Climatic Risk Analysis
in Conservation Agriculture in Varied Biophysical and Socio-economic Settings of Southern Africa

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List of Abbreviations and Acronyms

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AGRITEX	Agricultural, Technical and Extension Services, Zimbabwe
APSIM	Agricultural Production Systems Simulator
ARC	Agricultural Research Council of South Africa
AU-NEPAD	African Union's New Partnership for Africa's Development
CA	Conservation Agriculture
CFU	Conservation Farming Unit, Zambia
CGIAR	Consultative Group on International Agricultural Research
CIMMYT	International Maize and Wheat Improvement Centre
CIRAD	French Agricultural Research Centre for International Development
COMESA	Common Market for East and Southern Africa
DfID	United Kingdom Department for International Development
FAO	Food and Agriculture Organization of the United Nations
GART	Golden Valley Agricultural Research Trust, Zambia
ICRISAT	The International Crops Research Institute for the Semi-Arid Tropics
IPCC	Intergovernmental Panel on Climate Change
MACO	Ministry of Agriculture and Cooperatives, Zambia
NGO	Non Governmental Organization
PRP	Protracted Relief Programme
REOSA	FAO Regional Emergency Office for Southern Africa
SOFECSA	The Soil Fertility Consortium for Southern Africa
ZNFU	Zambia National Farmers Union

Foreword

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This network paper presents the findings of a study that traces how Conservation Agriculture (CA) has been implemented in South Africa, Zambia, and Zimbabwe and presents the results of simulation models of climatic risk and returns to investment in CA under varied bio-physical and socio-economic conditions.

Decades of conventional farming in southern Africa have seen much of the arable land in the region become prone to severe erosion and general degradation. Moreover, returns to farm investment, particularly in the smallholder sector, are declining as productivity and yields are low. Southern Africa experiences its fair share of devastating climate related natural disasters, droughts and floods. Within and across seasonal variability in rainfall amounts and distribution is another major challenge faced by farmers across the region. Along with direct impacts on crops, such climatic events also destroy other livelihood sources for communities through, for example, the loss of assets such as livestock.

Over the past few decades in southern Africa, there has been a concerted effort to promote sustainable farming through application of CA. With its three key principles of, i) minimizing mechanical soil disturbance, ii) maintaining a permanent organic soil cover and iii) diversifying cropping species grown in sequence or association, CA has the potential to provide a sustainable means of food production and food security. Notably, farmers need to apply these key principles with other good agronomic/management practices. While helping to conserve and regenerate the environment, CA has immense potential for generating income and providing opportunities for "green jobs" at the community and national level.

It is striking that despite several decades of promoting CA in southern Africa, many questions remain as to when and where CA is most appropriate. Farmers, scientists, policy makers and others continue to pose questions related to the appropriateness of CA given the diversity of climates, soils and their fertility, farming practices, crops, and technology transfer platforms in the region. Some of the questions include: Under what circumstances can farmers

reap optimal benefits from CA? What benefits can a farmer expect during the first year of converting to CA and what are the challenges? Can CA reduce the risk of crop losses due to climate variability? What happens if a farmer applies CA and the seasonal rainfall is below normal or variable in distribution? Is there adequate information to guide decision making by farmers and service providers?

This network paper attempts to provide answers to some of these questions. The author applied modelling simulations to disentangle some of the complexities in CA practice. By modelling the causal effects of CA under different rainfall and soil regimes over long periods of time, the author establishes a sound basis for predicting CA performance under the varied environments in southern Africa. Even though the results are derived from information from selected countries the results are broadly applicable, as most countries in the region share similar climatic, environmental and socioeconomic characteristics and challenges. The author has also shown that the risks around CA are not only environment-based but could also arise from the human element, when information and technology transfer is inadequately or poorly done. Risks also arise from inappropriately collected data and this can lead to misconceptions and doubts about the CA intervention.

It is arguably correct to say that the region still lacks adequate empirical data to support intensive modelling on CA. As CA gains greater momentum, it is hoped that improved availability of credible socio-economic, productivity and biophysical data will open up more opportunities to validate information and evidence related to CA suitability and

its appropriateness to farmers in different agro-ecological regions and farming systems in the region. In other agricultural subjects, modelling has proved to be an affordable, yet powerful tool to explore certain complex relationships and generate and extrapolate information for ex-ante in a wide range of situations and conditions.

To gain more insights into the role of modelling in CA decision making, the reader is encouraged to read the full paper which, as far as southern Africa is concerned, is one of the few of its kind on CA. The author couldn't have done all this work without the valuable contributions from members of the Conservation Agriculture Regional Working Group (CARWG) in southern Africa, coordinated by FAO and through which the study was formulated and implemented. In addition, the study was also facilitated by the National CA Taskforces in the three countries as well as farmers, staff from Government Institutes and relevant Parastatals, NGOs, Academic Institutes, Consultative Group on International Agricultural Research Centres [CGIARs], Donors, and FAO offices in the various countries visited and also from some Regional Institutions.

We hope that you will find this study motivating and informative in helping address some of the pertinent challenges and outstanding questions that have hampered wide-scale uptake of the CA intervention in southern Africa.

Cindy F. Holleman
Sub-Regional Emergency Coordinator of
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Executive Summary

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Productivity of rainfed cropping systems in southern Africa is far below potential, due to poor fertility of soils, paltry external resource use and poor quality of rainfall seasons, often associated with prolonged dry spells. Resource-conserving management systems that positively alter the soil-crop environment are perceived to mitigate against the negative impacts of limited access to production resources and climate change. This study sought to trace how conservation agriculture (CA) has been implemented in South Africa, Zambia and Zimbabwe, and define the niches where returns to investment in the context of CA are worthwhile for smallholder farmers under a changing climate. In the region, rainfall is projected to decline by an estimated 30% in the next 50 years. The key guiding question was on how CA (or its components) could be appropriately packaged to reduce climatic risk, in the face of large crop losses linked to soil moisture deficits, a phenomenon affecting millions of farming households in southern Africa.

The study involved interacting with farmers, and research and development practitioners from universities, the Food and Agriculture Organization of the United Nations (FAO), the Consultative Group on International Agricultural Research (CGIAR) centres, non-governmental organizations (NGOs), meteorological service providers and members of the national CA taskforces in South Africa, Zambia and Zimbabwe. Notably, the NGO (non-governmental organization) community in Zimbabwe has actively promoted CA, in the context of the protracted relief programme (PRP) originally funded by DfID (United Kngdon Department for International Development) and then by other development agencies. In Zimbabwe and Zambia, about 90% of the over 200 000 farmers practising CA were using planting basins, and at different residue use or crop rotation intensities. However, in most parts of Zambia and Zimbabwe, strong mixed crop-livestock interactions coupled with poor crop productivity of <3 tonnes ha^{-1} residues at harvest and compounded by termite activity, meant that residues were barely available in the fields by the beginning of the following rainfall season, except for small protected fields around homesteads.

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This also applied to South Africa's Limpopo province smallholder farmers. Reports of increased productivity for CA fields were widespread, strongly linked to early planting and efficient use of fertilizer resources, as well as significantly improved water capture, particularly in semi-arid environments. Farmers practising basins managed to get maize and sorghum yields of >1 tonnes ha^{-1} even in seasons with poor rainfall (<450 mm), in contrast to total crop failure for conventional ploughing. However, much of the positive messages were based on too confounded datasets in which fertilized CA plots were compared to unfertilized conventionally ploughed farmer practice. Though isolated, reports of basins inducing water logging during seasons with high rainfall in clayey soils suggest a need for in-depth research studies on appropriate basin configuration in different areas.

Conservation agriculture has received little external funding in South Africa, with equally little buy-in from policy makers in the past although their interest and support is increasing. Despite this, the Agricultural Research Council of South Africa (ARC) and other stakeholders have made available various CA options to smallholder farmers in the Limpopo, KwaZulu-Natal and the Eastern Cape provinces, without free inputs. Indications are that most smallholder farmers in these regions prefer the hand and animal-drawn mechanized systems (jab planter, rippers), but poor capital investment appears to curtail involvement of more farmers. This is in line with experiences in high potential agro-ecological areas in Zimbabwe where CIMMYT (International Maize and Wheat Improvement Centre) has promoted basic CA mechanization with smallholder farmers, but farmers are as yet to acquire their own CA equipment beyond what the researchers provided for the demonstrations.

Modelling exercises undertaken using the Agricultural Production Systems Simulator (APSIM) model (McCown et al., 1996) with main forcing variables as (i) soil texture (clay or sandy soils), (ii) presence or absence of residues, and (iii) early or late planting, confirmed the benefits of CA components in drier seasons, especially on soils with >30% clay. However,

additional water infiltration in seasons with >700 mm rainfall was not associated with additional crop yield gains. Currently, APSIM routines for simulating water-logged conditions tend to be inadequate. The challenge to effectively manage risk using CA in a practical way revolves around accessing accurate weather forecasts on a scale that can aid decision making, for at least the agricultural extension systems and the NGO community.

There is a dire need to harmonize CA packaging for different typologies of farms and farming system niches, at least at country level. For example, the inadequately trained NGO field staff are one of the major risk sources in CA dissemination, as they train farmers using their own inadequate grasp of CA concepts. This could be addressed through a well-formulated strategy of training for transformation. This would take both farmers and extension agents through a transitional phase of evaluating alternative methods for the different CA components. Adopting a flexible system where CA initiatives are coupled with alternative resource management strategies (e.g. integrated soil fertility management) to allow farmers and development partners to explore and capture diversity of technical innovations generated through participatory and empirical research, will likely stimulate spontaneous uptake of CA. Development of a targeted CA curriculum that adequately treats the theory of the subject together with the practical side, as currently constituted, must be integrated into such a strategy. There are also compelling grounds that point to strategic policy shifts to facilitate the medium to long-term benefits of CA to be realized as CA is not a quick-fix strategy. It is, therefore, recommended that CA initiatives should be at least five years long to allow extension agents and farmers to gain confidence during the often prolonged transitional phase from conventional ploughing.

There was limited availability of empirical data for the CA risk analysis, with most grey data originating from NGOs being unusable. Future CA research initiatives should, therefore, aim to generate more useful empirical data through carefully designed adaptive experiments with communities.

1. Introduction

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Poor access to production inputs, an inherently poor soil resource base, and unfavourable large variations in rainfall seasons have entrenched poor productivity in smallholder farms across southern Africa. Overlaying these socio-economic and inherent biophysical challenges has been the human induced land degradation from years of unsustainable cultivation. The mould-board plough, a basic mechanization tool that is used by smallholder farmers in many parts of southern Africa, has been linked to high rates of sheet erosion, a phenomenon that compromises the fertility of cropped lands. Recently, there have been compounding impacts of the HIV/AIDS pandemic on the capacity of households to produce food, in addition to other disease pandemics. In the face of these many challenges, several initiatives have been put forward to ensure sustained crop production in the smallholder sector. Among such initiatives has been the promotion of conservation agriculture (CA).

