving, erosion controlling and water-use efficient in the region. Firstly, except in the case where adoption has been accompanied by a change in power source (in particular, where adopters shift from animal draft power to human muscle power), CA dramatically reduces the time needed to establish a crop (Figure 1), as the number of operations required to prepare the land (and the intensity of these operations) is reduced. As a consequence, CA adopters in the region tend to plant their crop earlier than farmers using conventional land preparation: 12–23 days earlier in Zimbabwe [21]. Similarly, in Zimbabwe, the time of planting was found to be more important than the type of tillage in explaining the performance of different CA systems, with a 5% yield reduction per week planting was delayed [22].

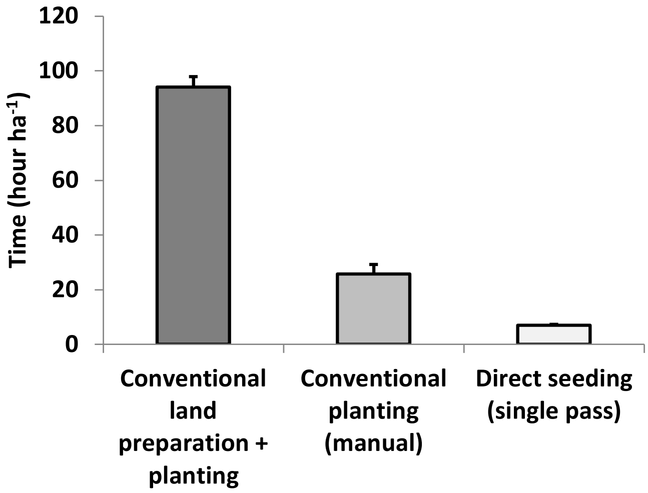

Figure 1. Comparison of the average time required for conventional land preparation and conventional planting of maize (land preparation using an animal drawn *maresha* and planting by hand), for conventional planting of maize only (following conventional land preparation), and for direct seeding of maize using a 2BFT-100 seeder powered by a 15 HP two-wheel tractor in an untilled land in Hawassa Ethiopia (source: [23]).

Secondly, in dry environments of Eastern and Southern Africa, CA generally improves rainwater use efficiency (Figure 2).

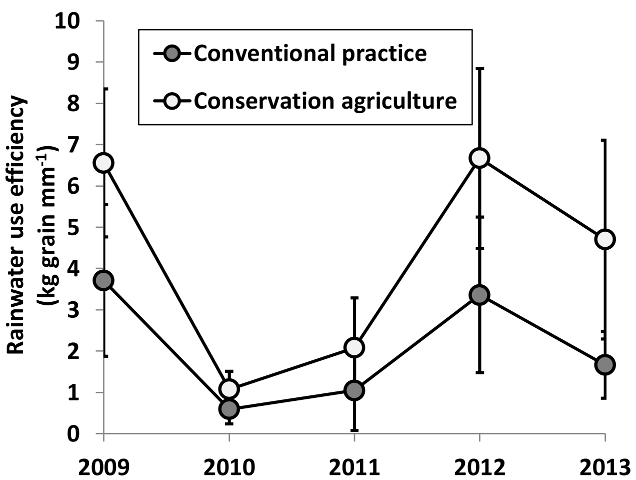

Figure 2. Comparison of rainwater use efficiency of maize during five consecutive seasons for conventional practice and conservation agriculture in Zimuto, Zimbabwe (source: calculated from [24]).

Thirdly, CA reduces water runoff and soil losses, even with moderate slopes (Figure 3), if sufficient quantities of crop residues are retained as surface mulch. In Zimbabwe, extensive studies in the 1990s clearly demonstrated the efficiency of CA in controlling sheet erosion on both sandy and clayey soils [25].

