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The integrated assessment of conservation agriculture practices as sustainable options for smallholder farmers

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1. Summary of research activities

1.1. Introduction and career

J'ai commencé mes activités de chercheur en mai 1991 en tant que coordinateur du projet de recherche en coopération VL.I.R. (Conseil Interuniversitaire de Flandre) '*Consolidation de la capacité du département Sciences du Sol de l'Ecole Nationale d'Agriculture de Meknès'* au Maroc. Au cours de ce projet (1991-1996), j'ai réalisé ma thèse de doctorat, qui a aussi permis de produire sept publications dans des revues à facteur d'impact (1.1 à 2.1). En mai 1997, j'ai été désigné par l'Université de Gent, Belgique comme coordinateur du projet VL.I.R. '*Strengthening soil and water conservation training and research in Ethiopia*', basé à *Mekelle University College*, Mekelle en Ethiopie. Au même temps, j'étais assistant-professeur au sein du Département de Conservation des Sols et des Eaux de cette université. J'ai participé à l'encadrement de deux doctorants éthiopiens, et j'ai assuré l'installation du laboratoire des sols et la coordination de l'ensemble des opérations de terrain. A cause de la guerre entre l'Ethiopie en Eretria, j'ai choisi d'interrompre ma mission en décembre 1999, et j'ai obtenu un poste comme chercheur/modélisateur au *CSIRO* à Perth en Australie dans le cadre d'un projet ACIAR (Australian Centre for International Agricultural Research): *Improving and maintaining productivity of eucalypt plantations in India and Australia*. Ce séjour au CSIRO m'a permis de publier huit articles dans des revues à facteur d'impact (1.0 à 4.8).

Recruté au CIRAD (Centre de coopération Internationale en Recherche Agronomique pour le Développement), j'ai été affecté en mars 2002 au Brésil – initialement pour une durée de huit mois- dans le cadre d'un projet de coopération avec l'Embrapa (Empresa Brasileira de Pesquisa Agropecuária) dans la région des Cerrados (Brasilia) sur le développement et fonctionnement des systèmes de culture sur couverture végétale (SCV) en agriculture entrepreneuriale. Pendant cette période initiale, j'ai proposé une nouvelle lettre de mission autour de l'évaluation et conception de systèmes de culture par modélisation. Cette note représentait une première réflexion pour un projet d'ATP: *Evaluation intégrée des performances de systèmes de cultures agroécologiques multi-espèces à base d'annuelles en zones tropicales* (MEDUSA). *Pendant* les quatre années qui ont suivi, j'ai animé les activités de modélisation des systèmes SCV et participé à l'encadrement de trois thèses de doctorat, qui ont permis de produire six publications dans des revues à facteur d'impact (0.4 à 4.8).

Depuis 2005, j'ai participé au projet européen SEAMLESS (www.seamless-ip.org -2005-2009), pour lequel ma fonction a été de coordonner le développement de modèles de simulations des dynamiques de carbone et azote dans le sol. Cette demande témoigne de la reconnaissance scientifique européenne que j'ai obtenue dans ce domaine. A partir de 2005, mes activités scientifiques se sont orientées vers l'Afrique avec une participation centrale dans le projet européen AfricaNUANCES (www.africanuances.nl), dans lequel j'ai animé le work package 'Systèmes de cultures'. En 2006, j'ai commencé à construire un projet scientifique en partenariat avec le Tropical Soil Biology and Fertility Institute (TSBF) de CIAT (Centro Internacional de Agricultura Tropical) dans le cadre du Sub-Saharan Africa Challenge Progamme (SSA-CP) du FARA (Forum for Agricultural Research in Africa). A partir de janvier 2007, ce projet s'est concrétisé par ma mise à disposition du TSBF à Harare au Zimbabwe pour trois ans. J'ai animé pour le TSBF les travaux de recherches autour de la modélisation des systèmes de culture et les analyses quantitatives du fonctionnement de l'exploitation agricole. En décembre 2009, je suis devenu le responsable régional du TSBF pour l'Afrique australe. J'ai animé une équipe CIAT-TSBF de six chercheurs et quatre doctorants avec de multiples partenaires d'organismes nationaux. J'ai également coordonné le projet SSA-CP: *Efficient Water and Nutrient Use in Cereal Grains Systems in Market-Based Conservation Agriculture Systems* avec financements du FARA. Mes activités de recherches au TSBF ont permis de produire douze publications dans des revues à facteur d'impact (1.4 à 2.9) et à un partenariat renforcé avec l'Université de Wageningen et le CIMMYT (Centro Internacional de Mejoramiento de Maíz y Trigo). En janvier 2010, je suis retourné à Brasilia pour un poste au sein de l'Embrapa-Cerrados, dans lequel je coordonne les activités de terrain du volet Brésil du projet ANR: *Processus écologiques et processus d'innovation technique et sociale en agriculture de conservation.* En parallèle, j'ai coordonné un autre projet de la Commission Européenne: *Conservation Agriculture in Africa: Analysing and Foreseeing its Impact - Comprehending its Adoption (www.CA2Africa.eu)* de 2010 à 2012. J'anime aussi la coopération entre le CIRAD et l'Embrapa sur l'agriculture de conservation en Afrique dans le cadre du projet ABACO de la Commission Européenne: *Agroecology-based aggradation conservation agriculture.* Depuis janvier 2013, j'ai commencé des activités de recherches en Amazonie, principalement avec un post-doctorant, sur la gestion de la fertilité des sols et l'intensification écologique des systèmes de culture. Actuellement, je co-encadre 4 thésards en doctorat. Mon index h de publication est actuellement 15.

1.2. The overall research framework: hierarchy of crop growth factors and the use of crop growth simulation models

The performance of crop production systems strongly varies in time and space, as a function of the biophysical, socio-economic and institutional environment. Often their analysis is complex because of confounding interactions that exist between environmental, socio-economic and institutional processes. It is helpful to first abstract from the socio-economic and institutional conditions and to describe crop production systems as a function of the biophysical environment only. An analysis of socio-economic and institutional conditions may then explain the opportunities and constraints of the use of a particular combination of growth factors and associated inputs in existing production systems.

The characterization of three groups of growth factors i.e. growth defining (CO_2-concentration, radiation, temperature, and genetic crop characteristics), growth limiting (water and nutrients) and growth reducing (weeds, pests and diseases), is a functional concept in the analysis of plant production systems at the field scale (Van Ittersum and Rabbinge, 1997). The concept defines a hierarchy of crop production levels. In the absence of effects of limiting and reducing factors, the maximum or so-called 'potential' production is realized for a given physical environment and for a plant species, as defined by CO_2 concentration, climate (radiation, temperature) and crop characteristics. Current production of systems is a result of growth limitation due to water and/or nutrient shortage and/or effects of growth reducing factors such as weeds and diseases. This concept allows also consideration of the principles of resource use efficiency (De Wit, 1992), in particular of water and nutrient use efficiency (Janssen, 1998).

The concepts of production levels and resource use efficiency have been operationalized in many crop growth and ecosystem simulation models. These simulation models can be used to compute potential, water-limited and nutrient-limited plant productivity under various climatic and soil conditions and for a range of existing or alternative management systems, and to describe and explain the magnitude of crop yield gaps.

I used a range of crop growth/ecosystem models (G'DAY, FIELD, CENTURY, DSSAT, STICS, APSIM, APES, QUEFTS) for investigating plant growth responses to soil fertility management and climate variability and change, and impacts of land-use on soil carbon (C). As a response to a need to improve the representation of soil C and nitrogen (N) cycles in models, I developed an organic matter decomposition sub-model for the G'DAY and APES models that advances the mechanistic treatment of the N mineralisation-immobilisation process during decomposition of plant residues and soil organic matter (SOM) (Fig. 1).

The use of a wide range of models in my studies reflects the need for using models that are customized to the specific simulation problem or research question addressed. Models should be as simple as the nature of their objectives allow, not be overloaded with unnecessary details, and have minimum data requirements (Sinclair and Seligman, 1996). We have addressed this issue in Affholder et al. (2012). In Adam et al. (2010) we developed a method to facilitate model restructuring and thus construct *ad hoc* crop growth models by a novel combination of software technology with expert knowledge.

With FIELD (Field-scale Interactions, resource use Efficiencies, and Long term soil fertility Development, Fig. 2) we developed a summary model that captures essential interactions determining the short- and long-term crop productivity of cropping systems in the tropics, while keeping a degree of simplicity that allows its parameterisation, use and dissemination. The term summary model has been coined to refer to an approach that summarises existing knowledge from underlying processes into simple functional relationships that describe the main responses of those processes at the higher integration level under study. In the case of FIELD, such processes are those governing productivity of the cropping system and long-term soil fertility. The approach combines the use of field data, expert knowledge and, whenever possible in terms of data availability, the use of detailed process-based crop growth models to generate the summary functions. In general, in designing simulation models a compromise must be found between the loss of accuracy introduced by aggregation (simpler models) and loss in precision through the accumulation of errors associated with the estimation of a large number of parameters in complex, non-aggregated models. When the scale of analysis is the farm system, generic simplified models of crop production rather than complex, detailed process-based crop growth models can be used to address questions on resource allocation at the farm. Though simpler models generally have less explanatory power, they often perform as well as, or better than complex models, while the uncertainty caused by both lack of data and imperfect knowledge of some processes is better managed (Brooks et al., 2001).

More details can be found in:

- Adam M., Ewert F., Leffelaar P.A., Corbeels M., van Keulen, H. and Wery, J. (2010) CROSPAL, software that uses agronomic expert knowledge to assist modules selection for crop simulation. Environmental Modelling and Software 25: 946-955.
- Adam, M., Corbeels, M., Leffelaar, P.A., Van Keulen, H., Wery, J. and Ewert, F. (2012) Building crop models within different crop modelling frameworks. Agricultural Systems, 113: 57-63.
- Adam, M., Wery, J., Leffelaar, P.A., Ewert, F., Corbeels, M. and Van Keulen, H. (2013) A systematic approach for re-assembly of crop models: An example to simulate pea growth from wheat growth. Ecological Modelling 250: 258-268.
- Affholder, F., Tittonell, P., Corbeels, M., Roux, S., Motisi, N., Tixier, P. and Wery, J. (2012) Ad hoc modeling in agronomy: What have we learned in the last 15 years? Agronomy Journal, 104: 735-748.
- Affholder, F., Poeydebat, C., Corbeels, M., Scopel, E. and Tittonell, P. (2013) The yield gap of major food crops in family agriculture in the tropics: Assessment and analysis through field surveys and modelling. Field Crops Research 143: 106-118.

- Chikowo, R., Corbeels, M., Tittonell, P., Vanlauwe, B., Whitbread, A. and Giller, K.E (2008) Using the crop simulation model APSIM to generate functional relationships for analysis of resource use in African smallholder systems: aggregating field-scale knowledge for farm-scale models. Agricultural Systems 97:151-166.
- Corbeels M., McMurtrie, R.E., Pepper, D. and O'Connell, A.M. (2005a) A process-based model of nitrogen cycling in forest plantations: I. Structure, calibration and analysis of the decomposition model. Ecological Modelling 187:426-448.
- Corbeels M., McMurtrie, R.E., Pepper, D. and O'Connell, A.M. (2005b) A process-based model of nitrogen cycling in forest plantations: II. Simulating growth and nitrogen mineralization of Eucalyptus globulus plantations in south-western Australia. Ecological Modelling 187:449-474.
- Nyombi, K., van Asten, P.J.A., Corbeels, M., Taulya, G., Leffelaar, P.A. and Giller, K.E. (2010) Mineral fertilizer response and nutrient use efficiencies of East African highland banana (Musa spp., AAA-EAHB, cv. Kisansa) Field Crops Research 117: 38-50.
- Tittonell, P., Zingore, S., van Wijk, M.T., Corbeels, M. and Giller, K.E. (2007) Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: Exploring management strategies across soil fertility gradients. Field Crops Research 100: 348-368.
- Tittonell, P., Corbeels, M., van Wijk, M.T. and Giller, K.E. (2010) FIELD – A summary simulation model of the soil-crop system to analyse long-term resource interactions and use efficiencies at farm scale. European Journal of Agronomy 32: 10-21.

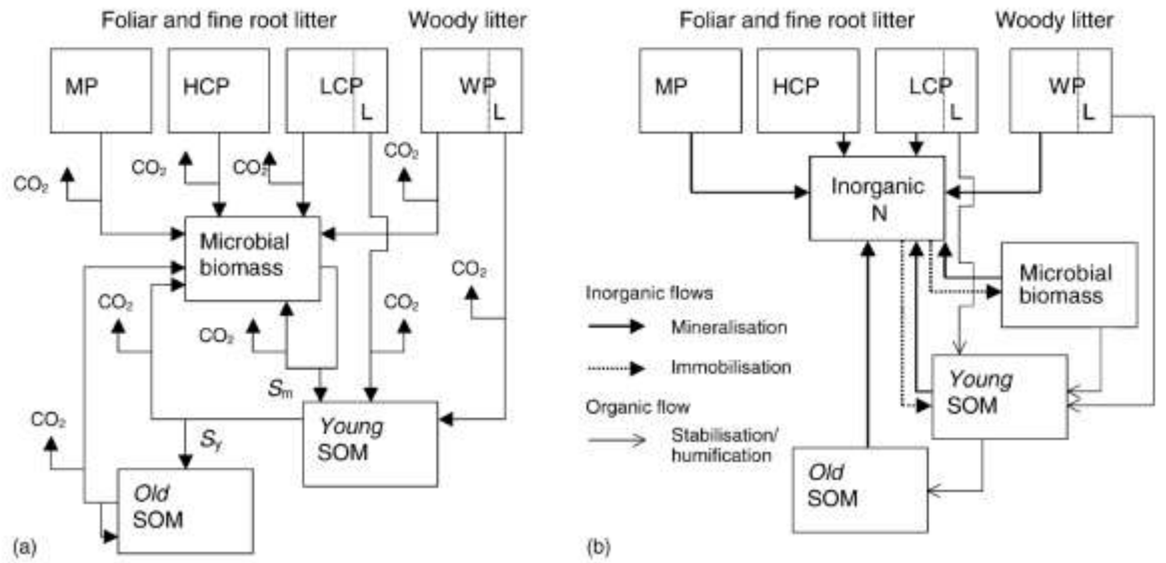

Figure 1. Pools and fluxes of (a) carbon and (b) nitrogen in the decomposition model of G'DAY (Comins and McMurtrie, 1993) and APES (Donatelli et al., 2010). MP, metabolic pool; HCP, holocellulosic pool; LCP, ligno-cellulosic pool; L, lignin; SOM, soil organic matter; Sm, stabilisation coefficient for microbial biomass; Sy, stabilisation coefficient for Young-SOM. Source: Corbeels et al. (2005a).

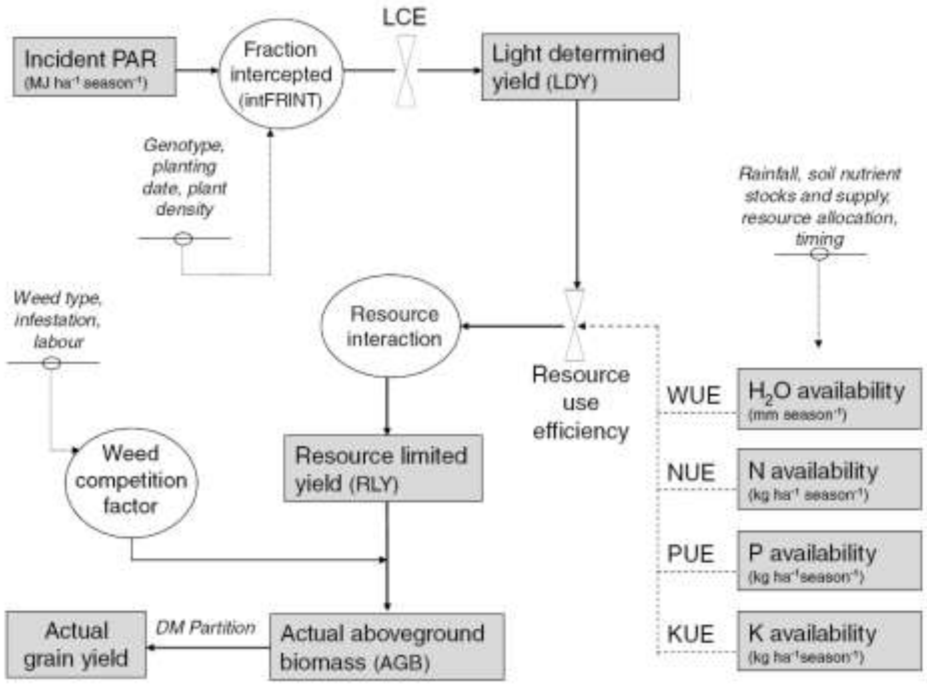

Figure 2. Schematic representation of the FIELD (Field-scale resource Interactions use Efficiencies and Long-term soil fertility Development) model for the simulation of resource interactions determining crop production. PAR: photosynthetically active radiation; intFRINT: seasonal fraction of intercepted radiation; LCE: light conversion efficiency; WUE: water use efficiency; NUE: nitrogen use efficiency; PUE: phosphorus use efficiency; KUE: potassium use efficiency. Source: Chikowo et al. (2008).

Within this general framework of hierarchy of crop growth factors and concept of resource-use efficiency, **I conducted my research with the overall aim to better understand and assess the biophysical constraints to crop productivity.** The emphasis was on N as it is in many situations the key nutrient limiting crop productivity, whilst at the same time it can cause several negative environmental effects (nitrate leaching and N_2O emission). I studied in detail the soil N cycling and plant N uptake processes in order to understand and improve N use efficiency of cropping systems (*Theme 1*). Predicting the amount and temporal variation of mineralized N during crop growth is essential for determining the optimal timing and amount of fertilizer N applications, and thus increasing N fertilizer use efficiency. I have contributed to an improved representation and prediction of the N immobilisation-mineralisation of N in crop growth and ecosystem simulation models (*Theme 2*). I subsequently used my expertise in modelling to better understand long-term effects of soil fertility management on crop productivity, with a special emphasis on the relationships between soil nutrient cycling and plant growth processes. This research embraced the concept of ecological intensification (Cassman, 1999) and contributed to the identification of ways to achieve this for eucalypt plantations in Australia and India, and maize-based cropping systems of smallholder farming systems in southern and eastern Africa (*Theme 3*). With my appointment at CIRAD in 2002, I started studying the practices of conservation agriculture (CA) with the aim to gain a better understanding of the biophysical functioning of these systems. I applied the above theoretical concepts and used crop growth models to analyse water and N use efficiency and (long-term) impacts on soil C and N as a way to evaluate CA as a resource-efficient cropping system (*Theme 4*).

In the following sections I briefly describe the main results of my research for each of the specific research themes (1-4)

1.3. Improved nitrogen use efficiency

Improving N use efficiency of cropping systems is the key to optimizing trade-offs between yield and environmental quality. It implies the need for a greater synchrony between crop N demand and N supply from SOM, organic amendments and chemical fertilizer. The demand for increased yields requires greater crop N accumulation, which in turns requires a larger pool of plant-available N in the soil, but which is more vulnerable to N losses via leaching and gaseous emissions (Cassman et al., 2002).