Conservation agriculture has gained much publicity in southern Africa, and has been actively promoted by the NGO community, farmer organizations, research institutions, FAO and regional institutions such as AU-NEPAD (African Union's New Partnership for Africa's Development) and COMESA (Common Market for East and Southern Africa), as an ecologically sound vehicle towards food security. Conservation agriculture requires that soil is minimally disturbed, adequate soil cover is maintained, and appropriate crop sequences are followed for efficient nutrient use and cycling. These three principles should be applied in combination with other good agronomic practices such as timeliness of operations and effective weed management. With CA, positive mutually reinforcing feedback is expected as increased water productivity in the face of increasing risks associated with climate change, creates more conducive conditions for farmers to invest and reverse years of soil physico-chemical degradation. Cropping systems in southern Africa are particularly at risk from unreliable rainfall, due to more frequent El Nino phenomenon development in the eastern tropical Pacific. For example, the Intergovernmental Panel on Climate Change (IPPC) projects that rainfall in most of southern Africa will decline by about 30% during the next 50 years (IPCC, 2007).

Experience in the region with smallholder farmers already indicates that strict adherence to the three key principles of CA is challenging. Some of the contributing factors include the past farmer training that rewarded excellent tillage (e.g. criteria for master farmer certification in Zimbabwe), the extent of crop-livestock integration and residue breakdown by termites. Therefore, adapted and niche-based CA alternatives have to be used to increase water productivity, mitigate climatic risks, restore and maintain soil fertility, and provide agro-ecological functions. The poor soil resource base, increasing pressure on land, and poor socio-economic environment curtails significant investments by smallholder farmers towards increased crop production. This calls for farmers to use farming methods, such as CA, that optimize resource-use efficiencies on current cropped lands. This would also reduce encroachment of virgin woodland by communities in search of fertility. CA provides farmers with the opportunity to regenerate and conserve rather than exploit the environments in which they derive their livelihoods.

The initial move for reduced tillage on large-scale commercial farms world-over was driven by the need to minimize crop production costs (fuel, wear and tear of machinery). In southern Africa, initial experimentation with reduced tillage systems on research stations and smallholder farms was based on ripping systems using ox-drawn plough beams mounted with ripper tines, and ridging using animal-drawn high-wing ridgers. Legume-cereal sequences, a key component of what currently defines CA, were seldom integrated in such experimentation. The results of years of study showed that in the short term, reduced tillage systems did not necessarily improve crop yields compared to conventional ploughing, but associated benefits such as reduced soil loss were immediate (Vogel, 1993; Munyati, 1997; Nyagumbo, 2008). Crop performances under these systems, including conventional ploughing, were variable, mainly driven by weather patterns.

Other than the increasing climatic risk that can be mitigated to some extent by CA, there is ample evidence to support that poor soil fertility and soil physical degradation are major limitations to food security in sub-Saharan Africa (e.g. Sanchez, 2002). Conservation agriculture is being promoted to arrest soil degradation and increase productivity with

low production costs (Steiner et al., 1998; Fowler and Rockström, 2001; Hobbs, 2007). This farming system could extricate millions of farmers from the vicious poverty cycles triggered by low rainfall, poor investment and soil degradation, provided (i) technical performance is refined to tackle the variability inherent to the physical environment – particularly climate change, and (ii) tradeoffs operating at the farm, village and community scales are taken into account.

In semi-arid areas, greater water capture through improved soil surface conditions, a more profuse root exploration and higher water retention capacity are essential to boost agro-ecosystem primary productivity, thereby providing the biomass necessary to secure the various CA functions. Experimental evidence has shown vast potential for increased water productivity and crop yields under CA (Rockstrom et al., 2008; Thierfelder and Wall, 2010). However, evidence has also shown potential for CA induced water-logging and poorer yields when there is a combination of high rainfall and perched water table due to some geological formations (e.g. Thierfelder and Wall, 2009). Evidence has been generated in Zimbabwe based on long-term tillage experiments, in which runoff was reduced to between 0% and 4% compared to 20% and 30% under conventional tillage on soils ranging from between 5% and 60% clay (Nyamadzawo et al., 2007; Nyagumbo, 2008). This had a direct positive effect of moderating the expression of dry spells on rainfed crops. Soil loss reduced to <5 tonnes ha^{-1} yr^{-1} by reduced tillage only, even without residue cover. With residues, soil loss was found to be negligible. Such dramatic soil-loss reductions are directly coupled with reduced near-surface soil nutrient losses; though mobile nutrients such as nitrates are expected to be managed better to counter potential increased leaching losses associated with CA enhanced infiltration. Leaching loss is an inherent phenomenon of sandy soils that can be managed through split applications of mineral N fertilizer.

Another key contribution of CA is the potential for enhanced carbon sequestration through increased soil aggregation. This should, however, be interpreted in context. For example, while soils with low clay content are known to have poor capacity to store C (Feller and Beare, 1997), small increases in soil C are known to be associated with significant increases in aggregate stability leading to a dramatic drop in runoff (Elwell, 1986).

2. Conservation Agriculture in Southern Africa

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Implementation of CA in southern African countries is at different stages driven by significant policy shifts in some countries and indifference in others, with support from partners such as FAO. The overarching factor seems to be the level of activity of the NGO community: it has played an advocacy role and strategically lobbied for external funding for the technology. CA has been promoted by NGOs with only little participation from the research community, leading to major knowledge gaps in the technology.

2.1 CONSERVATION AGRICULTURE IN ZAMBIA

The Zambia National Farmers Union (ZNFU) established the Conservation Farming Unit (CFU) in 1995 to develop and promote the adoption of conservation farming (CF) practices by Zambia's small-scale farming community; CF later transformed into CA. In 1999, the government of Zambia endorsed the promotion of CF as part of national extension policy. Since then, there has been proliferation of CA, promoted by NGOs funded by different agencies. The FAO has been instrumental in extending CA to thousands of farmers through working closely with the Ministry of Agriculture and Cooperatives (MACO) extension structures in 14 districts. The Golden Valley Agricultural Research Trust (GART), in conjunction with the University of Zambia, has provided backstopping with vital research components, albeit on a small scale.

Conservation agriculture in Zambia has had more favourable conditions for its uptake than elsewhere in the region, and is being adopted mainly in regions I and II (see Appendix A for details). In much of eastern Zambia where cattle have been decimated by disease, the traditional farming practices have had a lot in common with CA: adjustments are required on crop rotations and residue management. There was explicit recognition of cattle ownership in the development of CA guidelines. Cattle owners could use the *magoye* ripper while an elaborate basin technology using the wide-bladed *chaka* hoe was designed for non-owners to suit all crop types. Tillage is restricted to the precise area where the crop is to be sown (only 5%–15% of the surface area compared to full disturbance under conventional) with tilling depth only

sufficient to break through plough or hoe pans. Land preparation commences soon after harvest and is ideally completed in advance of the rainy season. A key requirement to reap the benefits of CA is the establishment of a precise and permanent grid of planting basins or planting furrows, within which successive crops are planted each year and mineral or organic nutrient resources (and lime at times) are accurately applied (www.conservationagriculture.org). However, the precise location of basins on sandy soils is not guaranteed as they are prone to complete destruction (e.g. during manual weeding operations), raising questions about potentially missing opportunities for capturing the residual effects of the previous year's application of nutrients.

In both categories (basins or rippers) the CFU, through GART, has developed a diversified production model of CA that integrates *Faidherbia albida* trees in the fields in order to reduce reliance on external fertilizer inputs. *F. albida* is an indigenous leguminous tree that has unique reverse phenology characteristics, shedding leaves during the rainy season. The crops directly benefit from N fixation and the decomposing high nitrogen leaves, with the trees minimally extracting soil water due to limited leaf transpiration. Data from GART indicate that soils sampled under mature *F. albida* in farmers' fields had more than double soil organic carbon and available phosphorus under the canopy than away (GART Year Book, 2008).

To date, over 120 000 smallholder farmers are reported to have already benefited from the use of CA in Zambia. In such a country where oil prices are comparatively high, with the associated knock-on effect on prices of many goods and services (transport, fertilizers and equipment), CA principles will most likely appeal to mechanized large-scale farmers who are eager to make a profit and ensure sustained production.

2.2 Conservation agriculture in Zimbabwe

In Zimbabwe, CA out-scaling started as a relief package, targeting vulnerable households. The technology has been promoted extensively through the PRP by more than 25 NGOs, reaching out to almost 130 000 farmers over a four-year period, mainly across three agro-ecological regions (Appendix B). Linking inputs to CA for vulnerable households provided a large pull factor, a tag that to date confounds objective evaluation of the CA technology. Training services of the NGO field staff have been provided by ICRISAT for the semi-arid regions of the country, while the Foundations for Farming (formerly known as the River of Life) has largely provided CA training to organizations implementing CA with communities in the relatively higher rainfall zones of the country. ICRISAT advocates for micro-dosing, an approach that involves efficient use of (at most) a third of the traditionally recommended fertilizer rates. Micro-doses of N fertilizer in the presence of large quantities of cereal residue cover may not be adequate to provide the crops with enough N, as mineral N will be limited in relation to C availability. It is important that when cereal residues are applied as soil cover, N should be applied at rates that provide adequate N for crop growth. The N application rate will depend on type and quantity of cereal residues, soil type, and temperature and rainfall regimes.

In Zimbabwe, the national CA taskforce maintains a database on NGO interventions, assesses areas that need to be explored, and coordinates key initiatives for efficient resource use by different players. Indications are that over 90% of smallholder farmers practising CA are involved with basins. The task force has produced extension guidelines on CA, with the Zimbabwean basin configuration of 15 cm × 15 cm × 15 cm being different from the 15 cm wide × 20 cm deep × 30 cm long basin design being promoted in Zambia. As mentioned in the manual, the crop rotation component of CA was vaguely attended to by the implementing NGOs. This is probably not surprising as an analysis by Mapfumo et al. (2001) showed that although farmers indicated their normal crop sequence was legume-cereal-cereal, the actual area sown to legumes was less than 5% of the cropped area. This can be partially explained by a combination of the lack of viable legume grain markets and the need by farmers to satisfy their staple food before they can diversify with legume crops.

Box 1: A CA success story in Gauteng, South Africa

Ten years ago, Mr Willem van der Walt, a commercial farmer in Limpopo province, decided to convert to CA after reading about the system in an Australian farming magazine. Out of 5 000 ha, the farmer initially experimented with 4 ha only. Total conversion to CA took four years due to necessary gradual changes to equipment tailored for CA systems. After ten years, an elaborate CA system has been developed which incorporates all three principles of CA (minimum soil disturbance, residue cover and crop rotations). Over the last ten years, compacted tractor wheel paths have been carefully maintained, with the rest of the cropped land now having friable soil with abundant soil biota. Normally difficult soils to work under either wet or dry conditions, the predominantly vertisols on the farm have been maintained amazingly friable. The farm has significantly increased soil water storage as evidenced by reduced runoff into a dam that the farmer shares with a neighbour. Drainage characteristics changed in a manner that attracted the attention of the neighbours, who initially protested about being deprived of potential water inflow to the dam, before they also decided to pursue the CA option. The farmer indicated that his harvests were more stable than during the pre-CA times, as his new cropping system has completely buffered his farm from mild droughts or dry spells due to increased rainfall infiltration.