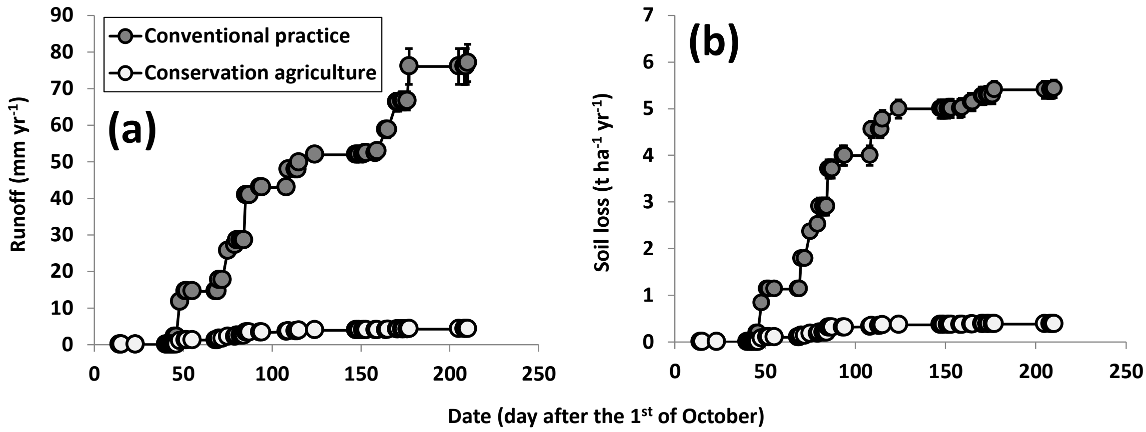

Figure 3. Comparison of (**a**) the cumulated water runoff and (**b**) the soil loss for conventional practice and conservation agriculture during the 1994/95 season in Hatcliffe, Zimbabwe, on a Fersiallitic clay soil with a 4.5% slope (source: [26]).

The niche where CA fits, from the understanding of what drives its adoption globally, is characterized by systems where (1) the energy available for crop establishment is limited and/or costly (including limited and/or costly labor and draft power); (2) delayed planting results in a significant yield decline (this point being a particular case of the previous); (3) yield is limited (or co-limited) by water; and/or (4) severe erosion problems threaten the short- to medium term productivity of farmland. Other technologies apart from those based on CA principles could be used to control erosion and increase water use efficiency (e.g., physical soil and water conservation structures [27], agroforestry [28], drought resistant genotypes [29]), but there are little alternatives to CA when it comes to minimizing the energy required to establish a crop. Therefore, we see constraint/cost of energy at land preparation/planting as a primary driver of CA adoption, and water-limited yield and severe erosion problems as secondary drivers.

How large is this niche in Eastern and Southern Africa? Firstly, many farming systems in the region are characterized by farm power shortage, including for land preparation and seeding [13]. This is the result of stagnating—or even declining—numbers of tractors (a result of the collapse of tractor hire schemes, which were popular up the 1990s) and numbers of draft animals (a result of increasing biomass shortage, diseases such as the East Coast Fever, and/or recurring droughts) in many countries. Human muscle power has also declined in many countries of the region as a result of an ageing and feminizing farming population (a consequence of rural-urban migration) and the HIV/AIDS pandemic, which has dramatically reduced the available labor force on-farm. Secondly, about 20% of Africa is characterized by strong to extreme water erosion [30]. In Eastern and Southern Africa, the Eastern African Highlands represent an extensive area considered a hotspot of erosion-induced soil degradation [31]. Thirdly, crop production is limited by water (or co-limited by nutrients and water) in large parts of Eastern and Southern Africa [32]. Therefore, in opposition to Giller and colleagues [2] who concluded that "*CA is inappropriate for the vast majority of resource-constrained smallholder farmers and farming systems*" in Eastern and Southern Africa, we argue that the niche where it fits in the region is large. The low adoption of CA in the region may thus reflect more poor targeting than unsuitability of CA. This niche is also likely to expand in the near future as (1) the cost of energy for farming operations is likely to increase (increasing cost of fuel [33]; increasing cost of maintaining draught animals due to feed shortage [34]; and increasing cost of labor due to rural-urban migration [35]); (2) the area affected by erosion is likely to expand as farming is moving into more marginal areas [36]; and (3) the area where yield is limited by water is likely to increase as a result of climate change, particularly in Southern Africa [37,38]. However, in large parts of this niche, the performance of CA is limited by other challenges. Below, we present case studies at different scales (plot-scale, farm-scale and landscape-scale) illustrating how CIMMYT and its partners are developing technical and institutional innovations to overcome some challenges that may be observed when implementing CA in the region.

3. Overcoming Challenges through Research and Development: Some Examples

The cases below only aim at illustrating how adaptive research can be used to overcome challenges when and if they arise during the implementation of CA. They were only selected to illustrate a diversity of possible challenges and their solutions: this choice implies by no means that the challenges selected are to be expected whenever CA is implemented in the region.