I have studied the N use efficiency in cereal cropping systems in Morocco and Brazil. Under the semi-arid conditions of Morocco, there was a dominant influence of soil moisture availability on the fertiliser N uptake by wheat (*Triticum aestivum* L.). Under Mediterranean conditions, there is a risk that N fertilizer stimulates a too vigorous vegetative growth of the wheat crop, which exhausts the soil water reserve at the expense of grain development at the end of the growing season. Nitrogen fertiliser recovery by the above-ground wheat crop was relatively low (30%) (Table 1). Losses accounted for less than 10% of the fertiliser applied at harvest of the wheat crop. A high amount of residual fertiliser N (>60%) remained in the soil of which little (<5%) was taken up by the sunflower (*Helianthus annuus* L.) crop in the following year. The results indicate the importance of the N immobilisation and re-mineralisation process as key to N use efficiency. Good estimates of soil N supply, together with the target yield, are the most important prerequisites for the determination of the best doses and timing of N fertiliser applications.

Under the sub-humid conditions of the Cerrados of Brazil, we found large quantities of residual mineral N in the soil at the start of the maize (*Zea mays* L.) growing season (50-125 kg N ha^{-1}), probably as a result of the high soil N mineralisation rates during the intercrop period. Large N losses via nitrate leaching may occur after harvest of the main crop due to continued rainfall, depending on the season (Fig. 3). Our results suggest that with the use of cover crops, in some instances, part of the N lost can be recovered for the next season, thereby increasing overall N use efficiency. However, this effect largely depends on how well the cover crop was established. Since in the Cerrados cover crops are grown in a period of the year with decreasing amounts of plant-available water in the soil, it is critical to sow those immediately after harvest of the previous main crop. In general, management practices such as cover crops or the use of organic manure, which try to re-couple the biogeochemical cycles of C and N show higher N use efficiency than single practices such as chemical fertilizer application methods or doses (Gardner et al., 2009).

More details in:

- Corbeels, M., Hofman, G. and Van Cleemput, O. (1998a) Analysis of water use by wheat grown on a cracking clay soil in a semi-arid Mediterranean environment: weather and nitrogen effects. Agricultural Water Management 38: 147-167.
- Corbeels, M., Hofman, G. and Van Cleemput, O. (1998b) Residual effect of nitrogen fertilisation in a wheat-sunflower cropping sequence on a Vertisol under semi-arid Mediterranean conditions. European Journal of Agronomy 9: 109-116.
- Corbeels, M., Hofman, G. and Van Cleemput, O. (1999a) Fate of labelled fertiliser ammonium-N applied to winter wheat (*Triticum aestivum* L.) in a Vertisol under semi-arid Mediterranean growing conditions. Nutrient Cycling in Agroecosystems 53: 249-258.
- Maltas, A., Corbeels, M., Scopel, E., da Silva, F.A.M. and Wery, J. (2009) Cover crop effects on nitrogen supply and maize productivity in no-tillage systems of the Brazilian Cerrados. Agronomy Journal 101: 1036-1046.

Table 1. Fate of applied nitrogen fertilizer (100 kg N ha^{-1}) to wheat in wheat-sunflower crop rotation on a Vertisol in Meknes, Morocco. Source: Corbeels et al. (1998).

Fertiliser N allocation	% Recovery
Winter wheat plant minus stubble[a]	30.0 ± 2.7
Sunflower plant	3.6 ± 0.4
Both plants (1)	33.6
Soil at harvest of sunflower crop (2)	49.7 ± 6.2
Total recovered (1 + 2)	83.3
Not recovered after first cropping season[a]	6.8 ± 4.8
Not recovered after second cropping season	9.9
Total not recovered	16.7

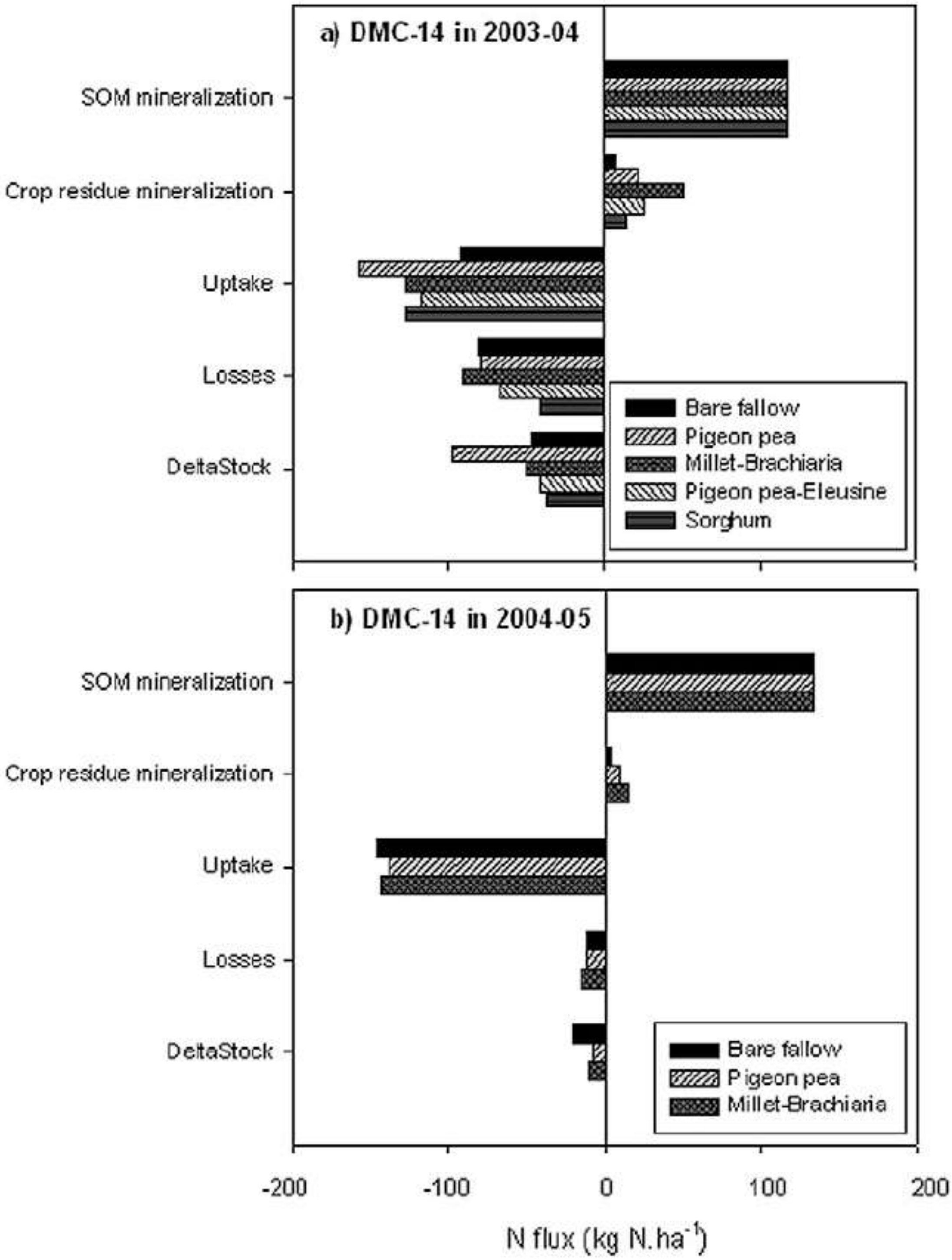

Figure 3. Soil mineral nitrogen balance under maize without nitrogen fertilizer as affected by cover crop treatment on a field in Rio Verde, Goias, Brazil that had been for 14 years under direct seeding management (DMC-14) (a) in 2003–04 with total rainfall of 1668 mm and (b) 2004–05 with total rainfall of 1334 mm, DeltaStock is the difference between soil mineral nitrogen contents in the soil profile (0–120 cm) at harvest and at sowing. Source: Maltas et al. (2009).

1.4. Simulation of nitrogen mineralisation

Predicting the amount and temporal variation of mineralized N during crop growth is essential for determining the optimal timing and amount of fertilizer N applications. In the last 80 years a number of mathematical models of different level of complexity have been developed to describe C and N mineralisation from SOM and organic residues (Manzoni and Porporato, 2009). Predicting N immobilization/mineralization during decomposition of crop residues, green manures and animal manure requires a modelling approach that takes adequate account of organic matter quality. The biochemical composition of organic residues influences largely the rate of N immobilisation or mineralisation during decomposition (Corbeels et al., 2000; Corbeels et al., 2003). Ecosystem and crop growth models include SOM sub-models of varying complexity. Most SOM models are based on the assumption that decomposition can be modelled by two to four conceptual pools that decay according to first-order kinetics with pool-specific rate constants. Organic residues have therefore been separated by different procedures into various chemical fractions including soluble C components, cellulolytic components, polyphenol and ligninic products. A robust estimation of the pool partitioning of organic matters, i.e. the fraction of their C and N allocated to rapidly and slowly decomposing pools is still today the topic of research work (Borgen et al., 2011; Dungait et al., 2012).

I have tested and used the Van Soest analysis as a method to quantify the plant litter pools for use in SOM simulation models such as NCSOIL (Molina et al., 1983). Results clearly showed that the concept of three Van Soest pools, decomposing independently at a specific rate constant, is only valid if the decomposition rates of the litter pools are reduced with time e.g. as a function of lignin content of the decomposing material. Moreover simulated N mineralisation is sensitive to the partitioning of the residue N to the various litter pools.

As a member of a research group in Australia on modelling of forests and forestry plantations, I developed on the basis of the experiences with NCSOIL a new SOM decomposition model that replaced the CENTURY model (Parton et al., 1987) in the ecosystem model G'DAY (Fig. 1). The motivation for modifying the SOM decomposition sub-model in G'DAY was the realization by the team from past work that improved soil models are needed for reliable predictions of sustainable forest productivity, impacts of future climate change and N deposition on the terrestrial C sink, the age-related decline in forest net primary productivity, and impacts of land-use change on productivity and C storage.

The key differences between this new SOM decomposition model and the previous one, based on the CENTURY model, are: (1) growth of microbial biomass is the process that drives N mineralisation-immobilisation, and microbial succession is simulated; (2) decomposition of litter can be N limited, depending on soil inorganic N availability relative to N requirements for microbial growth; (3) 'quality' of leaf and fine root litter is expressed in terms of biochemically measurable fractions; (4) the

N:C ratio of microbial biomass active in decomposing litter is a function of litter quality and N availability; and (5) the N:C ratios of SOM pools are not prescribed but are instead simulated output variables defined by litter characteristics and soil inorganic N availability.

The new decomposition model, with its improved mechanistic integrity, provides a relevant framework for studying C and N mineralisation as a set of interacting biological, physical and biochemical processes (Figure 4). It has been more recently incorporated in the APES crop growth model (Donatelli et al., 2010; Adam et al., 2012).

More details in:

- Corbeels, M., Hofman, G. and Van Cleemput, O. (1999b) Simulation by NCSOIL of net N immobilisation and mineralisation from substrate amended soils. Biology and Fertility of Soils 28: 422-430.
- Corbeels, M., O'Connell, A.M., McMurtrie, R.E., Grove, T.S., and. Mendham, D.S. (2002) Modelling changes in nitrogen mineralisation following conversion of improved pasture to eucalypt plantation. Agronomie 22:801-815.
- Corbeels, M., McMurtrie, R.E., Pepper, D. and O’Connell, A.M. (2005a) A process-based model of nitrogen cycling in forest plantations: I. Structure, calibration and analysis of the decomposition model. Ecological Modelling 187:426-448.

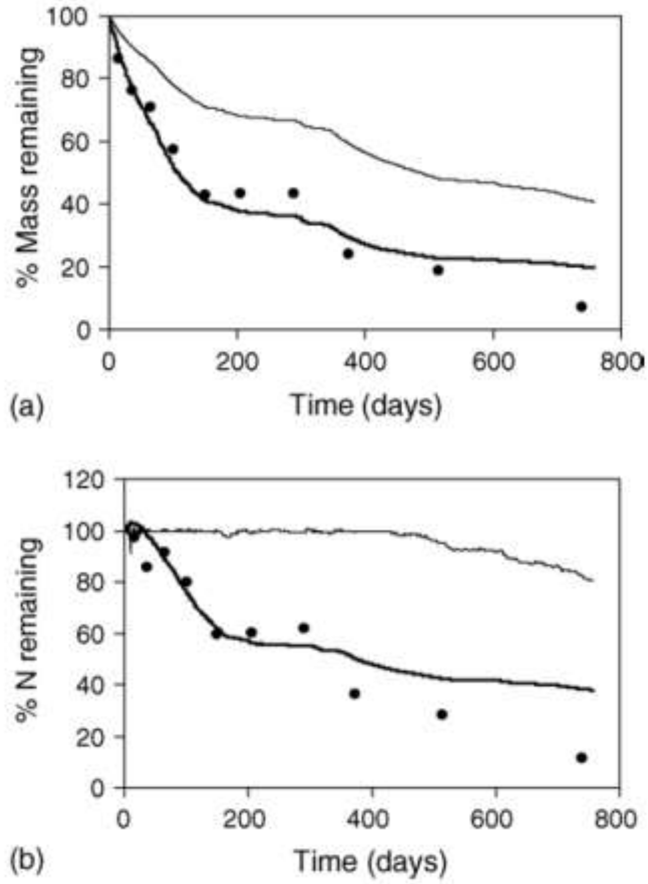

Figure 4. Measured (symbols) and simulated (lines) (a) mass and (b) nitrogen remaining from decomposing E. globulus leaf harvest residues in litterbags at Manjimup, south-western Australia. The fine line is simulation with previous soil organic matter decomposition model based on CENTURY (Parton et al., 1987), and the bold line is simulation with the new decomposition model of G'DAY. Source: Corbeels et al. (2005a).

1.5. Ecological intensification of cropping systems

Ecological intensification aims at closing the gap between average farm yields and the genetic yield potential without causing negative effects on the environment (Cassman, 1999). It implies a more efficient use of input of land, water, nutrients, energy or biological diversity for the production of food and fibre products, capitalising on ecological processes that regulate primary productivity. A more efficient and ecological use is needed to meet in a sustainable way the expected increase in food and energy demand in the coming years.

In my career I have done research on pathways of ecological intensification for two distinct crop production systems: 1) eucalypt plantations in south-western Australia and India; and 2) maize-based cropping systems in eastern and southern Africa.

Eucalypt forestry plantations

There is potential to significantly improve productivity of many eucalypt plantations in the world through more intensive management practices, such as fertilizer application and weed control (Mead, 2005). Frequent harvesting of short-rotation plantations results in large amounts of nutrients removed from the site. This removal causes in the longer term a decline in site fertility, resulting in lower plantation productivity. Field studies that we conducted in south-western Australia showed that productivity of eucalypt plantations on ex-pasture land is likely to decline rapidly because of decreasing soil N availability.

We have investigated the potential of legume intercropping for improving productivity of eucalypt plantations in India (Fig. 5). Cover cropping with legumes during the early phase of forest plantation growth (3 years) is an efficient pathway to enhance soil N supply and optimize the synchrony between N supply and tree N uptake, whilst reducing N losses through leaching. However, these effects did not translate into improved plantation growth in the 3 years of our study.

We hypothesized that improved SOM and N fertility may help ensure sustainable productivity over several rotations in the future. With the ecosystem G'DAY that was calibrated using data from eucalypt sites in south-western Australia, we simulated different scenarios of long-term management for eucalypt plantations. We found that the rate of decline in stemwood productivity is sensitive to rates of N removal in harvested stem and to harvest residue management, with burning of the harvest residues being the worst case scenario (Fig. 6). Simulations suggested that retention of harvest residues is helpful for maintaining stand productivity and reducing N losses, but that input of N in the form of chemical fertilizer or via legumes will be necessary to maintain current levels of productivity in the long term.

More details in:

- Corbeels, M., O'Connell, A.M., McMurtrie, R.E., Grove, T.S., and. Mendham, D.S. (2002) Modelling changes in nitrogen mineralisation following conversion of improved pasture to eucalypt plantation. Agronomie 22:801-815.
- Corbeels, M., McMurtrie, R.E., Pepper, D. A. and O'Connell, A.M. (2005c) Long-term changes in productivity of eucalypt plantations under different harvest residue and nitrogen management practices: a modelling analysis. Forest Ecology and Management 217: 1-18

- Mendham, D.S., Kumaraswamy, S., Balasundaran, M., Sankaran, K.V., Corbeels, M., Grove, T.S., O'Connell, A.M. and Rance, S.J. (2004) Legume cover cropping effects on early growth and soil nitrogen supply in eucalypt plantations in south-western India. Biology and Fertility of Soils 39: 375-382.

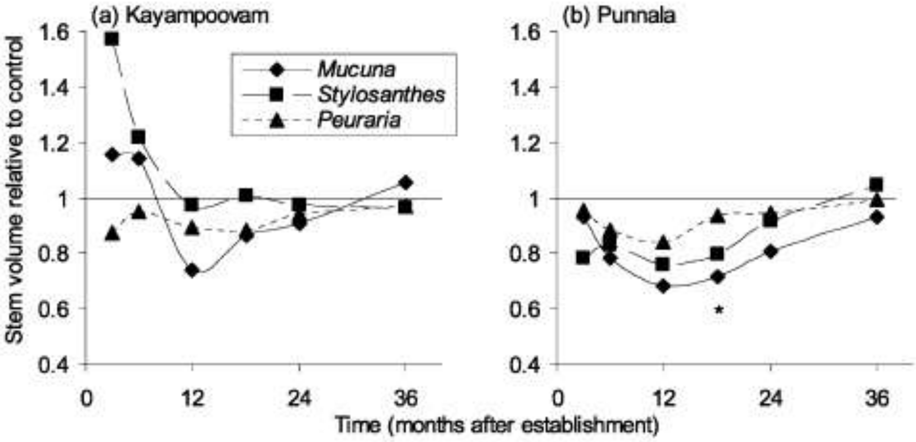

Figure 5. Eucalyptus tereticornis responses to legume treatments at Kayampoovam (a) and Punnala (b in Kerala, India relative to the control plots. Source: Mendham et al. (2004).

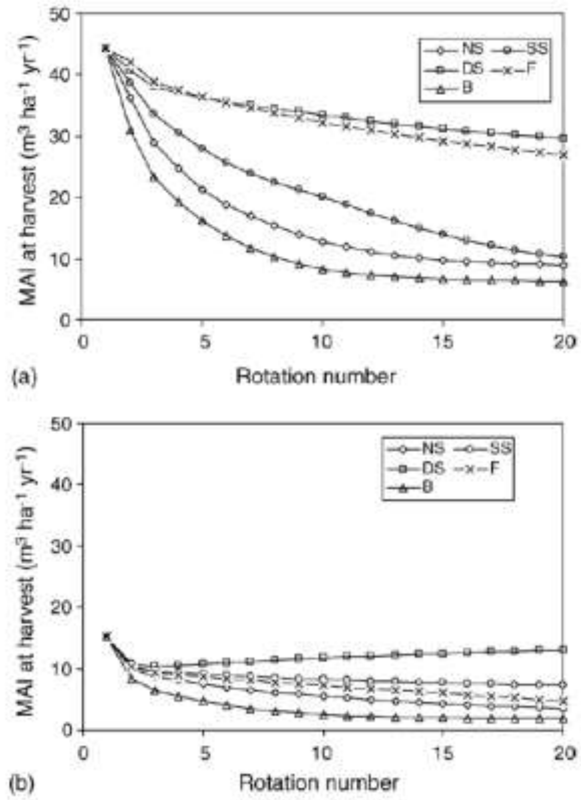

Figure 6: Simulated mean annual increment (MAI) at harvest over twenty Eucalyptus globulus rotations of 8 years under scenarios 1–5 for Manjimup (a) and Busselton (b) in south-western Australia. Simulations for each site were initialised by running the G'DAY model to quasi-equilibrium for legume based pasture. NS: stem harvesting with no harvest residues; SS: stem harvesting with retention of harvest residues; DS: double amount of harvest residues; B: stem harvesting with burn; F: stem harvesting with N fertiliser addition equal to N removed in stemwood harvest. Source: Corbeels et al. (2005b).