2.3 Commercial farmers and conservation agriculture: towards conservation agriculture variants in smallholder farms

Detailed discussions with large-scale commercial farmers with more than ten years experience with conservation farming in South Africa, Zambia and Zimbabwe pointed to CA as a system that can only be perfected through practice. Where initial errors have been allowed to have a positive feedback, great results manifested, leading to CA expansion to whole farm-scale. For example, a large-scale commercial farmer in South Africa's Limpopo province went through an intensive knowledge-exchange programme, supported by Australian CA farmers. Over a four-year period, the farmer managed to convert the entire 5 000 ha estate into CA with over 80% yield gains (Box 1).

Current rainfed maize and soyabean yields average 6 and 2.5 tonnes ha^{-1}, respectively, in an agro-ecology that is semi-arid (500–600 mm per annum).

While the narration in Box 1 represents a case in which CA has been successfully employed to increase crop productivity, increase profit margins and conserve soil moisture in a demonstrable way (reduce climatic risk), there were notable drivers towards such an achievement:
- As from the third season of commencing CA, the farmer completely separated (in space) the livestock component from the crop production unit. After combine harvesting, all the crop stover or stubble remained *in situ,* guaranteeing substantial annual crop residue inputs (see Photograph 1).
- The farmer maintained a small but critical number of skilled personnel that expertly operated the increasingly sophisticated farm machinery (e.g. 24-metre span planters, combine harvesters, precision herbicide sprayers). (See Photograph 2).

There was a noticeably high capital injection on the farm resulting in appropriate CA farm machinery and access to herbicides.

The farmer had agricultural training to university level and this enabled him to effectively use available scientific information to implement CA.

The above analysis points to the potential hurdles the average smallholder famer in southern Africa is likely to face when implementing all three principles of CA. For example, it is often not possible to separate the cropping and livestock components as these are intrinsically related in a communal setting. After harvesting field crops, livestock in many communities is allowed to freely graze during the off-season period. Alternatively, farmers manage residues by stocking them in places beyond the reach of livestock, and systematically feeding the livestock at a critical point during the dry season. Both residue management pathways point to the difficulties associated with ensuring adequate crop residues for soil cover. In a study on organic matter management on smallholder farms in Zimbabwe that involved detailed tracking of 120 households, Mtambanengwe and Mapfumo (2005) showed that more than 50% of *in situ* crop biomass had been lost to free-grazing animals within three months of harvest. The GART

Photograph 1. A mature CA system on a commercial farm in Gauteng, South Africa. On this farm, a combination of no-till, cereal-legume rotations and 100% in situ crop residue cover has resulted in near-zero soil loss, increased rainwater intake and high successes in producing some crop yield during drought years.

Photograph 2. Precision farming in CA. This herbicide spraying equipment senses green material under the canopy to send a precise herbicide spraying signal, thereby reducing quantities of herbicide used.

Year Book 2008 also states similar problems with having any meaningful residues in unprotected farmer fields in Zambia, where one would expect better successes due to sparse livestock populations. Therefore, smallholder farmers in mixed crop-livestock farming systems will only implement variants of CA as dictated by their local circumstances. Judging variants of CA should, therefore, be results based rather than strict adherence to set criteria that hinge on theoretical relationships that are dissociated from local farming systems or obtaining circumstances. The basins technology is a case that warrants mentioning in this regard. Increased crop productivity, due to timely planting, has been experienced by smallholder farmers in Zambia and Zimbabwe, who planted using basins without mulching.

3. Contextual Setting on CA Climatic Risk Analysis in Southern Africa

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Soils with poor nutrient content, particularly of N and P, are widespread in southern Africa, and this has been widely recognized as one of the pivotal causes of poor agricultural productivity. The use of fertilizers is still low with equally low nutrient-use efficiencies due to acute nutrient imbalances (Janssen, 1998). While soils of granitic origin are inherently poor, it is known that P availability to crops is heavily restricted by the iron and aluminum oxides in some environments that have otherwise more favourable mafic parent material (Sanchez et al., 1997). Recovery efficiencies depend on soil and plant characteristics, crop management, fertilizer dosage and timing, and season quality. Therefore, in the face of limited external resources, the question of how to efficiently target the available nutrients on the farms in a continuum of circumstances becomes critical (Giller et al., 2006).

3.1 RISK ANALYSIS IN CA

A major impediment to the improvement of rainfed agriculture is the vulnerability and risk associated with failing rains that compel the poor and vulnerable to invest (whether labour, input or, organic resources) substantially in maintaining soil productivity. Such risks are set to increase under current climate change in a region with high reliance on rainfed agriculture. In semi-arid areas, a false start of rain during the November and December period may be followed by a long dry spell and this can be fatal to crop establishment. Therefore, water-related problems are often complicated by occurrence of intra-seasonal dry spells that may coincide with critical stages of crop growth rather than total seasonal rainfall per se. A recent analysis by Mupangwa (2008) indicated that there has been no significant change in total annual rainfall over the past 50 years at five meteorological stations located in the Mzingwane sub-catchment, southern Zimbabwe. However, crop failures were reportedly common in the areas, suggesting that in-season rainfall distribution was playing a stronger part in influencing crop yields than total annual rainfall. Approaches that improve rainwater management and storage will reduce the probability of total crop failure in such environments. Conservation agriculture is a system that is perceived

to respond to climate-related uncertainties, driven by its ecologically sound principles. Therefore, the risk analysis involved the following key components:

- Assessing how vulnerability of smallholder farmers to climatic variability can be reduced by employing robust agro-ecological principles with farming communities to meet immediate food requirements.
- Analyzing the tradeoff between the positive effects of CA on the micro-environment (more moisture under residues, lower evaporation, increased biological activity) and the sometimes negative effects (e.g. termites, water logging and diseases).
- Getting insights on the capacity of targeted communities to implement a set of CA technological options, and identifying mechanisms that promote sustainable adoption of CA principles in line with the production goals of different communities (especially in mixed crop-livestock systems).

3.2 Water productivity and mitigation of climatic variability

In terms of increasing water productivity and coping with rainfall variability, soil water recharge can be expected to increase under CA over time due to improved infiltration and reduced soil evaporation, and subsequent changes in water balance in the deeper soil layers that can be exploited by the roots. Rainfall intensity in tropical environments is high (often >35 mm hr^{-1}), exceeding the conductivity of many soils (Nyamadzawo et al., 2007). Any interventions that will increase the residence time of rainwater on soil surface (and hence opportunity for infiltration) are likely to increase rainfall capture during intense storms, and maximize soil moisture buffer capacity for later crop growth stages that are sensitive to water stress. This study sought to determine if the CA-enhanced soil water buffer capacity is large enough to mitigate the increased dry spells associated with climate change induced rainfall variability, as stemming from climate change scenarios, and provide insights as to whether additional water conservation/harvesting measures are required.

Enhanced water productivity is also intrinsically linked to soil fertility. Nutrient deficiencies often affect crop biomass yield, masking the benefits of water availability. Janssen (1998) described the art of balancing to ensure optimum resource-use efficiencies. Any enhancement of nutrient availability for the crop will thus be a multiplier of the impact of CA on increased crop production, as more water is made available for productive transpiration (increased water-use efficiency), leading to greater biomass production as nutrient deficiencies are curtailed.

3.3 Basins for reducing climatic risk – a practical and theoretical framework

The guidelines to the basins CA technology as advocated by the Zimbabwe CA taskforce and the CFU of Zambia are both different. In Zimbabwe, the CA basins involve use of hand hoes to dig small pits of approximately 15 cm × 15 cm × 15 cm in dimension, while the Zambian CFU guidelines indicate basins of 15 cm × 20 cm × 30 cm. In both cases, however, the basins are made over a period stretching from June to October, effectively dealing with the problem of labour bottlenecks characteristic of conventional tillage systems at the beginning of the rainy/cropping season. Both organic and inorganic soil fertility amendments are precisely applied in the basins, with crop establishment possible with the first effective rains.

For South Africa and Zimbabwe, the currently recommended density is about 22 000 basins ha^{-1}, at 75 cm × 60 cm spacing in sub-humid agro-ecological zones, with two maize plants per basin (44 000 plants ha^{-1}). The basin spacing is adjusted to 90 cm × 60 cm for semi-arid zones (18 500 basins ha^{-1}). At 0.0225 m^2 per basin, the total area covered by the basins is approximately 415 m^2 ha^{-1} and 500 m^2 ha^{-1} for semi-arid and sub-humid environments, respectively, representing at most 5% soil disturbance. For Zambia, the basins are spaced at 90 cm × 70 cm, with three maize plants per basin This results in approximately 15 850 basins ha^{-1}. At 0.045 m^2 per basin, the total area covered by the basins is approximately 715 m^2 ha^{-1}, representing just over 7% soil disturbance. The two scenarios meet the criteria for minimum soil disturbance. Using the same principles, the total volume of basins as used in Zimbabwe and Zambia ranges between 63 m^3 ha^{-1} and 143 m^3 ha^{-1} respectively. The following models (see Tables 1 and 2) attempt to highlight the several scenarios that are possible,

depending on season quality (total rainfall amount, distribution and intensity of storms).

The assumptions and theoretical computations in Table 1 suggest that basins will reduce drought-induced risk or moderate the negative effects of dry spells, as has been noticed widely. While some of the water that is captured in the basins will diffuse to drier soil around, the net effect of this phenomenon will be to extend the period when moisture will be adequate. An extension by five days to the next rain event during critical growth stages, during which crop deterioration can be exponential, may separate success and failure of a crop. By contrast, Table 2 demonstrates a case in which the basins technology can potentially result in depressed yields due to too much water concentrating in the basins under high rainfall environments or during seasons with abnormally high rainfall. While there are currently few published data to substantiate this (e.g. Thierfelder and Wall, 2009), numerous Zimbabwe government extension service (AGRITEX) reports (and farmer testimonies) indicate that in some years, basins had forced farmers to scoop water from the basins during high rainfall episodes. In Zambia, an extension supervisor was quick to mention that farmers were to back-fill their basins as soon as they realized that the level of ponding in their fields would depress their yields. In related but somehow inverse water harvesting mechanical design, the no-till tied ridges technology has been reported to work well under sub-humid conditions as the elevated ridges prevented water logging during wet years, but failed in semi-arid zones where it was associated with poor crop establishment on the ridges (Vogel, 1993). This study also established that the mulch-ripping technique worked well in a semi-arid region if there were enough crop residues left on the soil surface from the previous season.

