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Crop production intensification options for smallholder farming systems of southern Africa

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Abstract

Soil fertility decline and erratic rainfall are major constraints to crop productivity on smallholder farms in southern Africa. Crop production intensification along with efficient use of chemical fertiliser is required to produce more food per unit area of land, while rebuilding soil fertility. The objective of this thesis was to identify appropriate crop production intensification options that are suitable to the socio-economic and biophysical conditions of selected smallholder maize-based farming systems in southern Africa. Three sites that formed a gradient of intensity of crop and livestock production were selected for the study. Murehwa in Zimbabwe is characterised by the largest intensity followed by Ruaca and lastly Vunduzi both in central Mozambique. In all three sites, maize is a key staple and cash crop. A literature review, field methods based on participatory research, and modelling tools were combined in analysing potential crop production options across an agricultural intensification gradient. A meta-analysis on maize grain yield under rain-fed conditions revealed that conservation agriculture required legume rotations and high nitrogen input use especially in the early years. Reduced tillage without mulch cover leads to lower yields than with conventional agriculture in low rainfall environments. Mulch cover in high rainfall areas leads to smaller yields than conventional tillage due to waterlogging, and improved yields under CA are likely on well drained soils. Crop productivity under conservation agriculture depends on the ability of farmers to achieve correct fertiliser application, timely weeding, and the availability of crop residues for mulching and systematic crop rotations which are currently lacking in southern Africa. An additive design of within-row intercropping was compared to a substitutive design with distinct alternating rows of maize and legume (local practice) under no-till in the Ruaca and Vunduzi communities of central Mozambique. Intercropping increased productivity compared to the corresponding sole crops with land equivalent ratios (LER) of between 1.0 and 2.4. Maize yield loss was only 6-8% in within-row intercropping but 25-50% in the distinct-row option. Relay planting of maize and cowpea intercropping ensured cowpea yield when maize failed thus reduced the negative effects of dry spells. The residual benefits of maize-pigeonpea intercropping were large (5.6 t ha^{-1}) whereas continuous maize (0.7 t ha^{-1}) was severely infested by striga (*Striga asiatica*). The accumulation of biomass which provided mulch combined with no tillage increased rainfall infiltration. Intensification through legume intercropping is a feasible option to increase crop productivity and farm income while reducing the risk of crop failure especially where land limitation. Cattle manure in combination with chemical fertiliser that included N, P, Ca, Zn, Mn were evaluated for their potential to recover degraded soils and to support sustainable high crop productivity in Murehwa, Zimbabwe over nine years. The experiment was established on sandy and clay soils in two field types. Homefields were close to the homestead and relatively more fertile than the outfields due to previous preferential allocation of nutrients. Maize grain yields in sandy soils did not respond to the sole application of fertiliser N (remained less than 1 t ha^{-1}); manure application had immediate and incremental benefits on crop yields in the sandy soils. A combination of 25 t ha^{-1} manure and 100 kg N gave the largest treatment yield of 9.3 t ha^{-1} on the homefield clay soils, 6.1 t ha^{-1} on clay outfield, 7.6 t ha^{-1} on sandy homefield and 3.4 t ha^{-1} in the eighth season. Despite the large manure applications of up to 25 t ha^{-1}, crop productivity and soil organic carbon build-up in the outfield sandy soils was small highlighting the difficulty to recover the fertility of degraded soils. Manure can be used more efficiently if targeted to fields closest to homesteads but this exacerbates land degradation in the outfields and increases soil fertility gradients. The NUANCES-FARMSIM model for simulating crop and animal productivity in mixed crop-livestock farming systems was used to perform trade-off analysis with respect to crop residue management, animal and crop productivity in Murehwa, Zimbabwe. Retaining all maize residues in the field led to severe losses in animal productivity but significant gains in crop productivity in the long-term. Yield increased 4 to 5.6 t farm^{-1} for RG1, and from 2.8 to 3.5 t farm^{-1} for RG2. Body weight loss was on average 67 kg per animal per year for RG1 and 93 kg per animal per year for RG2. Retention of all crop residues reduced farm income by US$937 and US$738 per year for RG1 and RG2 respectively. Farmers who own cattle have no scope of retaining crop residues in the field as it results in significant loss of animal productivity. Non-livestock farmers (60% of the farmers) do not face trade-offs in crop residue allocation but have poor productivity compared to livestock owners and have a greater scope of retaining their crop residues if they invest in more labour to keep their residues during the dry season. This study has revealed that crop production intensification options developed without considering the biophysical conditions as well as socio-economic circumstances of farmers are nuisances. External ideas should be used to stimulate local innovations to push the envelope of crop production without creating new constraints on resource use.

Key words: crop production, intensification, extensification, farming systems, tradeoff analysis, maize, legume, manure, fertiliser, southern Africa

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Chapter 1

General introduction

1.1 Poor crop productivity on smallholder farms in southern Africa

Poor soils and unreliable rainfall are the major constraints to food production and sustainability of smallholder agriculture in southern Africa. These challenges are further compounded by low incomes, labour and land constraints faced by the majority of smallholder farmers Sanginga and Woomer (2009). The high costs, lack of credit, delays in the delivery and poor transport and marketing infrastructure all hamper fertilizer use by smallholder farmers (Buresh and Giller, 1998); average application rates of 8 kg ha^{-1} are often mentioned (Sanchez, 2002). Locally, household and farm characteristics, social and human capital, and farmer perceived damaging effects of fertilisers on soil fertility hinder fertiliser use (Mapila et al., 2012). The net result is continuous soil nutrient mining (Stoorvogel et al., 1993). Nitrogen is commonly deficient; soil analyses and crop responses have also revealed small concentrations of plant available phosphorus in most of the cropped lands due to continuous cultivation.

Besides soil fertility, climate variability has been identified as the major constraint to agricultural productivity with rainfall variability (both within and across seasons) being the most critical (Phillips et al., 1998; Challinor et al., 2007). Inter-annual rainfall variability has increased since the late 1960s, and this is shown by droughts which have become more intense and widespread (Fauchereau et al., 2003). The risk of crop failure resulting from erratic rainfall is also a strong disincentive to the purchase and use of fertilizers on subsistence crops (Probert et al., 1995). Options that increase infiltration of rainwater and minimize evaporative losses such as conservation agriculture (Hobbs et al., 2008), or legume technologies that add N to the soil through biological nitrogen fixation (Giller, 2001) are desirable. However, these crop production options need to be adapted to the local biophysical, socio-cultural and economic conditions of the smallholder farmers in southern Africa.

1.2 Diversity of smallholder farming systems

The presence or absence of cattle across many regions in southern Africa often distinguishes the dominant farming system although maize appears to be a common major crop. Cattle are important for the provision of draught power, milk, manure, meat and as insurance and a symbol of wealth (Thornton and Herrero, 2001; Rufino et al., 2007). Maize is an important food security as well as cash crop for the majority of farmers in southern Africa (Dowswell et al., 1996). The combination of biophysical factors such as soil type and climate, socio-economic factors such resource ownership and access to markets determines farmers' production orientation within each locality. At farm level, limited labour and inadequate resources such as cattle manure or chemical fertilisers often force farmers to apply only on limited portions of the farm each year leading to heterogeneous soil fertility status across the fields (Mtambanengwe and Mapfumo, 2005; Tittonell et al., 2007). Success of crop production intensification options thus depends largely on site specific recommendations that considers local constraints and opportunities to improve crop yield (Cassman, 1999). To understand this diversity, three sites differing in population density, intensity of interaction between crop and livestock production, and input use were selected for this study (Section 1.7). The choice of crop intensification options tested in each site were based on review of previous work, socio-economic circumstances of farmers, as well as consideration to address their short and long-term needs.

1.3 State of the art: soil fertility replenishment options

A basket of technologies within the broad framework of integrated soil fertility management (ISFM) (Vanlauwe et al., 2010) include agroforestry, grain legumes, green manures, inorganic fertilizers, cattle manure, and conservation agriculture (CA). These have been proposed as possible solutions to address soil fertility decline and improve crop productivity on smallholder farms in Africa. Research has revealed that neither organic nor chemical fertiliser applied alone is good enough to improve crop productivity (Chivenge et al., 2009; Chivenge et al., 2011). Some of these strategies work well on research stations and in specific farmers' circumstances, but cannot be assumed to be appropriate to the majority of smallholder farmers in southern Africa (Mafongoya et al., 2006; Giller et al., 2009). A major challenge is therefore to identify appropriate crop production intensification options suitable to the biophysical and socioeconomic conditions for farmers.