3.1. Adapting Nitrogen Management to CA Systems

The adoption of CA drastically modifies N dynamics compared with conventional practices. Firstly, reduced or no tillage leads to lower N release from the mineralization of soil organic matter compared to ploughing [39]. Secondly, the retention of dead plant material with a wide C:N ratio (such as cereal residues) may lead to temporary N immobilization, even when retained as surface mulch and not incorporated in the soil [40]. As a result, N stress is commonly observed early in the season in CA systems leading to depressed plant vigor and growth [41]. Indeed, in a trial conducted in Zimuto Communal Area, Zimbabwe, the chlorophyll content (the "greenness" of a maize plant is a proxy for its N status) early in the season was found to be lower for maize in the CA treatment compared to maize in the conventional treatment when fertilized in a similar way (Figure 4a). However, from about 50 days after emergence to maturity, the trend was inversed, with maize in the CA treatment having higher chlorophyll content than maize in the conventional treatment (Figure 4a). CA may not lead to an increase in the crop N demand, but it appears to affect the timing of this demand (as illustrated by the two different curves in Figure 4a), seemingly with a higher demand early in the season and a lower demand later on.

However, N is a highly mobile nutrient and its availability to the crop is affected by rainfall amount and distribution (both highly variable in Eastern and Southern Africa) as well as water dynamics (e.g., surface run-off, evaporation) making recommendations on N fertilization for crop production in general and in CA systems specifically, challenging. SPAD (Single Photon Avalanche Diode) meters could be used to monitor the crop N status, but these devices are expensive, and their wide use by extension agents and other service providers is therefore unlikely in the near future. A cheaper alternative to predict in-season crop N requirements is the use of hand-held sensors measuring the Normalized Difference Vegetation Index (NDVI) of the crop canopy [41]. The company Trimble recently designed a "pocket" hand-held NDVI sensor, commercially available for a price of about US$500 per unit (Figure 4b). Equipped with such a device, a single extension agent could advise dozens of farmers on optimal N management at any time during the cropping season [42]. Based on this assumption, CIMMYT and its partners are currently calibrating the Trimble pocket hand-held NDVI sensor for maize and wheat in various agroecologies of Eastern and Southern Africa.

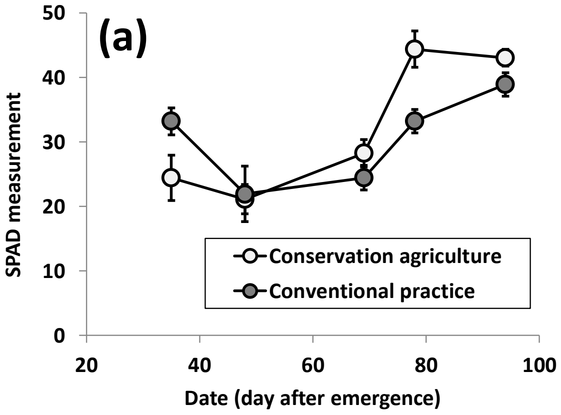

Figure 4. (**a**) Extent of SPAD (Single Photon Avalanche Diode) units–proxy of the chlorophyll content—measured on maize leaves under conventional practice and under conservation agriculture during the 2013/14 season in Zimuto, Zimbabwe (source: [43]); and (**b**) the “pocket” hand-held NDVI sensor from Trimble [44] (photo courtesy of Trimble Navigation).

3.2. Adapting Water Management to CA Systems

The adoption of CA drastically modifies soil water dynamics compared with conventional practices (e.g., infiltration, runoff, evaporation). This modification often affects crop production positively in areas where water is a major limiting factor, such as large parts of Southern Africa [45]. Elsewhere, it may have neutral or even negative consequences for crop production. Although the retention of an organic mulch generally improves water infiltration and reduces evaporation and runoff, it may also exacerbate problems of waterlogging in high rainfall areas, thus depressing plant growth [46]. Conversely, with the retention of insufficient quantities of crop residues as surface mulch, which is common in Eastern and Southern Africa where productivity is low and where there are several competing uses for crop residues [47], CA may lead to lower rainwater infiltration and lower yield, particularly on soils that are prone to crusting and compaction [48], until the physical properties of the soil are improved. This, however, can take several years.

In such contexts (negative effect of surface mulching or insufficient quantities of crop residues available for mulching), CA systems have to be adapted for the water balance to be improved and the short-term crop productivity not to be affected negatively. This can be achieved by purposefully increasing the surface rugosity in these systems. For example, CIMMYT, Mekelle University, and other partners adapted a CA system in Northern Ethiopia based on semi-permanent raised beds, reshaped every year with the traditional *maresha* plough ([9]; Figure 5a). Tef (*Eragrostic tef* (Zucc.)Trotter), a major crop in this part of Ethiopia, is a short cereal for which grain cannot be harvested without harvesting the major part of the straw as well. Thus, when the preceding crop is tef, the quantity of biomass retained as mulch is insignificant. In such cases, however, results from a long-term experiment (on a slope of 3%) demonstrate that semi-permanent raised beds reduce water runoff by more than half compared to conventional practices (Figure 5b). Similar adaptations have been made in other parts of Eastern and