Table 1. Quantitative treatment of risk reduction through basins technology under rainfall limited environments

Zimbabwe/South Africa: Model 1	Zambia: Model 1
Assumption: If an area receives 400 mm, and there is 5% integrated seasonal runoff into basins as described above:	*Assumption:* If an area receives 400 mm, and there is 5% integrated seasonal runoff into basins as described above:
• Total runoff = 5% of 400 mm = 20 mm = 0.02 m • Volume of runoff water = runoff rainfall × total surface area excluding total basins area (10 000 – 415) = 0.02 × 9 585 = 192 m^3. Therefore, 192 m^3 of water goes into the basins that cumulatively measure 415 m^2 The 192 m^3 water on surface area of 415 m^2 is equivalent to additional rainfall of 192/415 = 0.46 m = 460 mm • Therefore, total rainfall per basin = actual direct rainfall + runoff into basins = 400 + 460 = 860 mm • With basin technology, 400 mm can support a successful maize crop as effective rainfall will be 860 mm	• Total runoff = 5% of 400 mm = 20 mm = 0.02 m • Volume of runoff water = runoff rainfall × total surface area excluding total basins area (10 000 – 715) = 0.02 × 9 285 = 186 m^3. Therefore, 186 m^3 of water goes into the basins that cumulatively measure 715 m^2 • The 186 m^3 water on surface area of 715 m^2 is equivalent to additional rainfall of 190/500 = 0.26 m = 260 mm • Therefore, total rainfall per basin = actual direct rainfall + runoff into basins = 400 + 260 = 660 mm • With basin technology, 400 mm can support a successful maize crop as effective rainfall will be 660 mm
Alternatively – the basins can be potentially recharged 192/63 = 3 times as the total basin volume is 63 m^3 ha^{-1}	Alternatively – the basins can be potentially recharged 186/143 = 1.3 times as the bigger basins have a cumulative volume of 143m^3 ha^{-1}

NB: This is an over-simplification as basins get back-filled during the course of the cropping season, but it is a plausible attempt towards increased insights on basins functioning.

Table 2. Quantitative treatment of rainfall capture through basins under high rainfall environments

Zimbabwe/South Africa: Model 2	Zambia: Model 2
Assumption: If an area receives 800 mm, and there is 5% integrated seasonal runoff into basins as described above: • Total runoff = 5% of 800 mm = 40 mm = 0.040 m • Volume of runoff water = runoff rainfall × total surface area excluding total basins area (10 000 – 500) = 0.040 × 9500 = 380 m³. Therefore, 380 m³ of water goes into the basins that cumulatively measure 500 m² • The 380 m³ water on surface area of 500 m² is equivalent to additional rainfall of 380/500 =0.76 m = 760 mm • Therefore, total rainfall per basin = actual direct rainfall + runoff into basins = 800 + 760 = 1550 mm. • With basin technology, 800 mm can potentially induce localized water logging as effective rainfall >1 500 mm within a season	*Assumption:* If an area receives 800 mm, and there is 5% integrated seasonal runoff into basins as described above: • Total runoff = 5% of 800 mm = 40 mm = 0.040 m. • Volume of runoff water = runoff rainfall × total surface area excluding total basins area (10 000 – 715) = 0.040 × 9285 = 371 m³. Therefore, 371 m³ of water goes into the basins that cumulatively measure 715 m² • The 341 m³ water on surface area of 715 m² is equivalent to additional rainfall of 341/715 =0.52 m = 520 mm • Therefore, total rainfall per basin = actual direct rainfall + runoff into basins = 800 + 520 = 1352 mm • With basin technology, 800 mm can potentially induce water logging

4. Towards Modelling a Conservation Agriculture System

Experimental results on reduced tillage systems in southern Africa are not easily available. CIMMYT has spearheaded a large research programme on CA in Mozambique, Zambia and Zimbabwe which compares rippers, direct seeding and basins to conventional ploughing. Fertilized at the same level, CA and conventional ploughing had no significant maize grain yield separation until after the third year on course sandy soils in semi-arid Zimbabwe (Christian Thierfelder, personal communication). Research at ICRISAT on clay loam soil resulted in no differences between basins, ripping and ploughing that used similar fertilizer and planting times over a three-year period (Mupangwa, 2008).

Conservation agriculture approaches tend to diverge between implementing partners. For example, many NGOs have compared CA with conventional ploughing when CA plots were at a comparative advantage in terms of nutrient use and crop variety. Research scientists and academics will surely not entertain such datasets – CA works in promoting crop productivity, but this also applies to conventional tillage under good management (e.g. integrated soil fertility management). Sound empirical data to separate these approaches is urgently needed. Approaches for ensuring adequate mulching in CA are also contentious. Residues are already inadequate at harvest time, even before animals graze during the dry season or partial decomposition losses occur (comminution by termites and other soil organisms) due to current crop-residue productivity that is largely <3 tonnes ha^{-1}, the threshold requirement to meet the minimum 30% soil cover. Use of *in situ* crop residues is the ideal, but some practitioners have recommended importation of external residues (e.g. *Hyparrhenia* spp, tree-leaf litters) from non-cropped lands or crop residues generated using conventional ploughing methods from other fields to make up for the shortfall. The latter strategy may be viewed as extractive and unsustainable, i.e. promoting CA in one plot and depleting nutrients from conventionally ploughed fields.

Limited use of herbicides to control weeds is a challenge for CA. For example, there are no recorded cases of herbicide purchases by farmers in much of Zimbabwe where CA is being promoted, with use confined to demonstration plots where researchers

supply the herbicides and knapsacks. In Zambia, herbicides used by farmers are provided via the voucher-input support system. In the absence of herbicides, farmers resort to use of hand hoes and dig some perennial deep-rooted weeds, as deep as 15 cm, effectively disturbing the soil and compromising the CA principles. Vogel (1994) reported that reduced tillage techniques quickly developed a severe perennial weed problem, with rhizomes giving such weeds a head start the following season, and making such systems unattractive for smallholder farmers. This introduces higher level questions and challenges in simulation modelling of an already complex system, even when all key principles are adhered to.

4.1 SIMULATION MODELLING AS A TOOL FOR CLIMATIC RISK ANALYSIS IN CA

Approaches to studying and understanding resource-use efficiency in smallholder cropping systems have taken centre stage in various past and current research efforts in the region (e.g. Mtambanengwe and Mapfumo, 2005). The underlying causes of poor resource-use efficiencies have been well explored, chief among which are the interacting effects of poor soil physical environment, nutrient imbalances, moisture deficits and weed management problems (Zingore et al., 2007). Essentially, management of resources has to be tackled at the scale of the farming system or household, because decisions on resource allocation are often made at this scale. Cropping systems modelling is one approach that can be employed to understand systems better. To estimate crop productivity, simulation models must be sensitive enough to simulate the effects of biophysical heterogeneity and management strategies, such as residue use, tillage options and crop-weed interactions.

Empirical data on soil processes in CA systems and crop yields in southern Africa are scarce. Therefore, use of a dynamic simulation approach to capture non-linear relationships in resource-use dynamics is a vital tool. Outputs can then be integrated in simple summary models as knowledge on the system increases. The APSIM model, an example of a detailed simulation model of crop growth, water, N and P soil processes was chosen to generate more risk-analysis insights regarding CA. Application of APSIM was done with the knowledge that though complex models such as this have more explanatory power, there is often too much uncertainty caused by both the lack of data and imperfect knowledge on some processes.

4.2 THE APSIM MODEL

APSIM is a dynamic crop growth model that combines biophysical and management modules within a central engine to simulate cropping systems (McCown et al., 1996). APSIM was chosen because it has already been successfully applied to simulate maize-fertilizer experiments and legume-cereal sequences in east and southern Africa (Shamudzarira and Robertson, 2002; Delve and Probert, 2004), and elsewhere in studies ranging from soil-water relations to crop-weed interactions (e.g. Probert et al., 1998; Stewart et al., 2006; Chikowo et al., 2008). APSIM version 5.3 was configured with the MAIZE module, the soil water module SOILWAT2, the soil N module SOILN2, the residue module SURFACEOM and the soil P module SOILP. This model configuration simulates water, C, N and P dynamics and their interaction within crop/soil systems that is driven by daily weather information. It calculates the attainable crop yields that are defined by temperature and solar radiation and limited by water, N and/or P. The SOILN2 module simulates the transformations of C and N in the soil. These include soil organic matter (SOM) decomposition, N immobilization-mineralization, nitrification and de-nitrification. The SOM is divided into three pools: the BIOM (labile C) pool notionally representing the more labile soil microbial biomass and microbial products, and the more resistant HUM divided into inert C and decomposable pools comprising the rest of the SOM.

The SOILP module simulates the dynamics of P in the soil. A conceptual labile P pool determines soil P availability for crop uptake. As with N, P mineralization is linked to C dynamics. Decomposition of organic matter can thus result in mineralization or immobilization of P depending on the C:P ratio of the different organic pools decomposing or being synthesized. Phosphorus uptake is based on labileP status modified by correction factors representing the P sorption characteristics of the soil and P uptake capacity of the plant. The SOILWAT2 module uses

a multilayer, cascading approach for the soil-water balance. SURFACEOM considers the aboveground residues that can be removed from the system, incorporated into the soil or left on the soil surface. In simulations where communal grazing of animals was not controlled, the GRAZE function was activated to leave no more than 10% of the crop-residue biomass on the soil surface. Under fenced-off scenarios, 90% of the residues were allowed to be present on soil surface at the beginning of a new crop in CA.

4.3 APSIM MODEL PARAMETERIZATION

APSIM requires daily values of rainfall, maximum and minimum temperature, and solar radiation. Two weather data sets were used (i) Matopos Research Station (Bulawayo, Zimbabwe) long-term data, broadly representing the semi-arid environments of southern Africa that have average annual rainfall of about 600 mm or below, and (ii) Harare long-term data, with average annual rainfall of about 800 mm, representing sub-humid environment areas that are less prone to droughts. Each module in APSIM requires a number of inputs. For SOILWAT2, the inputs include soil bulk density, soil water at field capacity and wilting points, and two parameters, U and CONA, which determine first and second stage soil evaporation. The latter parameters were set at 6 mm and 3.5 mm day^{-1} respectively, values accepted for tropical conditions such as those described here. The water contents at wilting point and field capacity were derived on the basis of soil bulk density (BD), clay or sand fraction following van Keulen (1995) transfer functions:

- Soil water at field capacity = [0.3697 – 0.35 (sand content)] × BD/1 000
- Soil water at wilting point = [0.0074 + 0.39 (clay content)] × BD/1 000

After a rainfall event, a proportion of water in excess of field capacity that drains within a day was specified through a coefficient, SWCON, which was varied depending on soil texture. Clay soils have characteristic values <0.6 while sandy soils that have high water conductivity can have values >0.8. Using a root exploration parameter, maize roots were restricted to extracting water to a maximum depth of 0.6 m under conventional tillage (so as to relate to poorer root

distribution due to hard pans) and to a depth of 0.9 m under CA, although the total profile depth was set at 1.2 m in both cases.

The input parameters for SOILN2 include organic C, the fraction of HUM carbon or BIOM C, and mineral N. Concentrations of organic C were informed from soil maps for different textured soils for the topsoil (0–15 cm) and estimated for the deeper layers using an exponential decline in organic C with depth as employed in the CENTURY model (Tables 3 and 4). The fraction of BIOM C at sowing was set to 0.03 for the topsoil layer, declining to 0.01 at >0.7 m depth, where the HUM C pool is usually dominant. Top soil mineral N (0–20 cm) was initialized at between 5 and 40 kg ha^{-1} (nitrate + ammonium-N), depending on soil type and time of planting. Simulations with early planting had mineral N set at the higher end of the SOM-determined potential mineral N flush, while little starter N was set for crops planted three weeks after the start of the rainfall season. This is informed by mineral N dynamics data from Chikowo et al. (2003). Early planted crops reap the benefits of nitrogen flush which results from a burst in microbial activity in soil with the early rains, i.e. the birch effect (Birch, 1964). The input parameters for SOILP include labile P and P sorption characteristics of each soil layer. Labile P data was estimated from past research on P on both sandy and clayey soils. Estimated low to moderate P sorption for topsoil of 80–100 mg kg^{-1} was used as actual measurements for P sorption were not available.

