Chapitre I

Une option *climate-smart* pour l'agriculture familiale ?

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Synthèse

Introduction

Le changement climatique (CC) fait aujourd'hui consensus au sein de la communauté scientifique, et l'agriculture est la première cause de l'enrichissement de l'atmosphère en méthane et en protoxyde d'azote. Dans ce contexte, l'Afrique sub-Saharienne (ASS) doit augmenter sa production agricole de 77% pour répondre aux besoins alimentaires de sa population d'ici 2050. Il est donc primordial de développer une agriculture *climate-smart*, basée sur trois piliers définis par la FAO : (i) augmenter durablement la productivité agricole, (ii) atténuer le CC et (iii) s'adapter au CC. Une recherche du terme '*climate-smart agriculture*' (CSA) dans la littérature scientifique nous a permis d'identifier huit études depuis 2012 : Trois études restreignent la définition à un seul pilier ; les quatre autres utilisent la définition complète. Dans cette étude, nous nous cantonnons à la définition de la FAO.

L'agriculture de conservation (AC), telle que définie par la FAO, suit les trois principes de (i) travail minimal du sol, (ii) couverture permanente et (iii) rotations. Afin de palier au problème de perte de fertilité des sols et de baisse de production en agriculture familiale en ASS, les systèmes en AC sont aujourd'hui diffusés à grande échelle à travers des projets de développement. Cette technologie a pour but d'apporter des effets agronomiques, économiques, environnementaux et sociaux positifs ; et se traduit par un éventail des systèmes de cultures dans la littérature. Dans cette étude, nous considérons comme AC tout système, dès lors qu'il respecte, au moins, le principe de travail minimum du sol.

L'objectif de cette étude est d'évaluer dans quelles mesures l'AC peut être considérée comme une option CSA pour l'agriculture familiale en ASS, en alternative aux systèmes traditionnels sur labours. Nous avons donc cherché des indices dans la littérature scientifique pour comprendre comment l'AC peut répondre aux trois piliers de CSA.

Approche méthodologique

Accroître durablement la productivité est un objectif commun à tous les projets de développement agricole dans les contextes contraints de l'agriculture familiale. L'impact de l'AC sur les rendements en ASS a fait l'objet de plusieurs revues, relatant un manque de données, une efficacité de l'AC sur le long-terme mais des résultats mitigés sur le court-terme. En se basant sur les études à long-terme (plus de 5 ans) recensées dans la méta-analyse de Corbeels et al. (2014), nous avons tenté de compléter ces résultats. Nous avons aussi identifié les études qui analysent les impacts économiques de l'AC dans les exploitations familiales en ASS.

Le non-labour et la conservation de mulch organique en AC peuvent modifier les propriétés physiques, chimiques et biologiques du sol ; ce qui peut alors modifier la respiration du sol et donc les émissions directs de CO_2, CH_4 et N_2O. Nous avons donc retenu les études qui relatent l'impact de l'AC sur les émissions de gaz à effet de serre. Les sols cultivés sont aussi considérés comme des puits potentiels de carbone (C) et l'AC comme un moyen de compenser le CC par une séquestration de ce C dans le sol. Nous avons donc retenus les études qui décrivent l'impact de l'AC sur le C du sol en ASS.

S'adapter au CC signifie s'adapter à des changements de température, de concentration on CO_2 dans l'atmosphère et de régime pluviométrique. En ASS, on prévoit jusqu'à 2°C d'augmentation de température pour ce siècle et une augmentation en fréquence et en intensité des évènements pluvieux extrêmes. On peut supposer qu'au fil des années, les programmes de recherche et de sélection variétale permettront de proposer des cultivars qui soient adaptés à ces changements. Mais l'efficacité réside aussi dans la combinaison avec pratiques agricoles adaptées. Dans le cas de l'AC, le mulch permet de diminuer le ruissellement ; ce qui est envisagé comme moyen efficace pour tamponner le stress hydrique et faire face au changement pluviométrique annoncé en ASS. Nous avons donc tenté de vérifier cette capacité de l'AC en se basant sur les études retenues par Corbeels et al. (2014).

Augmentation durable de la productivité

D'après les études que nous avons identifiées, il semble que l'AC ait la capacité d'augmenter les rendements. Ceci est du, sur le long-terme, à un accroissement de la fertilité du sol, notamment grâce à la rétention d'un mulch de matière organique. Il semble aussi que l'impact sur les rendements soit d'autant plus rapide que les conditions hydriques sont limitantes. Ces résultats sont donc en accord avec les trois revues de la littérature. D'un point de vu économique, parmi les 12 études retenues, nous avons observé des résultats contrastés. Certaines études observent un impact positif de l'AC lié à l'augmentation des rendements ou une diminution de la charge de travail. D'autres relatent un impact négatif lié aux coûts des intrants, à l'absence de marché pour les nouvelles cultures introduites, ou encore à la diminution des rendements la première année de transition vers l'AC.