Southern Africa to minimize runoff and maximize infiltration in CA systems with little or insignificant quantities of surface mulching. For example, planting basins—commonly used in hand-hoe based CA systems of Southern Africa—have been found to improve water harvesting and increase the soil moisture content compared to conventional land preparation in Zimbabwe and Zambia [49]. Similarly, through a study conducted across semi-arid areas of Ethiopia, Kenya, Tanzania and Zambia where little or no surface mulch was retained, Rockström and colleagues [50] consistently found that opening rip-lines—created by using an animal drawn modified plough or a chisel-tined ripper—increased water infiltration compared with conventional practices and led to higher maize and tef yields.

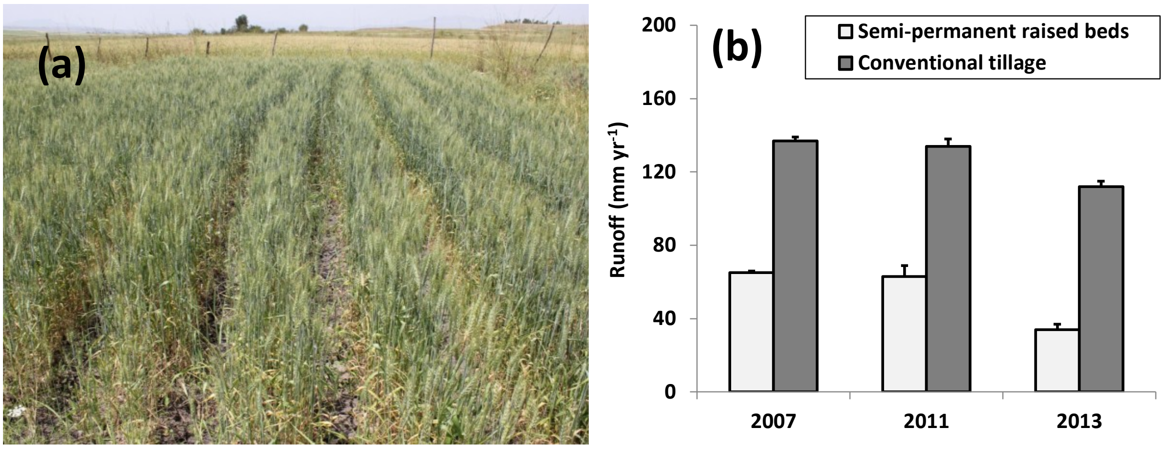

Figure 5. (**a**) Wheat planted on semi-permanent raised beds reshaped every year with the tradition *maresha* plough in Gum Selesa, Northern Ethiopia; and (**b**) cumulated runoff in 2007, 2011, and 2013 following conventional tillage and using semi-permanent raised beds in Gum Selesa, Ethiopia, with the retention of insignificant quantities of biomass in the semi-permanent raised bed as the preceding crop during these years was tef (source: [9]).

The examples above demonstrate that CA principles should only be viewed as a means to an end. It is important to focus on processes (in this case, water infiltration) rather than technologies (surface mulching). When the primary driver of CA adoption is increasing water use efficiency, increasing soil moisture is not enough: additional moisture should translate into productivity gains and/or stability. However, this is not always the case. In Southern Ethiopia, CIMMYT and the Ethiopian Institute of Agricultural Research found that CA significantly increased the quantity of soil water under sole maize at the time of harvest (Figure 6a). However, no significant difference was found in maize yield between these two treatments (Figure 6b): the extra rainwater harvested and stored in the CA treatment was not converted into extra grain. In comparison, when a legume intercrop (common bean) was included in the CA treatment, soil moisture at maize harvest time was significantly lower than in the sole maize CA treatment, implying that more soil water was used by the crops (Figure 6b), and an additional grain yield (maize and bean) of about 2 $t \cdot ha^{-1}$ was harvested.