The most readily available nutrient source to smallholder farmers is cattle manure although its effectiveness in improving crop yields is limited to a great extent by the poor nutrient contents and the small amount produced relative to cropped areas (Giller et al., 1997; Mugwira, 1998; Zingore et al., 2008). The potential of legume based technologies is limited by lack of information, seed costs, and poor market infrastructure (Graham and Vance, 2003). Conservation agriculture is limited by small crop productivity and the competition for crop residues between alternative uses (Giller et al., 2009; Rufino et al., 2011). Agroforestry trees and green manures used for soil fertility improvement are adopted by farmers when they have multiple uses such as contribution to the household diet (Giller, 2001). The suggested and most promising intensification options are those based on integrating legumes into the maize-based farming systems, and use of cattle manure due to the low cost and local availability (Mafongoya et al., 2006). New insights are needed on how these will fit in farming systems of different land use intensities, constraints and opportunities.

1.4 A new pathway: the paradigm of ecological intensification

The Green Revolution in the 1960s was based on the use of high yielding varieties, large quantities of fertilizer, pesticides, herbicides and intensive management to meet the food demands of an increasing population (Douglas et al., 2002). The side effects of intensification soon followed marked by reduction in biodiversity, increased incidence of pests and diseases due to monocropping, reductions in soil quality and pollution (Conway and Barbie, 1988; Matson et al., 1997). Concerns about the long-term sustainability and environmental consequences of such high input use and management required new approaches to sustainable agriculture (Conway and Barbie, 1988; Matson et al., 1997; Tscharntke et al., 2005). The paradigm of ecological intensification of agriculture means manipulating nature's functions to design sustainable production systems that use less inputs and leads to positive biophysical and socio-economic outcomes (Cassman, 1999; Doré et al., 2011; Hochman et al., 2011; Tittonell and Giller, 2013). It entails efficient use of pesticides, chemical fertilizers, water and fossil fuels, and development of locally adapted varieties. Thus, the major pillar of ecological intensification is increasing resource use efficiency i.e. resource capture efficiency × resource conversion efficiency (Trenbath, 1986; de Wit, 1992).

Ecological intensification in developed and developing countries will take different pathways in the short term. In the developed countries reductions in fertiliser inputs are needed due to environmental concerns (e.g. Tamminga, 2003). In Africa fertiliser inputs need to be increased to sustain large crop productivity while minimizing negative effects on the environment. In less favourable environments such as those in southern Africa, feasible ecological intensification options include integration of crop and livestock production, increased crop diversification, and agroforestry systems that promote nutrient and soil conservation (e.g. Cassman and Harwood, 1995; Mafongoya et al., 2006). Tittonell and Giller (2013) also suggested that manipulating planting dates, crop spacing, cultivar selection and weeding intensities may be important to achieve large crop productivity. Recently, Ryschawy et al. (2012) identified mixed crop-livestock systems as the most suitable pathway to environmental and economic sustainable agriculture although there is no guarantee that inputs are always used efficiently and that outputs are always positive on the environment.

1.5 Trade-offs in resource allocation

The smallholder farming sector of southern Africa is dominated by the maize-based mixed crop-livestock systems (Dixon et al., 2001). In these systems, manure and mineral forms of nutrients to apply to the whole farm are often limited (Giller et al., 2011). The use of scarce crop harvest residues for livestock feed during the dry season limits the options available for carbon input into the fields. In situations of erratic rainfall, crop residues maybe needed for soil cover to increase infiltration and reduce moisture losses (Adekalu et al., 2007), thus creating strong trade-offs between crop and livestock productivity (Rufino et al., 2011). Poor crop productivity in combination with the importance attached to cattle intensifies the trade-offs for crop harvest residue uses. Quantification of trade-offs is needed for crop and animal production to identify a farm level pathway that reduces competition for crop residues uses and to improve farm benefits from both crop and animal production.

1.6 Rationale of the study

Previous initiatives and proposed technologies have often failed to alleviate problems of soil fertility and food production on smallholder farms as they have been promoted based on their technical efficiencies obtained with adequate nutrients and optimum management but without consideration of the diversity and complexity of the livelihoods of farmers (Giller et al., 2011). According to van Ittersum (2011), *the low hanging fruit has been plucked* suggesting that the easier ways to improve crop production are no longer feasible; new innovative options are needed. Expansion of crop production through opening additional land is no longer feasible due to increasing population and a limited land resource base. On the other hand fertiliser inputs are beyond the reach for most smallholders and low-cost nutrient input sources are limited. There is a need for crop production systems that use nutrients and water more efficiently to maximise productivity because these resources are limited under the conditions of southern Africa.

An understanding of the biophysical and socioeconomic factors that influence the smallholder environment, as well as the farmers' goals and aspirations is required in order to design sustainable crop production systems (Ojiem et al., 2006). There is need to consider the variations caused by differences in farm size, quantity, type and condition of livestock, soil and crop management, food consumption patterns, sources of income, and production objectives among the different farmer resource groups (Shepherd and Soule, 1998; Tittonell et al., 2005). New crop production systems should be effective within the constraints of farmer resource endowment, and acceptable risk (Snapp et al., 2003).

The major hypothesis of this thesis is that crop production intensification options differ in importance according to bio-physical and socio-economic conditions of farmers. It thus follows that locally adapted options are more appropriate in removing the binding constraints of poor soils, unreliable rainfall and drought that are characteristic of southern Africa.

1.6 Objectives

In this study, I attempt to identify appropriate crop production intensification options that are suitable to the socio-economic and biophysical conditions of selected smallholder maize-based farming systems in southern Africa with emphasis on building soil fertility.

Specific objectives

a) To characterize three selected contrasting maize-based smallholder farming systems in southern Africa and to identify the major opportunities and constraints to crop production intensification.
b) To review literature on the long-term effects of no-tillage and/or residue retention management on maize grain yield under rain-fed conditions, and to draw lessons on the appropriateness of these management options for smallholder farmers in southern African.
c) To explore the potential of maize-grain legume intercropping to alleviate the biophysical and socio-economic constraints faced by smallholder farmers in central Mozambique.
d) To evaluate the potential of cattle manure application to improve crop productivity and rebuild fertility in degraded soils in smallholder mixed crop-livestock farming systems in Murehwa, Zimbabwe.
e) To quantify trade-offs and identify opportunities for crop residue uses in a smallholder mixed crop-livestock systems in Murehwa, Zimbabwe.

1.7 Study setting

The study was performed in Zimbabwe and Mozambique. I intentionally selected sites with contrasting maize based-farming systems depending on the intensity of integration between crop and livestock production. The intensity of crop-livestock integration was important as it defines nutrient availability especially where farmers cannot afford mineral fertilisers. A gradient of intensity of crop production can be established from Murehwa, Zimbabwe to Ruaca and through to Vunduzi in Mozambique (Table 1.1, Fig. 1.1). In all three sites, maize is the key staple and cash crop. In Murehwa, farmers generally manage a mixed crop-livestock system with one large field close to the homestead demarcated into smaller plots fenced and a few others scattered away from the homestead and not fenced. Use of both manure and fertilizer is prevalent although quantities are often not sufficient to meet crop needs. In Ruaca and Vunduzi, farmers increase production through extensive cultivation i.e. a large area gives more yield even though the amount obtained per unit area is the same or smaller. Distance to outfields where maize for sale is normally grown ranges between 4-8 km. Slash and burn is a very common system of land clearance and input use is marginal; farmers in Ruaca use cattle manure only in vegetable gardens. The different socioeconomic and biophysical conditions in the study sites were used to develop the research questions for on-farm experimentation.

Table 1.1 Major attributes and differences in the study sites in Murehwa, Zimbabwe and Ruaca and Vunduzi in central Mozambique.