Atténuation du changement climatique

L'impact de l'AC sur les émissions directes de gaz à effet de serre est très peu renseigné dans la littérature scientifique. Les résultats préliminaires, souvent mesurés en laboratoire, sont contradictoires et toutes les études s'accordent sur la nécessité de mettre en place des dispositifs à plus large échelle pour une variété de cultures afin de mieux cerner les impacts potentiels de l'AC. Au sujet de la séquestration du C dans les sols, les études identifiées en ASS rejoignent les conclusions des revues scientifiques faites par ailleurs. Le stockage du carbone se fait essentiellement dans les couches superficielles du sol, i.e. les 30 premiers centimètres. La stabilité de ce carbone est donc questionnée : peut-on envisager une séquestration durable du carbone étant données les pratiques agricoles actuelles et notamment le retour occasionnel au labour pour diverses raisons ?

Adaptation au changement climatique

Les études recensées suggèrent qu'il y a un seuil aux alentours de 900-1000 mm de pluviométrie annuelle. En dessous de ce seuil, l'AC semble mieux exprimer son potentiel et augment les rendements alors qu'au-delà les rendements sont inchangés voire diminués, en moyenne. Seulement, certaines études suggèrent que l'impact de l'AC sur les rendements ne dépend pas nécessairement de la quantité totale mais plutôt la distribution des pluies. Ainsi, dans un contexte aléatoire, l'AC semble permettre une sécurisation des semis et de la levée, et une diminution du stress hydrique pendant la croissance.

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Si la capacité de l'AC à participer au pilier 'atténuation du CC' reste à creuser dans le contexte de l'ASS, nous avons vu au travers de différentes études que l'AC peut augmenter la productivité et peut s'adapter au CC. Ce potentiel de l'AC est essentiellement assuré par le maintien d'un mulch organique sur la surface des sols cultivés. Seulement, notre étude montre que l'impact de l'AC est extrêmement dépendent des conditions agro-environnementales et socio-économiques. Or, les zones agroécologiques où l'AC peut exprimer tout son potentiel sont des zones où l'une des difficultés majeures est de produire suffisamment de biomasse pour maintenir un mulch, et la compétition avec l'élevage est importante. Cela ouvre donc vers une problématique plus large : l'AC, définie par ses trois principes, est-elle réellement adaptée aux contextes africains limités en ressources ? Ne faut-il pas proposer des systèmes plus adaptés ?

1. Introduction

1.1. Climate-smart agriculture

Today, climate change is a fact which gathers consensus among the scientific community. It is generally believed that humans are causing most of it through activities that increase concentrations of greenhouse gases (GHG). Agriculture has been identified to be the primary cause of global increases in methane and nitrous oxide concentrations in the atmosphere (IPCC et al., 2013). In this context of climate change, developing countries face the challenge of achieving food security. It is estimated that agricultural production has to increase by 77% to meet the food demands by 2050 (Alexandratos and Bruinsma, 2012). Thus, there is an imperative need to develop an agriculture that simultaneously mitigates GHG emissions and adapts to climate change in order to sustainably enhance production. In addressing both food security and climate change challenges, the concept of climate-smart agriculture (CSA) recently emerged at the Hague Conference on Agriculture, Food Security and Climate Change (FAO, 2010). CSA aims to contribute to the achievement of sustainable development goals and integrates the three, economic, social, and environmental, dimensions of sustainable development. CSA is composed of three main pillars (FAO, 2013): (i) sustainably increasing agricultural productivity; (ii) reducing or removing GHG emissions; and (iii) adapting and building resilience to climate change. Launching a search on the online Scopus database (Elsevier B.V., 2014. http://www.scopus.com/), we found eight peer-reviewed articles using the concept of 'climate-smart agriculture'. Three studies have narrowed down the definition of CSA to one particular aspect of the concept. Buysman and Mol (2013) and Ahmed et al. (2013) defined CSA as practices that reduce GHG emissions; and Xiong et al. (2014) defined it as an optimal match of cultivars and management to climate in order to obtain the highest attainable yield. The remaining studies have used the concept in its wholeness (Harvey et al., 2014; Nyamadzawo et al., 2014; Schroth et al., 2014; Siedenburg et al., 2012; Singh, 2012). In this study, we adhere the FAO definition of CSA.

1.2. Conservation agriculture

The FAO (2014) defines conservation agriculture (CA) as crop cultivation that follows the three principles of (i) minimal soil disturbance, (ii) permanent soil cover, and (iii) crop rotations. In sub-Saharan Africa (SSA), CA has been widely promoted and disseminated through development projects to address the productivity depletion in smallholder farming systems. This technology is expected to provide agronomic, economic, environmental, and social benefits. A large variety of cropping systems are referred to as CA in the literature. In this paper, we adopted a broad definition of CA including all cropping systems labeled as CA as long as they apply, at least, the principle of minimal soil disturbance.