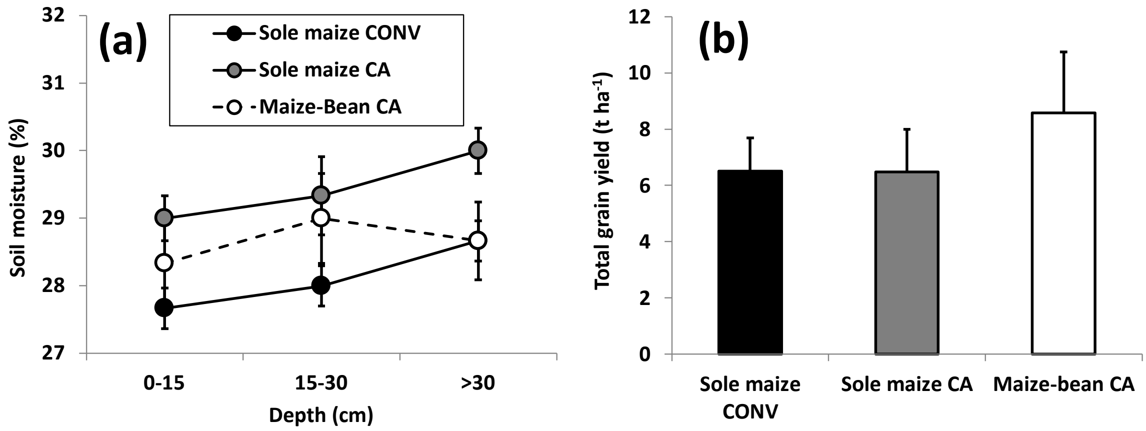

Figure 6. (**a**) Soil moisture at maize harvest; and (**b**) total grain yield (maize and bean) for sole maize under conventional practice (CONV), for sole maize under conservation agriculture (CA) and for maize-bean intercropped under conservation agriculture in 2013 in Hawassa, Ethiopia (source: [51]).

3.3. Controlling Pests in CA Systems

Stem borers are the most damaging insect pests for cereals in Africa [52]. Crop residues carry over larval populations form one season to the next. Annual crop rotation is an effective control method, but this practice is rare in most of Eastern and Southern Africa. Alternative recommended control methods involve removal, destruction or burying (through tillage) of crop residues. Therefore, the retention of crop residue as surface mulch and the suppression of tillage, two pillars of CA, may increase the population of stem borers. In Southern Ethiopia, where the stem borer species *Busseola fusca* (Fuller) is a main cause of maize yield losses, CIMMYT and Wageningen University are testing low-cost management options that stimulate the population of natural enemies of stem borers (predators and parasitoids). Through this research, perennial elements of the farming landscape—such as hedgerows and ensete (*Ensete ventriculosum* (Welw.) Cheesman) fields—have been proved to act as reservoirs of generalist predators such as rove beetles (Figure 7a) and ants (Figure 7b), as well as parasitoid wasps (data not shown).

Building on this preliminary data, CIMMYT and Wageningen University are testing various landscape configurations to advise on the design of farming landscapes that are pest suppressive, thanks to the judicious reorganization of maize fields and perennial elements, alleviating a major challenge to CA in the area. A similar approach could be used elsewhere in the region, where CA has been found to increase the abundance of certain pests, such as white grubs (larvae of *Phyllophaga* ssp. and *Heteronychus* spp.) in Mozambique and Malawi [24].

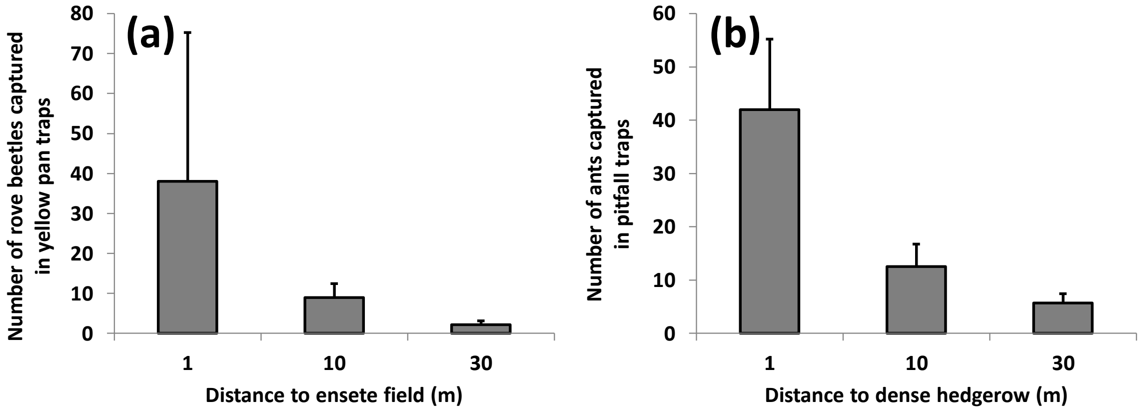

Figure 7. (**a**) Average number of rove beetles captured during a 72 h period in yellow pan traps located in maize fields 1 m, 10 m and 30 m of an ensete field; and (**b**) average number of ants captured during a 72 h period in pitfall traps located in maize fields 1 m, 10 m, and 30 m of a dense hedgerow (Source: [53]).