African maize-based cropping systems

In sub-Saharan Africa there is compelling evidence that food production is low because of low soil fertility (Giller et al., 2006). Relieving the constraint of low soil fertility is primordial for achieving ecological intensification of production systems with a more efficient use of the other available resources. The African green revolution aims to intensify agriculture through the dissemination of integrated soil fertility management (ISFM), i.e. a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm, combined with knowledge on how to adapt these practices to local conditions (Vanlauwe et al., 2010).

I have conducted research on the integration of the ISFM principles in maize-based cropping systems in Zimbabwe, Mozambique and Kenya. Resource use efficiencies were highly variable within and across heterogeneous farms in these regions, as a result of soil variability and farmers' management decisions, affecting crop responses to applied nutrients. Typically, fields close to the homestead (homefields) are relatively more fertile than fields further away (outfields) due to previous preferential allocation of nutrients. We choose soil organic C as the indicator of soil quality and agronomic sustainability because of its impact on other physical, chemical and biological indicators of soil quality.

Combined experimental work and modelling showed that exclusive use of chemical fertilizer without paying attention to organic matter resulted in a sharp decline in maize productivity on smallholder farms in north-east Zimbabwe (Fig. 7 and 8). The application of manure was required to restore soil C in depleted outfields and increase maize productivity. The current farmer's practice of allocating manure and fertiliser to homefields exacerbates land degradation in the sandy fields and increases soil fertility gradients but results in the most harvest for the farm. On clay soils, manure may be targeted to outfields and mineral fertiliser to homefields to increase total crop productivity. Consistent application of good-quality manure in combination with mineral fertilisers can be an effective option to improve crop yields, nutrient-use efficiency, SOM and moisture conservation in mixed crop-livestock farming systems in north-eastern Zimbabwe.

Result from a similar study in western Kenya showed that locally available animal manure applied at affordable rates for smallholder farmers in the study area have a weak effect on restoring the productivity of degraded soils, which may discourage farmers from investing efforts in soil. As in Zimbabwe, the combined application of manure with small amounts of chemical fertilizer generates more attractive responses in the short term. In this sense, mineral fertilizers are a clear option for soil fertility management by smallholder farmers in areas of high population densities such as western Kenya, characterized by small farm sizes that prevent the practice of fallow or growing green manures, small nutrient inflows from communal grazing lands via animal manure, and generalized soil degradation. However, when large amounts of C and nutrients are removed every season from the fields with the crop harvest residues there is a serious risk of further soil C decline and soil degradation, causing the soils to become non-response to chemical fertilizer.

Especially in situations of insufficient chemical fertiliser inputs, legume intercropping may provide another pathway for ecological intensification. Results from on-farm experiments that we conducted in central Mozambique have shown that the relatively higher crop productivity (and related nutrient-use efficiency) and economic benefits of the maize–legume intercropping systems compared to sole maize cropping were attractive to farmers to address their critical objectives of food security and cash income, although intercropping required 36% more labour compared with the monocrops. Moreover, intercropping with short duration crops such as cowpea can reduce risk of crop failure under erratic rainfall that is characteristic of central Mozambique.

More details in:

- Chikowo, R., Corbeels, M., Mapfumo, P., Tittonell, P., Vanlauwe, B. and Giller, K.E. (2010) Nutrient capture and recovery efficiencies, and crop responses to a range of soil fertility management strategies in sub-Saharan Africa. Nutrient cycling in Agroecosystems 88: 59-77.
- Rusinamhodzi, L., Corbeels, M., Nyamangara, J., Giller, K.E. (2012) Maize-grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. Field Crops Research 136: 12-22.
- Rusinamhodzi, L., Corbeels, M., Zingore, S. Nyamangara, J., Giller, K.E. (2013) Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. Field Crops Research (in press).
- Tittonell, P., Zingore, S., van Wijk, M.T., Corbeels, M. and Giller, K.E. (2007) Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: Exploring management strategies across soil fertility gradients. Field Crops Research 100: 348-368.
- Tittonell, P., Corbeels, M., van Wijk, M.T., Vanlauwe, B. and Giller, K.E. (2008) Targeting nutrient resources for integrated soil fertility management in smallholder farming systems of Kenya. Agronomy Journal 100: 1511-1526.
- Tittonell, P., Vanlauwe, B., Corbeels, M. and Giller, K.E. (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant and Soil 313:19-37.
- Zingore, S., Tittonell, P, Corbeels, M, van Wijk, M.T. and Giller, K.E (2011) Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. Nutrient cycling in Agroecosystems 90: 87-103.

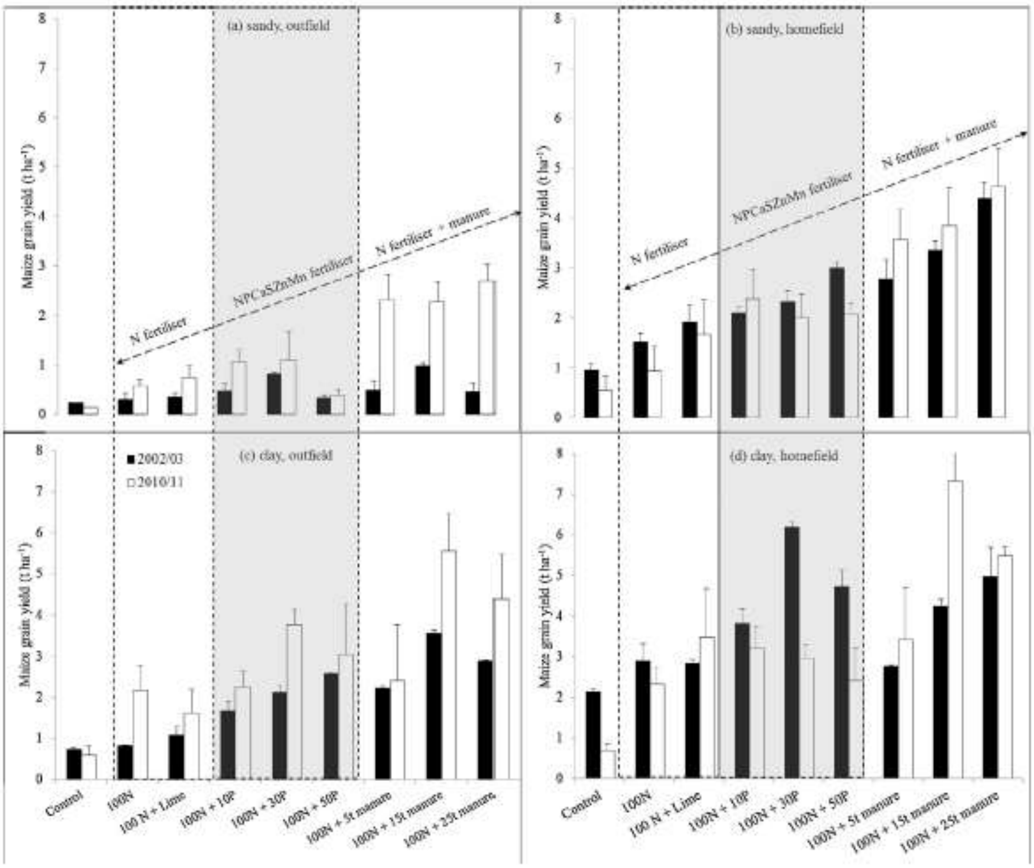

Figure 7. Maize grain yield gaps in (a) sandy outfield, (b) sandy homefield, (c) clay outfield, and (d) clay homefield under different management strategies at the start (2002) and end (2011) of a field experiment in Murehwa, north-eastern Zimbabwe. NPCaSZnMn refers to the treatment which received N, P, Ca, S, Zn and Mn in the form of chemical fertilizer, error bars are the standard error of mean. Source: Rusinamhodzi et al. (2013).

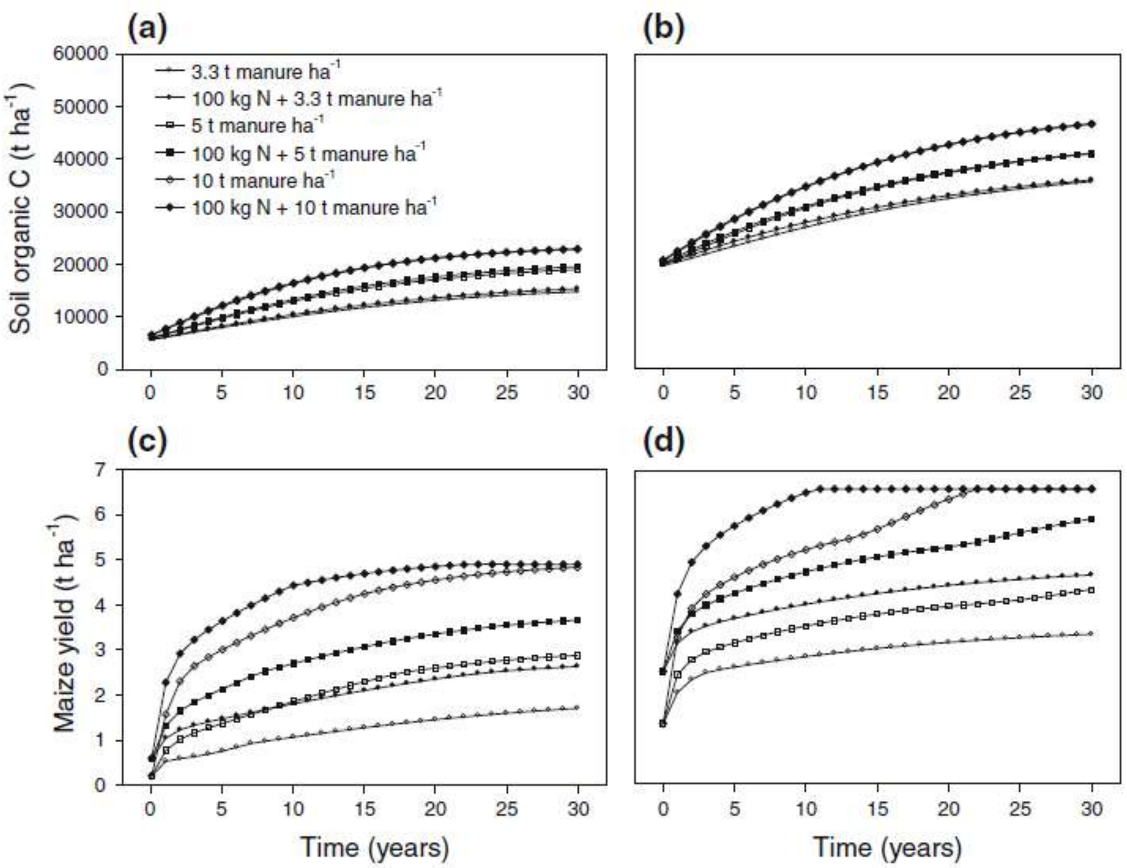

Figure 8. Simulated effects of long-term application of different rates of manure on replenishment of soil organic carbon on degraded (a) sandy (a) and (b) clay soils, and restoration of maize productivity on the (c) sandy and (d) clay soils in north-eastern Zimbabwe. Source: Zingore et al. (2011).

1.6. Conservation agriculture as a resource-efficient cropping system

Conservation agriculture 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 or associations (www.fao.org/ag/ca/). Conservation agriculture systems are promoted as a means to maintain or actually increase crop productivity and soil C. From a recent review that we conducted, we can conclude that CA can result in yield benefits in the long term, but in the short to medium term – and this can be up to 15 years – no yield benefits or yield decreases are just as likely.

More details in:

- Rusinamhodzi, L., Corbeels, M., van Wijk, M.T., Rufino, M.C., Nyamangara, J. and Giller, K.E. (2011) Long-term effects of conservation agriculture practices on maize yields under rain-fed conditions: lessons for southern Africa. Agronomy for Sustainable Development 31: 657-673.

In my research I have studied CA systems in relation to two major biophysical crop growth limiting factors: water and N, and have analysed the effects on dynamics of soil C as an integrated indicator for assessing soil quality and cropping system sustainability.

Water use efficiency

It is generally claimed that a major benefit of CA technologies is the conservation of water through reduced soil evaporation and water runoff as a result of mulching with crop residues, giving rise to higher water-use efficiencies and better yields (Hobbs, 2007; Kassam et al., 2009).

We used a crop growth simulation model (STICS, Brisson et al., 2003) that was adapted for simulating the effects of mulching, to unravel the complex interactions of CA on water use which are often difficult to quantify from field experiments alone. The modified version of STICS considered that a mulch of surface residue affects soil water content through three processes: (1) rainfall interception and subsequent mulch evaporation; (2) radiation interception with associated reduction of soil evaporation, and (3) reduction of water runoff.

The simulation study showed that under the semiarid conditions of La Tinaja in Mexico (525 mm annual rainfall) even small amounts of surface residues are effective at reducing water loss (surface runoff and soil evaporation), giving rise to higher water-use efficiencies and better yields with smaller risks of crop failure (Table 2). However, under the wetter conditions of the sub-humid tropical Cerrado region in Brazil (1400 mm rainfall), potential gains in water through a decrease in runoff and evaporation are largely offset by increased drainage losses with possible leaching of nutrients. As a consequence, under the Cerrado conditions, the impact of crop residue mulching on grain yield in CA systems is small and the use of cover crops as nutrient recyclers becomes crucial.

More details in:

- Scopel, E., da Silva, F.A.M., Corbeels, M., Affholder, F. and 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.

Table 2. Simulated (STICS model) maize grain yield and water balance components for La Tinaja, Mexico and Planaltina, Brazil. Source: Scopel et al. (2004)

Site	SR_0 ($Mg\ ha^{-1}$)	Y ($Mg\ ha^{-1}$)	T (mm)	Es (mm)	Em (mm)	R (mm)	D (mm)
LT	0	2.9 (1.2)	162 (68)	280 (44)	0 (0)	65 (18)	0 (0)
LT	1	3.3 (1.1)	181 (62)	241 (40)	12 (2)	65 (18)	1 (4)
LT	6	4.1 (0.8)	231 (45)	120 (21)	63 (9)	65 (18)	6 (15)
P	0	7.3 (1.2)	337 (49)	506 (59)	0 (0)	187 (48)	280 (187)
P	1	7.5 (1.1)	347 (48)	448 (51)	22 (3)	187(48)	306 (194)
P	6	7.9 (1.1)	370 (37)	244 (32)	113 (17)	187(48)	387 (210)

LT: La Tinaja; P: Planaltina; SR_0: initial mass of surface residue; Y: grain yield; T: transpiration; Es: soil evaporation; Em: evaporation from surface residue; R: runoff; D: drainage.
Means of simulated values using 25 (La Tinaja) and 30 (Planaltina) years rainfall data with = 5 mm day^{-1}, $b = 0.2$, $\delta = 5$, $\gamma = 1$, and with other model parameters the same as those in Table I. Values in parentheses are standard deviations of means.

Impact on soil nitrogen availability and nitrogen use efficiency

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 (Corbeels et al., 2003). If repeated additions of large amounts of crop residues lead to a greater soil C content in time, it may lead to a greater net N mineralization once a new equilibrium is achieved.

Little experimental data are available on long-term effects of residue mulching on soil N availability. Based on a chronosquence of fields of different age under CA in the Cerrado region of Brazil, we estimated that soil N mineralization increased with about 2.5 kg N ha^{-1} $year^{-1}$ under CA practice on an typical Oxisol (Fig. 9). The increase was mainly attributed to the larger soil total N content. These results indicate that even in the medium term (10 years), continuous CA cropping has limited implications for N fertilization recommendations on Oxisols in the Cerrado region, since the extra soil N supply represents less than 20% of the common N fertilization dose for maize in the region.

A field study that we conducted in the Cerrados suggested higher use efficiency of chemical fertilizer with maize grown on a 14-year old CA field compared to a 3-year old CA field, but the study was not conclusive, because other factors such as pest attacks may have interfered.

More details in:

- Maltas, A., Corbeels, M., Scopel, E., Oliver, R., Douzet, J.M., da Silva, F.A.M. and Wery, J. (2007) Long-term effects of continuous direct seeding mulch-based cropping systems on soil nitrogen supply in the Cerrado region of Brazil. Plant and Soil 298: 161-173.

- Maltas, A., Corbeels, M., Scopel, E., da Silva, F.A.M. and Wery, J. (2009) Cover crop effects on nitrogen supply and maize productivity in no-tillage systems of the Brazilian Cerrados. Agronomy Journal 101: 1036-1046.

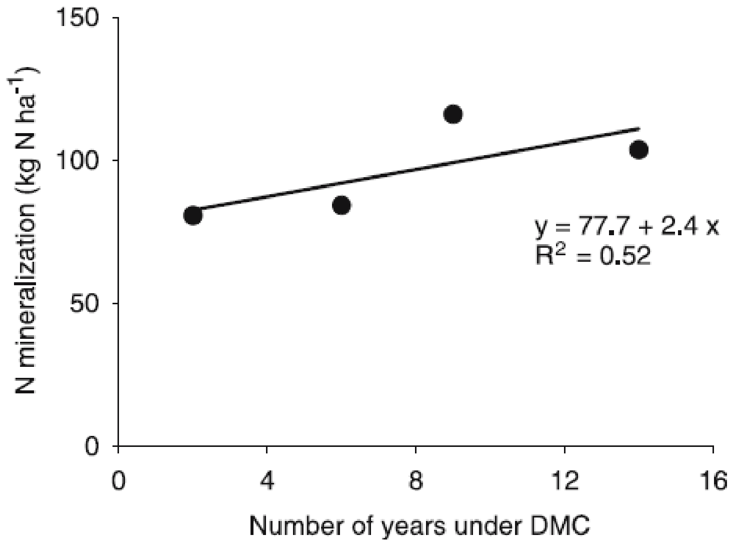

Figure 9. Soil nitrogen mineralization in an Oxisol in the Cerrado region of Brazil during the maize growing season (120 days) estimated from laboratory incubations and corrected for soil temperature and moisture in fields of different ages under direct seeding with mulching (DMC). Source: Maltas et al. (2007).

Impact on soil carbon

We have observed in the savannahs of Brazil and Zimbabwe that rates of decline in soil C when land is converted from forest to agriculture are rapid, with more than 50% of the soil C being lost within 10–15 years depending on climate and soil conditions. A common claim is that no-tillage with residue mulching will halt this decline and leads to accumulation of soil C (e.g. Kassam et al., 2009).
A chronosequence study of fields of different age under CA that we conducted on a clay Oxisols in the Cerrado region of Brazil showed that continuous CA cropping significantly increases organic C in the 0–30 cm topsoil layer with on average 1.9 Mg C ha^{-1} $year^{-1}$ (Fig. 10). This is a high value compared to other studies in the region (Batlle-Bayer et al., 2010), which can be explained by the diverse cropping practices associated with no-tillage. It is clear that no-tillage systems with a second crop have more potential to sequester C than no-tillage systems with only one crop per year. Furthermore, differences

in soil texture also play a role. Clay soils have a larger proportion of stabilized soil C that will be less affected upon tillage, compared to sandy soils (Chivenge et al., 2007).
We used the linked plant-soil G'DAY ecosystem model to separate the effects of tillage and cropping systems and found that increases in soil C are mainly due to increased plant biomass production and retention in CA systems rather than reduced or no-tillage. Thus, benefits of enhanced soil C and soil fertility with CA are more a function of increased inputs of organic matter as mulch, than of no-tillage.
Another important mechanism of increased soil C storage or decreased soil C losses in CA fields compared to conventionally tilled fields is the reduction of erosion under CA due to maintenance of surface mulch. In a field experiment in La Tinaja in Mexico soil C erosion losses were reduced by more than half under CA systems relative to conventional tillage systems. Soil C levels increased with about 25 % over a 5-year period under CA compared with conventional tillage both through increased C inputs and reduced C losses. The increase in soil C under CA principally occurred in the top 5 cm of the soil profile.