4.4 BUILDING THE SIMULATION SCENARIOS

Simulation modelling scenarios between CA and conventional ploughing were differentiated by broad management and forcing factors in Table 5. These broad management factors apply to CA based on both ripping and basins, but should be viewed as aligned more to basins in this report. In conventional ploughing, no residues were allowed on the soil surface at time of planting, while in CA there was a range of possible scenarios, based on level of grazing, a function of the strength of crop-livestock interactions. Weed pressure was integrated into simulations to capture the issues that had been discussed with several stakeholders. APSIM predicts below-ground

competition for resources by simulating water, N and P extraction for each species in turn, with the order of extraction alternated between species each day (McCown et al. 1996). Total absorbed radiation is distributed between species based on differences between leaf area profiles, plant height and light extinction co-efficients of species. To study the depressive effects of weeds, maize was either (i) planted alone from the onset, or (ii) intercropped with an annual grass weed as from five weeks after emergence at a weed density of 20 plants m^{-2}. Introducing weeds at a later stage than maize planting was observed to more closely mimic the effect of poor weed control due to reduced labour availability. Introducing weeds at the same time as maize was associated with too much competition, with weeds quickly out-competing the maize crop. A weed-free crop represented a scenario in which farmers appropriately used herbicides to control weeds or where adequate labour for timely manual weeding was available.

In simulations with residues, the C:N ratio of 75 was used for cereals. Soil moisture was set at 10% of water-holding capacity at the initialization of the simulations, as from 1 October of each year, so as to capture early rains, if any. Maize was sown at 3.6 plants m^{-2} in semi-arid environments (Matopos weather data) and at 4.4 plants m^{-2} in sub-humid environment (Harare weather data). The genetic co-efficients for Seed Co maize varieties SC403 and SC635 were used for the semi-arid and semi-humid environments, respectively. In the simulations, 15 kg P ha^{-1} P was applied at planting for both the semi-arid and sub-humid climate, while N application rates were varied. A modest 60 kg N ha^{-1} was used in the simulations using the semi-arid climatic data, while 90 kg N ha^{-1} was used for the sub-humid environment. Ammonium nitrate fertilizer was applied in two equal splits; the first application was between two and three weeks after emergence, and the second at between six and seven weeks after emergence, if adequate soil moisture was available during these windows. Planting was also on condition that rainfall had cumulated >30 mm at the start of the season. In all long-term simulations to investigate the stability of CA versus conventional ploughing across rainfall seasons/typologies (seasons from 1978 to 2008), all soils variables were reset on the 1 October of each year to values in Tables 3 and 4, for generic clay and sandy soils, respectively. This would facilitate investigating the influence of CA across season typologies.

Table 3. An example of detailed soil properties parameterization used for specifying APSIM simulations for a generic clay soil down the soil profile

Soil layer	0–20 cm	20–40 cm	40–60 cm	60–90 cm	90–120 cm
Soil water parameters					
Layer thickness (m)	0.20	0.20	0.20	0.30	0.30
Bulk density (kg m^{-3})	1 250	1 300	1 300	1 300	1 300
Field capacity (m^3 m^{-3})	0.38	0.44	0.45	0.46	0.46
Wilting point (m^3 m^{-3})	0.25	0.27	0.28	0.28	0.28
SWCON	0.60	0.60	0.60	0.60	0.60
Soil N parameters					
Organic C (g kg^{-1})	15	7.0	4.0	3.0	3.0
Nitrate-N (mg kg^{-1})	15	7.0	1.5	0.5	0.5
HUM C fraction	0.60	0.70	0.80	0.90	0.95
BIOM C fraction	0.03	0.02	0.01	0.01	0.01
Soil P parameters					
Labile P (mg kg^{-1})	10.0	4.0	3.0	2.0	1.0
P sorption (mg kg^{-1})	100	100	200	200	200

Note: Soil-water relations derived using van Keulen (1995) transfer functions. Only soil-derived mineral N was altered to reflect the effect of early or late planting.

Table 4. An example of detailed soil properties parameterization used for specifying APSIM simulations for a generic sandy soil down the soil profile

Soil layer	0–20 cm	20–40 cm	40–60 cm	60–90 cm	90–120 cm
Soil water parameters					
Layer thickness (m)	0.20	0.20	0.20	0.30	0.30
Bulk density (kg m^{-3})	14500	1450	1400	1400	1400
Field capacity (m^3 m^{-3})	0.15	0.16	0.16	0.16	0.16
Wilting point (m^3 m^{-3})	0.08	0.08	0.09	0.09	0.10
SWCON	0.75	0.75	0.75	0.70	0.70
Soil N parameters					
Organic C (g kg^{-1})	6.0	5.0	3.0	2.0	2.0
Nitrate-N (mg kg^{-1})	5.5	4.0	1.5	0.5	0.5
HUM C fraction	0.60	0.70	0.80	0.90	0.95
BIOM C fraction	0.03	0.02	0.01	0.01	0.01
Soil P parameters					
Labile P (mg kg^{-1})	5.0	2.0	1.0	1.0	1.0
P sorption (mg kg^{-1})	80	80	100	150	200

Note: Soil-water relations derived using van Keulen (1995) transfer functions. Only soil-derived mineral N was altered to reflect the effect of early or late planting.

Table 5. Management factors used to differentiate CA and conventional tillage in smallholder farming communities of southern Africa

Factor/forcing variable	Conservation agriculture	Conventional agriculture
Crop residues Moderate rainwater infiltration	• 0% of harvest-time residue present on surface • 80% of harvest-time residue	• 0% of harvest-time residue present on surface (either grazed by animals or incorporated during ploughing or burnt)
Time of planting Soil-derived mineral N high with early planting	• Early (first rains) • Late (four weeks after first rains)	• Early (first rains) • Late (four weeks after first rains)
Fertilizer resources Organic and mineral fertilizers	• Efficient targeting	• Higher losses
Weed pressure A function of labour and financial resources	• No weeds (if herbicides used), or • Moderate weeds present five weeks after emergence	• No weeds at planting (see Vogel, 1994) • Annual weeds become a problem with limited labour
Soil texture Determines water-holding capacity	• Sandy soils (85% sand) • Clayey soils (55% clay)	• Sandy soils (85% sand) • Clayey soils (55% clay)
Climatic data Long-term data	• Both semi-arid and sub-humid	• Both semi-arid and sub-humid
Runoff response curve Partitioning of infiltration and runoff	• Curve number 60 used to estimate effect	• Curve number 85 used to estimate effect

4.5 KEY SIMULATION MODELLING RESULTS

Long-term simulations with semi-arid climatic data set indicated that during the first year, the differences in maize yields between CA and conventional ploughing were largely apparent during seasons with below normal rainfall (Figure 1). When rainfall was too limited (e.g. 1982/83 season with 230 mm and 1991/92 season with 176 mm in-crop rainfall respectively) there was total crop failure for both CA and conventional ploughing. An interesting contrast between CA and conventional ploughing was observed for the 1980/81 drought year in which 241 mm was simulated to produce some maize grain under CA whereas no yield was achieved with conventional ploughing. Simple regression analysis of in-crop rainfall and simulated maize grain yields produced strikingly similar graphs (Figure 2). However, closer examination of the illustration reveals an important separation as indicated by less dense yield points along the x-axis for CA when rainfall is limited. This means that the probability of getting

some yield with CA is greater when rains fail, part of the useful utility of CA that makes it particularly attractive in marginal rainfall areas. Reliable probabilities on the frequency of acute droughts that are associated with complete crop failure under whatever interventions and those moderate droughts where CA can make a difference are therefore needed to inform strategic planning.

When sub-humid climatic data were used, and same planting time and fertilizer was adopted, no differences could be simulated for both early and late planted crops using the two cropping systems for clay and sandy soils (Figure 3A and Figure 4A).

Aggregated 30 year simulation results indicated that CA approaches produced higher maize yields than conventional ploughing under semi-arid conditions (Figure 3B). The late-planted crop (often common due to lack of draught power) under sandy soils in semi-arid environments, was simulated to perform particularly poor (Figure 4B) probably due to a combination of no benefit from soil-derived mineral N, and poor water-holding capacity. Crop establishment
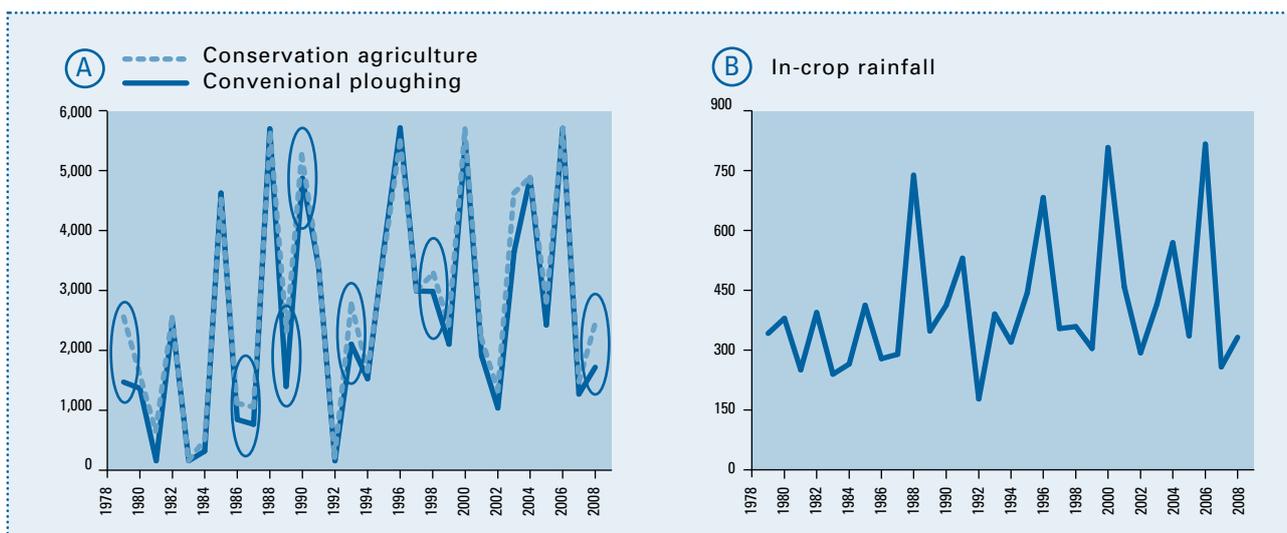

Figure 1. Simulated maize grain yields for a clay soil in a semi-arid environment

(A) Simulated maize grain yields for a clay soil using 30 years of Matopos climatic data (semi-arid) for the period 1978–2008 under conventional ploughing and CA, and (B) corresponding in-crop rainfall. Crops were planted with first effective rains each year and no weeds were introduced in both cases. Eclipses in (A) show years when CA and conventional ploughing yields were significantly separated.

problems result in crop stands in farmers' fields that are usually much less than the targeted 3.6 plants m^{-2} for the semi-arid regions. This may help to explain why the simulated maize grain yields appear to be higher than what is normally achieved by farmers.