3.4. Sharing Biomass in CA Systems

Competition between soil mulching and livestock feeding has been stated as one of the main challenges to CA implementation in Africa, which is dominated by mixed crop-livestock systems [47]. Although CA systems can be adapted to perform satisfactorily—in the short-term—with minimum quantity of residue retained as mulch (see Section 3.2), regular inputs of organic material are needed in the long-term to maintain soil organic matter. As animal manures and plant biomass (other than crop residue) are both scarce and bulky (their collection, transport and application are labor-intensive, constraining their use as amendment), and as crop residues represent the most abundant organic material available to farmers [54] while their retention *in situ* does not require any labor, solutions have to be devised for crop residues to be shared—in the long-term—between the livestock and the soil.

CIMMYT and the University of Addis Ababa have recently analyzed an example of collective action where a community implemented farmland exclosure *i.e.*, the application of year-round zero-grazing in farmland [55]). The implementation of this institutional (rather than technological) innovation resulted in more standing biomass in the farmland, in the form of trees (and grass on the contours to a lesser extent). Thus, more tree biomass could be used as livestock feed (Figure 8a), releasing significant crop residues to be retained in the field: the proportion of crop residue retained in the fields within the farmland exclosure was double that in neighboring fields open to aftermath grazing (Figure 8b), after eight years of implementation of farmland exclosure. Moreover, because more wood was available, livestock dung was less used as fuel and more as soil amendment. Compared with the neighboring farmland open to aftermath grazing, the soil organic matter content in the topsoil was almost double in the farmland exclosure, and the mean tef yield was about 70% higher. Interestingly, these shifts in biomass utilization did not affect negatively livestock density and productivity, which both remained similar inside and outside the farmland exclosure.

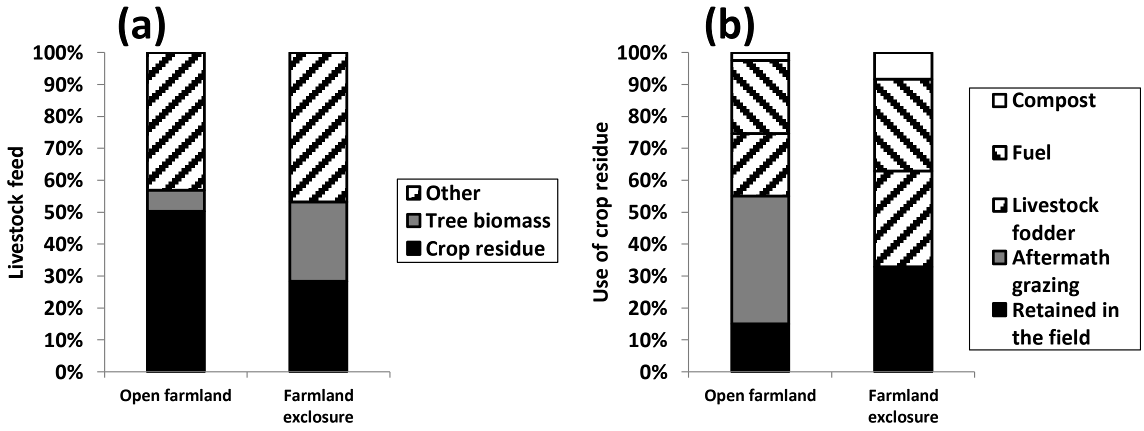

Figure 8. (**a**) Composition of the biomass fed to livestock in open farmland (*i.e.*, subject to aftermath grazing) and in farmland exclosure (*i.e.*, where livestock is excluded throughout the year); and (**b**) distribution of crop residue by use in farms in open farmland and in farmland exclosure (source: [55]).

This example illustrates that competition for crop residues in mixed crop-livestock systems is not a barrier to the adoption of CA, but a challenge that can be overcome through appropriate interventions, such as farmland exclosure. Baudron and colleagues [56] and Mupangwa and Thierfelder [57] have highlighted a number of additional interventions that can reduce crop residue tradeoffs for African smallholders and concluded that the question should not be "if", but "how" crop residues can fulfill the need of both the soil and the livestock.