More details in:

- Corbeels, M., Scopel, E., Cardoso, A.N., Bernoux, M., Douzet, J.M. and Siqueira Neto, M. (2006) Soil C storage potential of direct seeding mulch-based cropping systems in the Cerrados of Brazil. Global Change Biology 12: 1773-1787.
- Scopel, E., Findeling, A., Chavez Guerra, E. and Corbeels, M. (2005) The impact of direct sowing mulch-based cropping systems on soil erosion and C stocks in semi-arid zones of western Mexico. Agronomy for Sustainable Development 25: 425-432.
- Siqueira Neto, M., Scopel, E., Corbeels, M, Cardoso, A.N., Douzet, J.M., Feller, C., Piccolo, M.C, Cerri, C.C. and Bernoux, M. (2010) Soil carbon stocks under no-tillage mulch-based cropping systems in the Brazilian Cerrado: an on-farm synchronic assessment. Soil and Tillage Research 110: 187-195.

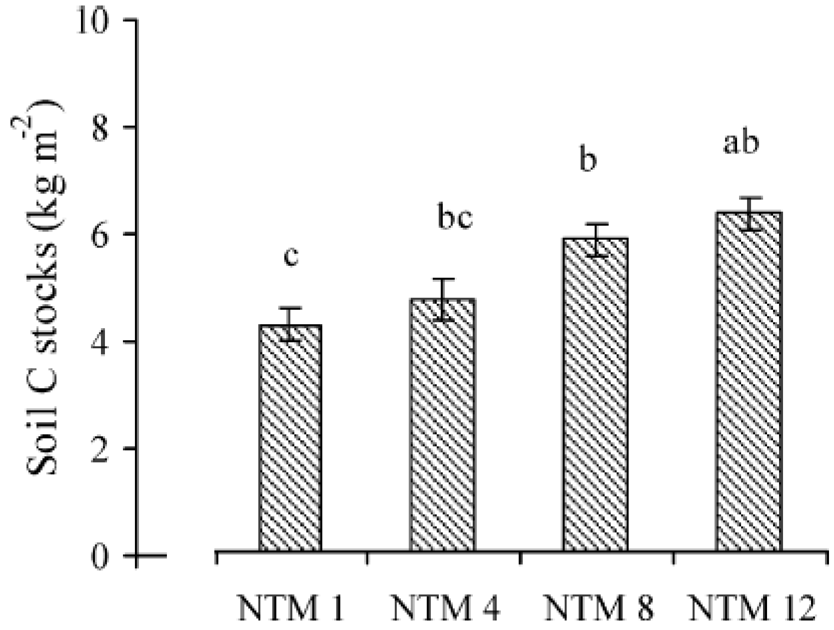

Figure 10. Soil organic carbon stocks (kg m^{-2}) in the top 0–30 cm soil layer under different land-use systems and from fields with different years under no-tillage management (NTM) in the southwest Goias State, Brazil. Treatments with the same letter did not differ using the t-test ($p < 0.05$). Source: Siqueira Neto et al. (2010).

2. Scientific project

The integrated assessment of conservation agriculture practices as sustainable options for smallholder farmers

2.1. Context and objectives

The demand for food will increase substantially in the coming decades. It is estimated that by 2050 human population will have increased to about 9 billion (from 7 billion today). Moreover, many of these people in countries with emerging economies will consume more meat, which requires relatively more kilograms of cereals for feed production. It has been shown that as income grows, so does expenditure on livestock products (Nonhebel and Kastner, 2011). Current food production, expressed in grain equivalent (GE), is estimated at about 7 GT GE. Future demand for the 9 billion people will rise to about 12GT GE (Van Ittersum, 2011). Moreover, demand for biomass for energy purposes is likely to increase dramatically. The increased demands for food, feed and energy clearly require that crop productivity has to increase substantially during the coming decades.

The increase can come from an increase in agricultural area or an increase in the crop yields per ha. There is considerable scope for cropland expansion in Latin America and Africa because many natural ecosystems possess conditions that are suitable for crops. However, conversion of these natural ecosystems into cropland is unwanted give their crucial role in preserving natural habitats and biodiversity, and protecting the climate system. The most legitimate way of increasing production is through higher yields per hectare with a more efficient use of the available resources and without causing environmental damage. Indeed, it is now clear that intensification and specialization of agricultural production accomplished through the use of high-yielding crop varieties, chemical fertilizers and pesticides, irrigation, and mechanization have had a negative impact on the environment and on ecosystem services. Increasing environmental concerns have laid emphasis on the need to more sustainable agricultural practices (Matson et al., 1997). It calls for an ecological intensification of agriculture (Cassman, 1999).

Conservation agriculture is seen as a concept for resource-efficient agricultural crop production that is based on an integrated management of soil, water and biological resources combined with external inputs (www.fao.org/ag/ca/). It is generally claimed that through practicing CA water- and nutrient-use efficiencies of the cropping systems are increased, thereby minimizing nutrient losses to the environment (e.g. Kassam et al. 2009). Conservation agriculture is therefore increasingly considered as a promising alternative for coping with the need to increase food production on the basis of more sustainable cropping practices. As such, it is an option for ecological intensification. With the implementation of CA practices one specifically seek to address the problems of soil degradation resulting from agricultural practices that deplete the organic matter and nutrient content of the soil with higher crop yields and lower production costs (e.g. Gowing and Palmer, 2007; Hobbs, 2007).

Worldwide about 106 million ha of arable land are under CA (Kassam et al., 2009). Conservation agriculture has been a success with large-scale mechanised farmers in countries such as USA, Brazil and Argentina (Table 3). On the other hand, adoption rates of CA by smallholder farmers, especially in sub-Saharan Africa remain low. Some of the reasons for low adoption that were identified from past and on-going CA development and dissemination projects, include: (1) competing uses for crop residues, preventing their availability for mulching; (2) limited access to herbicides necessary to control weed infestation when soils are not tilled; (3) limited access to no-till equipment; (4) the reallocation of labour, especially to weeding, often implying more work for women; (5) the knowledge-intensive nature of implementing CA; and (6) the promotion of CA as a sealed package with little consideration for the diversity of farmers and local practices (Corbeels et al., 2010).

Table 3. Adoption of conservation agriculture for selected countries over the past 30 years (in 1000 ha and in percentage of total arable cropland area in 2009.)

	in 1000 ha	CA % of cropland
Argentina	19719	58.8
Brazil	25502	38.3
Australia	12000	26.9
Canada	13481	25.9
USA	26500	15.3
South Africa	368	2.4
Zambia	40	0.8
Kenya	33	0.6
Zimbabwe	15	0.4
Mozambique	9	0.2
Morocco	4	0.1

Source: Kassam et al. (2009)

To tackle the challenges of the development and dissemination of complex management systems such as CA, I think that we can in part learn from the experiences in Latin America, especially in Brazil. Conservation agriculture was initially introduced in Brazil by progressive (and wealthy) farmers of the southern state of Panama (Ekboir, 2003). In search of finding ways to control severe soil erosion they travelled to the USA to learn about the local no-tillage systems and to purchase direct-seeding equipment. From the southern subtropical states of Brazil the practice of no-tillage expanded to the central tropical region of the Cerrados. No-tillage practices were adapted to local conditions by innovative farmers with problem-solving support from input supply companies, research and extension organizations, universities and international donors. Brazil has also seriously invested in research, and developed technologies to suit smallholder farmers. For example, Brazil is the leading country that manufactures CA equipment for smallholder farmers (e.g. direct seeders for animal traction or hand jab planters).

Farming systems, especially those of smallholder farmers, are highly variable in terms of e.g. soils, production activities and orientation and resource endowment (Giller et al. 2011). From several CA projects with smallholder farmers around the world, it has become evident that CA has to be tailored to their local resource-constrained conditions to make it more suitable to them (Wall, 2007; Giller et al., 2009; Erenstein et al., 2012). This challenge of developing CA practices that are adapted to local conditions demands a close articulation with research activities. The assessment, design and dissemination of CA practices have to be done while embracing the diversity and spatio-temporal variability of smallholder farming systems. Active participation of farmers through action research is necessary to facilitate co-learning and co-innovation around CA. Aspects that need to be considered in the overall assessment of CA practices include: farmers' production objectives and constraints, expected costs (requirements in terms of inputs, equipment, labour but also knowledge and confidence about the performance of CA), benefits (especially in the short term), and production and financial risk of CA, input supply and marketing, and technical advice (Erenstein, 2003; Giller et al., 2009; Mazvimavi and Twomlow, 2009).

The general objective of my research project is to assess CA systems as viable and sustainable options for smallholder farmers - that is, options that are technically sound, economically attractive, and socially acceptable. This demands research from a multi-scale, multi-stakeholder and interdisciplinary perspective.

To do this, different system-analytical methods are employed, combining participatory research, farm typologies, data mining, experiments and modelling tools to identify the feasibility, impact and trade-offs of implementing CA in the short and long term. Simulation modelling has an important role to play in the evaluation (and design) approach of cropping systems, through its use in prescriptive studies (projections, predictions, and explorations), scenario analyses, and in our understanding of when and whether local adaptation of CA principles may be an appropriate way to address the needs of smallholder farmers. In general, simulation models have become important tools for assessing, *ex ante*, the impact of new technologies, policy interventions and climate change on agricultural systems. **Thus, the *ex-ante* identification of situations where, when and for whom CA works and which form of CA is appropriate to the local farmers forms the core of my research.**

My research project contains four specific research axes which receive attention in my current projects or for which I plan new activities. These are:

1. **At field scale: a better understanding of the short- and long-term crop yield responses to CA**
2. **Quantifying the trade-offs at farm scale and above with the implementation of CA**
3. **Understanding the farming context: pre-conditions and constraints to adoption of CA**
4. **Quantifying the potential of CA to mitigate climate change effects on crop productivity**

Research axis 1 concentrates on the agro-ecological dimension of CA as a strategy for sustainable cropping; whilst research axes 2 and 3 deal with the socio-economic and institutional dimensions of sustainability, which -at least- are equally important for the successful adoption of CA as a sustainable cropping practice by farmers. Research axis 4 addresses an important aspect of sustainability, i.e. resilience of agriculture production to climate change.
It is clear that the four research axes show close interlinks and together form the basis for an integrated assessment of CA as a viable and sustainable option for smallholder farmers. It contributes to answering the questions where, when and for whom CA works and which form of CA is appropriate to the local farmers.

These research topics respond to the mandate of the research unit *Systèmes de Culture Annuels* (SCA - 102) of CIRAD, and in particular to the priority research axes of the CESCA team (*Conception et Evaluation de Systèmes de Culture Annuels*) that are the quantitative analysis, evaluation and design of agro-ecosystems.

After a brief description of the general methodological framework and tools applied in my research work, I will deal with the four research topics. In presenting these, examples of currently on-going or recently past research conducted will be presented.

2.2. The general methodological framework and tools

How can research respond to the multiple challenges of evaluating and developing CA practices that are viable and adapted to the local conditions of smallholder farmers? It must consider the multiple scales (field, farm and regional scales) at stake as represented in Figure 11, in which technical performance of CA (i.e. the field scale) is but one of the criteria for CA assessment and design. At each scale, factors exist that determine whether or not CA is a viable option to farmers, leading to adoption.

Each scale has its own analytical tools or models for analysis. The performance of CA at *field scale*, may be assessed using biophysical crop-soil models such as APSIM (Keating et al., 2003), DSSAT (Jones et al., 2003), or STICS (Brisson et al., 2003). At *farm and village scales*, trade-offs in the allocation of resources (e.g. cash, labour, land, nutrients) become important in determining how CA may fit into a given farm. Introducing CA often implies a profound alteration of resources flows at farm scale, where e.g. several competing uses for crop residues exist (e.g. organic fertiliser, fodder, fuel or construction material). Models that recognize the heterogeneity of farming systems and allow to explore trade-offs between different options at farm level may be used to assist our understanding and ability to target technologies such as CA within complex farming systems. Trade-off analysis can be done using simple models of crop-livestock farming systems, with bio-economic household models or with biophysical dynamic simulation models coupled with optimisation algorithms and objective functions representing farmers' priorities. Land use problems and competing uses for crop residues among different types of farmers also require analysis at the village scale, at which negotiations for land use and resource allocation take place. At this scale multi-agent based models can help in analysing the complex actions and interactions of farmers and other actors with a view to assessing their effects on the agro-ecological resources (Bousquet and Page, 2004). At a *regional scale* i.e. farming context or external environment, factors such as the marketing infrastructure and the institutional dimensions become important (Ehui and Pender, 2005). These latter factors and others can be analysed with qualitative expert-based assessment tools.

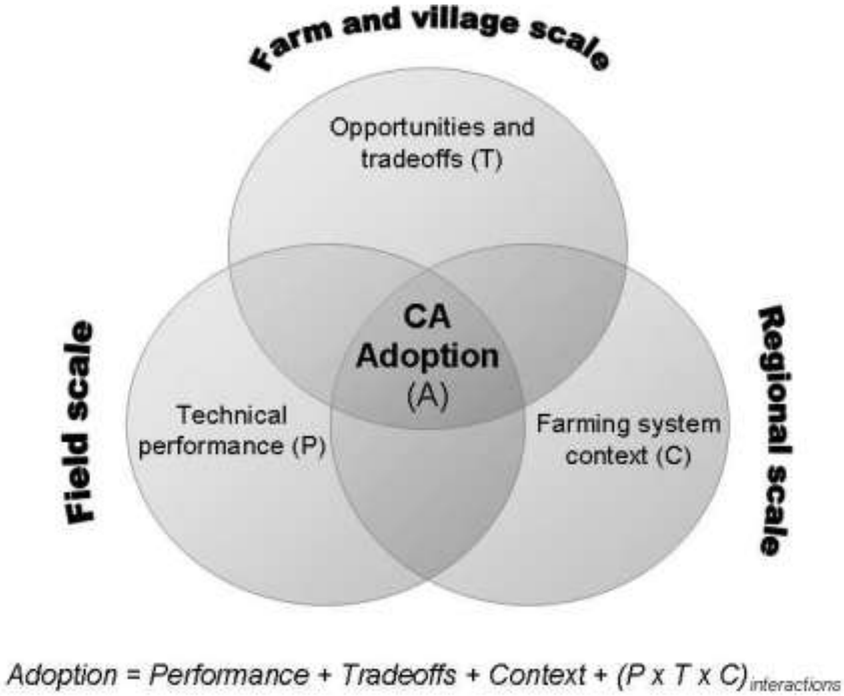

Figure 11: *The determinants of adoption of conservation agriculture (CA). Adoption (A) is conditioned by its technical performance (P), subject to the opportunities and tradeoffs (T) that operate at farm and village scales and constrained by different aspects of the context (C) in which the farming system operates, including market, socio-economic, institutional and policy conditions defining the innovation system and the variability inherent to the physical environment (e.g. climate change). These groups of determinants have interactive effects in conditioning the adoption of CA plus several interactions across scales (e.g., the performance of CA at field plot scale on a certain soil type may be conditioned by the amount of crop residues that can be kept as mulch; but these residues may be the only source of fodder for the village herd during the dry season).*

2.3. Research areas

2.3.1. At field scale: a better understanding of short- and long-term crop yield responses to CA

This research axis will deal with the following specific objectives:

(i) To identify the causes of the short-term yield reductions under CA and how they can be avoided

(ii) To better represent the effects of CA on soil-plant processes in process-based crop growth models in order to better simulate (long-term) crop responses to CA

On-going projects:

- *Feasibility of conservation agriculture practices across farming systems: what fits where and when? (PhD project, L. Rusinamhodzi, Wageningen University)*
- *ABACO: Agro-ecology based aggradation-conservation agriculture: Targeting innovations to combat soil degradation and food insecurity in semi-arid Africa (EU funded project)*
- *Understanding the conditions for success and failure of CA in Africa (CCFAS –IFAD funded project)*

Short-term effects of CA on crop yields have been found to be variable (positive, neutral or negative yield responses, Fig. 12). This variability is principally the result of the interacting effects of crop requirements, soil characteristics and climate (Table 4). For example, one of the beneficial effects of CA is improved rainwater use efficiency through improved water infiltration and reduced evaporative water losses. Under conditions where moisture is limiting crop yields, this may improve yields in the short term (e.g. Scopel et al., 2004; Thierfelder et al., 2013). But, under more humid conditions and on poorly drained soils the same effect can cause waterlogging resulting in yield depression (Thierfelder and Wall, 2013).

Short-term positive yield responses are important, because they determine to a large extent the attractiveness of CA to farmers, and some of the negative effects presented in Table 4 discourage the adoption of CA (see Corbeels et al., submitted). This is especially true for resource constrained smallholder farmers, who often have short-term time horizons and immediate needs (see Pannell et al., submitted). Therefore, it is vital to better understand the causes of the often-observed short-term yield reductions and to identify how they can be avoided.

We will conduct a meta-analysis of effects of CA practices on crop yields under rain-fed conditions in sub-Saharan Africa. Through meta-analysis we will contrast and combine results from different CA experiments in the hope of identifying patterns among study results, sources of disagreement among those results, or interesting relationships that may come to light in the context of the different studies. This should allow an increased understanding of under which biophysical conditions CA leads to, respectively, positive and negative short-term crop yield responses.

Depending on the mulch of crop residues and crop and site-specific characteristics, some productive benefits from CA accumulate over time as mulching arrests soil degradation and gradually improves the soil in biological, chemical and physical terms (e.g. Erenstein, 2002; Scopel et al., 2005). Therefore, crop yield responses to CA over a longer time period tend to be neutral to positive (Fig. 12). Retention of crop residues under CA is expected to increase soil C compared to conventional, tillage-based cropping where residues are taken from the field. This is seen as an important process explaining the increased soil productivity and crop yields over time under CA compared to the conventional systems (e.g. Hobbs, 2007). Crop growth simulation models have been used to simulate and predict these long-term effects on crop yields under CA (Sommer et al., 2007; MacCarthy et al., 2009). Whether these models capture all the major mechanisms involved remains, however, an open question.