Table 1: Literature search methods

Literature search methods to assess the adequacy of conservation agriculture to the three climate-smart agriculture pillars in peer-reviewed literature

CSA pillar	CA objectives	Data source	Keywords (within title, keywords and abstract sections)	Screening criteria (studies must meet all the listed conditions)	Number of studies
Sustainable increase in productivity	Increase in yield	Corbeels et al. (2014)		(i) study duration ≥ 5 years	7
	Increase in income	Scopus online database	[‘conservation agriculture’ or ‘no till*’ or ‘zero till*’ or ‘minimum till*’ or ‘mulch’] and [‘livelihood’ or ‘income’ or ‘revenue’ or ‘cash’ or ‘economic*’]	(i) located in sub-Saharan Africa (SSA) (ii) economic data (margin, income, return, …) (iii) comparison to conventional treatment	12
Climate change mitigation	reduction of GHG emissions	Scopus online database	[‘conservation agriculture’ or ‘no till*’ or ‘zero till*’ or ‘minimum till*’ or ‘mulch’] and [‘co2’ or ‘n2o’ or ‘ch4’]	(i) located in SSA (ii) data on CO_2, CH_4, or N_2O emissions (iii) comparison to conventional treatment	5
	Increase in soil carbon sequestration	Scopus online database	[‘conservation agriculture’ or ‘no till*’ or ‘zero till*’ or ‘minimum till*’ or ‘mulch’] and [‘mitigation’ or ‘greenhouse’ or ‘co2’ or ‘carbon’ or ‘sequestration’]	(i) located in SSA (ii) data on soil carbon content (iii) comparison to conventional treatment	27
Climate change adaptation	Water stress buffering	Corbeels et al. (2014)		(i) data on total seasonal rainfall (ii) data on yield for each season	29

1.3. Aim and scope of this study

The objective of this study is to evaluate CA as a potential climate-smart option for smallholder farmers in SSA, finding evidence in the peer-reviewed literature about the capacity of CA, as compared to conventional tillage-based farming (CV), to meet the requirements of each pillar of CSA. We first assessed the extent to which CA can sustainably increase agricultural productivity, this pillar being the primary goal of CA dissemination in SSA. We then evaluated the capacity of CA to mitigate climate change, and to adapt to climate change, these two pillars being the very core of the CSA concept.

2. Approach

Theoretically CA aims to improve crop productivity through the enhancement of ecological, agronomic and management functions (Figure 4). While this main objective of CA is completely in line with the first pillar of CSA, it may also contribute to the objectives of the two other 'climate change' pillars of CSA. The expected beneficial functions resulting from the combination of the three principles of CA are intertwined and, hence, the objectives are expected to be achieved simultaneously. However, for an ease of understanding and to remain consistent throughout the study, we focused on each objective independently. Thus, our literature search was organized as presented in Table 1, systematically comparing CA with CV practice.

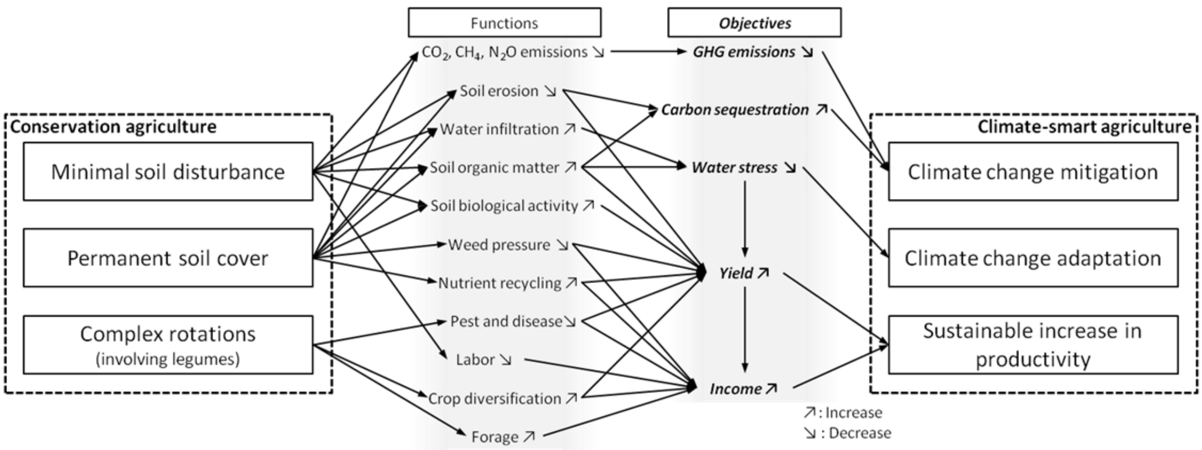

Figure 4: Conservation agriculture & climate-smart agriculture
Diagram showing the adequacy of the potential functions of conservation agriculture in meeting the objectives of climate-smart agriculture (original scheme inspired from literature review and K. Naudin Ph.D. thesis)