The conditions set for CA option in the modelling exercises confirmed early soil profile recharge for CA compared to conventional ploughing, especially on the clay soils. In many instances, sandy soils were largely indifferent to CA or conventional ploughing cases as field capacity for top soil was attained as long as cumulative rainfall was >50 mm in the first two weeks of the season. The differences in soil water recharge between CA and conventional ploughing on the clay soils disappeared when cumulative rainfall was over 100 mm within four weeks; otherwise CA maintained its higher water content. Apparently once sub-soil layers are at field capacity, deep drainage is poorly captured in APSIM, probably contributing to the little differences observed throughout most of the season. These results point to CA as useful in early rainwater intake into soils, a phenomenon that is expected to buffer crops

from future dry spells. In practice, basins tend to get naturally back-filled in sandy soils or during manual weeding in heavier soils, diminishing their utility to capture late season rainfall.

The model simulated no significant maize yield differences between CA and conventional ploughing when fertilizer management was similar, and when no weeds were introduced in both cases (sandy and clay soils) during the first year (Figures 3A and 4B). However, yields were generally higher for CA in semi-arid environments. When weeds were eliminated in CA through appropriate herbicide use (or effective weeding) and a weed pressure of 25 plants/m^2 was associated with conventional ploughing, maize yields were depressed by between 20% and 40% in conventionally managed fields. Larger maize-yield losses due to intercropped weed competition were apparent in seasons with poor rainfall. These simulations, however, used only one weed species that was intercropped with maize. The cumulative, non-additive effects of several species, each at a density below its own threshold, may cause yield reduction
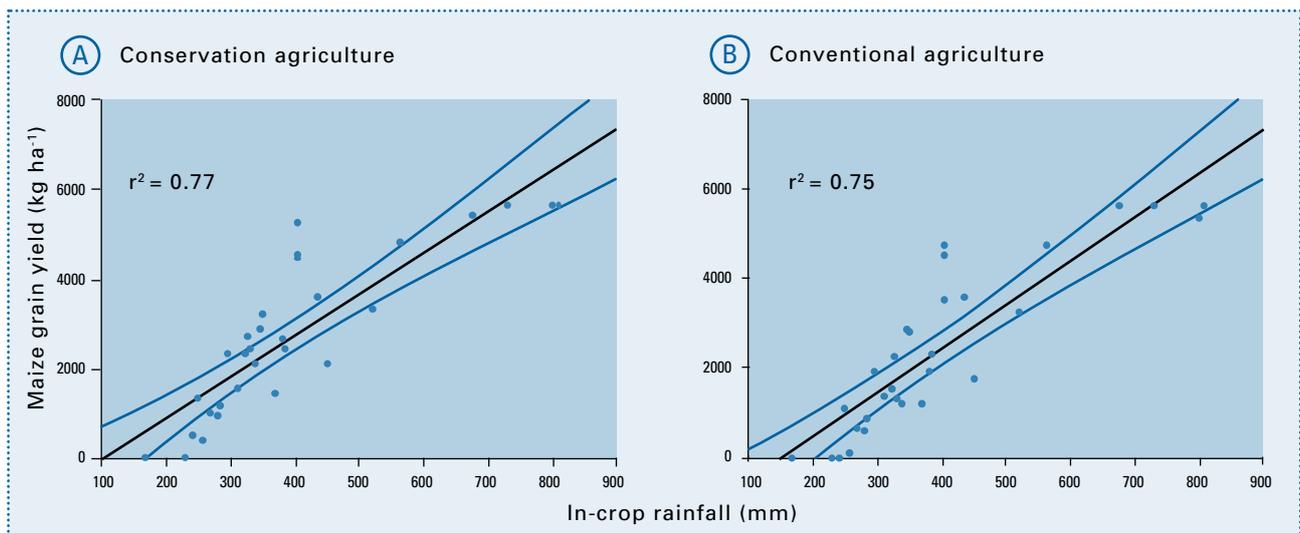

Figure 2. Simulated maize grain yields as a function of in crop rainfall

Simulated maize grain yields as a function of in-crop rainfall for (a) conservation agriculture and (b) conventional ploughing, based on 30-year simulations on a clay soil using Matopos climatic data (semi-arid) for the period 1978–2008.

in an unpredictable way that may be difficult to model. In other words, a numerical estimate of weed density may not necessarily provide a dependable estimate of associated crop yield loss. More challenges to modelling crop-weed interactions on a field scale include the spatially variable occurrence of weeds, whereby distinct high weed infestation patches exist in a field, while a large proportion of the same field may be infested at low weed density (Gerhards et al., 1997). As with APSIM, the vast majority of models treat weed populations as if they were uniformly distributed across the fields (Holst et al. 2007). Technical knowledge on competitiveness and yield effects of specific weed species or a mixed weed community is still incomplete (Zoschke and Quadranti, 2002). There is need to couple weed analysis approaches with farm labour availability, and produce reasonable labour-weed functions that can accurately predict production in a given set of weather and soil fertility conditions under CA.

- Time of planting had highly significant effects on maize yields (Figure 3 and Figure 4). This is the phenomenon that makes the basins technology work really well for the vulnerable farmers who have no draught livestock to prepare their fields for planting with first rains.
- In semi-arid environments, the basin technology resulted in better yields for both early and late planted crops. Despite the larger initial labour requirements associated with the basins in the context of reduced labour availability due to HIV/AIDS, the cumulative positive impacts of this technology in the medium to long term on diverse ecological benefits will most likely offset the difficulties encountered during the early years of CA implementation. Furthermore, farmers have been reported to cope with labour shortage by working in groups when implementing labour intensive operations such as the initial digging of the planting basins.
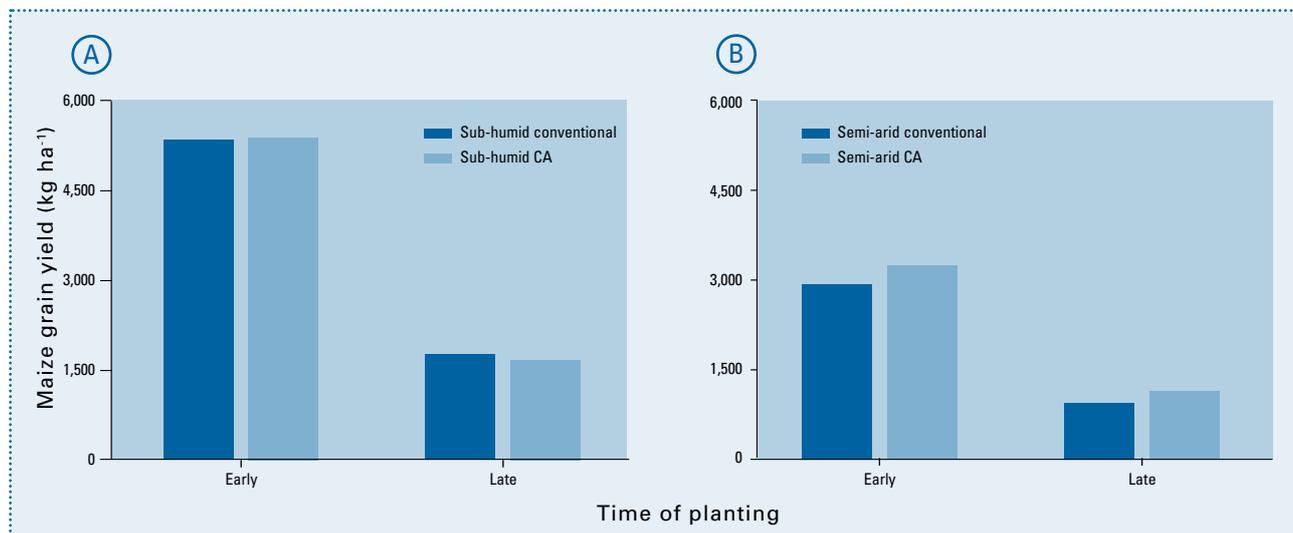
Figure 3. Summarized long term simulations of maize yields on clay soils

Summarized long-term simulations of maize yields on clay soils (A) in sub-humid environments of southern Africa under conventional ploughing and CA, and (B) in semi-arid environments under conventional ploughing and CA practices. No weeds were introduced in both cases. The early crop was planted as soon as the cumulative rainfall was >25 mm at the beginning of the rainfall season, while the late crop was planted four weeks later.
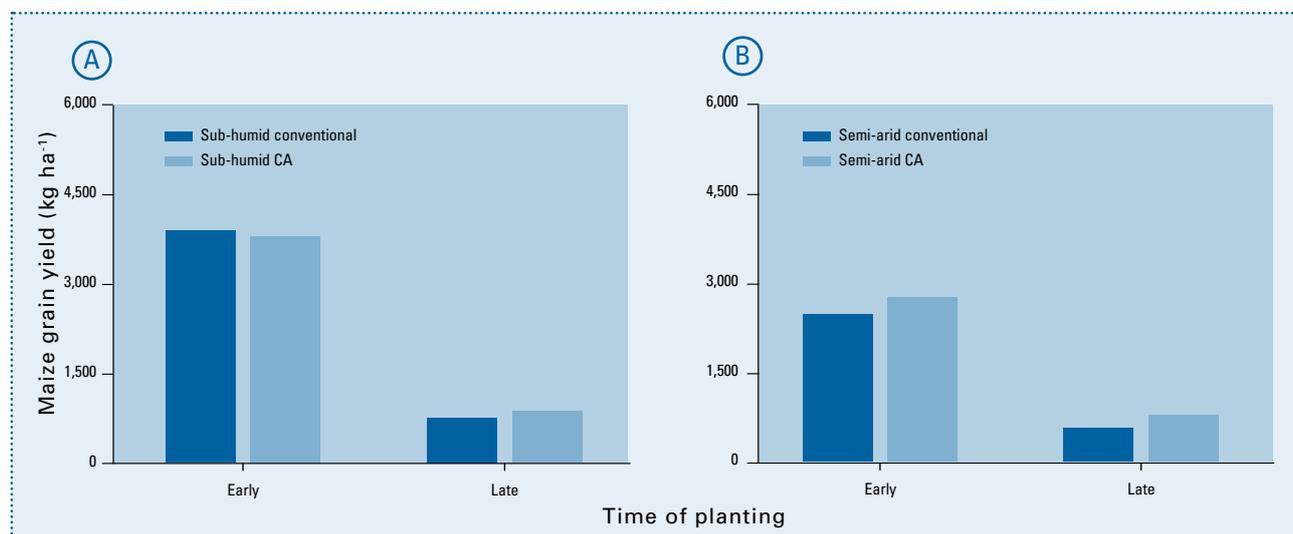

Figure 4. Summarized first year long term simulations of maize yields on sandy soils

Summarized first year long-term simulations of maize yields on sandy soils, (A) in sub-humid environments of southern Africa under conventional ploughing and CA, and (B) in semi-arid environments under conventional ploughing and CA practices. No weeds were introduced in both cases. The early crop was planted as soon as the cumulative rainfall was >25 mm at the beginning of the rainfall season, while the late crop was planted four weeks later.