We used the crop growth model DSSAT (Jones et al., 2003) to simulate maize yields from a 6-years experiment conducted by CIMMYT on a Lixisol at the Monze Farmer Training Centre (16° 24’ S, 27° 44’ E, 1103 m.a.s.l.) in Zambia (Thierfelder and Wall, 2009; Thierfelder et al, 2013). The experimental site is characterized by a sub-humid subtropical climate with an average annual rainfall of about 750 mm. Rains start in November and end in April. The occurrence of prolonged dry spells during the rainy season is common. Two tillage treatments from the experiment were considered: (1) the conventional tillage (mouldboard plough) treatment (CT) with removal of the crop harvest residues, and (2) the CA treatment with the use of an animal traction direct seeder and crop residue mulching. The data showed significant higher maize grain yields under CA compared to CT during the first, fifth and sixth year of the experiment; soil C was significantly higher in the CA treatment from the third year onwards (Thierfelder et al., 2013). We first calibrated DSSAT against observed data from the CT treatment and then ran the model for the CA treatment. DSSAT uses daily weather, crop and soil parameters as input to predict crop growth and yield. With the model we assumed that the following four soil properties vary with tillage: 1) bulk density; 2) saturated hydraulic conductivity; 3) the soil runoff curve number, and 4) soil water content at saturation. The soil properties after a tillage event are input and they change back to a settled value, following an exponential curve that is a function of cumulative kinetic energy since the last tillage operation. A mulch of crop residues affects three soil water-related processes in the model: 1) rainfall interception by the mulch; 2) reduction of soil evaporation rates, and 3) reduction of surface water runoff. Soil organic matter dynamics were simulated with the CENTURY model (Parton et al., 1987; Porter et al., 2010). The model succeeded to represent the observed yield increases under CA compared to CT, if we assumed a restricted root development under CT resulting in lower water uptake. This assumption was based on the observed root-hampering plough pan under the CT treatment, which disappeared over time under CA.

We then run the model for 40 consecutive years for the two treatments, with generated weather data that were based on observed data (1978-2007) from the Magoye weather station (16° 00′ S, 27° 36′ E, 1027 m.a.s.l). Long-term simulated maize grain yields and soil C are shown in Figure 13. Under CA soil C levels remained more or less constant during the initial years, while under the CT treatment there was a significant decrease, which is in agreement with the observations. According to the model predictions soil C was after 40 years more than 5 tons ha^{-1} lower under CT compared to CA (Fig. 13b). However, this differentiation in soil C levels had no long-term effect on the simulated grain yields. Grain yields were principally determined by the rainfall amounts and distribution, with constantly higher yields under CA compared to CP as a result of the soil moisture conservation effects of mulching (Fig. 13a). From these results we may conclude that– at least for the conditions of the present study- the mechanisms of increased soil C and associated supply of N represented in the model did not explain observed long-term crop yield increases. Our results corroborate the conclusion of a similar modelling study under tropical, semi-arid conditions using APSIM (Probert, 2007), stating that the simulated effects of retention of maize or wheat residues on average long-term crop production are modest. Certainly, CA induces more complex changes in soil properties over time that affect long-term crop yield responses, such as better soil structure and increased soil biological activity, but which common crop growth models do not simulate.

We will aim at a better representation of the complex interactive effects of CA on soil processes and crop growth in crop simulation models – so that long-term responses of crops to CA can be better simulated and predicted.

Table 4. Factors determining potentially positive or negative crop yield responses to implementation of conservation agriculture. Source: Giller et al. (2009).

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
		Increased soil N mineralization
		Increased soil aggregation
Negative	Soil nutrient immobilization	Soil compaction (coarse-textured soils)
	Poor germination	Soil acidity
	Increased weed competition	Aluminum toxicity
	Occurrence of residue-borne diseases	Reduced mixing of organic matter into the soil
	Stimulation of crop pests	
	Waterlogging (poorly drained soils)	

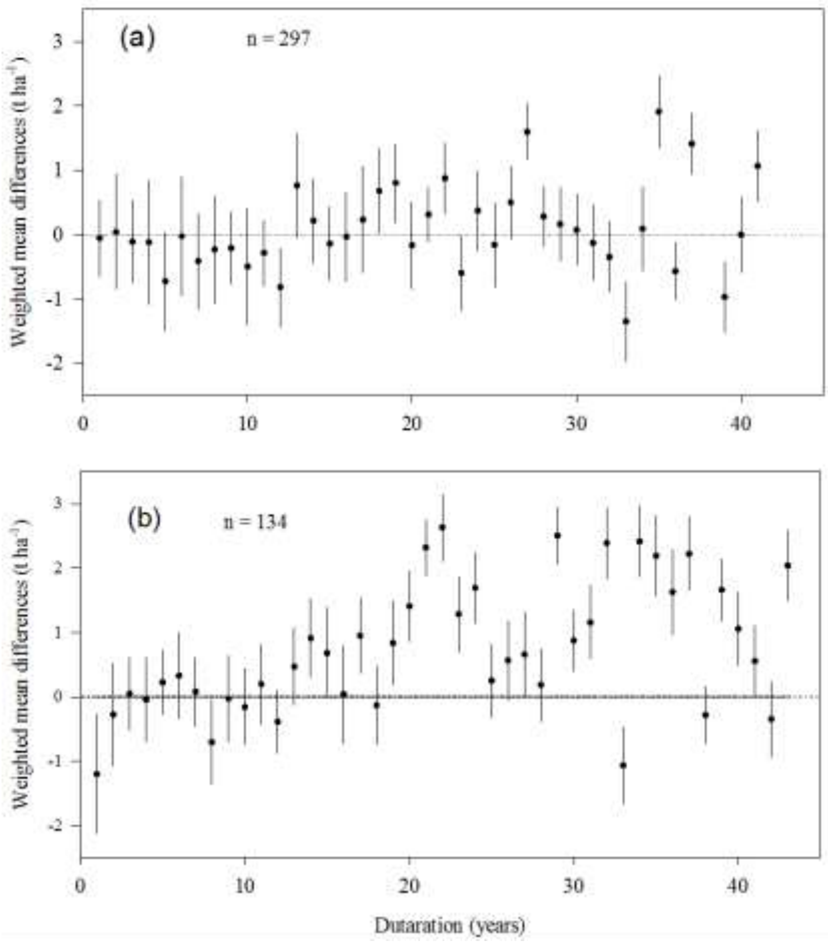

Figure 12. Weighted mean differences in maize grain yield over time between a) continuous no-tillage and continuous conventional tillage and b) between continuous no-tillage including rotations and continuous conventional tillage. Data are from published experiments under semi-arid and sub-humid conditions (adapted from Rusinamhodzi et al., 2011).

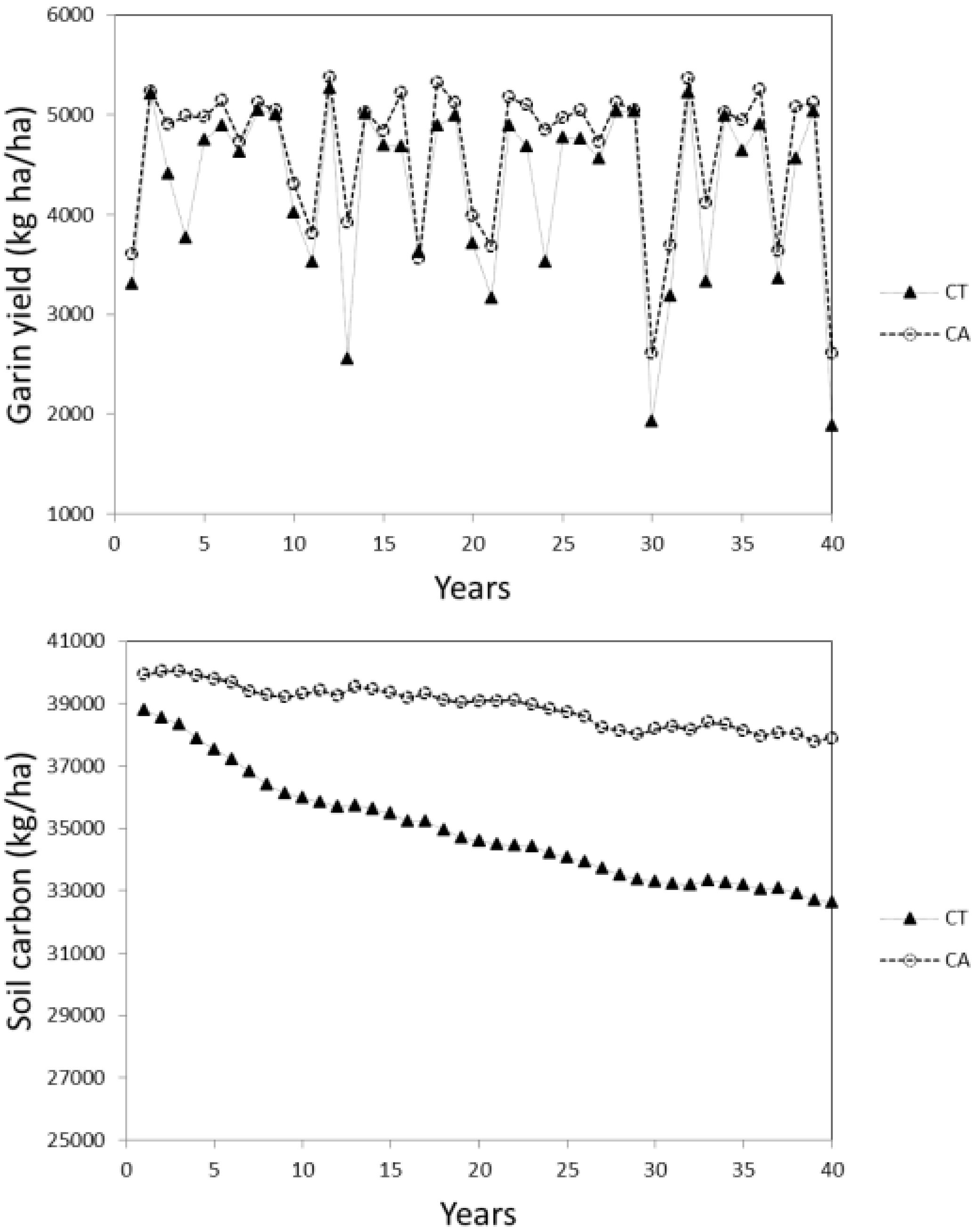

Figure 13. Simulated (DSSAT model) maize grain yields (a) and soil carbon (b) under conventional (CT) and conservation agriculture systems (CA) at the Monze Farmer Training Centre experimental site in Zambia.

2.3.2. Quantifying the trade-offs at farm scale and above with the implementation of CA

This research axis will deal with the following specific objectives:

(i) To analyse and quantify the trade-offs at farm scale that exist with the implementation of CA using a coupled biophysical and socio-economic modelling tool

(ii) To quantify the farm level benefits related to the allocation of crop residues for livestock feed or for soil fertility management in mixed crop-livestock smallholder systems in sub-humid and semi-arid regions of Africa

(iii) To analyse best farm management practices on smallholder farms on the Amazonian pioneers' front that are in compliance with current legal requirements to maintain at least 50% of forest cover on the farm property

(iv) To analyse and quantify the impacts of different scenarios of crop residue uses at the village scale on soil fertility and farm productivity

(v) To contribute to the development of modelling frameworks to support community-based management of natural resources

On-going projects:

- *Feasibility of conservation agriculture practices across farming systems: what fits where and when? (PhD project, L. Rusinamhodzi, Wageningen University)*
- *Analyse de flux de biomasse et des transferts de fertilité à l'échelle du territoire villageois en Afrique sub-sahélienne: Opportunités d'intégration fonctionnelle agriculture –élevage (PhD project, Tidiane Diarisso, SIBAGHE, Montpellier)*
- *ABACO: Agro-ecology based aggradation-conservation agriculture: Targeting innovations to combat soil degradation and food insecurity in semi-arid Africa (EU funded project)*
- *Post-doc project (CIRAD): The intensification of cropping systems - can it conserve forest resources on farms along the Amazonian transect?*

Trade-offs at the farm scale

The implementation of CA requires a number of substantial changes in farming practices, with the magnitude and value of the changes likely being household specific (Erenstein, 2002). As a result, the practice of CA profoundly alters the flow of resources (nutrients, labour and cash) at the scale of the farm (and above), and hence strong trade-offs exist when implementing CA.

Lack of sufficient biomass for effective mulching due to poor crop productivity or to competing uses for crop residues in crop-livestock systems is one of the major constraints of CA adoption by smallholder farmers in sub-Saharan Africa, especially in sub-humid and semi-arid regions (Erenstein, 2002; Giller et al., 2009). In these parts of sub-Saharan Africa, cereal residues are often the only source of feed available to livestock during the dry season. They are preferentially fed to livestock, because livestock is of great importance for the farm livelihoods for a number of reasons such as: for milk and meat production, for traction, for the manure produced and as an investment and insurance against risk. In many mixed crop-livestock farming systems of Africa keeping crop harvest residues on the field as soil cover, and thus not feeding them to livestock, would result in strong trade-offs in livestock production. Even, the crop residues from farms that have little or no livestock are grazed in their fields or sold as feed.

A deeper understanding of how farmers prioritize the competing uses for crop residues and what the resulting effects are on farm productivity is required. The analysis of trade-offs in crop residue use at farm scale can be done using bio-economic household models (e.g. Affholder et al., 2010) or with biophysical dynamic simulation models coupled with optimisation algorithms and objective functions representing farmers' priorities (Tittonell et al., 2007).

We started exploring these trade-offs using a simple model of crop-livestock production for a case study in the semi-arid Zambezi Valley in northern Zimbabwe. This is a region that is characterized by low rainfall (450-650 mm) with severe dry spells during the growing season, resulting in low crop biomass production levels and high pressure on the crop residues (Baudron et al., submitted). Sorghum, maize and cotton are the main crops grown on the farms in the region. The Crop-Livestock Interaction at Farm-scale (CLIF) model was built to analyse the trade-offs and synergies that exist between crop and livestock production. Field and farm data were collected from surveying 176 farms in the study region. The interactions between the crop and livestock subsystems of the farms in the study region that were considered were: (1) cattle feeds during the dry season on sorghum harvest residues not retained as soil cover on the fields; (2) cattle provides manure for increased sorghum production, and (3) cattle provides traction for land preparation and weeding, i.e. the area of cropland of a farm is a function of the number of cattle. As expected, the number of cattle that can be kept on a farm per unit area of sorghum is strongly and negatively correlated with the fraction of sorghum residues retained as soil cover on the field (Fig. 14a). Since crop growth is limited by N, fertilization with N has an effect on the relationship. On the other hand, the density of cattle grazing on a field had a small effect on the sorghum yields per unit area (Fig. 14b). According to the model, mulching the field with crop residues had similar effects on crop yields in the long term, as the application of the available manure from cattle. When considering also the role of traction that cattle plays, a positive relationship appeared between cattle number and total crop production of the farm (Fig. 14c and d). For example, the model predicts that a farm produces an average of 3.2 tons of grains (no cotton) with no cattle, 2.9 tons of grains and 4.7 tons of cotton with two cattle heads, and 3.5 tons of grains and 7.9 tons of cotton with four cattle heads in the case of low N fertilization. These results illustrate the key importance of cattle traction in the study area. Cultivating an area as large as possible is an important risk adverse strategy that farmers adopt in this region, where farming is more constraint by labour than by land. It is clear that in this context, crop harvest residues are in the first place fed to cattle, impeding large-scale dissemination and adoption of CA practices with crop residue mulching.

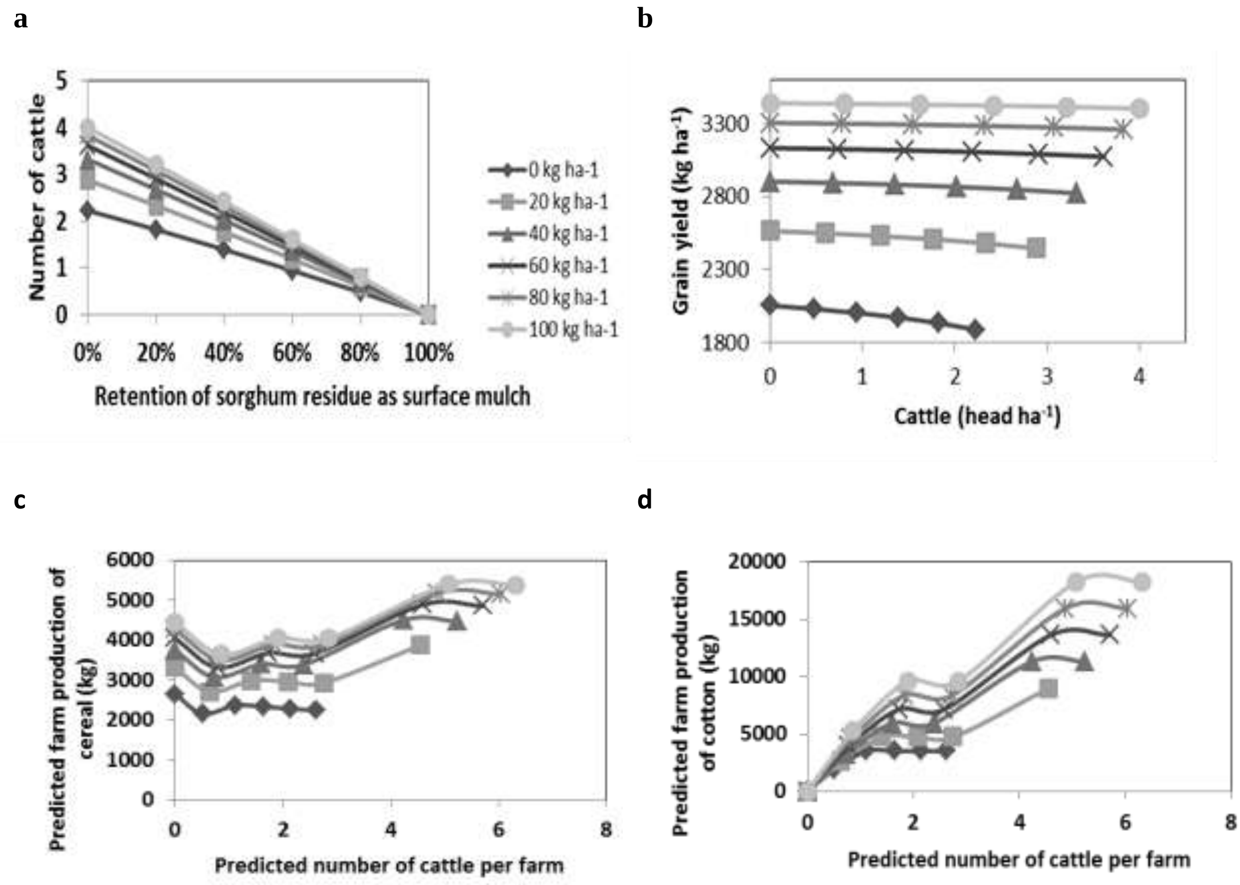

Figure 14. (a) Number of cattle that can be fed during the dry season on crop harvest residues per surface area of sorghum; (b) sorghum grain yield as a function of the number of cattle sustained per surface area of sorghum; (c) farm production of cereals as a function of number of cattle owned by the farm, and (d) farm production of cotton as a function of number of cattle owned by the farm. Results apply to smallholder farms in the Zambezi Valley in northern Zimbabwe and were obtained with the Crop- Livestock Interaction at Farm-scale (CLIF) model and for different levels of nitrogen fertilization. (adapted from Baudron et al., submitted).

In further research we will use the more complex NUANCES-FARMSIM model (Van Wijk et al., 2009, Fig. 15) to simulate and understand the trade-offs in the use of available resources on smallholder farms. The basic approach used in the NUANCES-FARMSIM model is that of the use of the hierarchy in growth and production factors and of the determination of efficiencies to define production levels (Van Ittersum and Rabbinge, 1997; Van de Ven et al., 2003). Different sub-models are combined in NUANCES-FARMSIM (Fig. 15). The sub-model FIELD (Tittonell et al., 2008) simulates crop production and the dynamics of C and nutrients in the soils, and LIVSIM (Rufino et al., 2009) simulates animal production and reproduction of the herd. The models are linked dynamically and management is described using decision rules (Rufino et al., 2011). Manure accumulation and C, N and phosphorus dynamics of manure are simulated using the HEAPSIM sub-model (Rufino et al., 2007). We will further develop the model to incorporate socio-economic aspects, in particular labour constraints and cash flows.