2.1. Sustainable increase in productivity

In the low-productive context of smallholder farming, crop yield improvement is often the first objective when implementing an innovative agricultural technology or cropping system. The ability of the new technology to achieve this objective is a major criterion for farmers' adoption. For CA, the impact on yield has been the topic in recent reviews. . Giller et al. (2009) reported the lack of empirical evidence for clear positive impacts of CA on crop yields in the resource-constrained contexts of smallholder farming in SSA. The authors concluded that, in the short-term yield losses or no yield benefits were just as likely, whilst yield benefits were observed in the long-term, although it may take up to 10 years to achieve this. In a meta-analysis of maize yield responses to CA under sub-humid and semi-arid conditions worldwide, Rusinamhodzi et al. (2011) confirmed the increase in yield under CA compared to that of CV in the long-term, specifying the importance of soil texture and rainfall conditions. Recently, Brouder and Gomez-Macpherson (2014) published a scoping review of the impact of CA on yields in smallholder farming systems in SSA and south Asia. They pointed out the need to set up well-designed experiments to allow making strong general conclusions about benefits of CA. Their review of empirical CA studies also suggested that short-term impact of CA on yield compared to that of CV was null or even negative, but a positive long-term impact could be observed, particularly if a mulch of crop residues is maintained on the soil surface. In our study we used the published CA studies that were retrieved in the in the meta-analysis of crop responses to CA in SSA by Corbeels et al. (2014) and selected the longer term studies (five years and more) to verify whether a positive trend in crop yields could be observed under CA as compared to the yields under CV.

The implementation of CA into smallholder production systems may increase crop yields but also farm income (Corbeels et al., 2014a). Shifting from CV to CA involves changes in farm organization, labor allocation, and input uses at farm level which may lead to a better – or not – economic return of investment (Pannell et al., 2014). To verify this, we ran a literature search on the online Scopus database to assess the economic changes related to the implementation of CA in SSA, comparing economic output of CA and CV systems.

2.2. Climate change mitigation

Through reduced tillage and residue conservation, CA practices modify soil physical, chemical and biological properties. These changes may alter soil respiration, and hence soil CO_2, CH_4, and N_2O direct emissions. Thus, we ran a literature search on the online Scopus database to assess the extent to which CA soil direct GHG emissions in SSA. This aspect being poorly documented, we directly transcribed the main results as reported in each study.

Agricultural soils are a potential sink for carbon (C) (Bernoux et al., 2006; Lal, 2004; Paustian et al., 1997). The original interest in CA was related to its potential to conserve soil and to enhance soil fertility by reducing soil erosion, soil organic matter decline and soil structural breakdown. Since then, CA has increasingly been endorsed as a practice to mitigate climate change through its potential to sequester soil carbon. Several studies have been conducted in SSA to assess the potential of CA to sequestrate soil C and increase soil fertility. We ran an extensive search focusing on the impact of CA on soil C sequestration, comparing CA with CV. For each study, we calculated the C gain in favor of CA treatment at a given soil depth as the difference between the average C content under CA and CV treatment at the end of the experiment. The C gain was only calculated when differences in C content were significant. When more than two CA systems were compared to CV, we only considered the CA system which applies the maximum CA principles.

2.3. Adaptation to climate change

Climate change will principally affect agricultural production through three main processes: (i) temperature changes; (ii) changes in atmosphere GHG concentration; and (iii) changes in precipitation, i.e. length, amounts, and distribution of rainfall. While there is consensus that temperature and CO_2 concentrations will continue to increase during the 21st century, projections regarding length, total rainfall amounts, or distribution of the rainy season are highly variable and uncertain (IPCC et al., 2013). In SSA, climate projections indicate a maximum global warming of 2°C at the end of the century and they suggest steady total seasonal rainfalls but a delay of the onset of the rainy season and an increase in intensity and frequency of extreme events such as drought or heavy rainfall during the rainy season. An increase in temperature would lead to a shortening of cropping cycle and, hence, a decrease in productivity in most of the cropping system x environment scenarios in SSA (Shrestha et al., 2012). However, it is likely that breeding programs will evolve along with the change in climate, supplying varieties adapted to higher temperature. Regarding the changes in rainfall regimes, breeding can also provide varieties less sensitive to water stress (Bänziger et al., 2006). However, it will be important to combine agronomic management with crop-breeding improvements (Tittonell and Giller, 2013). CA's major potential to mitigate negative effects of climate change lies in the conservation of soil water as a result of mulching. We chose to focus on impact of the CA systems on yield under contrasting rainfall conditions, bearing in mind that the rainfall distribution within the rainy season, and the onset of the rainy season are predicted to change in the future. Thus, comparisons between current contrasted rainfall distributions may help evaluating the potential of CA as regard the projected rainfall changes in SSA.

We based our review on the published studies reported in the meta-analysis of crop responses to CA in SSA by Corbeels et al. (2014). For each study, we calculated the yield response to CA as the difference between the yield under CA and CV treatment for a given fertilization level and rainy season. The yield response was only calculated when yield differences were significant. When more than two CA systems were compared to CV, we only considered the CA system that includes the maximum CA principles.