Attribute	Site		
	Murehwa	Ruaca	Vunduzi
Mean annual rainfall (mm)	800	1000	800
Predominant soils	Sandy	Sandy	Sandy
Altitude (masl)	1300	700	300
Main crop	Maize	Maize	Maize
Largest land size (ha)	3	15	7
Cattle ownership (% of HHs)	40	25	0
Manure use in main crop	Yes	No	No
Fertiliser use in main crop	Yes	No	No
Population density (km^{-2})	104	22	25

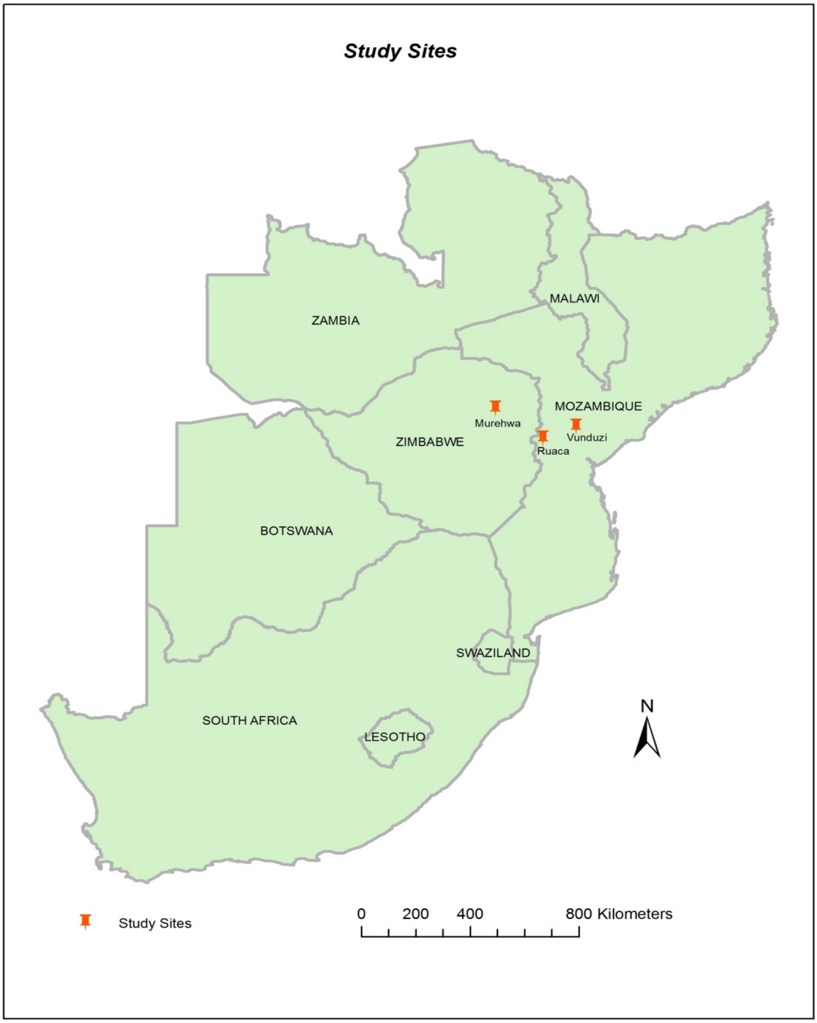

Fig. 1.1. Map of southern Africa showing the geographical location of Murehwa in Zimbabwe, and Ruaca and Vunduzi in central Mozambique.

1.8 Thesis outline

Chapter 2 is a literature review that provides an understanding of the effects of long-term tillage and/or residue retention practices on maize grain yield under contrasting soil textures, crop rotation, N fertiliser input and rainfall. The relationship between annual rainfall variability and its effect on maize grain yield is also explored using data from southern Africa. The analysis is used to draw major lessons on the suitability of conservation agriculture practises for southern Africa because in this region there is a strong need for effective water conservation practices to avert the devastating effects of erratic rainfall.

In Chapter 3, I present an explorative study on maize-grain legume intercropping in smallholder farming systems (Ruaca and Vunduzi) of central Mozambique. This study was motivated by the outcome of the literature review which identified legume integration as a key requirement to improve crop productivity. This paper evaluates the suitability of maize-legume intercropping to alleviate the biophysical and socio-economic constraints faced by smallholder farmers in Ruaca and Vunduzi communities, central Mozambique. I discuss the technical performance of the intercrop systems in relation to the socio-ecological environment and farmers' goals in these two sites.

Chapter 4 uses data from a long-term experiment to identify and explore pathways to restore soil fertility in degraded outfields using a combination of mineral fertilisers and cattle manure in Murehwa, Zimbabwe. I discuss how limited manure quantities can be allocated across the fields to maximise crop productivity benefits in the context of the smallholder mixed crop-livestock systems. Chapter 5 quantifies the intensity of trade-offs in crop residues uses across farm types in smallholder mixed crop-livestock farming systems in Murehwa, Zimbabwe. The implications of crop residue management on crop and livestock productivity are assessed in order to identify opportunities to optimize use of crop residues for soil fertility and livestock feed.

In Chapter 6**,** I place the crop production intensification options into the broader context of the smallholder farming systems in southern Africa. The nuances and nuisances of each option are discussed in relation to opportunities and constraints across farming systems. The implications of the findings of this thesis are discussed in relation to the design of productive and sustainable farming systems. Lastly, the major conclusions drawn from the study and recommendations for future research are highlighted.

Chapter 2

A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions

This chapter has been published as:

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Chapter 2- A meta-analysis of maize grain yield under CA

Abstract

Conservation agriculture is being promoted through reduced tillage, permanent soil cover and crop rotations across many regions of the world to meet the high demands for food from a dwindling land resource base while enhancing soil fertility. Recently there has been a sustained promotion of conservation agriculture in southern Africa to encourage its adoption in the predominantly maize (*Zea mays* L.) based farming systems. However, maize yields under rain-fed conditions are often variable and there is need for analyses that help to unravel the factors that contribute/affect crop yield under conservation agriculture practice and to identify windows of opportunity for improved impact in southern Africa. Maize grain yield data from long-term experiments (at least 5 years) under rain-fed conditions were analysed to provide an understanding of the combined effect of long-term tillage and / or residue retention on maize grain yield under contrasting soil textures, nitrogen input and climate through a meta-analysis. Variability of yield with time was measured through stability analysis. Analyses showed a clear increase in maize yield over time with conservation agriculture practices that include rotation and high input use in low rainfall areas, but there was no difference in system stability under those conditions. We observed a strong relationship between maize grain yield and annual rainfall with an average r^2 of 0.63. The following conclusions were made from the meta-analysis: (a) mulch cover in high rainfall areas leads to lower yields due to waterlogging (92% of data), (b) reduced tillage with no mulch cover leads to lower yields in semi-arid areas (56% of data), (c) conservation agriculture practices require high inputs especially N for improved yield (73% of data), (d) increased yields are obtained with rotation but calculations often do not include the variations in rainfall within and between seasons (63% of data), (e) rainfall is the most important determinant of yield in southern Africa and no tillage and mulch management practice in its present form can offset the detrimental effects of rainfall variability (average r^2=0.63) , (f) soil texture is important in the temporal development of conservation agriculture effects, improved yields are likely on well drained soils (85% of data), and (g) most experimental designs were poorly formulated resulting in effects being incorrectly attributed to the interacting components of conservation agriculture. Based on these observations, we propose a simple experimental design that can help to unravel the effects of tillage, mulch and rotation on crop yields. It is clear from this analysis that conservation agriculture needs to be targeted and adapted to specific bio-physical conditions for improved impact. Success of conservation agriculture in southern Africa will depend on the promotion of other good agronomic practices such as correct (amount and type) fertiliser application, timely weeding and systematic crop rotations.

Key words: conservation agriculture/ maize grain yield / meta-analysis/stability analysis/ rain-fed conditions/ southern Africa

Chapter 2- A meta-analysis of maize grain yield under CA

2.1 Introduction

Knowledge of specific crop responses to tillage and surface crop residues as affected by soils, climate and N fertilisation is necessary in the selection of appropriate tillage and crop residue management strategies for improved crop production (Aina et al., 1991). Smallholder agriculture in southern Africa is characterised by mouldboard ploughing and hand-hoeing that is often thought to lead to land degradation and excessive nutrient losses (Fowler and Rockstrom, 2001; Knowler and Bradshaw, 2007). To combat this scourge, conservation agriculture is being promoted through reduced tillage, permanent soil cover and crop rotations (FAO, 2008). The effectiveness of conservation agriculture for controlling excessive water run-off and soil erosion is well documented (Adams, 1966; Alberts and Neibling, 1994; Choudhary et al., 1997; Barton et al., 2004; Scopel et al., 2004a) and it is expected that this contribution can be measured in terms of crop yield. Other benefits associated with conservation agriculture include reduction in the input costs for crop production and profit maximisation (Dumanski et al., 2006; Knowler and Bradshaw, 2007).