We will apply the model to a case study of mixed crop-livestock farming systems in north eastern Zimbabwe to quantify the farm level benefits related to the allocation of maize crop residues for livestock feed or for soil fertility management (Rusinamhodzi et al., in prep). The hypotheses are that under the smallholder crop-livestock systems in Zimbabwe, non-livestock owners can re-build soil fertility and crop productivity best by retaining crop residues in the fields, while livestock owners can derive the most benefits if they offer crop residues to livestock and use manure for soil fertility replenishment.

In work in Brazil, we will apply NUANCES-FARMSIM to analyse best farm management practices on smallholder farms on the Amazonian pioneers' front. The study area is located in Uruará on the Transamazon Highway in the state of Pará. This region stands for one of the most prototypical colonization efforts in the Brazilian Amazon, which represents four decades of frontier and colonization dynamics and where family agriculture on small properties is the most prevalent land-use model. Currently, farmers rely heavily on the practice of slash and burn for their soil fertility management, releasing in the form of ashes the nutrients accumulated in forest biomass. This practice is often regarded as being the main cause of soil degradation and deforestation. The present extension of protected areas (over 50 %, in the state of Pará) tends to block the expansion of the traditional frontiers operating at the expense of the forest preservation on the farms. The challenge is therefore to make agricultural production more profitable per unit area, including the development of forest products (wood and non-wood products). A sub-model for forestry production and forest products (wood and non-wood) will be developed and integrated into NUANCES-FARMSIM.

A better integration of the crop-livestock and forestry subsystems of the local farms has high potential to increase resource-use efficiency and profitability of the farm. Conservation agriculture is here also seen as an option for ecological intensification. The restoration of soil fertility is a key element of the success of CA in terms of productivity and impact on the environment. The hypothesis is that CA practices without the use of fire are a viable option for family farmers in the Amazon, when they are designed to fit within their specific socio-ecological contexts. They improve land-use efficiency and present potential for agricultural frontier stabilization, in compliance with current legal requirements to maintain at least 50% of forest cover on the farm property.

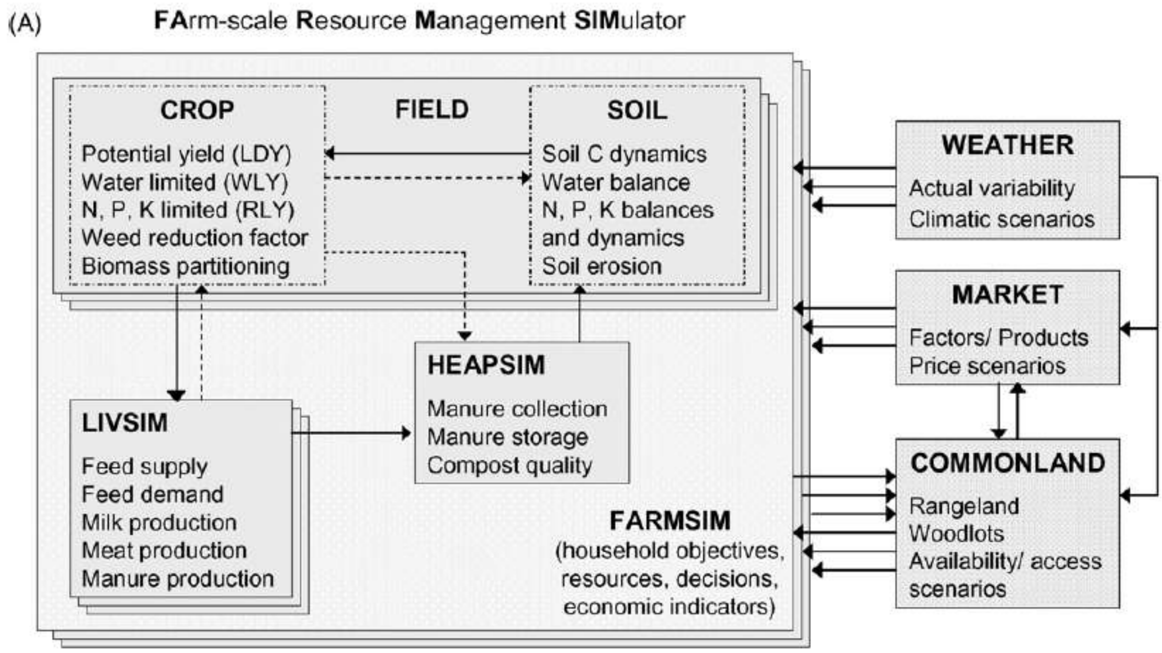

Figure 15. Schematic representation of the relationships between the different modules of the NUANCES-FARMSIM model. The various modules simulating soil-crop (FIELD), livestock (LIVSIM) and manure storage (HEAPSIM) dynamics are functionally integrated through C and nutrient flows (full and dotted black arrows). The household module dictates management and allocation of the various farm resources, represented by land, labour, water, nutrients and financial resources (grey arrows). Different instances of FIELD and LIVSIM represent the various crop and livestock activities on the farm, while different instances of FARMSIM represent different farm types in a community. The different modules run in parallel, updating information and capturing feedbacks at each time step. Climate and market conditions are driving variables to the farm system, affecting also the availability of common resources at village scale (COMMONLAND). Off-farm opportunities and income are elements of the wider livelihood system, within which the farm system operates. Source: Tittonell et al. (2010).

Trade-offs at the village scale

In many regions of Africa, especially in the agro-pastoral farming communities, livestock are allowed to graze freely on the fields after crop harvest. The traditional common right of free grazing makes that crop residues are non-private products for farmers. Negotiations for allocation and use of crop harvest residues take often place at the village scale, and communal decisions on the use of crop residues may override the effects of individual management. It is evident that under this situation the competition for residues between use for soil fertility replenishment and for livestock feed is even more pronounced. Commonly, cattle owners graze their herds during the day on the fields of non-cattle farmers and then collect the manure produced during night kraaling near their homestead to fertilize their own fields. This implies a net transfer of C and nutrients from non-cattle farmers to cattle owners, at the expense of soil fertility decline in the fields of the former. Thus, the utilization of crop residues as surface mulch in CA systems by individual farmers contradicts the current observations of communal-based management strategies and modifies the flows of biomass, energy, C and nutrients at village scale substantially, prioritizing the crop over the animal production systems and creating severe trade-offs between the different uses and users (e.g. crop farmers versus pastoralists) of crop residues. Such trade-offs must be understood and quantified to support discussions and negotiations between the different (types of) farmers on the use of the available biomass at the village.

Current research is tackling the analysis of these types of trade-offs at the scale of the village in two case studies in Burkina Faso. Demographic growth in the savannah zone of West Africa has led to the quasi disappearance of the traditional practices for management of soil organic matter that were based on shifting cultivation with fallow, or on manure transfer agreements between farmers (Dugué et al., 2004). As a result, organic amendments in the form of crop residues have increasingly become important levers for the management of soil fertility in this zone. However, soil fertility management has often been studied at the scale of the plot. There are few approaches that take into account all the production facilities operated by the farmer at farm level, and even fewer studies exist at the scale of the village. Frameworks for consultation between the various actors involved in natural resource management in the village have been developed in the region (Dongmo et al., 2012), but these approaches do not have tools that allow a prospective analysis of the impacts of the resulting communal decisions on the agro-ecological resource base.

The main objective of the study is to assess the impacts of different scenarios of crop residue uses at the village scale on soil fertility and farm productivity to contribute to the development of frameworks for community-based management of agro-pastoral resources. The methodological approach includes the construction of a multi-agent based model. Multi-agent based modelling is a robust approach for analysing and simulating complex systems involving multiple agents (actors or stakeholders), each with their unique views, perspectives and behaviour. (Bousquet and Page, 2004). As such, it is an ideal tool for analysing participatory management of natural resources, because multiple agents with their own unique style of decision-making can be represented. It also recognizes the strong connections and interactions between and among the actors. The tool can also take into account the unique ways each agent endowed with cognitive abilities perceives, reflects, constructs strategizes, acts and reacts to the changing resource environment as it is impacted by all the actors/agents. Through the modelling of agents' behaviours and interactions, properties emerge that can be observed at the level of the system.

2.3.3. Understanding the farming context: pre-conditions and constraints to adoption of CA

This research axis deals with the following objectives:

(i) To analyse the local conditions and constraints that affect CA adoption

(ii) To provide a simple guide as to where and to whom CA works, or what conditions (spatial, temporal and hierarchical) need to be satisfied if CA is going to go to scale.

On-going projects:

- *Understanding the conditions for success and failure of CA in Africa (CCFAS –IFAD funded project)*

It has been argued that successful adoption of a new technology, such as CA, is pre-conditioned by market mechanisms, social and/or institutional frameworks, policy, and cultural aspects (Sumberg, 2005; Mazvimavi and Twomlow, 2009). We have observed that in many projects that promote CA, these 'higher-scale' conditions for adoption are often poorly considered. In fact, most projects create their own enabling environment for the implementation of CA practices by providing technical and/or financial support (e.g. the purchase of inputs for farmers by the project), but once this stops the majority of farmers revert to their former crop management practices.

To analyse the local conditions and constraints that affect CA adoption, we developed a Qualitative expert-based Assessment Tool of CA adoption (QAToCA, Ndah et al. 2012). The tool assesses the relative CA adoption potential in a given region (or project) and diagnoses the supporting and hindering factors to CA adoption. The tool was built based on conceptual models of innovation systems, diffusion theories and relevant literature. The factors are grouped under seven thematic areas: (1) characteristics of CA as an object of adoption; (2) capacity of promoting organizations; (3) attributes of diffusion strategy; (4) institutional frame conditions at regional level; (5) institutional frame conditions at village level; (6) market conditions at village and regional level, and (7) community's perception at village and regional level. Each thematic area is further declined in a series of operational questions that address the particular factors. QAToCA is meant as a self-assessment tool directed to regional experts, research teams and managers of development projects enabling them to assess their CA project along a systematic list of questions and criteria, to reflect on their CA related activities and to eventually adjust or redesign them on the basis of a more explicit understanding of the problems and opportunities with the development and dissemination of CA. It gives a quick overview of information on the CA status and adoption potential. We have used to tool to analyse CA adoption in seven case studies across Africa (Table 5). For each of these case studies, a one day workshop with multi stakeholders who are involved in the CA development and dissemination activities of the related projects, was organized during which the QAToCA tool was applied.

The overall results of the exercise in terms of rate of potential CA adoption are shown in Table 5. It has to be noted that a high CA adoption potential for some case studies takes into account the likelihood of adoption of the three CA principles, but inclusive with the chance of partial adoption of one or two principles of CA . Most often, farmers experiment and tend to adopt one or two of the CA principles as an eventual entry point to full adoption once benefits are perceived for the enhancement of their personal goals (Triomphe et al., 2007). Farmers go through a learning process before full adoption (Pannell et al., 2006).

The most outstanding observation from the QAToCA analysis in the seven case studies is the recurrent assessment that market conditions for inputs and outputs are not in place for the adoption of CA to take place. This has been evaluated in 6 out of the 7 case studies. Only in the Malawian case study good market conditions are considered to be fulfilled for potential adoption of CA. Probably, this explains to a large extent the success of CA in the Malawian project. Estimates show that Total Land Care (the main implementing organization of the project) has reached out to about 32 000 farmers who are now practicing CA on a total surface area of 12 830 ha (NCATF, 2012). Market conditions scored especially low in the Zimbabwean case study, which obviously is related to the current fragile economic situation in the country. In general, good market conditions should essentially been seen as prerequisite conditions for adoption as they are mostly outside the control or influence of the project. Unless these prerequisite conditions are met, there can be no prior expectation of CA adoption.

The capacity of the promoting organization to develop and promote CA and attributes of CA dissemination strategies' received high scores in most case studies (Table 5). In general the positive appraisal of the CA dissemination strategy can be attributed to the use of participatory learning and extension approaches such as the Farmer Field Schools (Kenya, Tanzania) or the Lead Farmer approach (Malawi), and that were considered as effective for the dissemination of CA by the experts.

More surprisingly, the institutional (political) frame conditions regional (and village) level were evaluated as rather good in several case studies. In most of the study regions, CA is endorsed as a sustainable cropping practice by national and local institutes. In particular, the national governments of Kenya, Tanzania, Zimbabwe, Malawi and Zambia have incorporated CA in their strategic plans for the development of the agricultural sector. The question, however, remains how effective are these institutes and policy that are put in place in promoting CA. More research is needed on the question of public policies and institutional arrangements and factors that support or hinder the diffusion and adoption of innovations.

Looking into the specific factors that may explain adoption or non-adoption of CA, the QAtoCA analysis revealed that, while some are recurrent, others are specific to the region or project. The 'complexity of CA as a practice' came up in three case studies (Kenya, Zambia and Zimbabwe) as a main hindering factor to adoption of CA (Table 5). It has been argued that the number of practices that are required to be changed with CA at the same time necessitates a major transformation in crop and soil management practices (Erenstein, 2002). Conservation agriculture is a knowledge-intensive cropping practice that needs capacity building with farmers and extension services. Other recurrent constraints to CA adoption were the availability and accessibility (cost) of markets for CA inputs (specialized no-tillage implements, (legume) seeds, and herbicides), the availability of social networks for interacting on CA and the competition for crop residues with its use ad livestock feed (see above). The latter was clearly brought in relation with the practice of free grazing – and was by many experts seen as the bottleneck for CA adoption by the smallholders in Africa. The existence and strength of farmers' social networks and local organizations have been shown to be positively related to adoption in a number of studies (Pannell et al., 2006). The availability of basic infrastructure for marketing, which is linked to the overall poor market conditions (see above), was seen as a main hindering factor in the Kenyan case study. In the Tanzanian, Zimbabwean and south-western Burkina Faso case study, the lack of quality control structures (certification) was evaluated as a main constraint for CA adoption. It was related to difficulty to differentiate as to which farmers practice 'full' CA and which ones only partially implement CA or are just involved in some kind of CA-related activities results. The identification of this constraint is probably related to the awareness by the experts that there is a need for optimal management in order to obtain the full benefits from CA. Lastly, the level of administrative set up was seen as a hindering factor in the Zambian case study, while land access, ownership and use, was identified as a main hindering factor for the case studies both in Malawi and Zambia. There is ample evidence that secure land use rights promote investments in land such as with CA or conservation practices in more general (e.g. Neef, 2001).

In future research we will use and further test and develop the QAToCA tool. A set of new case (project) studies will be analysed in project sites from the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), selected upon discussions with the appropriate CCAFS regional program leaders, and in case studies linked to grants from the International Fund for Agricultural Development (IFAD) that focus on the promotion of CA in southern (CIMMYT) and West Africa (ICRAF/ACT). The final aim is to provide a simple guide as to where and to whom CA works, or what conditions (spatial, temporal and hierarchical) need to be satisfied if CA is going to go to scale.

Table 5. Preconditions and constraints for adaption of conservation agriculture in seven case studies in sub Saharan Africa – as assessed by the QAToCA tool.

Case study	Project	Adoption potential	Thematic constraints	Thematic supports	Specific hindering factors (score =0)
Bungoma, Kenya	CA-SARD project, adaptation, development and scaling up of CA systems (direct seeder and jab planter)	82%	-Market conditions	-Attributes of dissemination strategy -Political and institutional framework at regional level	-Complexity of CA -Residue and seed requirement versus availability -Availability of basic market infrastructure
Karatu, Tanzania	CA-SARD project, adaptation, development and scaling up of CA systems (direct seeder and jab planter)	83%	-Market conditions	-Capacity of promoting institutions -Attributes of dissemination strategy	-Availability of quality control structures
CFU, Zambia	Conservation farming unit, Adaptation and scaling up of CA (principally planting basins)	75%	-Market conditions - - Institutional frame conditions at village level	-Capacity of promoting institutions -Attributes of dissemination strategy -Political and institutional framework at regional level	-Cost of CA and liquidity issue -Complexity of CA -Availability of social networks -State/level of administrative set-up -Land access and ownership -Household spatial distribution -Availability of market for outputs -Accessibility of market for outputs -Acceptability of CA by young farmers
South-west Zimbabwe	CIMMYT projects, research and development of CA systems	62%	-Market conditions	-Capacity of promoting institutions -Political and institutional framework at regional level	-Cost of CA and liquidity issue -Complexity of CA -Availability of social networks -Residue and seed requirement versus availability - Machinery requirement versus availability -Flexibility/adaptability -Lack of communication channels -Availability of quality control structures -Availability of market for outputs -Accessibility of market for outputs -Acceptability of CA by young farmers
Central Malawi	CIMMYT and Total Land Care project, research, development and dissemination of CA	87%	- Institutional frame conditions at village level	-Capacity of promoting institutions -Attributes of dissemination strategy -Political and institutional framework at regional level -market conditions	-Land access and ownership
South-western Burkina Faso	PRODS/PAIA pilot project, introduction, adaptation, and dissemination of CA systems	82%	-Market conditions	Capacity of promoting institutions -Political and institutional framework at regional and village level	-Availability of quality control structures
Zai System, Burkina Faso		80%	-Market conditions	-CA characteristics Capacity of promoting institutions -Political and institutional framework at regional and village level	-Availability of social networks -Availability of market for outputs

2.3.4. Quantifying the potential of CA to mitigate climate change effects on crop productivity

This research axis will deal with the following objectives:

(i) To quantify climate change effects on crop productivity through simulation modelling

(ii) To quantify the potential of CA to mitigate negative effects of climate change on crop productivity

On-going projects:

- *Assessing the effect of climate risk on agricultural productivity and on farmers' livelihoods in southern Mali (PhD project, Bouba Traore, Wageningen University)*
- *ABACO: Agro-ecology based aggradation-conservation agriculture: Targeting innovations to combat soil degradation and food insecurity in semi-arid Africa (EU funded project)*

Since the early 1990s the Intergovernmental Panel for Climate Change (IPCC) has provided evidence of accelerated global warming and climate change. The last IPCC report concludes that the global temperature in the last 100 to 150 years has increased by 0.76 ± 0.19°C (IPCC, 2007). Providing evidence of global trends in rainfall is complex because of large regional differences, gaps in spatial coverage and temporal shortfalls in the data. Rainfall generally increased over the 20th century in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia (IPCC, 2007). Furthermore, there is evidence for increases in the frequency of both severe droughts and heavy rains in many regions of the world. Climate change due to greenhouse gas emissions is expected to further increase temperature and alter precipitation patterns. In sub-Saharan Africa, climate change is expected to manifest as an increased irregularity of rainfall, with a stronger impact on the reliability of the onset and duration than on the total amount. This is particularly true for semi-arid regions, where a wider inter-annual variability is recorded.

An analysis of the impacts of climate changes on a global scale from 1980 to date done by Lobell et al (2011) indicates that global maize and wheat production declined by 3.8 and 5.5%, respectively, relative to a counterfactual without climate trends. For soybeans and rice, yield increases in one region and losses in another largely balanced out. Another study based on statistical crop models and climate projections for 2030 (Lobell et al., 2008) indicates that maize production in southern Africa and sorghum in Sudano-Sahelian West Africa are likely to suffer most from yield losses due to climate change. These results demonstrate the importance of short-term climate change for crop production and ask for adaptation strategies to lessen the future severity of climate change impacts on food production.