Table 2: Conservation agriculture & economics

List of the 12 peer-reviewed articles measuring economic benefits of conservation agriculture (CA) as compared to conventional agriculture (CV) in sub-Saharan Africa

Ref.	Location	Duration (Years)	Cropping system	Tillage	Soil cover	Conservation agriculture			Economic indicator	Unit	Under CV	Under CA
						P1	P2	P3				
1	Ghana	7	M	CV; NT		**X**			Net benefit	US \$ ha^{-1}	73 88 63	521 344 159
2	Cameroon	3	IR	CV; NT		**X**			Labor costs	US \$ ha^{-1}	290	577
3	Nigeria	5	M	CV; NT	RRt; RI	**X**	**X**		Relative costs	ha^{-1} kg^{-1}	1 1	~1.7 ~5
4	Ghana	2	M; S	CV; NT		**X**			Net return	US \$ $acre^{-1}$		NS
5	Kenya	2	M/S	CV; MT		**X**			Net benefits	US \$	48 1136 -51 914	-620 1783 703 2990
6	South Africa	13	M	CV; MT; NT		**X**			Mean return	R ha^{-1}	1680	1814
7	Malawi	3	M; M/Pp	CV; NT	RI; RRt	**X**	**X**		Gross margin	US \$ ha^{-1}	344	705
8	Malawi	6	M; M/Pp	CV; NT	RRm; RRt; RI	**X**	**X**		Net return	US \$ ha^{-1}	130 670	497 822
9	Burkina Faso	2	Sg	CV; NT	RRt	**X**	**X**		Economic benefit	€ ha^{-1}	32 151 66 -66	95 92 30 -59
10	Zambia	4	M; x/M; x/y/M	CV; NT	RRm; RRt	**X**	**X**	**X**	Gross margin	US \$ ha^{-1}	~800 ~720 ~480 ~420	~600 ~520 ~550 ~350
11	Ethiopia	2	T	CV; MT; NT		**X**			Gross margin	Birr ha^{-1}	1374 1319	-108 520
12	Zambia	4		CV; MT; NT		**X**			Gross margin	10^3 ZMK ha^{-1}	-270	2213

Ref : 1: (Aflakpui et al., 2007); 2: (Ambassa-Kiki et al., 1996); 3: (Anazodo et al., 1991); 4: (Dalton et al., 2014); 5: (Guto et al., 2011); 6: (Lawrance et al., 1999); 7: (Ngwira et al., 2012a); 8: (Ngwira et al., 2013); 9: (Elisée Ouédraogo et al., 2007); 10: (Thierfelder et al., 2013a); 11: (Tulema et al., 2008); 12: (Umar et al., 2012).

Cropping systems: /: crop succession; IR: Irrigated rice; M: Maize; Pp: Pigeonpea; S: Soybean; Sg: Sorghum; T: Tef; x and y: other crops.

Tillage: CV: Conventional tillage; MT: Minimum tillage; NT: No-tillage.

Soil cover: RI: Residue incorporation; RRm: Residue removal; RRt: Residue retention.

Conservation agriculture: P1: Minimal soil disturbance; P2: Permanent soil cover; P3: crop rotations with legumes.

Under CA: NS: Non-significant difference with CV.

~: graph estimates.

3. Sustainably increasing crop productivity

3.1. Long-term impact on yield

Variable results were observed among the seven studies reporting paired CV-CA comparisons for five years or more. Four studies observed positive impact of CA on yield. While Lal (1995) did not notice any trend along the years of CA practice but immediate increase in yield, Araya et al. (2012) and Osuji (1984) observed beneficial effect of CA after five years of application, attributing the yield improvement to the aggradation of soil fertility under CA through the enhancement of soil physical, chemical, and biological properties. Comparing contrasted agroecological zones of Zimbabwe, Thierfelder and Wall (2012) specified that beneficial impact of CA would appear sooner if soil moisture is a limiting factor for crop growth and later under non water-stressed environments because of the slow aggradation of soil fertility. The three other studies did not come to the same conclusions. In a Nigerian savannah area, Anazodo et al. (1991) observed lower yields under no-till because of soil strength, limited root development, aeration issues and weed pressure. In sub-humid western Kenya, Paul et al. (2013) did not observe significant yield difference because of limited water stress in the studied region. In Ethiopian Highlands, Erkossa et al. (2006) concluded that the appropriate land preparation method depended on the crop and a six year experimentation was not long enough to draw any conclusion.

Our results are in line with the findings of three earlier reviews (Brouder and Gomez-Macpherson, 2014; Giller et al., 2009; Rusinamhodzi et al., 2011). CA has the potential to sustainably increase crop yields mainly due to the increase in soil fertility over time. The long-term improvement of soil fertility is principally attributed to the retention of mulch on the soil surface. Climate conditions are, however, also key determinants of the time required to observe beneficial impact of CA on yield. For instance, in a water-limited context, CA alleviates the soil water stress constraint and allows an immediate increase in yield.

3.2. Economic impact

We extracted 26 paired CV-CA comparisons of economic data from 12 studies on smallholder farming in SSA. Among these comparisons 8, 1, and 17 reported respectively negative, null, and positive higher economic benefits under CA than under CV (Table 2).