Conservation agriculture emerged in the 1970s mostly in the USA and became an acceptable practice in the USA, Brazil, Argentina, Canada and Australia mainly because of its ability to combat increased soil erosion and land degradation, and because of lower fuel costs (Dumanski et al., 2006; Harrington, 2008). Conservation agriculture is mostly adopted by large scale mechanized farmers with the concomitant widespread use of glyphosate for weed control (Derpsch, 1999; Derpsch, 2005). Conservation agriculture was developed and adopted widely by farmers in South America mainly because it significantly reduced soil erosion, decreased labour costs and generally led to higher income and a better standard of living for the farmers (Ribeiro et al., 2007; Lahmar, 2010).

Implementing conservation agriculture in Africa, particularly the semi-arid regions, presents challenges different from where conservation agriculture originated. In semi-arid regions (300–500 mm annual rainfall), particularly southern Africa, success of conservation agriculture depends on the ability of farmers to retain crop residues and to ensure adequate weed control (Giller et al., 2009). Farming systems are predominantly mixed crop-livestock systems with low crop productivity and most crop residues are grazed *in situ* by livestock or transported to the kraal to improve quantity and quality of manure (Murwira, 1995; Mapfumo and Giller, 2001; Erenstein, 2002; Zingore et al., 2007). Rainfall is unimodal and erratic with high variability both within and between seasons, and droughts are common (Challinor et al., 2007) Combined mechanical and hand weeding are the preferred and cheaper weed control methods, and use of herbicides is uncommon (Siziba, 2007). Crop rotations are often non-systematic with maize grown continuously for 3-5 years, and are aimed at exploiting residual fertility rather than at benefiting the following crops in the rational sequence (Mapfumo and Giller, 2001). Fertiliser use is inadequate mainly due to high transaction costs and inefficiencies throughout the production and consumption chain (Quinones et al., 1997). On the other hand, the little fertiliser available is often not the correct type required for various crops and most farmers are not familiar with its correct usage (Sanginga and Woomer, 2009).

Manipulating tillage and mulch management to improve water infiltration and reduce water loss from the soil surface in crop fields has potential to substantially improve crop yields and soil conditions in the semi-arid tropics (Hussain et al., 1999; Findeling et al., 2003; Tarkalson et al., 2006). Conventional tillage practices alter soil structure and increase porosity of the upper layer. This increases the initial water infiltration into the soil but total infiltration is often decreased by subsoil compaction (Aina et al., 1991; Azooz and Arshad, 1996; Gómez et al., 1999). Cultivated soils may lose a lot of rainfall as run-off and large amounts of soil through erosion (Duley, 1940). Intensive rainfall on bare soil leads to surface sealing and soil compaction, resulting in localised waterlogging and poor soil infiltration (Castro et al., 2006). The mulch component of conservation agriculture controls soil erosion by reducing raindrop impact on soil surface, decreasing the water runoff rate and increasing infiltration of rainwater (Lal, 1989; Barton et al., 2004). Under semi-arid conditions mulches also play an important role in conservation of soil water through reduced soil evaporation (Scopel et al., 2004a). In theory, reduced tillage and surface cover increase soil water available for crop growth by increasing infiltration and by limiting run-off and evaporation losses (Fig. 2.1). However, mulching is not positive in all circumstances; under continuous rainfall mulches have little effect on soil water status (Unger et al., 1991). Prolonged dry periods may also cause the benefits of mulching to diminish due to continued evaporation (Jalota and Prihar, 1990). Intensive rainfall in mulched fields can cause waterlogging because of reduced evaporation (Araya and Stroosnijder, 2010) leading to reduced soil aeration (Cannell et al., 1985).

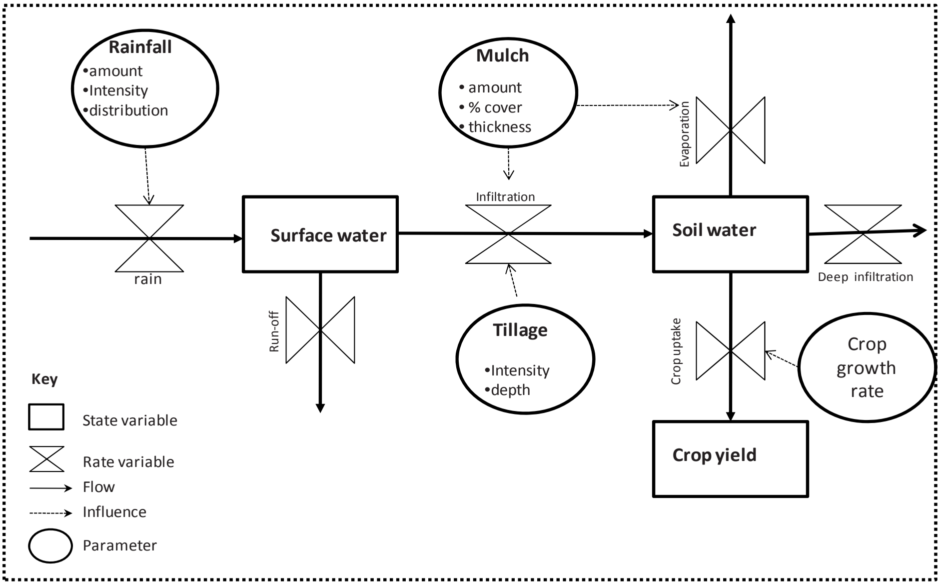

Fig. 2.1. The major components of the conservation agriculture practice at the soil-atmosphere interface showing how tillage and mulch management affect infiltration, soil moisture availability and crop growth. Tillage alters soil structure and increase porosity of the upper layer and enhances the initial infiltration while mulch reduces raindrop impact on soil surface, increasing infiltration of rainwater and reducing evaporation.

Interactions between the components of conservation agriculture and their effects on crop yields are complex and often site-specific and long-term experiments are necessary to provide a better understanding. They provide unique information on the sustainability of crop production systems and the interactions between management practices and the broader environment (Powlson et al., 2006). Sustainability is defined as the ability of a system to maintain productivity despite major disturbances such as intensive stress or a large perturbation (Conway, 1985; Hansen, 1996). Practically, long-term experiments enable observations on changes in crop growth patterns and management effects on slow-moving factors such soil organic matter which cannot be done in any other way (Jenkinson, 1991; Mitchell et al., 1991). They are important for designing cropping systems with high and stable crop yields and low production risk (Raun et al., 1993;

Stanger et al., 2008). We analysed maize grain yield data from rain-fed long-term studies on tillage and residue management from semi-arid to sub-humid environments. Maize grain yield is important because it is the staple food crop for most of southern Africa where it constitutes more than 50% of the diet for most people and can be grown under widely varying rainfall and edaphic conditions (Eicher, 1995; Smale, 1995; Sileshi et al., 2008). We mainly focused on one of the pillars of sustainable land management which is to maintain or enhance productivity (Dumanski and Smyth, 1994). Crop yield is important because it is the most common and useful parameter used to evaluate the acceptability by farmers of any production practice (Gameda et al., 1997; Abeyasekera et al., 2002).

The objective of this paper was to use data from long-term studies to provide an understanding of the effects of long-term tillage and/or residue retention practices on maize grain yield under contrasting soil textures, crop rotation, N fertiliser input and climate through meta-analysis. An analysis of the relationship between annual rainfall variability and maize grain yield was also carried out using data from southern Africa. This meta-analysis was used to draw major lessons for southern Africa because in this region there is a strong need for effective soil and water conservation practices to avert the effects of recurrent droughts. Analysing data from other regions provide an indication of the likely impact (*ex ante*) on food security of promoting reduced tillage and mulch-based cropping practices. It was also intended to understand the interactions between maize yield and rainfall, given its high variability under the climatic conditions of southern Africa.