Although the biggest benefits will likely result from relative costly measures including the development of new crop varieties and expansion of irrigation, relatively inexpensive changes, such as shifting planting dates or switching to an existing drought tolerant crop variety, may moderate negative impacts (Lobell et al., 2008). Conservation agriculture has been suggested as a key low-cost strategy to lessen negative impacts on crop production from climate change (e.g. Kassam et al., 2009). Results from field experiments (e.g. Rockström et al., 2008; Thierfelder and Wall, 2009; Thierfelder and Wall, 2012) suggest that CA systems have a higher adaptability to climate change because of the higher effective rainfall use due to higher water infiltration and therefore minimum surface water run-off and soil erosion as well as greater soil moisture holding capacity. A mulch of crop residues protects the soil surface from direct impact by high-energy raindrops, it prevents surface-sealing, improves soil surface aggregate stability and permeability and thus enhances the infiltration capacity of the soil (up to 50% - e.g. Scopel et al., 1998), while at the same time minimizing soil evaporation (up to 25% - e.g. Allen et al., 1998). Increased soil moisture holding capacity may occur as a consequence of the build-up of SOM. In particular for degraded sandy/coarse soils, this may amount over time to an additional increase of soil moisture holding capacity (up to 40% http://hydrolab.arsusda.gov/soilwater/Index.htm). Through their effects on soil water conservation, CA systems can reduce crop yield variations and productive risk making the crop production system more reliable. As such, CA systems represent a potential strategy to cope with climate variability and may make farmers less vulnerable to climate change. However, very little quantified information exists on interactive effects of climate change and CA on crop productivity and on the potential of CA to mitigate negative effects from climate change.

At one level of climate analyses, research can focus on the probability of climatic events of known importance to farmers such as the start of the growing season, the frequency of dry spells within the season, the frequency of high intensity erosive rainfall events, the impact of prolonged wet spells on plant disease or the length of the growing season itself (e.g. Stern and Cooper. 2011). The outputs of such analyses provide a useful framework for making medium-term strategic choices concerning agricultural practices that are directly influenced by single or a combination of climatic events.

We analysed long-term trends in climate variability and change for southern Mali and related this to long-term crop productivity (Traore et al., in press). Main findings of the study indicate that minimum daily air temperature changed significantly with an average increase of 0.06°C per year during the period from 1965 till 2005, whereas maximum daily air temperature showed no significant change. The start date of the rainy season determines the length of the season, while the start and end date of the rainy season were not correlated. Yields of cotton, sorghum and groundnut were characterized by annual variability without any clear trend over the years. Analyses of climate variables and crop yields showed a significant effect of annual rainfall amount on cotton yield: on average 1 mm of rain is converted into 2 kg of cotton, assuming a linear relationship. However, the relationship looked more like a sigmoid or even step-like function, where there is large variation at intermediate values of total annual rainfall (Fig. 16). The variation in crop yields was related to the rainfall distribution within the rainfall season, with dry spells being key determinants of crop yield. Changes in temperature have no significant effect on crop production. Overall, the study shows that climate change effects are still hard to detect, even over a time series of 30 years.

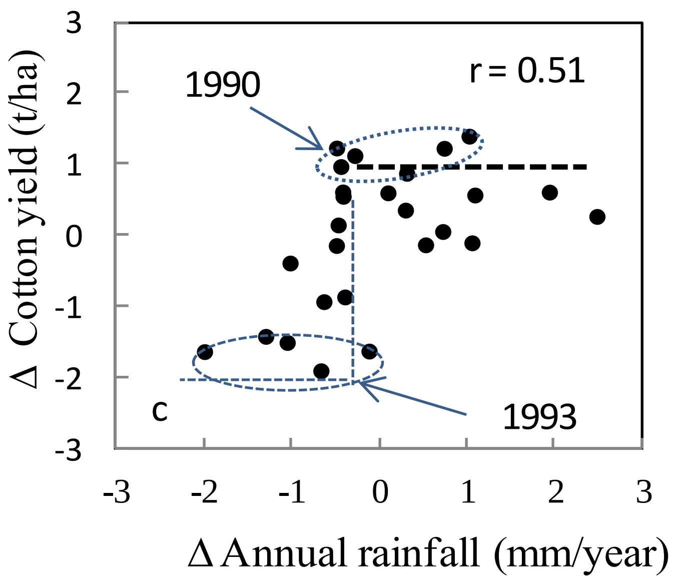

Fig. 16: Changes in mean yields of cotton (t ha^{-1}) against change in minimum temperature, maximum temperature, and annual rainfall in the long-term experiment conducted from 1965 to 1993 at N'Tarla agricultural research station in Mali. Source: Traore et al. (in press).

A further step is the use of process-based crop growth models that integrate the impact of variable weather with a range of soil, water and crop management choices. Such models are widely used to forecast potential impacts of climate change on future agricultural productivity and to examine options for adaptation by local stakeholders and policy makers (White et al., 2011). The models, usually driven by daily climatic data, can be used to predict the impact of medium-term climate variability on the probability of success of a range of crop, water and soil management strategies. The use of such models, with long runs (30 years or more) of daily climatic data thus provides a quicker and much less costly opportunity of 'accelerated learning' compared with the more traditional multi-location, multi-seasonal and multi-factorial field trails.

I have started using crop growth models to predict crop responses to climate change in southern and western Africa. For example, we have used the DSSAT model (Jones et al., 2003) to simulate maize grain yield response to climate change in Zimbabwe. In the region, rainfall is projected to decline by an estimated 10% by 2030 (Lobell et al., 2008). The crop growth model DSSAT (Jones et al., 2003) was calibrated and tested using data from a CA experiment conducted by CIMMYT at the Henderson Research Station (17°35' S, 30°38'E, 1136 m.a.s.l.) near Harare in Zimbabwe (Thierfelder and Wall, 2009). The site is characterized by a sub-humid subtropical climate with an average annual rainfall of about 880 mm. Rain falls during summer from November until early April, but the occurrence of prolonged dry spells that may coincide with critical stages of crop growth, is common. Average annual temperature is about 22°C. The site has a slope of about 5 to 7 % and the soil was classified as a dystric Arenosol. For the modelling exercise, two tillage treatments were considered: (1) the conventional farmer's practice of ploughing the soil to a shallow depth (10 to 15 cm) without retention of crop residues (CT); (2) the no-tillage practice using a direct seeder with retention of crop residues (about 2 ton DM ha-1) on the soil surface (CA). We ran the model to simulate maize yields for water-limited conditions under the present climate using 45 years of daily climatic data (baseline scenario, BS) from Harare and under three plausible future rainfall scenarios for the region. These were: (1) a 15% decrease in annual rainfall, RS; (2) a 15% increase in the duration of dry spells, DS; and (3) the combination of scenarios 1 and 2, RDS. Each scenario also comprised a temperature increase of 1.1°C. The scenarios were constructed using the stochastic weather generator LARS-WG (Semenov and Barrow, 1997). We predicted water-limited maize grain yield for the Henderson site under the 4 weather scenarios (including the baseline climate) and for the 2 tillage treatments (CT and CA) over 45 years. Planting date was during the last week of October. Under the baseline scenario simulated maize grain yield was on average about 720 kg ha^{-1} higher under CA than under CT (Table 6). This was mainly due to increased water availability as a result of decreased runoff under CA compared to CT. Predicted yields varied broadly, from a minimum of 1003 kg ha^{-1} to a maximum of 6483 kg ha^{-1} depending on seasonal rainfall amount and distribution. As expected, average grain yields for both tillage practices were lower for future climate scenarios (Table 6). The simulation results indicate that the impact of a 15% increase in the duration of seasonal dry spells (DS scenario) is at least as large as that of a 15% decrease in annual rainfall (RS scenario). Under the RDS scenario of decreased rainfall with longer dry spells, the model predictions suggest a decrease in maize grain yields of about 25 to 30%, which is in agreement with the value (30%) projected for southern Africa in a broad-scale analysis by Lobell et al (2008). The cumulative distribution functions of simulated maize grain yield for the BS and RDS climate scenarios under CT and CA are presented in Figure 17. Under the current climate the probability of producing at least 3000 kg ha^{-1} grains is 41 and 67% for respectively CT and CA. Under future climate, due to water stress the probability drops to respectively 15 and 43%. The results indicate that the negative impact of climate change can be mitigated by adopting CA in the 'normal' years, but with a higher risk of lower yields in the 'good' and 'bad' years.

In current research, we are refining the above climate change scenarios (using IPPC projections and projections based on, respectively, yearly and monthly historical trends), and also including other sites in southern Africa (Chirat et al, in prep) and West Africa (Bouba et al., in prep).

Table 6: Effect of climate change scenarios on maize yield (kg ha^{-1}) as simulated using DSSAT under conventional tillage (CT) and conservation agriculture (CA) for the Henderson site nearby Harare, Zimbabwe. Variation coefficient in parenthesis

	BS	RS	DS	RDS
CT	3107 (0.39)	2607 (0.35)	2577 (0.41)	2254 (0.43)°
CA	3830 (0.35)	3166 (0.34)	3328 (0.37)	2832 (0.40)

BS: baseline weather scenario
RS: a 15% decrease in annual rainfall,
DS: a 15% increase in the duration of dry spells
RDS: the combination of scenarios RS and DS.

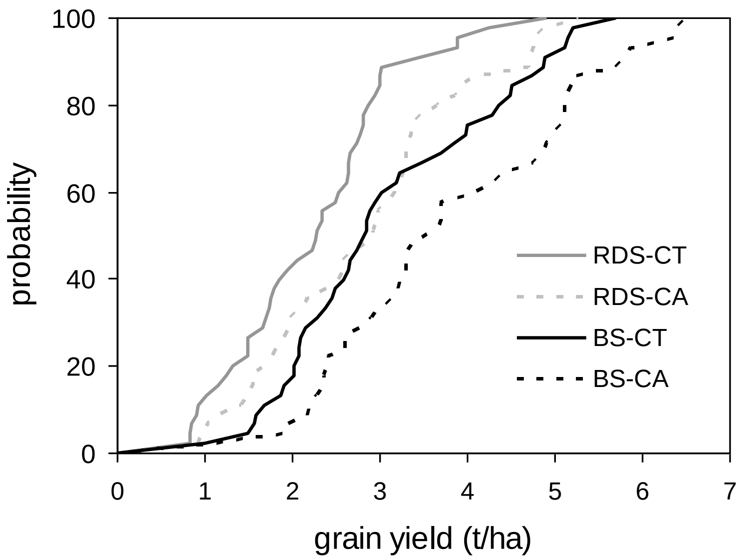

Figure 17. Cumulative probability functions of maize grain yield as simulated by DSSAT for the BS (baseline weather) and RDS (15% decrease in annual rainfall and 15% increase in the duration of dry spells) climate scenarios (45 years) under conventional tillage (CT) and conservation agriculture (CA) for the Henderson site nearby Harare, Zimbabwe.

This type of simulation modelling can be very useful in answering a wide range of ‘what if’ questions in the context of climate variability and change in any given location, mirroring the questions that are frequently asked by farmers. In this way it can contribute directly to enhanced and more resilient coping and adaptive strategies by providing valuable insights and answers in more quantitative terms. Indeed, experience in Zimbabwe and elsewhere has shown that providing ‘on the spot’ answers to farmers’ climate risk management concerns through the use of laptop computers and simulation models aroused enormous interest amongst farmer groups and has great potential to directly help farmers in their decision making (Dimes et al., 2003).

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Van Wijk M.T., Tittonell P., Rufino M.C., Herrero M., Pacini C., de Ridder N. and Giller K.E. (2009) Identifying key entry-points for strategic management of smallholder farming systems in sub-Saharan Africa using the dynamic farm-scale simulation model NUANCES-FARMSIM. *Agricultural Systems* 102: 89-101.

Wall P. C. (2007). Tailoring conservation agriculture to the needs of small farmers in developing countries: An analysis of issues. *Journal of Crop Improvement* 19: 137–155.

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Zingore S., Tittonell P, Corbeels M, Van Wijk M.T. and Giller K.E. (2011) Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. *Nutrient cycling in Agroecosystems* 90: 87-103.

4. Curriculum Vitae

Personal information	
First name(s) / Surname(s)	**CORBEELS, Marc**
Address(es)	SHIS QI 26 Conj 6 Casa 3, Lago Sul, CEP 71660-210 Brasilia, DF, Brazil
Telephone(s)	+55 61 35264314 Mobile: +55 61 91974061
Fax(es)	+55 61 33889879
E-mail	corbeels@cirad.fr
Nationality	Belgian
Date of birth	27.03.1965
Gender	Male
Work experience	
Dates	January 2010 onwards
Occupation or position held	Senior researcher
Main activities and responsibilities	- leading an EU-funded research project (7th framework) on impact and adoption of conservation agriculture in Africa; www.CA2africa.eu - developing research and collaboration between Brazil, Africa and France on integrated soil fertility management /conservation agriculture with a systems approach - co-supervising 5 PhD students (Brazil, Mali, Zimbabwe, Burkina Faso) on farming systems research
Name and address of employer	Centre de coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), France- based at Empresa Brasileira de Pesquisa Agropecuária (Embrapa)-Cerrados in Brasilia, Brazil
Type of business or sector	Agricultural research for development
Dates	January 2007 – December 2009
Occupation or position held	Senior researcher

Main activities and responsibilities	- leading research projects on integrated soil fertility management, conservation agriculture – integrating the innovation platforms approach- in Zimbabwe, Malawi and Mozambique at TSBF, Southern Africa - leading simulation modelling research activities at TSBF Southern Africa - workpackage leader 'cropping systems' of an EU-funded research project (6th framework): AfricaNuances www.africanuances.nl - co-supervising 3 PhD students (Netherlands, Uganda, Mozambique) on cropping systems and simulation modelling
Name and address of employer	Centre de coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), France- seconded to Tropical Soil Biology and Fertility Institute of the Centro Internacional de Agricultura Tropical (TSBF-CIAT), Harare, Zimbabwe
Type of business or sector	Agricultural research for development
Dates	February 2002 - December 2006:
Occupation or position held	Senior Research Scientist
Main activities and responsibilities	- conducting research on soil fertility and plant growth, including simulation modelling, in the Cerrados - co-supervising 3 PhDs and MSc research work
Name and address of employer	Centre de coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), France- based at Embrapa-Cerrados in Brasilia, Brazil
Type of business or sector	Agricultural research for development
Dates	December 1999 – January 2002:
Occupation or position held	Research Scientist
Main activities and responsibilities	- conducting post-doctoral research on plant-soil modelling in eucalypt plantations in western Australia and Kerala, India - responsible for the simulation modelling work at the research group
Name and address of employer	Commonwealth Scientific and Industrial Research Organisation (CSIRO)-Division of Forestry and Forest Products in Perth, Australia
Type of business or sector	Forestry research
Dates	May 1997 - December 1999:
Occupation or position held	Assistant-professor
Main activities and responsibilities	- responsible for BSc courses in soil chemistry and fertility - setting up and running a laboratory for soil chemical and physical analyses - supervising PhD and BSc research at Mekelle University
Name and address of employer	University of Gent, Belgium under the VL.I.R. (Flemish Inter-University Council) project 'Strengthening soil and water conservation training and research in Ethiopia' -based at the Department of Soil and Water Conservation of the Mekelle University College (MUC), Ethiopia
Type of business or sector	Agriculture research and education
Dates	May 1991 - April 1997:
Occupation or position held	Research Assistant
Main activities and responsibilities	- setting up and running a laboratory for soil and plant analysis - training of laboratory technicians - organizing field trials on soil fertility management - carrying out PhD research on N fertilizer management for cereals on the Sais plateau, Morocco
Name and address of employer	University of Gent, Belgium under the VL.I.R. (Flemish Inter-University Council) project 'Strengthening of the capability of the Soil Science Department at the National Agricultural School of Meknès (ENA), Morocco'. –5 years based at ENA in Meknès, Morocco.
Type of business or sector	Agricultural research for development

Education and training

Dates: 1993 -1997

Title of qualification awarded: PhD

Principal subjects/occupational skills covered: Thesis Title: 'Nitrogen availability and its effect on water limited wheat growth on Vertisols in Morocco'

Name and type of organisation providing education and training: University of Ghent, Belgium

Dates: 1983 - 1988

Title of qualification awarded: Agricultural Engineer

Principal subjects/occupational skills covered: Agronomy, soil science, statistics

Name and type of organisation providing education and training: Catholic University of Leuven, Belgium

Personal skills and competences

Mother tongue(s): **Dutch**

Other language(s): **French, English, Portuguese**

Self-assessment	**Understanding**				**Speaking**				**Writing**	
European level (*)	Listening		Reading		Spoken interaction		Spoken production			
French	C2	Proficient user	C2	Proficient user	C1	Proficient user	B2	Independent user	B2	Independent user
English	C2	Proficient user	C2	Proficient user	C1	Proficient user	C1	Proficient user	C2	Proficient user
Portuguese	B2	Independent user	B1	Independent user	B2	Independent user	B1	Independent user	B1	Independent user

(*) Common European Framework of Reference for Languages

Social skills and competences:

- Team work: I have worked in various teams in different institutional (Universities, CSIRO, CIAT, CIRAD) and cultural (Morocco, Ethiopia, Australia, India, Brazil, Zimbabwe) settings
- Very good ability to adapt to multicultural environments, gained though my work experience abroad in many countries of Africa, in Brazil, Australia and India.
- Good communication skills gained through my experience as project and team leader

Organisational skills and competences:

- Demonstrated leadership with strong experience in scientific project and team management. (I am currently coordinator of an EU-funded project with 10 partner institutes from Europe and Africa)

Technical skills and competences:

- Trained in project cycle management and monitoring and evaluation of projects and programmes
- Good skills in farming systems analysis research as proven by extensive list of published paper in this field
- Good knowledge of the CGIAR system, without any current commitment in Centres management or projects.