Higher economic benefits under CA were mainly due to either a decrease in labor (Ambassa-Kiki et al., 1996; Anazodo et al., 1991; Ngwira et al., 2013, 2012a) or an increase in yield without significantly changing production costs (Aflakpui et al., 2007; Guto et al., 2011; Lawrance et al., 1999; Elisée Ouédraogo et al., 2007; Umar et al., 2012). The decrease in labor was observed regardless the type of farming (hand-based, animal-drawn or mechanized). The increases in yield were attributed to different factors: in Ghana, demonstration plots were considered to be more carefully managed than farmers' plots (Aflakpui et al., 2007); in South Africa, CA plots were more responsive to fungicides (Lawrance et al., 1999); and in Burkina Faso, CA plots allowed better water conservation (Elisée Ouédraogo et al., 2007)

Lower economic benefits under CA were caused by different factors. In Zambia, the decrease in gross margin under CA was due to the introduction of cotton and sunnhemp into the rotation with maize (Thierfelder et al., 2013a). The first crop yielded less than maize for the same sale price, and the second crop did not allow any economic return because of the absence of market for sunnhemp seed. In Ethiopia, zero-tillage resulted in lower gross margin because of an high increase in labor for hand-weeding (Tulema et al., 2008). In Ghana, net return difference between CV and CA depended on yields and herbicide prices (Dalton et al., 2014). While CA reduced by half the costs of land preparation, it was compensated by a decrease in yield or an increase in herbicide costs during the two years of the experiment. In the short-term, it resulted in no significant economic difference between CV and CA.

4. Mitigating climate change

4.1. Greenhouse gas emissions

Very little results on CA impacts on GHG emission have been reported in the peer-reviewed literature in SSA (Table 1). In the highlands of Madagascar, Rabenarivo et al. (2014) indicated that mulching increased CO_2 emission but reduced N_2O emissions because of N immobilization. In the same region, Baudoin et al. (2009) observed an increase in N_2O fluxes under CA in the short-term because of anaerobic conditions due to the increase in soil water content, but Chapuis-Lardy et al. (2009) did not observed significant N_2O emissions differences between CV and CA treatments over the whole cropping season. In a humid savanna zone of the Ivory Coast, Koné et al. (2008) observed an increase in CO_2 emissions under maize cropping with legume cover crops as compared to conventional cropping. In the western Kenya Highlands, Baggs et al. (2006) observed an increase in CO_2 and N_2O emissions in the short-term, depending on the nitrogen and lignin contents of the residue, but a decrease in N_2O emissions under no-tillage without significant changes in CO_2 or CH_4 emissions. No general conclusion can be drawn from these results, and the five studies agreed on the necessity to run experiments on longer-term and larger-scale to encompass the variability of soil and crop types in SSA.

4.2. Soil carbon sequestration

We found 27 studies that report data on soil C contents comparing CV and CA treatments in SSA (Table 1). Among the large variety of crop species, crop rotations, tillage types, and soil cover management, we identify the potential of CA to increase the soil C content in the top layer (Table 3), reaching a maximum increase in C concentration of 10.5 g kg^{-1} at the 0-10 cm depth after 3 years, depending on the cover crop species (Lal et al., 1978). Below 20 cm depth, the few reported evidence suggested that CA slightly enhanced soil C content, and it could even reduce C content as observed by Loke et al. (2012) in South Africa with a maximum C depletion of 0.63 g kg^{-1} at 15-25 cm depth under 32 years of no-till. These observations are in line with conclusion drawn in Europe, and northern and southern America. In a recent review, Powlson et al. (2014) concluded that C sequestration through no-till agriculture was limited and overstated: the increase in soil C contents mainly happens near the surface and the soil would lose any soil C benefit as soon as it has been cultivated under CV, as it is commonly done every few years. A meta-analysis under Mediterranean climate (Aguilera et al., 2013) showed high C sequestration rates for practices that combine external organic inputs with cover crops or reduced tillage; the highest response being achieved by the practices applying largest amounts of C inputs. Another meta-analysis of paired CV tillage/no-till experiments (Luo et al., 2010) showed that no-till did not enhance soil total C stock down to 40 cm and C sequestration was regulated by cropping frequency. In Brazil, a review also reported an increase in soil C content down to 40 cm under CA, indicating promising strategy for GHG emissions mitigation (Bernoux et al., 2006).

Table 3: **Conservation agriculture & soil carbon content**
Soil carbon content gain for each soil layer referred to in Supplementary Materials. NS: Non-significant

Depth (cm)	n	NS	Soil carbon gain (g kg-1) Minimum	Median	Maximim
0-5	7		0.2	1.9	5.2
0-10	8	3	-1.7	6.2	10.5
0-15	5	2	0.24	2.9	5.4
0-20	8	1	0.27	2.42	4.47
0-30	4	1	0.83	1.4	5.5
5-10	2	1		2.9	
10-15	1	1			
10-20	6	3	3	3.3	9
15-25	1			-0.63	
15-30	3	1	2.2	2.8	3.4
20-30	3	2		0.9	
25-35	1	1			
30-40	1			1	
30-45	2	1		3.4	
35-45	1			0.9	
45-60	1	1			
50-60	1			0.9	

Our results suggest that CA improves soil C content. But, we were unable to distinguish soil C content changes due to tillage management, soil cover, crop rotation, or the interaction between these factors. In particular, the mulch amount is a key value to better understand the capacity of CA to sequester C. It is admitted that the increase in soil C content is mainly due to the retention of biomass on the soil surface (Corbeels et al., 2006). However, this information was omitted in the large majority of studies. For a better quantification of the potential of CA to sequester CA, there is a need to detail comprehensive methodologies and standardize research approaches (Derpsch et al., 2014).