5. Conclusions and Recommendations

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- *In semi-arid environments, the application of CA results in more stable crop yields across different types of seasons.* Simulation modelling indicated that the effects of CA on water recharge were more important in clayey soils than sandy soils, which is effectively linked to early saturation of water holding capacity of sandy soils. Therefore, the basins and ripping CA-centered approaches will yield more water intake-related benefits for niches with heavier soils, while the mulching component is essential to preserve the limited soil water on light textured soils that have inherent poor soil water storage capacity. Smallholder farmers in southern Africa are mainly in semi-arid environments, and are therefore likely to benefit from the increased yield stability that is associated with CA.

- *In the short term, there are limited benefits of CA in sub-humid environments* during years with adequate rainfall; yields could be affected by water-logging. However, evidence from a commercial farm case study presented in this report (Box 1) indicates that farmers will accrue benefits as they master the CA techniques and lower weed problems on the farms over time – an experiential pathway to full technology adoption. The anticipated long-term improvements to soil due to addition of residues, retarded C turnover and reduced soil erosion associated losses may make investments in CA worthwhile if local farming system parameters are not in serious conflict with immediate CA requirements.

- While there is unequivocal evidence on the benefits of CA in cropping systems risk reduction, especially regarding the basins technology in rainfall-limited environments, *the current CA training approach and CA manuals in some countries need to be revisited to align with empirical data insights from elsewhere.* For example, the guide to conservation agriculture in Zimbabwe (Farming for the Future) reports maize yields with mineral N fertilizer under conventional ploughing of about 0.8 tonnes ha^{-1} compared to yields of 1.3 tonnes ha^{-1} for unfertilized basins in a semi-arid environment; this is in sharp contrast to a recent study (Mupangwa, 2008) that showed that nitrogen fertilizer increased maize yields in each season regardless of the tillage system used

in a semi-arid environment. While presentation of data in this format is predictably a deliberate strategy to reinforce the benefits of basins, it is conversely counterproductive as the benefits of mineral N fertilizer under conventional tillage are irrefutable (e.g. Zingore et al., 2007).

- *Most benefits of CA in the first year are mainly due to early planting and improved management*, especially with the basins system. An important question arises from these assertions: Is it possible to do basins at the farm-scale level or limit this to about 0.6 ha which is the estimated size that can be effectively managed by an average family? The household could then use the extra arable land for production of other crops, including trees, to generate cash income and produce fuel and fodder crops. However, in some communities, labour related to weeding, largely provided by women and children, is limiting. Currently there are no indications that the labour associated with the production of basins will not be added to this burden.

- Recognizing that CA is a complex technology, Wall (2007) advocated for *intensive community-based extension approaches to smoothen the shift from conventional agriculture*. However, this approach still needs to be emphasized and strengthened, e.g. among the NGO community (that has direct contact with thousands of farmers) across the region. The understanding of CA has been more divergent in the development community that has, unfortunately, largely shouldered the responsibility of driving the CA agenda which in itself becoming a source of risk. It has to be explicitly stated that CA is a knowledge intensive system, and that NGOs and other stakeholders involved with CA should invest more in training their field staff. Thus, the primary risk aligned with CA may well be associated more with wayward implementation, relegating climatic risk to the periphery.

- The uptake of CA by farmers outside the input support network has been slow, despite the exposure during field days in communities. The inputs 'tag' around CA may well be one of the reasons for resistance on the part of those not accessing the inputs.

- *In situ* mulching, one of the three major pillars of CA, will require innovations to be realized in many communal settings with a significant livestock component as crop residues are used as cattle feed, and in many cases the residues left on the fields are grazed communally after harvest (e.g. Siziba, 2007). Often cropped fields lie bare only four months after the last harvest. Approaches for promoting CA have to change and targeting should not be confined to the resource poor farmers. Training a small part of a community and those without livestock does not optimize benefits from CA as the richer farmers will have no interest to control their livestock to save residues for CA to work. For CA, the benefits of using a complete system of technologies are far more than the sum of the individual benefits of the components.

- Implementation of CA has tended to relegate or deliberately ignore positive strides made in other realms of farming systems and integrated crop and livestock management research, thereby creating fertile grounds for unnecessary criticism and a risky environment for promotion of CA in mixed crop-livestock systems. For example, the introduction of CA into a community that has a high regard for livestock has to be shrewd manner. It needs to recognize local values while not shying away from explicitly explaining the necessary ingredients for CA to work. Future investments by developmental agencies around CA should, therefore, aim at programmes that create environments of trust for all. This can be achieved by infusing more participatory inclined methodologies, an approach that has been proven to produce effective and sustained buy-in by communities (beyond project life-span) .

- There are compelling grounds for calling for strategic policy shifts to facilitate the medium to long-term benefits of CA to be realized. For example, programmes on CA (whether research or developmental) often fail to realize their full potential due to short-term nature of funding. It is recommended that CA interventions should be at least five years in extent for farmers to gain confidence during the often prolonged change-over phase from conventional ploughing to CA.

- Empirical data to validate a detailed model for CA are scarce. There is a serious lack of adaptive research on CA in different environments to refine niches where the technology can drive development and poverty alleviation. Adaptive research is urgently required on the impacts of CA systems on different kinds of smallholder systems by studying which principles of CA, and under which conditions these principles contribute to the effects sought in terms of food production and land rehabilitation in the face of climatic variability. For example, it was not clear on what empirical data the currently used basin designs are based (considering also the different designs among countries with overlapping agro-ecologies). There is, therefore, scope to research on basin design in order to optimize the associated benefits in water-limited environments. A recent review on CA by Giller et al. (2009) has opened an opportunity for scientists working on CA, as well as the development community, to more aggressively pursue adaptive research to fine tune the technology to local agro-ecosystems.

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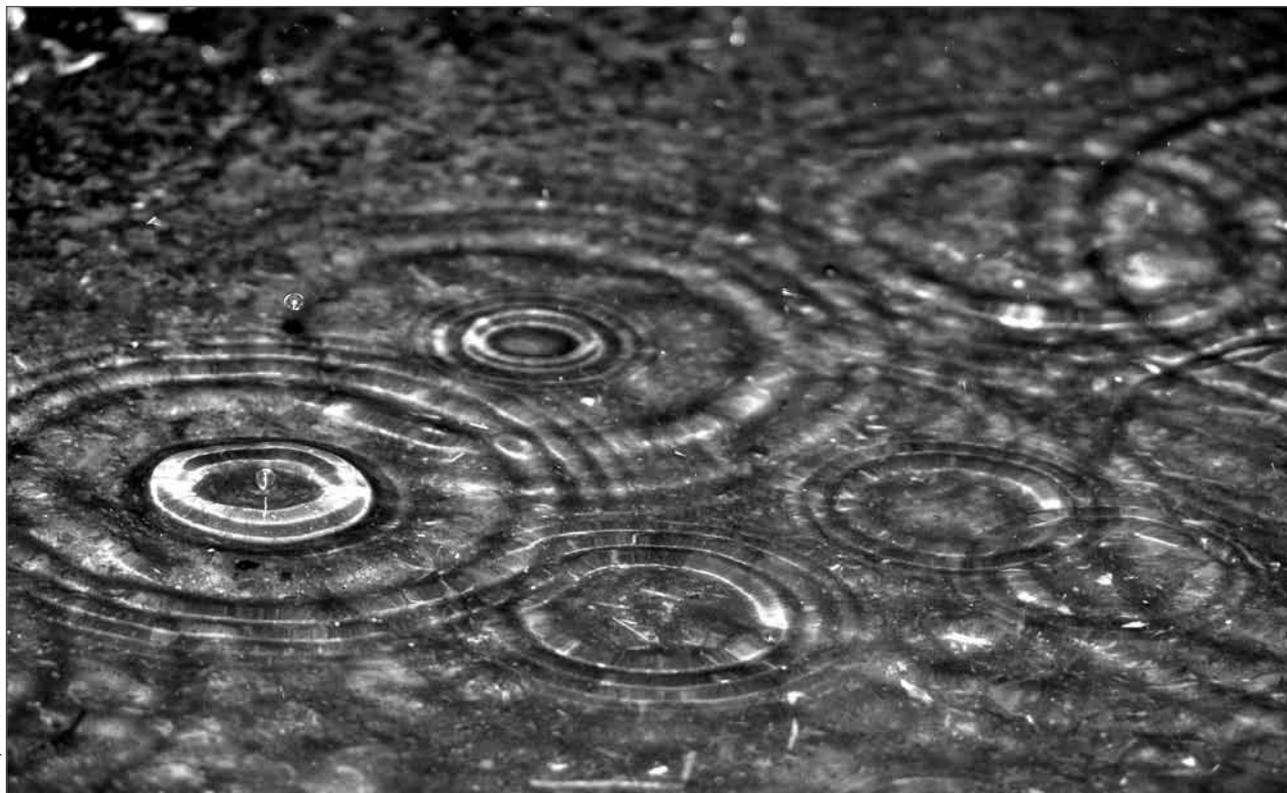
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Appendix A: Zambia Agro-ecological Regions