4. The Need for an Iterative, Multi-Scale Approach

The four cases above (Section 3) illustrate the importance of focusing on processes (e.g., N dynamic, water infiltration, dynamics of pests and their natural enemies, impact of grazing) rather than technologies (e.g., reduced or no tillage, surface mulching). In Eastern and Southern Africa, CA has too often been promoted as a goal in itself, and too rarely as a means to an end (and when it did, it was often promoted as a means to the wrong end, such as the promotion of CA to increase yields, which inevitably takes 2–5 cropping seasons until a significant yield benefit is observed, Thierfelder and colleagues [58] except where water is a major limiting factor or where delayed planting leads to severe yield penalties). The success or failure of CA interventions should not be measured by the intensity of tillage or by the quantity of surface mulch in the target area, but by the impact of the intervention on e.g., cost of production, erosion control and water productivity. This implies that attention should be placed on understanding who the target groups ("clients" of the innovation) are, and what their demand is (e.g., performance, cost, labor demand), similarly to the design-specification process used in the industrial and commercial sectors [6].

The four cases also illustrate the importance of an iterative approach. As biophysical processes are being modified by the adoption of CA, new challenges emerge (e.g., buildup of the populations of residue-borne pests, see Section 3.3) as well as new opportunities (e.g., additional available soil moisture, see Section 3.2), both calling for the adoption of new innovations (e.g., stimulation of the populations of natural enemies of pests, inclusion of an additional crop to increase rainwater productivity), which in turn bring additional challenges and opportunities. This calls for mechanisms to enable interaction, collective learning and adaptive management between farmers and other stakeholders who are key to bring about the desired change (e.g., private sector, development institutions, extension services, and local policy makers). This can be provided by multi-stakeholder innovation platforms, which have become increasingly popular in agricultural R&D [59].

The four cases above also illustrate the importance of a multi-scale approach (Sections 3.1 and 3.2 describe processes at plot-scale, Section 3.3 describes a process at farm-scale and Section 3.4 describes a process at landscape-scale). Processes at a given scale both control and are controlled by higher scaled processes (*i.e.*, "panarchy"; [60]). For example, pest control at farm-level is an emerging property arising from nurturing natural enemies in some patches of the farm (see Section 3.3). Conversely, residue retention in a given plot is conditioned by grazing arrangement at landscape-level (see Section 3.4). This implies that research needs to target each of these scales with adequate approaches and methods. We see the role of research at plot-level as designing (and re-designing) innovative systems; at farm-level as adapting to the local socio-ecological context of different farm types; and at landscape/community level as accompanying scaling-out/up (Figure 9). Below, we describe each of these iterative steps, as used by CIMMYT and its partners in Eastern and Southern Africa.

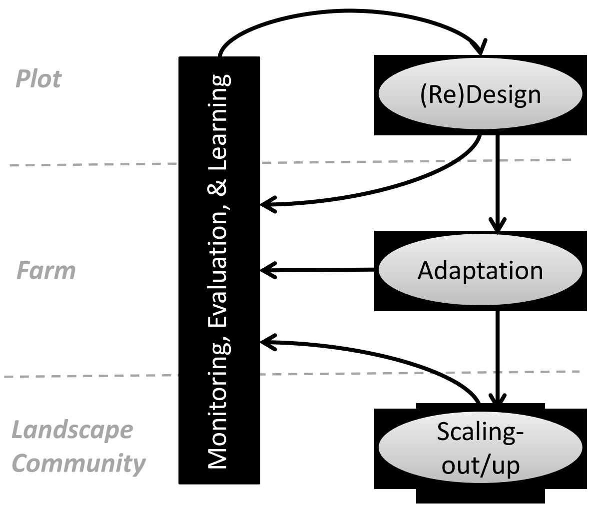

Figure 9. Schematic representation of a proposed iterative and multi-scale research and development approach for conservation agriculture and other complex combinations of technologies aiming at sustainable intensification.

Design. Following a diagnostic conducted within the multi-stakeholder innovation platform, and highlighting constraints and opportunities of the current farming systems, specifications of the desired innovation should be spelt out (e.g., performance, cost, labor demand, skills needed). Researchers may then design new systems, based in these specifications, their expertise and experience and knowledge from other locations (innovation *de novo*, [61]). The point here is to enable researchers to express their creativity, and generate a diversity of systems that meet the specifications and perform well from a biophysical point of view, before "fusing" academic knowledge with local knowledge. For such fusion to take place, we feel it is important for researchers to first "make an offer" of technological innovations and demonstrate these innovations in controlled environments. Confronting academic and local knowledge too early could limit the "creativity" of researchers (participatory "lock in"): broadening the range of what is possible is a fundamental role of research. Controlled environment (such as in on-farm experiments) also allow for detailed measurements to be taken, in order to better understand underlying mechanisms (e.g., nutrient dynamics, soil biology). Data on these processes can also be used for the calibration of mechanistic models and run "virtual experiments" [62]. It is also useful for these trials in controlled environment to be run as long-term ones, for biophysical constraints to be identified in the trials before they occur on adopting farms, and for effective anticipation of challenges.