5. Adapting to climate change

The set of studies embodied a wide range of types of climate (Supplementary materials) with very different rainfall regimes, from a 165 mm short rainy season in semi-arid North Eastern Tanzania (Enfors et al., 2011) to a 1500 mm rainy season in the tropical rainforest of Western Nigeria (Agboola, 1981). Among the 178 paired CV-CA yield comparisons, we observed no significant impact of CA on yield in 58% cases, yield penalty in 16%, and yield gain in 26% of the cases. The review showed that positive yield response under CA occurs mainly when total seasonal rainfall is lower than 900 mm (Figure 5). Beyond this threshold, CA tends to have no - or even negative - impacts on yield. Contrary to the findings of Baudron et al. (2012) and Enfors et al. (2011), these results suggest that CA increases soil water availability under poor rainfall conditions, resulting in higher crop yields. Under wetter conditions this impact on water balance has no effect on crop yields (Rusinamhodzi et al., 2011; Sissoko et al., 2013). The most negative CA impact on yield (87% lower yield compared to CV) was observed in a study in Nigeria with 1000 mm of annual rainfall (Anazodo et al., 1991). This poor performance was "*attributed to high soil strength which probably offered mechanical impedance to root growth and proliferation,* [...] *aeration problems,* [...] *high weed growth*". The highest yield gain under CA (228% higher yield compared to that under CV) was observed under no-till with mulch in Nigeria for a 637 mm rainy season (Lal, 1995). The author did not focus on correlation between rainfall amount and CA efficiency, but he highlighted that under low water retention capacity "*it is the frequent occurrence of gentle rains that determines crop growth and yield, rather than the total seasonal amount per se*".

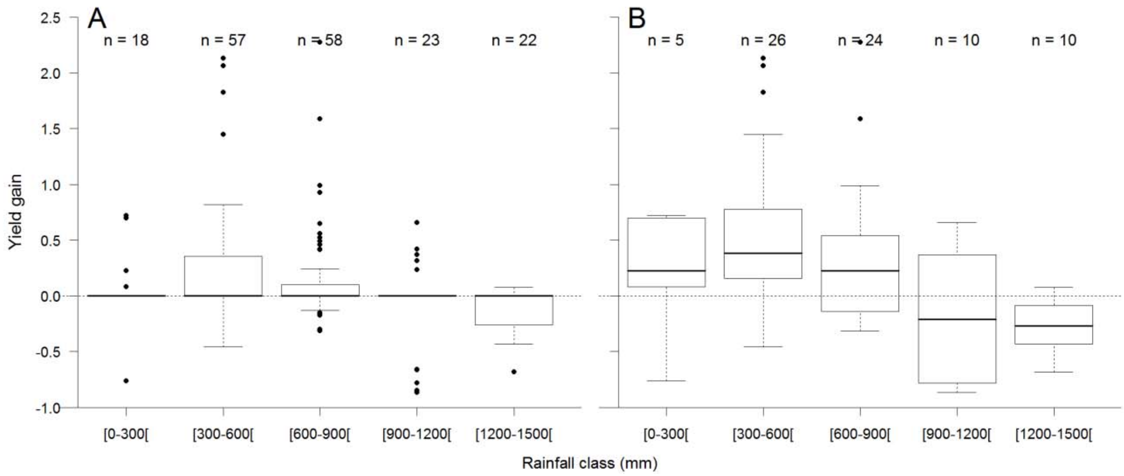

Figure 5: Conservation agriculture & rainfall
Yield gain in favor of CA for different rainfall classes considering non-significant differences with CV as null (A) or excluding non-significant difference (B).

Besides total seasonal rainfall, rainfall distribution within the season appears to be a key determinant of CA impact on crop production. In northern Ethiopia, Araya et al. (2012) reported a better rainfall use efficiency under CA, particularly at the beginning of the rainy season. Despite the frequent dry spells, the crop emergence was faster because of a better water infiltration which limited water stress under CA. Similar results were observed in Nigeria (Obalum et al., 2011) where higher yield under no-till was attributed the higher soil moisture at the beginning of the rainy season under erratic distribution of rainfall. In Zimbabwe, Mupangwa et al. (2007) observed a better crop stand with planting basins because of a higher soil moisture at the beginning of crop growth. However, it did not translate into higher yield as compared to conventional tillage based system due to severe water underwent under both treatments during the second half of the rainy season. These results suggest an ability of CA to secure sowing and crop emergence through an increase in soil moisture at the beginning of rainy season. It also suggests that CA could offset negative impact of dry spells during rainy season.