2.2 Materials and methods

2.2.1 Meta-analysis

Maize grain yield data was obtained from long-term studies (> 5 years) on tillage and crop residue management under rain-fed conditions established in semi-arid and sub-humid environments from across the whole world. Treatments had to be from randomised plots with at least three replications. Studies (see Table 2.1) were obtained from refereed journals, book chapters or peer reviewed conference proceedings through online searches. Our search was comprehensive including the following keywords and their combinations: conservation agriculture, long-term, reduced tillage, no-tillage, maize yield, corn yield, sub-humid, semi-arid, rain-fed, southern Africa. We also contacted key experts who are working on conservation agriculture. We collected information on climate (mainly rainfall), altitude, soil texture of the experimental site, agronomic management (rate of N fertiliser applied) as reported by the primary authors (Table 2.1). These factors were considered to have significant influence on the effect sizes. Data required for the meta-analysis was in the form of treatment mean ($\overline{X}$), its standard deviation ($SD_{\overline{X}}$) and the number of replicates (n) mentioned in the experimental design. Several authors presented statistical data in different formats such as standard error ($SE_{\overline{X}}$) and coefficient of variation ($CV\%$). These forms were converted to standard deviation ($SD_{\overline{X}}$) using the following equations: $SD_{\overline{X}} = SE_{\overline{X}} \times \sqrt{n}$ and $SD_{\overline{X}} = (\frac{CV\%}{100}) \times \overline{X}$.

Table 2.1 The studies used in the meta-analysis, showing the country where the experiment was carried out, the duration of the experiment, soil texture at the experimental site, mean annual precipitation (MAP) for the duration of experiment and nitrogen (N) applied to the experiment. The abbreviations CP refers to conventional ploughing, NT to no-tillage, and NTM is no-tillage with mulch.

Reference	Country	Treatments	Duration (years)	Soil texture	MAP	N application (kg ha^{-1})
Wilhelm and Wortmann (1991)	USA	CP, NT	16	Sandy loam	720	113
Karen et al.(1988)	USA	CP, NT	12	Loam	1120	168, 202
Griffith et al. (2000)	USA	CP, NT	12	Silty clay Loam	420	210, 311
Linden et al.(1997)	USA	CP, NT, NTM	12	Silty loam	820	0, 100, 200
Lal, (1993)	Nigeria	CP, NT, NTM	8	Sandy loam	700	100
Vogel, (2003)	Zimbabwe	CP, NT	9	Sandy	800	50, 83
Moyo, (2000)	Zimbabwe	CP, NT	9	Sandy	500	50, 83
Nehanda (2009)	Zimbabwe	CP, NT	8	Clay	800	50, 83
Olson and Ebelhar (1987)	USA	CP, NT	10	Silt loam	600	218
Wilhelm et al. (1996)	USA	CP, NT	7	Silty clay loam	570	0, 70, 140
Thiagalingam et al.(1995)	Australia	CP, NT	5	Loam	900	0, 20, 40, 80,160
Iragavarapu and Randall (1994)	USA	CP, NT	11	Clay loam	1400	200
Acharya and Sharma (2004)	India	CP, NT, NTM	6	Clay loam	2500	120
Sisti et al. (2007)	Brazil	CP, NT	6	Clay		48, 60
Jin et al. (2000)	China	CP, NTM	8	Silty loam	700	150
Karunatilake et al. (2008)	USA	CP, NT	8	Clay loam		-
Mazzoncini et al. (2005)	Italy	CP, NT	16	Silty loam	700	188
Dam et al.(2002)	Canada	CP, NT, NTM	12	Loamy sand	430	180
Fischer et al. (1986)	Mexico	CP, NT, NTM,	5	Clay	603	50, 100
Rice et al. (2001)	USA	CP, NT	21	Silty loam	550	0, 84, 168, 336
Ghuman and Sur (1994)	India	CP, NTM	5	Sandy loam	920	80
Karlen et al. (1994)	USA	NT, NTM	10	Silty loam		168, 202
Ismail et al. (2002)	USA	CP, NT, NTM	21	Silty loam		0, 84, 168, 336
Nyagumbo, (1985)	Zimbabwe	CP, NT	8	Sandy	800	180
Dick and Van Doren, Jr. (2005)	USA	CP, NT	43	Silty clay loam	400	340
Govaerts et al. 2005	Mexico	CP, NT	6	Silty loam	600	120

Meta-analysis allows quantitative analyses of experimental results reported by other authors and the estimation of effect sizes (Glass, 1976; Ried, 2006; Borenstein et al., 2009). The analysis increases the statistical power available to test hypotheses, and differences in response between treatments under different environments (Gates, 2002; Borenstein et al., 2009). The effect size found in each individual study can be considered an independent estimate of the underlying true effect size, subject to random variation. All studies contribute to the overall estimate of the treatment effect whether the result of each study is statistically significant or not. Data from studies with more precise measurements are given more weight, so they have a greater influence on the overall estimate (Gates, 2002). However, meta-analysis has potential weaknesses due to publication bias and other biases that may be introduced in the process of locating, selecting, and combining studies (Egger et al., 1997; Noble, 2006). Publication bias is the tendency on the part of investigators, reviewers, and editors to submit or accept manuscripts for publication based on the direction or strength of the study findings (Dickersin, 1990). To overcome these challenges, our searches were carried out online in order to get results from all parts of the world as long as they originated from semi-arid and sub-humid environments. We identified the factors in our analysis such as mean annual precipitation, soil texture and N fertiliser input which could affect the effect sizes and employed the random effects model (Ried, 2006).

2.2.2 Treatments for the meta-analysis

In our analysis we were interested in treatments that could allow effects of tillage and mulch on maize grain yield to be disaggregated (Table 2.2). The effect of tillage was analysed by comparing conventional tillage and no-tillage treatments, and therefore conventional tillage was used as the control treatment. No-tillage without rotation was compared with no-tillage with rotation to determine the effect of rotation thus no-tillage without rotation was used as the control treatment. Similarly effect of mulching was analysed by comparing no-tillage without mulch and no-tillage with mulch, and therefore no-tillage without mulch was the control treatment. Moderators of maize yield response were; crop rotation, soil texture, mean annual precipitation and N input.

Table 2.2. A short description of the tillage treatments used for the evaluation of tillage and mulch effects on maize yield.

Tillage management option	Short description
Conventional tillage (CT)	Mouldboard ploughing is the major means of seedbed preparation and weed control; most crop residues are eaten by livestock and the little left are buried in the soil. The most widely practiced tillage technique used by communal farmers with animal draught power in southern Africa.
No-tillage/reduced tillage (NT)	Practice of minimising soil disturbance, ranges from reducing the number of tillage passes, tillage depth or stopping tillage completely. Weed control is accomplished primarily with herbicides.
No-tillage + rotation (NTR)	As described in (2) above. Main crop of maize in a rotation sequence with legumes such as soybean (*Glycine max*) or cowpea (*Vigna unguiculata* (L.) Walp).
No-tillage + mulch (NTM)	No-tillage plus previous crop residues to achieve at least 30% soil cover after planting. Generally referred to as conservation agriculture (CA) treatment.

2.2.3 Meta-analysis calculations

In our analysis, we used the mean difference (Equation 1.1) in yield between the treatment and control because of its ease of interpretation (Ried, 2006). The yield difference is also more relevant when comparing potential gains to required investment and input costs (Sileshi et al., 2008). To obtain overall treatment effects across studies, the differences between treatment and control were weighted (Equation 1.3). The weight given to each study was calculated as the inverse of the variance (Equation 1.2). The random effects model was the most appropriate model to calculate effect sizes as it assumed that studies were drawn from different populations and this could influence the treatment effect. Soil texture, nitrogen input, crop rotation and amount of seasonal rainfall were chosen as covariates and their effect tested on the magnitude of response (mean differences) each with a time component. Due to asymmetry in data distribution between treatments and covariates, conservation agriculture practices (NT, NTR and NTM) were combined together when analysing the effects of covariates. Rainfall was categorised using long-term mean annual of sites to form mean annual precipitation (MAP) classes as low (< 600 mm), medium (600–1000 mm) and high (>1000 mm) based on FAO guidelines (Fischer et al., 2001). Soil texture was categorised as clay, sandy, loamy and silt clay loam (Brown, 2003) and N fertiliser input was categorised as low (<100 kg ha^{-1}) and high (>100 kg ha^{-1}) (Osmond and Riha, 1996).