Conservation agriculture is being practised mainly in regions I and IIa.
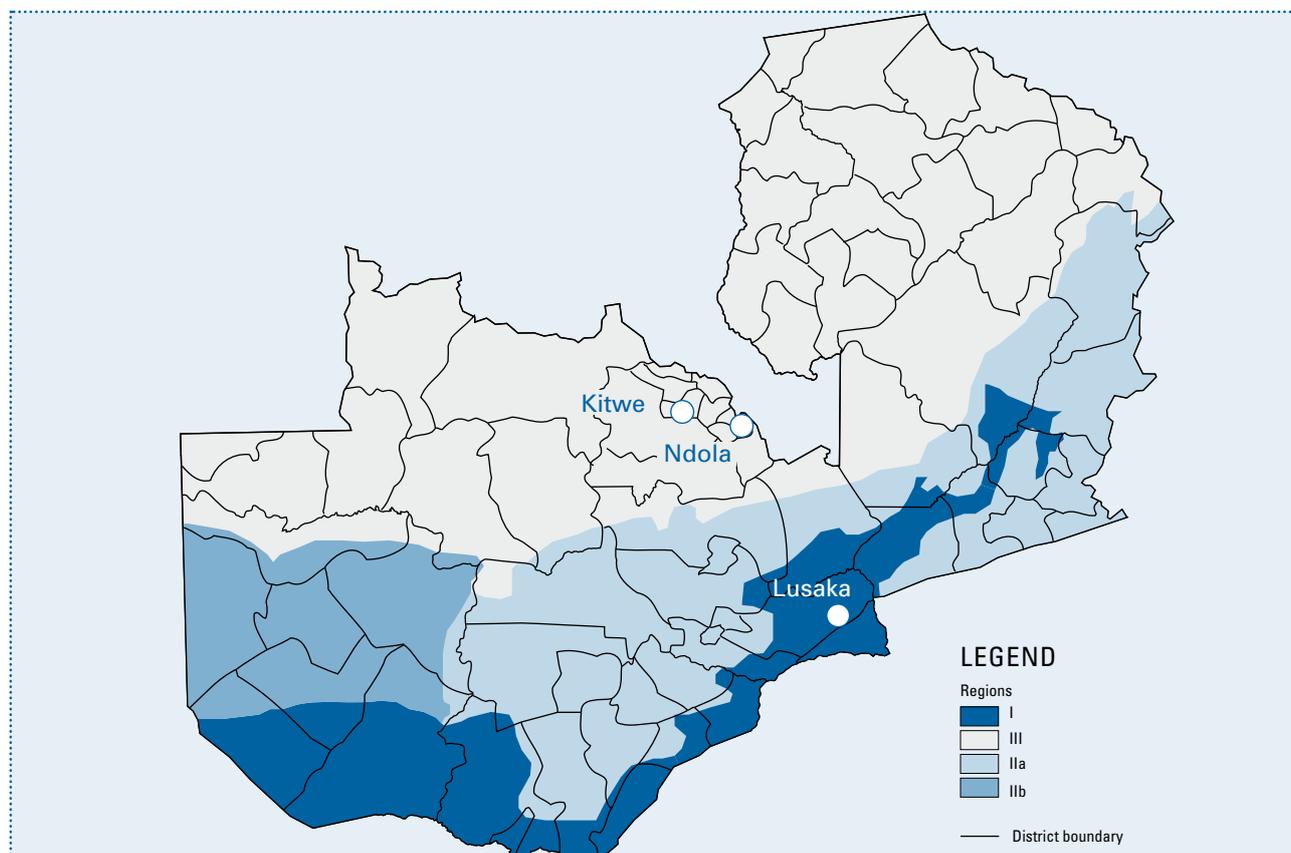
| Agro-ecological region and location	Area (km²)	Land (%)	Annual rainfall (mm)	Length of crop grow- ing season (days)	Main soil group type classification	Important agricultural management constraints or hazards
I South, southeast Zambia	150 524	20	<750	60–90	Luvisols, Vertisols, Leptosols, Arenosols	Drought, soil erosion, flash floods.
IIa Central to eastern Zambia	198 155	25	750–1 000	90–150	Lixisols, Luvisols, Vertisols, Acrisols	Acidification, soil erosion, soil organic matter loss (chemical, physical and biological degradation).
IIb Western Zambia	37 630	5	750–1 000	90–150	Arenosols, Gleysols, Histosols, Podzols	Low general soil fertility conditions, high infiltration rates, flooding in plains, soil acidity.
III Northern, Luapula Copperbelt and northwestern Zambia	376 310	50	>1 000	140–200	Acrisols, Ferralsols, Gleysols	Soil acidity, low bases retention capacity, low soil organic matter, soil degradation.

Appendix B: Zimbabwe Agro-ecological Regions

LEGEND
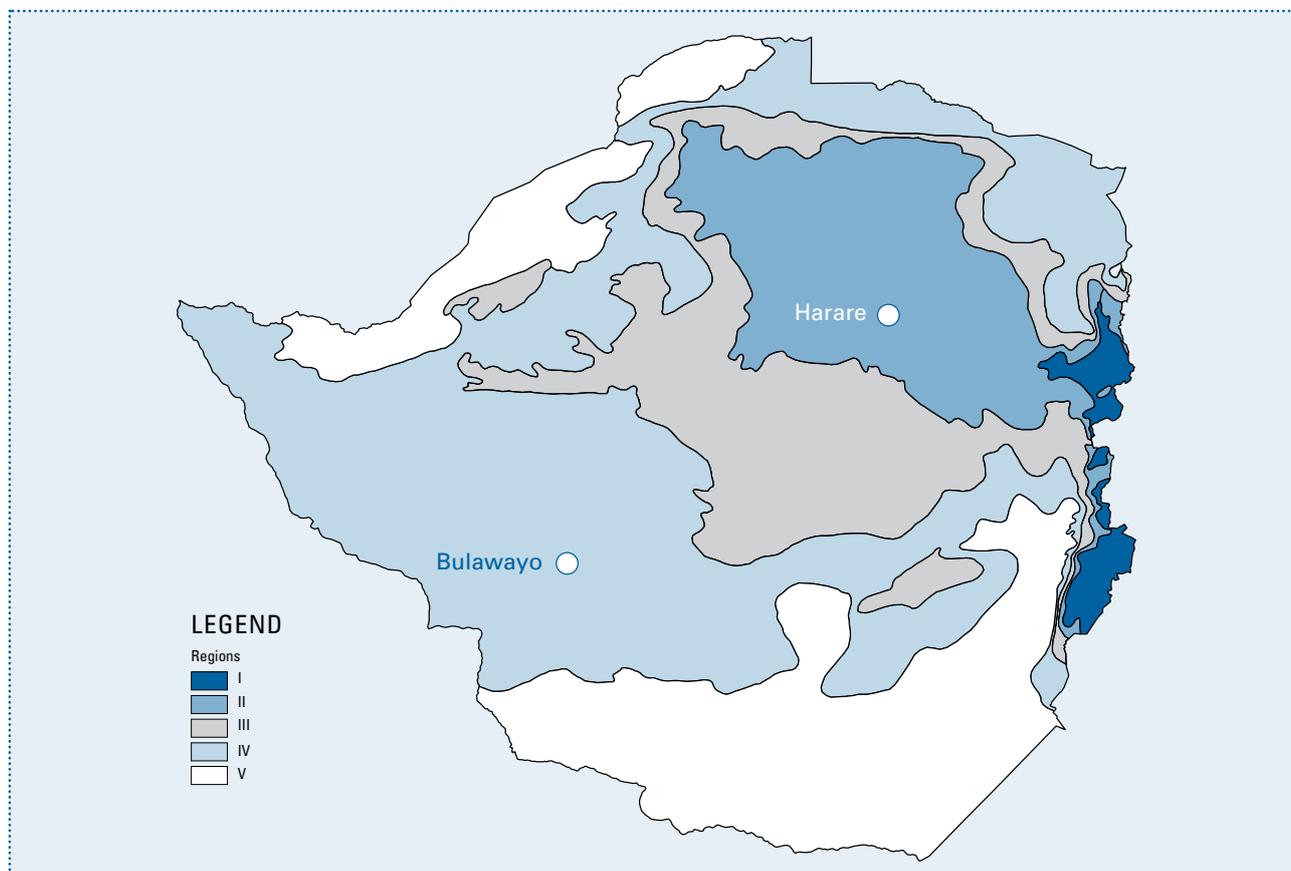
Regions
- I
- II
- III
- IV
- V

Conservation agriculture is being implemented with farmers in the context of the protracted relief programme across regions III to V.

Agro-ecological region	Annual rain-fall (mm)	Length of crop growing season (days)	Main soil type/characteristics	Rainfall characteristics/agricultural activities
I Eastern highlands	>1000	>170	Deep and highly weathered soils with Fe and Al phosphate-fixing properties.	Humid environment with plantations being prominent.
II Northern central Zimbabwe	750–900	120–150	Clay loams and sandy soils.	Ideal for rainfed maize and tobacco production.
III Central Zimbabwe	650–750	90–140	Sandy and infertile soils.	Mid-season dry spells common.
IV Large tracks of the semi-arid western Zimbabwe	450–600	90–125	Deep Kalahari sands a dominant feature.	Increasingly risky crop production environment. Water conservation measures are recommended.
V Mostly southern Zimbabwe and the Zambezi basin	>450	70–125	Sands with pockets of vertisols. Sometimes sodic soils develop.	Unreliable rainfall. Complete crop failure a common phenomenon. Ideally an environment for livestock ranching.

Appendix C: Top soil clay content for South African soils
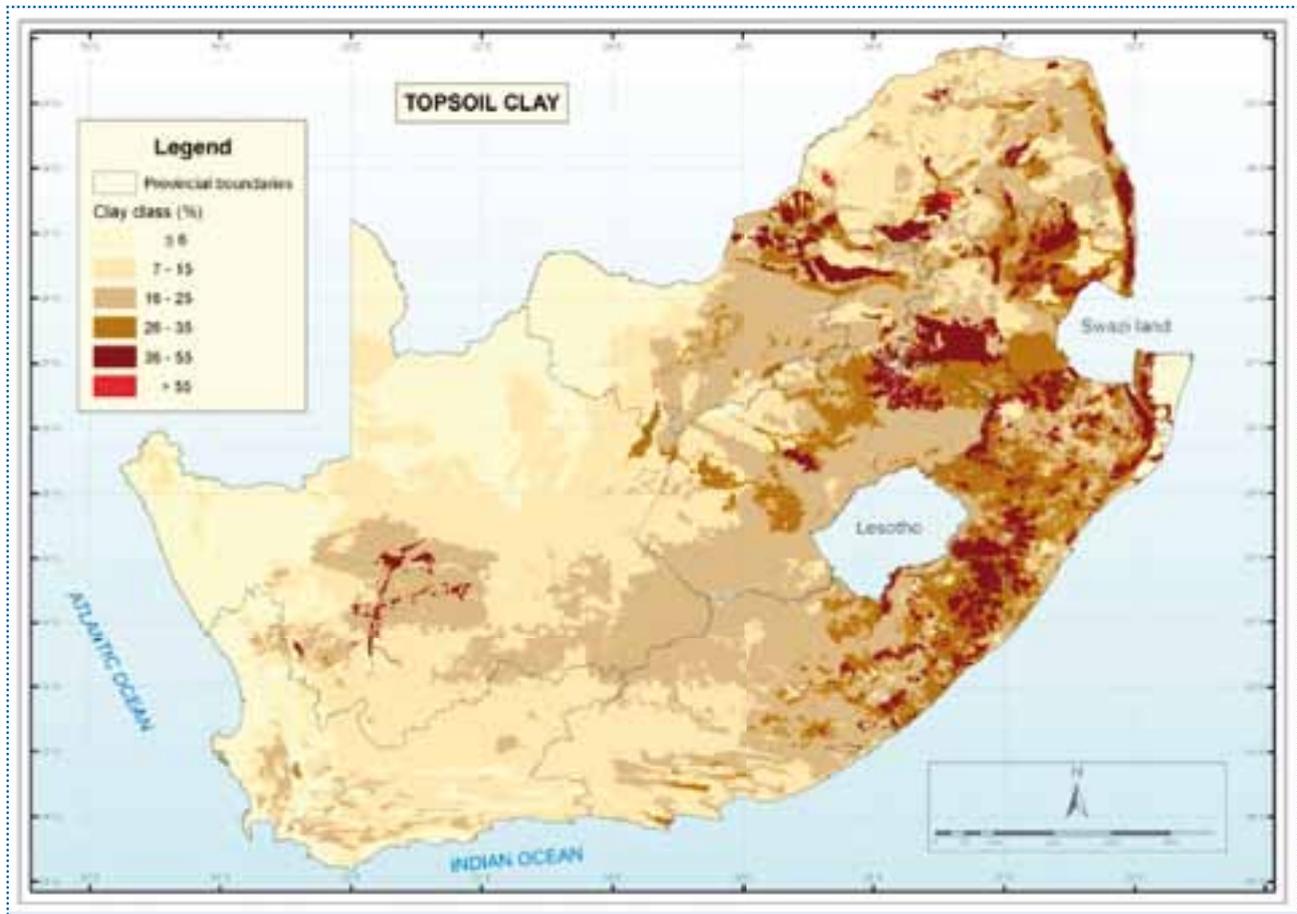
Vast areas have soils with <15% clay, while water management is critical in pockets of clayey soils in the semi-arid northern Limpopo province.