Rainfall changes predictions are uncertain in Africa. Our review indicates that CA could express its potential under a decrease in total seasonal rainfall, a delay of the rainy season onset or an increase in dry spell frequency within the season. However, the set of studies also illustrates the site-specific impacts of CA on soil water conservation and water use efficiency. Under CA practices, the mulch of crop residues held on the soil surface intercepts rainfall, decreases surface water runoff and limits soil evaporation (Findeling et al., 2003; Lal, 1976; Scopel et al., 2013). The increase in water infiltration does not necessarily infer better rainwater use efficiency. It can result in an increase in water drainage (Scopel et al., 2004) and the impact on water balances and subsequently on yield depends on the soil characteristics, particularly its water storage capacity in the rooting zone, the rainfall distribution during the season, and the synchrony between dry spells (or rainfall episodes) and the crop development stages which determines the water stress underwent during crop growth.

6. Is CA a climate-smart option for all family farmers in SSA?

6.1. The key role of mulching into the achievement of CSA

Our findings reflected the complexity of functions interactions and the simultaneity of objective achievements (Figure 4). It confirmed the major role of mulching in the achievement of CSA pillars. Retention of crop residues improves the soil fertility principally as a result of an increase in soil C content. Increased soil fertility translates into an increase in yield which subsequently translates into economic benefits, if production costs are unchanged. The mulch is also a protective layer that enhances water infiltration. Combined with the increase in soil organic matter, it can improve water conservation and buffer water stress.

However, retaining a permanent mulch of crop residues on the soil surface is very challenging on smallholder farms in SSA (Erenstein, 2003; Giller et al., 2009). Combined with the limited rainfall, particularly in semi-arid Africa, and the limited access to fertilizers, small amounts of biomass are produced. Besides, under mixed crop-livestock farming, there can be competing uses for this biomass , for example as fodder (Corbeels et al., 2014a). Most of the studies reported considered the mulch as an efficient mean to restore soil fertility without providing quantitative data on mulch characteristics. We can assume that the ability of mulch to increase soil fertility or reduce water runoff will depend on the amount retained on the surface, the type of crop residues, and its chemical composition. Quantifying these effects could also help making relevant trade-offs between the use as mulch or livestock feed without jeopardizing one or the other farm activity (Baudron et al., 2014; Naudin et al., 2014). For instance, in Zimbabwe Mupangwa and Thierfelder (2013) showed that using biomass for both mulch and fodder purposes was possible without reducing maize yield.

6.2. CA ability to be climate-smart is local-specific

This paper reports evidence of the ability of CA to be climate-smart, but it also helps to better understand under which circumstances.

The increase in yield in the long-term is attributed to the progressive increase in soil fertility. In the shorter-term, the increase in yield is less likely, but when it happens, it is attributed to the ability of CA to offset water stress through mulching. CA mainly expresses its potential under low and/or erratic rainfall conditions. But, under such conditions, farmers struggle to produce biomass and the competition with livestock is severe. Thus, there is a need to better apprehend the biomass flows at the farm- and village-level to optimize the use of this biomass for both mulch and fodder (Andrieu et al., 2014).

Regarding economic benefits, CA impact is very site- and farm-specific, depending on many factors such as crop type, household structure, market price of farm inputs and outputs, social organization, or support from national institutions. Further studies at the farm-level would be necessary to fully apprehend the economic potential of CA. However, reporting evidence from smallholders throughout SSA is a preliminary approach to better identify the economic benefits and constraints in order to tailor and adapt CA cropping systems to each socio-economic context. We showed that labor and herbicides costs are key determinants of the economic success of CA implementation.

6.3. Conclusion: CA is not necessarily climate-smart in SSA

The focus on the three main pillars of CSA enabled a better analysis of CA. It suggests that the two are not as congruent as often implied, i.e. it doesn’t seem that CA is necessarily climate-smart in the context of the African systems examined. Available literature reported evidence of the capacity of CA to contribute to the 'productivity' pillar of CSA through an increase in soil fertility, crop yields, and economic benefits. However, it is also suggested that increasing yield may not be the primary benefit of CA except in cases under low rainfall areas where waterlogging is not pronounced as part of seasonal rainfall variability. This means that CA can also contribute to the 'adaptation' pillar of CSA by buffering water stress, but negative impact on yields could also be observed under wetter conditions. The contribution of CA to the 'mitigation' pillar remains unanswered. C accumulation is observed in the top soil layer (30 cm) but there is an apparent failure for C enrichment at lower depth. This may not translate into sustainable forms of C sequestration under predominant agronomic practices (Powlson et al., 2014). Occasional tillage, changes in cropping sequences, weeding regimes (e.g. mechanical versus herbicides), disease and pest management methods, and changes in environmental conditions (temperature, rainfall variability) could alter the C balance. This is an area requiring further research. Moreover, the increase in soil C content, and more generally the increase in organic matter alter soil properties. On the bases of available data, the direct impact on soil GHG emissions remains unclear. The few reported studies did not allow concluding on the impact on GHG emissions. Further studies considering the associated trace gas fluxes must be carried out to evaluate the possible compensatory phenomena (Bernoux et al., 2006).