$$Mean\,difference\,(MD) = mean_{treated} - mean_{control} \quad (0.1)$$

$$weight_i = \frac{1}{\text{var}\,iance_i} = \frac{1}{SD_i^2} \quad (0.2)$$

$$Weighted\ mean\ difference\,(WMD)_{overall} = \sum_{i=1}^{i=n} (weight_i * MD) / \sum_{i=1}^{i=n} weight_i \quad (0.3)$$

$$CI_{95\%} = mean_{overall} \pm (1.96 * (\text{var}iance_{overall})^{0.5}) \quad (0.4)$$

$$Variance_{overall} = \frac{1}{\sum_{i=1}^{i=n} weight_i} \quad (0.5)$$

2.2.4 Rainfall variability and maize yields

In sub-Saharan Africa, when sufficient nutrients are available, rainfall variability (both within and across seasons) is the most critical determinant of crop yield (Waddington, 1993; Phillips et al., 1998). In this region, 89% of cereal production is rain-fed (Cooper, 2004). We evaluated the relationship between maize yield and annual rainfall variability in southern Africa using non-linear regression (Bergamaschi et al., 2007). We used data from three sites with sub-humid climate where long-term conservation agriculture experiments were established in 1988: (i) the Institute of Agricultural Engineering (17º42' S, 31º06' E , 1600 m above sea level and 18 km north of Harare), (ii) Domboshawa Training Centre (17º35' S, 31º10' E, 1600 m above sea level and 33 km north of Harare), and (iii) Makoholi Research Station (19º 34'S, 30º 47' E, 1200 m above sea level and 270 km south of Harare). The first site is characterised by deep, well-drained, red clay soils while Domboshawa Training Centre (DTC) and Makoholi Research Station are characterised by inherently infertile granite-derived sandy soils (Nyamapfene, 1991). Both Institute of Agricultural Engineering and Domboshawa Training Centre receive rainfall of about 750 to 1 000 mm per year but Makoholi Research Station receives between 450 and 650 mm per year (Vincent and Thomas, 1960; Moyo, 2003).

2.2.5 Yield stability analysis

A stable system shows a small change in response to changes in the environment (Lightfoot et al., 1987). We regarded each tillage practice as a system and the stability of the system in this study is measured by linear regression of treatment yield against the environmental mean yield; the environmental mean is the average of all the treatments in a given year (Piepho, 1998; Hao et al., 2007; Grover et al., 2009). A regression coefficient smaller than one indicates a higher stability (Bilbro and Ray, 1976). The regression model is shown in Equation 1.6

$$y_{ij} = \mu_i + \beta_i u_j + d_{ij} \qquad (0.6)$$

where y_{ij} is the treatment mean of the i^{th} treatment at the j^{th} environment, μ_i is the i^{th} treatment mean in all environments, β_i is a regression coefficient corresponding to the i^{th}

treatment, u_j is an effect of the j^{th} environment and d_{ij} is a random deviation from the regression line (Eberhart and Russell, 1966; Piepho, 1998).

2.3 Results and discussion

2.3.1 Summary statistics of weighted mean differences

Summary statistics showed large variations in maize yield among the treatments across the regions considered (Fig. 2.2). Reduced tillage with rotation had a positive overall effect on maize yield while reduced tillage (with or without mulch) and continuous maize had negative overall effect on yield compared with the control. Lal (1997) observed that tillage treatments were only significant in three out of eight seasons but maize yield depended more on the amount of rainfall received and its distribution during the season. This observation clearly shows that besides tillage and mulch management, more factors are important for maize yield increases thus we explore these factors in the sections that follow.

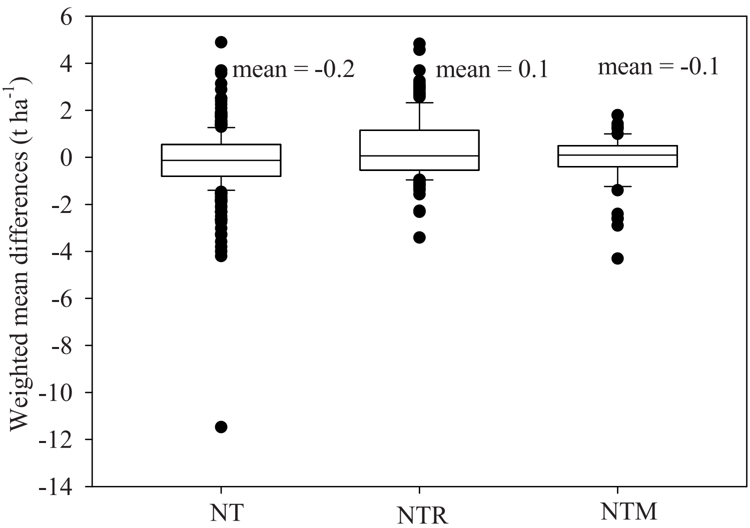

Fig. 2.2. Summary statistics of maize grain yield weighted mean differences (t ha^{-1}) in the treatments used for the meta-analysis. The middle lines are the median values, data show that no-tillage with continuous maize had the largest range but the smallest mean.

2.3.2 Reduced tillage, continuous maize

There was no change in weighted mean differences in maize grain yield over time, and therefore no-tillage had no positive effect on maize yield compared with conventional tillage (Fig. 2.3). Results showed that in the first 10 years, crop yields were lower than the conventional tillage practice. At the beginning of the experiment, reduced tillage practices often resulted in smaller yields than the control, but this was not true for all years. These results are similar to results of (Kapusta et al., 1996) who reported no difference in yield between no-tillage and conventional ploughing on poorly drained soils after 20 years of continuous no-tillage. Dam et al. (2005) reported that after 11 years, maize yields were not affected by tillage and residue practices but climate-related differences seemed to have a greater influence on the variation in yields. When residues were completely removed, yield reductions for maize were attributed to decreased soil water storage and excessive surface soil temperatures, especially in climates where conditions of moisture stress occurred during the growing season (Doran et al., 1984). Evidence from Switzerland showed that ploughing could be dispensed under cool moist conditions without loss in yield for crops such as wheat and rape but with maize, no-tillage resulted on average over 10% less yield than in tillage experiments (Anken et al., 2004).

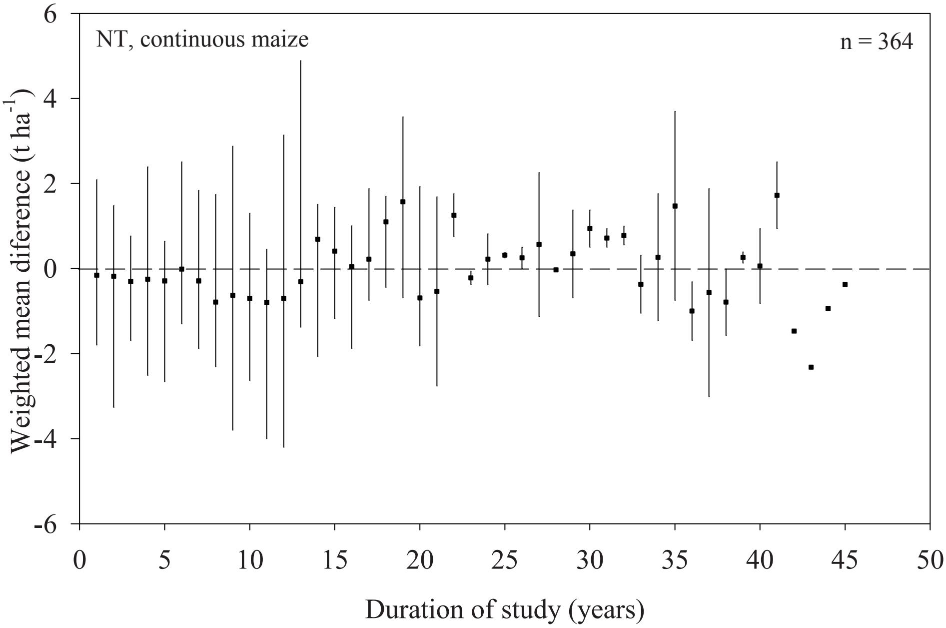

Fig. 2.3. Weighted mean differences in maize grain yield over time between continuous no-tillage and continuous conventional tillage. Effect sizes show yield benefits in some years but yield decreases in other years, overall there is no clear effect.