Adaptation. The farm-scale is a critical scale for R&D, as this is the scale at which decisions (in terms of adoption and resource allocation) are made. It is also the scale where innovative systems are being adapted through co-construction between academic and local knowledge [61]. Besides studying this process of adaptation and what Brown [63] has described as "*fusion knowledge*, *neither strictly local or traditional, nor external or scientific*", the role of research in this phase is to understand how innovative cropping systems fit in existing farming systems. Tradeoffs are conspicuous in African smallholder farms, which are generally resource-constrained. Understanding how the adoption of CA modifies these trade-offs is thus fundamental (e.g., [64]). Understanding the way farmers combine different technologies [65] and the sequence of this adoption (described as a "ladder" by Aune and Bationo [66]) is another research area of prime importance at this scale. The question of which farms to work with is a crucial one. Ensuring that the selected farms are representative of the overall population is important for the sake of replicability, and this can be achieved by selecting a stratified sample of farms based on a typology of farms. Typologies have become "fashionable" in the recent few years and various methodologies, all with their strengths and their weaknesses, are commonly used to delineate typologies, from (quantitative) statistical methods [67] to (qualitative) participatory methods involving experts and farmers [68]. Working with "positive deviants" [69], who would be described as "statistical outliers" for a particular farm type, could yield additional insight.

Scaling-up/-out. Ultimately, adoption of innovations "at scale" is the goal of any R&D intervention. "Scaling-out" is the spread of the innovation from farmer to farmer, within a particular landscape, while "scaling-up" is the institutional expansion that accompanies the geographical spread of the innovation [70]. Scaling-out/up is relatively downstream on the R&D continuum. Nonetheless, research has a crucial role to play in this phase, to serve as a catalyst for and to better understand the social processes that accompany the spread of innovation, and to propose interventions within multi-stakeholder innovation platforms that foster collective action (see Section 3.4 for example) and new partnerships (e.g., with the private sector). In addition, new research questions arise from the change of scale (related to e.g., delivery systems of inputs, enabling policies and institution), what Coe and colleagues [71] call research "in" development.

Monitoring, *Evaluation and Learning*. The iterative approach depicted on Figure 9 calls for a continuous monitoring and evaluation of the innovations being designed, adapted and scaled out/up, and a continuous learning. Multi-stakeholder innovation platforms are well designed for such process, which must be markedly participatory. The process should also be multi-scale–as what makes the best resource management within a CA system (e.g., allocation of crop residue to soil mulching *vs.* livestock feeding) depends on the scale at which trade-offs are analyzed [64]—and multi-criteria, to capture the economic, environmental and social dimensions of CA. The MESMIS (Spanish acronym of the Framework for Assessing the Sustainability of Natural Resource management Systems) offers an interesting framework to achieve such a multi-scale and multi-criteria monitoring and evaluation [72]. MESMIS is designed to evaluate the performance of complex systems in an interdisciplinary and participatory manner. It is primarily a tool for system re-design that has been well tested in developing countries. It is also purposefully designed for cyclic processes such as the one proposed here (Figure 9). The cycle includes six steps, with the first three steps aiming at characterizing the system and the last three steps aiming at integrating information and making a decision about the management of the system: (1) definition of the evaluation object; (2) determination of the critical points; (3) selection of diagnostic criteria and indicators; (4) measurement and monitoring of indicators; (5) presentation of results; and (6) conclusions and recommendations.

5. Conclusions

Delineating the niche where CA fits in African smallholder farming systems has become a burning issue. We argue that previous studies focusing on the topic have offered limited insights and may have approached CA from the wrong angle. They assumed CA to increase yield in the short-term (which only occurs in rare cases: where yields are strongly limited by water or where delayed planting leads to severe yield penalties) and confused challenges to CA (for which R&D can offer solution) for being barriers to adoption. When understanding CA as being an energy-saving, erosion-controlling, and water use efficient set of principles, the niche where CA fits in Eastern and Southern Africa appears large, and increasing. We recognize the low adoption of CA in the region, but argue that it may be more the result of poor targeting than of the unsuitability of CA for farmers in the region. However, applying CA in any part of this niche requires local adaptation, which can be achieved through multi-stakeholder innovation platforms, supported by an iterative, multi-scale R&D approach as described in this paper.

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Author Contributions

The original idea of the paper was the first author's. All authors contributed data and contributed to the writing of the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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