Computer skills and competences:

- Very good command of Microsoft Office™ tools (Word™, Excel™ and PowerPoint™) and good knowledge of computer programming languages: Fortran and C++

Other skills and competences	- Evaluator of several project proposals (international cooperation) for the Flemish Inter-University Council. - Member of the editorial board of Plant and Soil (2004-2009) and Field Crops Research (2009-onwards) - Reviewer for several international journals in the domain of agronomy, soil science, agricultural systems

5. Publications and (co-)supervision of students

5.1. Peer reviewed journals:

-submitted-

- **Corbeels, M.,** de Graaff, J., Ndah, T.H., Penot, E., Baudron, F., Naudin, K., Andrieu, N., Chirat, G., Schuler, J., Nyagumbo, I., Rusinamhodzi, L., Traore, K., Mzoba, D.H. and Adolwa I.S. (2013) Understanding the impact and adoption of conservation agriculture in Africa: a multi-scale analysis. Submitted to *Agriculture, Ecosystems and Environment.*
- Pannell, D.J., Llewellyn, R. and **Corbeels, M.** (2013) The farm-level economics of conservation agriculture for resource-poor farmers. Submitted to *Agriculture, Ecosystems and Environment.*
- Ndah, H.T., Schuler, J., Uthes, S., Zander, P., Traore, K., Mphatso, S.G., Nyagumbo, I., Triomphe, B. and **Corbeels, M.** (2013) Adoption and adaptation potential of Conservation Agriculture in sub-Saharan Africa: results from five case studies. Submitted to *Environmental Management*
- Baudron, F., Delmotte, S., **Corbeels, M.**, Herrera, J.M. and Tittonell, P. (2013) Multi-scale trade-off analysis of cereal residue use for livestock feeding vs. soil mulching in the Mid-Zambezi Valley, Zimbabwe. Submitted to *Agricultural Systems.*
- Andrieu, N, Vayssières, J., **Corbeels, M.,** Blanchard, M., Vall, E. and Tittonell, P. (2013) Multi-level biomass use trade-offs in cereal-based systems of West Africa: a village case study from the Sudano-Sahelian zone of Burkina Faso. Submitted to *Agricultural Systems.*
- Costa Junior, C., **Corbeels, M.,** Píccolo, M.C., Siqueira Neto, M., Feigl, B.J., Cerri, C.E.P., Cerri, C.C., Scopel, E., Lal, R. and Bernoux, M. (2013) Evolution of soil C stocks under no-tillage systems in Rio Verde (Goiás state - Brazil): comparing the synchronic and diachronic approaches. Submitted to *Soil and Tillage Research*
- Pacini, G.C., Colucci, D., Baudron, F., Righi, E., **Corbeels, M.,** Tittonell, P. and Stefanini, F.M. (2013) Combining multi-dimensional scaling and cluster analysis to describe the diversity of rural households. Submitted to *Experimental Agriculture*

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1. Traore, B., **Corbeels, M.,** van Wijk, M.T., Rufino, M.C. and Giller, K.E. (2013) Effects of climate variability and climate change on crop production in southern Mali: Evidence from a long-term experiment. *European Journal of Agronomy* (in press).
2. Rusinamhodzi, L., **Corbeels, M**., Zingore, S. Nyamangara, J. and Giller, K.E. (2013) Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. *Field Crops Research* (in press).

3. Ndah, H.T., Schuler, J., Uthes, S., Zander, P., Triomphe, B., Mkomwa, S. and **Corbeels, M**. (2013) Adoption potential for conservation agriculture in Africa: A newly developed assessment approach (QAToCA) applied in Kenya and Tanzania. *Land Degradation and Development.* (in press)

4. Marsden, C., Nouvellon, Y., Laclau, J.P., **Corbeels, M.,** McMurtrie, R.E., Stape, J.L., Epron, D. and Le Maire, G. (2013) Modifying the G'DAY process-based model to simulate the spatial variability of Eucalyptus plantation growth on deep tropical soils. *Forest Ecology and Management* 301: 112–128.

5. Affholder, F., Poeydebat, C., **Corbeels, M.,** Scopel, E. and Tittonell, P. (2013) The yield gap of major food crops in family agriculture in the tropics: Assessment and analysis through field surveys and modelling. *Field Crops Research* 143: 106-118.

6. Adam, M., Wery, J., Leffelaar, P.A., Ewert, F., **Corbeels, M.** and Van Keulen, H. (2013) A systematic approach for re-assembly of crop models: An example to simulate pea growth from wheat growth. *Ecological Modelling* 250: 258-268.

7. Scopel, E., Triomphe, B., Affholder, F., Da Silva, F.A.M., **Corbeels, M.,** Xavier, J.H.V., Lahmar, R., Recous, S., Bernoux, M., Blanchart, E., De Carvalho Mendes, I. and De Tourdonnet, S. (2013) Conservation agriculture cropping systems in temperate and tropical conditions, performances and impacts. A review. *Agronomy for Sustainable Development* 33: 113-130.

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8. Valadares Xavier J.H., Gomes M.C., Sacco dos Anjos F., Cibeli Ramos de Almeida S., Nascimento de Oliveira M., Scopel E., **Corbeels M.,** Muller A.G. (2012) Metodologia multicritério de apoio à decisão como ferramenta para availiação de sistemas de cultivo de milho. *Cadernos de Ciência & Tecnologia* 29: 89-131.

9. Adam, M., **Corbeels, M.,** Leffelaar, P.A., Van Keulen, H., Wery, J. and Ewert, F. (2012) Building crop models within different crop modelling frameworks. *Agricultural Systems* 113: 57-63.

10. Rusinamhodzi, L., **Corbeels, M.,** Nyamangara, J. and Giller, K.E. (2012) Maize-grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. *Field Crops Research* 136: 12-22.

11. Affholder, F., Tittonell, P., **Corbeels, M.,** Roux, S., Motisi, N., Tixier, P. and Wery, J. (2012) Ad hoc modeling in agronomy: What have we learned in the last 15 years? *Agronomy Journal* 104: 735-748

12. Tittonell, P., Scopel, E., Andrieu, N., Posthumus, H., Mapfumo, P., **Corbeels, M.,** van Halsema, G.E., Lahmar, R., Apina, T., Rakotoarisoa, J., Mtambanengwe, F., Pound, B., Chikowo, R., Naudin, K., Triomphe, B. and Mkomwa, S. (2012) Agroecology-based aggradation-conservation agriculture (ABACO): targeting innovations to combat soil degradation and food insecurity in semi-arid Africa. *Field Crops Research* 132: 168-174.

13. Baudron, F., Andersson, J.A., **Corbeels, M**. and Giller, K. E. (2012) Failing to yield? Ploughs, conservation agriculture and the problem of agricultural intensification. An example from the Zambezi Valley, Zimbabwe. *Journal of Development Studies* 48: 393-412

14. Baudron, F., Tittonell, P., **Corbeels M.,** Letourmy, P. and Giller, K.E. (2012) Comparative performance of conservation agriculture and current smallholder farming practices in semi-arid Zimbabwe *Field Crops Research* 132:117-128

15. Adam, M., Belhouchette, H., **Corbeels, M.**, Ewert, F., Perrin, A., Casellas, E., Celette, F. and Wery, J. (2012) Protocol to support model selection and evaluation in a modular crop

modelling framework: An application for simulating crop response to nitrogen supply. *Computers and Electronics in Agriculture Journal* 86: 43-54.

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16. Moussadek, R., Mrabet, R., Dahan, R., Douaik, A., Verdoodt, A., Van Ranst, E. and Corbeels, M. (2011) Effect of tillage practices on the soil carbon dioxide flux during fall and spring seasons in a Mediterranean Vertisol. *Journal of Soil Science and Environmental Management* 2: 362-369.
17. Nkala, P., Mango, N., **Corbeels, M.,** Veldwisch, G.J. and Huising, J. (2011) The conundrum of conservation agriculture and livelihoods in Southern Africa. *African Journal of Agricultural Research* 6: 5520-5528.
18. Baldé, A.B., Scopel, E., Affholder, F., **Corbeels, M.**, Da Silva, F.A.M., Xavier, J.H.V. and Wery, J. (2011) Agronomic performance of no-tillage relay intercropping with maize under smallholder conditions in Central Brazil. *Field Crops Research* 124: 240-251.
19. Baudron, F., **Corbeels, M**., Andersson, J.A., Sibanda, M. and Giller, K.E. (2011) Delineating the drivers of waning wildlife habitat: The predominance of cotton farming on the fringe of protected areas in the Mid Zambezi Valley, Zimbabwe. *Biological Conservation* 144: 1481-1493.
20. Zingore, S., Tittonell, P., **Corbeels, M.**, van Wijk, M.T. and Giller, K.E. (2011) Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. *Nutrient cycling in Agroecosystems* 90:87-103.
21. Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., **Corbeels, M**., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C. and Vanlauwe, B. (2011) Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agricultural Systems* 104:191-203
22. Rusinamhodzi, L., **Corbeels, M.,** van Wijk M.T., Rufino, M.C., Nyamangara, J., and Giller, K.E. (2011) A meta-analysis of long-term effects of conservation agriculture on maize yields under rain-fed conditions: lessons for southern Africa. *Agronomy for Sustainable Development* 31: 657-673.
23. Giller, K. E., **Corbeels, M**., Nyamangara, J., Triomphe, B., Affholder, F., Scopel, E. and Tittonell, P. (2011) A research agenda to explore the role of conservation agriculture in African smallholder farming systems. *Field Crops Research* 124, 468–472.
24. Da Silva, F.A.M., Scopel, E., **Corbeels, M**. and Affholder, F. (2011) Ajuste e calibração do módulo balanço hídrico do modelo STICS, num sistema de plantio direto de milho-milheto, em condições do Cerrado brasileiro. *Revista Brasileira de Agrometeorologia* 16: 203-213.

-2010-

25. Siqueira Neto, M., Scopel, E., **Corbeels, M**, Cardoso, A.N., Douzet, J.M., Feller, C., Piccolo, M.C, Cerri, C.C. and Bernoux, M. (2010) Soil carbon stocks under no-tillage mulch-based cropping systems in the Brazilian Cerrado: an on-farm synchronic assessment. *Soil and Tillage Research* 110: 187-195.

26. Chikowo, R., **Corbeels, M.**, Mapfumo, P., Tittonell, P., Vanlauwe, B. and Giller, K.E. (2010) Nitrogen and phosphorous capture and recovery efficiencies, and crop responses to a range of soil fertility management strategies in sub-Saharan Africa. *Nutrient cycling in Agroecosystems* 88:59-77.

27. Adam, M., Ewert, F., Leffelaar, P.A., **Corbeels, M.**, van Keulen, H. and Wery, J. (2010) CROSPAL, software that uses agronomic expert knowledge to assist modules selection for crop simulation. *Environmental Modelling and Software* 25: 946-955.

28. Nyombi, K., van Asten, P.J.A., **Corbeels, M**., Taulya, G., Leffelaar, P.A. and Giller, K.E. (2010) Mineral fertilizer response and nutrient use efficiencies of East African highland banana (Musa spp., AAA-EAHB, cv. Kisansa) *Field Crops Research* 117: 38-50

29. Tittonell, P., **Corbeels, M**., van Wijk, M.T. and Giller, K.E. (2010) FIELD – A summary simulation model of the soil-crop system to analyse long-term resource interactions and use efficiencies at farm scale. *European Journal of Agronomy* 32: 10-21.

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30. Nyombi, K., van Asten, P.J.A., Leffelaar, P.A., **Corbeels, M.,** Kaizzi, C.K. and Giller, K.E. (2009) Allometric growth relationships of East Africa highland bananas (*Musa* AAA-EAHB) cv. Kisansa and Mbwazirume. *Annals of Applied Biology* 155: 403-418

31. Giller, K.E., Witter, E., **Corbeels, M**. and Tittonell, P. (2009) Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research* 114: 23-34

32. Maltas, A., **Corbeels, M**., Scopel, E., da Silva, F.A.M. and Wery, J. (2009) Cover crop and nitrogen effects on maize productivity in no-tillage systems of the Brazilian Cerrados. *Agronomy Journal* 101: 1036-1046.

33. Baudron, F. **Corbeels, M**., Monicat, F. and Giller, K.E. (2009) Cotton expansion and biodiversity loss in African savannahs, opportunities and challenges for conservation agriculture: a review paper based on two case studies. *Biodiversity and Conservation* 18:2625-2644.

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34. Tittonell, P., Vanlauwe, B., **Corbeels, M**. and Giller, K.E. (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. *Plant and Soil* 313:19-37.

35. Tittonell, P., **Corbeels, M**., van Wijk, M.T., Vanlauwe, B. and Giller, K.E. (2008) Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of Kenya: explorations using the crop-soil model FIELD. *Agronomy Journal* 100: 1511-1526.

36. Chikowo, R., **Corbeels, M**., Tittonell, P., Vanlauwe, B., Whitbread, A., and Giller, K.E (2008) Using the crop simulation model APSIM to generate functional relationships for analysis of resource use in African smallholder systems: aggregating field-scale knowledge for farm-scale models. *Agricultural Systems* 97:151-166.

-2007-

37. Maltas, A., **Corbeels, M**., Scopel, E., Oliver, R., Douzet, J.M., Da Silva, F.A.M. and Wery, J. (2007) Long-term effects of continuous direct seeding mulch-based cropping systems on soil nitrogen supply in the Cerrado region of Brazil. *Plant Soil* 298, 161-173.

38. Pepper, D.A., Eliasson, P.E., McMurtrie, R.E., **Corbeels, M.**, Ågren, G.I., Strömgren, M. and Linder, S. (2007) Simulated mechanisms of soil N feedback on the forest CO_2 response. *Global Change Biology* 13, 1-17.

39. Tittonell, P., Zingore, S., van Wijk, M.T., **Corbeels, M.** and Giller, K.E. (2007) Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: Exploring management strategies across soil fertility gradients. *Field Crops Research* 100: 348-368.

-2006-

40. **Corbeels, M.**, Scopel, E., Cardoso, A., Bernoux, M., Douzet, J.M. and Siqueira Neto, M. (2006) Soil carbon storage potential of direct seeding mulch-based cropping systems in the Cerrados of Brazil. *Global Change Biology* 12: 1773-1787.

41. da Silva, F.A.M., Pinto, H.S., Scopel, E., **Corbeels, M**. and Affholder, F. (2006) Dinâmica da água nas palhadas de milho, milheto e soja utilizadas em plantio direto. *Pesquisa Agropequaria Brasileira* 41: 717-724.

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perspective. Poster presented at the international symposium on eucalypt productivity EUCPROD, 10-15 November 2002, Hobart, Australia.

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137. Fagroud, M., Van Meirvenne, M. and **Corbeels, M**. (1997). Variabilité spatiale de la texture et conséquence pour la récolte de tournesol dans un champ à Meknès, Maroc. Pédologie-Themata. 2: 61–63.

138. **Corbeels, M**., Hofman, G. and Van Cleemput, O. (1997) Response of rainfed bread wheat to nitrogen fertiliser on Moroccan Vertisols. In: Fertilization for Sustainable Plant Production and Soil Fertility (Eds. O. Van Cleemput, S. Haneklaus, G. Hofman, E. Schnug and A. Vermoesen) 11th International World Fertilizer Congress, 7-13 September 1997, Gent, Belgium, p. 90-100.

139. **Corbeels, M**., Hofman, G. and Van Cleemput, O. (1996) Nitrogen fertilizer use by winter wheat under rain-fed conditions in semiarid Morocco. In: Transactions of the 9th Nitrogen Workshop, Braunschweig, Germany, p. 403-406.

5.4. Supervision of students (since 2000):

- PhD students

PhD	Co-signed publications
1. **Fernando Macena de Silva,** 2004. Parametrização e modelagem do balanço hídrico em sistema de plantio direto no cerrado brasileiro. *Universidade Estadual de Campinas, Campinas, Brazil.* **(Co-supervision)**	24, 41, 47, 115, 127, 128, 129
2. **Marcos Siqueira Neto,** 2006. Estoque de carbono e nitrogênio do solo com diferentes usos no Cerrado em Rio Verde, Goias. *Centro de Energia Nuclear na Agricultura (CENA), Piracicaba, Brazil.* **(Co-supervision)**	25, 40, 110, 122, 125
3. **Alexandra Maltas** 2007. Analyse par expérimentation et modélisation de la dynamique de l'azote dans les systèmes sous semis direct avec couverture végétale des Cerrados brésiliens. *Centre international d'études supérieures en sciences agronomiques (Supagro), Montpellier, France.* **(Co-supervision)**	32, 37, 88, 109, 117, 121
4. **Kenneth Nyombi,** 2010. Understanding and improving East Africa highland cooking banana (AAA-EA) cultivation in Uganda: An experimental and simulation study. *Wageningen University, the Netherlands.* **(Co-supervision)**	28, 30, 105
5. **Myriam Adam,** 2010. Development of a generic crop growth modelling framework. *Wageningen University, the Netherlands.* **(Co-supervision)**	6, 9, 15, 27, 59, 79, 91, 103, 114
6. **Frederic Baudron,** 2011. Integrated evaluation of cotton-based systems in the Mid-Zambezi Valley in Zimbabwe. *Wageningen University, the Netherlands.* **(Main co-supervisor)**	13,14,19,33, 107
7. **Leonard Rusinamhodzi,** 2013. (public defence scheduled for July 2013). Feasibility of conservation agriculture practices across farming systems: what fits where and when? *Wageningen University, the Netherlands* **(Main co-supervisor)**	2, 10, 22, 64, 67, 73, 74, 80, 83, 84, 87

8. Tidiane Diarisso, (public defence scheduled for December 2013). Analyse de flux de biomasse et des transferts de fertilité à l'échelle du territoire villageois en Afrique sub-sahélienne: Opportunités d'intégration fonctionnelle agriculture–élevage. *Université de Montpellier II, Ecole doctorale SIBAGHE, Montpellier, France.* **(Co-supervision)**	72
9. Bouba Troare, (public defence scheduled for March 2014). Climate change in Mali: Effects on famer livelihoods and agricultural productivity. *Wageningen University, the Netherlands.* **(Co-supervision)**	1, 63, 93
***10.* Murilo Rodrigues de Arruda,** (public defence scheduled for June 2014). Understanding the driving forces of land use change and assessing scenarios for sustainable farming in the Brazilian Cerrados: the case of the South-west of Goiás. *Wageningen University, the Netherlands.* **(Co-supervision)**	65
***11.* Pablo Modernel,** (public defence scheduled for December 2016). Evaluation and analysis of environmental impacts of livestock grazing family farming systems in the temperate Pampas of South America. *Wageningen University, the Netherlands.* **(Main co-supervisor)**	

- **MSc students**

	Publications
1. Elisabeth Heagney, 2001. Soil particulate organic matter effects on nitrogen availability after afforestation with *Eucalyptus globulus* in south-western Australia. *University of New South Wales, Australia*.	48
2. Nelia Doucene, 2002. Analyse des effets des systèmes de culture à base de semis direct avec couverture végétale (SCV) sur l'accumulation de la matière organique des sols et sur la productivité des cultures dans les Cerrados brésiliens. *Université de Paris XII, France.*	40, 110, 111, 122, 125
3. Thilo Besançon, 2007. Weeding strategies for maize production in Bukoba, Tanzania. *University of Firenze, Italy*	

4. Alfred Nyambane, 2008. Determination and evaluation of genetic coefficients of dual purpose soybean varieties for the CROPGRO-soybean model using variety screening trials in Kenya. *Kenyatta University, Kenya.*	
5. Pieter Jan Clauwaert, 2008. Analyzing diversity within farming systems in the Mid-Zambezi valley and opportunities for no-tillage systems. *University of Leuven, Belgium*.	19
6. Federico Pancaro, 2008. Comparative analysis of Conservation Agriculture and Conventional Tillage cropping systems using the APSIM model. *University of Firenze, Italy.*	78
7. Tim Franken, 2009. Evaluation of nutrient and water management strategies for increasing maize productivity under irrigation in semi-arid southern Malawi. *University of Leuven, Belgium.*	
8. Luiza Padoa, 2010. Effects of Conservation Agriculture on soil macrofauna and C and N levels in the Cerrado of Brazil. *Université Montpellier II, France.*	66
9. Zied Ahmed, 2011. Identification des possibilités d'intensification écologique des productions végétales dans les exploitations issues de la réforme agraire et en voie de spécialisation laitière au Brésil central, à l'aide de modèles de décision stratégique à l'échelle des exploitations. *Institut Agronomique Méditerranéen de Montpellier, France.*	
10. Eliann Ferreira, 2012. A evolução de longo prazo de estoques de carbono sob plantio direto no Cerrado. *Universidade de Londrinas, Brazil.*	
11. Raymond Kofi Sakyi, 2013. Crop responses to conservation agriculture in sub-Saharan Africa. *Georg-August-Universität Göttingen, Germany.*	