2.3.3 No-tillage, maize-legume rotation

There was an increase in yield in no-tillage with rotation over no-tillage without rotation as shown by the positive overall weighted mean difference (Fig. 2.4) in maize – legume rotations. Most of the studies reporting crop yields with rotation showed positive effects in no-tillage systems agreeing with the results of (Karlen et al., 1991; Karlen et al., 1994), who reported that rotations are likely to produce higher yields across soil fertility regimes. Higher yield for no-tillage in rotation than in monocropping is attributed to a combined effect of multiple factors that include reduced pest infestations, improved water use efficiency, good soil quality as shown by increased organic carbon, greater soil aggregation, increased nutrient availability and greater soil biological activity (Van Doren et al., 1976; Griffith et al., 1988; Hernanz et al., 2002; Wilhelm and Wortmann, 2004; Agyare et al., 2006; Kureh et al., 2006). Other authors report that the yield increase is often higher in low-yielding environments than in high-yielding environments (Lauer and Oplinger, 1996; Porter et al., 1997). The higher yield increase of rotated crops is low-yielding environments means that this production strategy shows promise for most environments in southern Africa. The results of the meta-analysis suggest that rotation should be an integral component of tillage practices for supplying nutrients to maize (Francis and King, 1988; Chikowo et al., 2004) and also for breaking pests and disease life cycles as found in other studies (Jordan and Hutcheon, 2003; Sandretto and Payne, 2007).

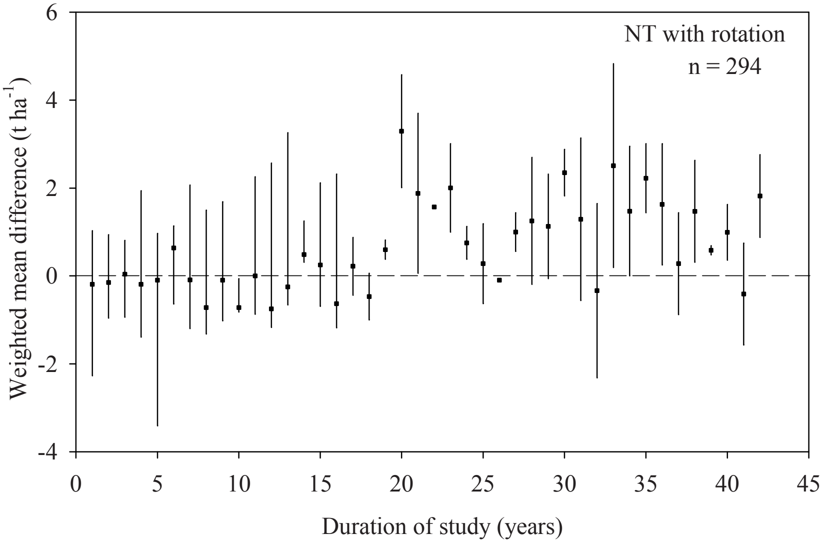

Fig. 2.4. Weighted mean differences in maize grain yield over time between no-tillage with rotation and continuous conventional tillage without rotation. Although effect sizes are generally positive, real yield benefits start after 20 years of production.

2.3.4 No-tillage with mulch, continuous maize

There was no effect of no-tillage + mulch on yield over the conventional tillage, and after 10 years there even seems to be strong negative effect (Fig. 2.5). These results are in contrast with the general belief that conservation agriculture effects emerge in the long-term. Results from the Laikipia conservation agriculture project in Kenya show that maize yields were virtually the same under plots managed under conventional tillage and those managed under conservation agriculture (Kaumbutho and Kienzle, 2007). Mulch cover associated with no-tillage practices promotes soil water retention (Blevins et al., 1971) and reduces soil temperature (Burrows and Larson, 1962) which delays maize emergence and early-season growth. Some authors (Van Doren et al., 1976; Mupangwa et al., 2007) have also found that neither mulching nor tillage practice had a significant effect on maize grain yield on different soil textures and Lal (1997) reported positive effect of no-tillage + mulch in only 3 of 8 seasons. It has been observed that the effectiveness of mulch is limited in environments of limited rainfall (Tolk et al., 1999). The lack of clear benefits on maize grain yield with mulch suggests that it may be better to allocate crop residues as livestock feed instead of keeping it for mulch. Probert (2007) did a modelling exercise using long-term experimental data and concluded that retaining increasing proportions of residues reduces evaporation and run-off but the long-term average yields show only small effects of residue retention on crop yields and the transpiration component of the water balance. Probert (2007) further observed that with no change in transpiration, the reductions in run-off and evaporation must be balanced by increases in drainage. These findings are further supported by a similar modelling exercise using data from Brazilian Cerrados (Scopel et al., 2004a). Vogel (1993) suggested that no-tillage in combination with tied ridging is the most suitable tillage technique for the sub-humid regions because it prevents waterlogging and increased root depth; whereas mulching is likely to be the best conservation tillage technique for the semi-arid regions due mainly to reduced topsoil water losses.

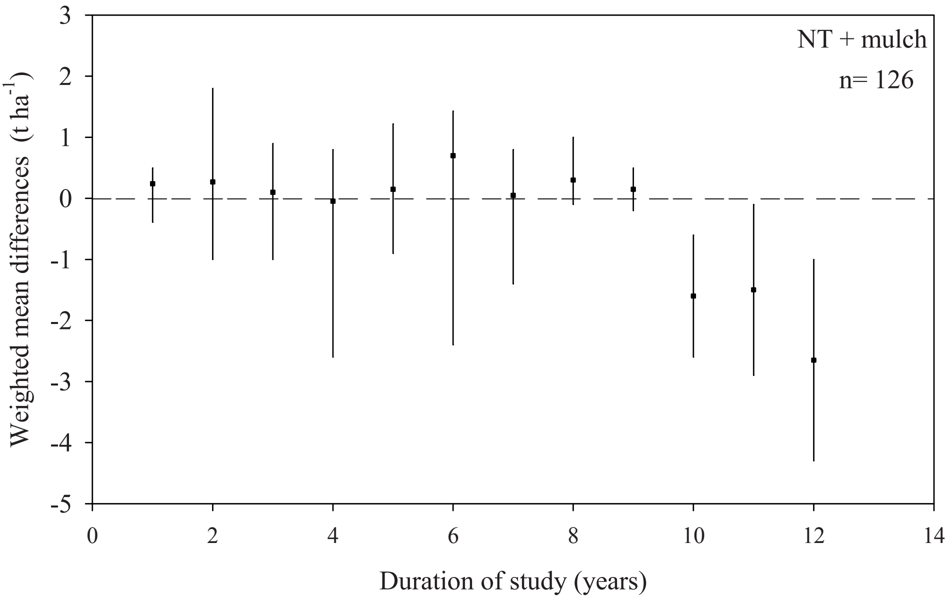

Fig. 2.5. Weighted mean differences in maize grain yield over time between continuous no-tillage + mulch and continuous conventional tillage without mulch.

2.3.5 Effect of mean annual rainfall and rainfall variability

2.3.5.1 Effect of mean annual rainfall

Maize yield was higher with conservation agriculture practices (NT, NTR and NTM) when mean annual precipitation was below 600 mm and lower when mean annual precipitation was above 1000 mm (Fig. 2.6). This might be attributed to moisture conservation in low rainfall areas under conservation agriculture and compromised drainage in high rainfall areas. These results agree with Hussain et al. (1999) who reported that yields under conservation agriculture practices were 5–20% lower than under conventional tillage practices in wet years, but were 10–100% higher in relatively dry year. Higher crop yield with the conservation agriculture practice than with conventional tillage in a dry year was also reported by Lueschen et al. (1991). Temporal variability in yield is mainly affected by environmental factors with precipitation having the strongest effect (Hu and Buyanovsky, 2003; Mallory and Porter, 2007; Grover et al., 2009).

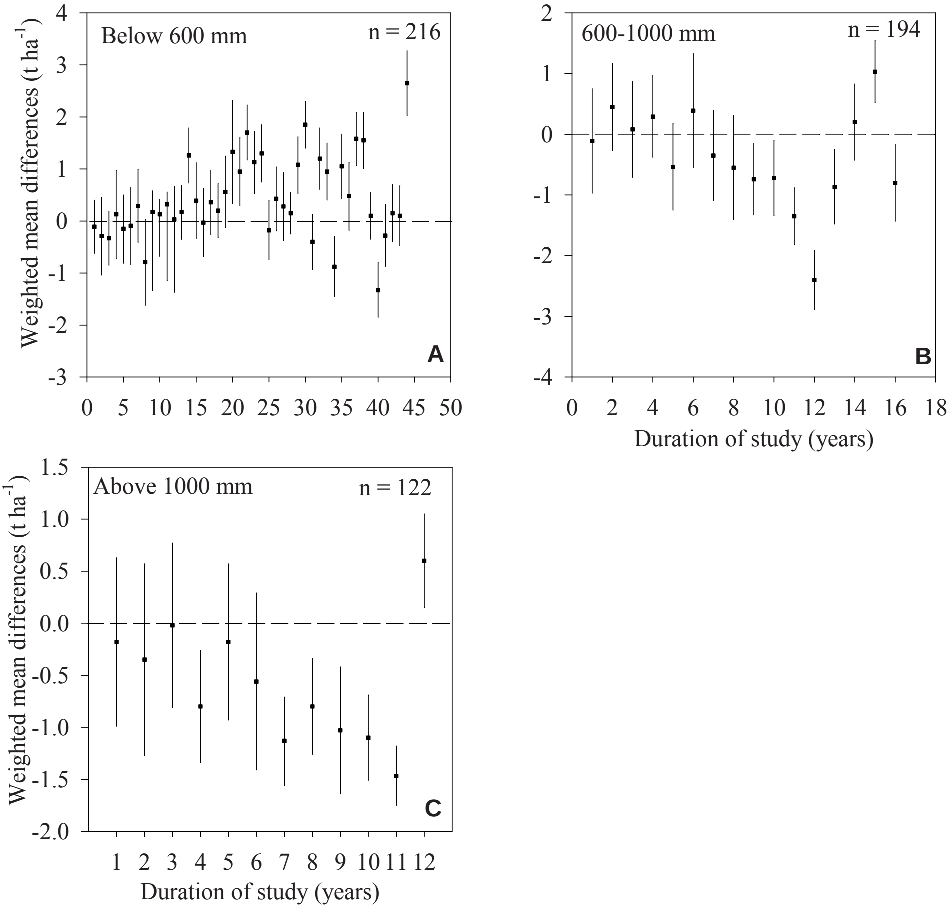

Fig. 2.6. Weighted mean differences between conservation agriculture practices (NT, NTR and NTM) and conventional tillage over time as affected by mean annual precipitation. A, effect sizes show clear yield benefits with time when annual rainfall is below 600 mm. B, effect sizes do not show a clear trend in yield benefits when annual rainfall is between 600 and 1000 mm. C, effect sizes show a clear decrease in maize yield under conservation agriculture when mean annual precipitation is above 1000 mm.

2.3.5.2 Effect of rainfall variability

Variation in total seasonal rainfall across seasons was responsible for major yield fluctuations across treatments in the 3 experiments of the dataset that were conducted in Zimbabwe (Fig. 2.7). Rainfall was highly variable across sites and across seasons, at Domboshawa, rainfall varied between 438 and 1396 mm with a mean value of 823 mm. It caused low yields across all treatments especially in 1989/90, 1991/92 (drought year) and 1996/97. At the Institute of Agricultural Engineering, rainfall ranged between 481 and 1163 mm with a mean of 889 mm. At Makoholi, rainfall was low but variation between seasons was very high (between 164 mm and 998 mm) with a mean of 559 mm. In two seasons of contrasting total rainfall, the conventional tillage practice had considerable higher yields than the mulched and reduced tillage treatments, suggesting the absence of benefits of tillage when extreme weather events occur. The low yield during the high rainfall years could be attributed to inefficient water use due to waterlogging that affected nutrient uptake and crop growth (Griffith et al., 1988). The water conservation effect of mulch on maize yield under low rainfall was not observed during the drought of 1991/92 (Nehanda, 1999; Moyo, 2003). The temporal development of conservation agriculture effects in these three sites seems to be affected more by the amount of seasonal rainfall and soil texture rather than by tillage and mulch management practices. At Domboshawa and Makoholi, both sites characterised by sandy soils, recorded virtually zero grain yield during drought years. There are greater chances of conservation agriculture effects developing at the Institute of Agricultural Engineering which is characterised by a combination of fertile red clay soils and good seasonal rainfall averaging 850 mm in most seasons. The build-up of conservation agriculture effects on sandy soils is a challenge because sandy soils readily lose soil quality during continuous cropping due to compaction, loss of organic matter and acidification (Juo et al., 1996).

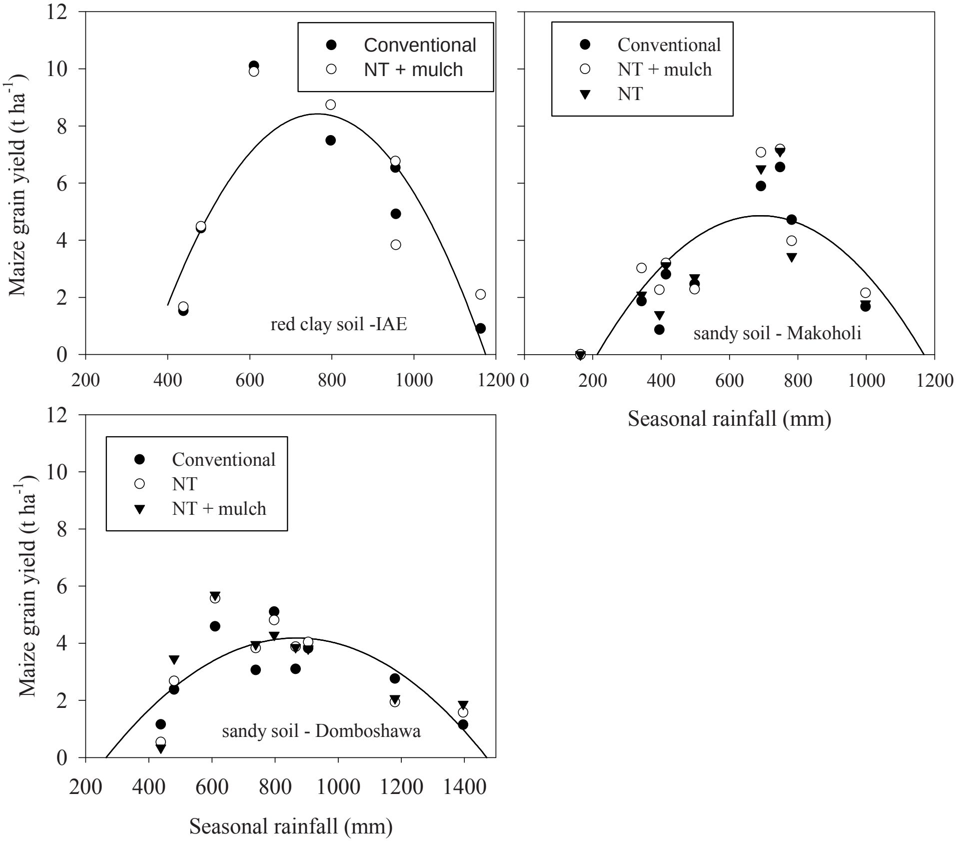

Fig. 2.7. The relationship between total annual rainfall and maize grain yield as affected by tillage practice from long-term sites in Zimbabwe. There was a strong correlation between the amount of rainfall and maize grain yield as rainfall accounted for on average 63% of the variation in all sites.

2.3.6 Effect of soil texture

Analysis with soil texture and duration of experiment showed that in clay soils weighted mean differences were mostly negative but were positive in both loam and sandy soils (Fig. 2.8). There was no significant difference between conservation agriculture treatments (NT, NTR and NTM) and conventional tillage on maize yield on silt clay loams with time. However, there was an improvement in maize grain yield on loamy and sandy soils. Dick and Van Doren (1985) also reported yield reductions of maize associated with no-tillage on heavy clay, very poorly drained soils and suggested crop rotations and use of disease resistant cultivars as possible solutions. However, Van Doren et al. (1976) reported that maize grain yields are insensitive to tillage over a wide range of soil textures, cropping systems, climate conditions, and experiment durations as long as equal plant densities and adequate weed control were maintained. The reduction in crop yields on poorly drained soils under conservation agriculture was also reported by (Griffith et al., 1988). Increased yields on well drained soils are attributed to more efficient use of water and improved physical properties (Griffith et al., 1986). Low yields in poorly drained soils are attributed to allelopathy (Yakle and Cruse, 1984) and plant pathogens (Tiarks, 1977). Kapusta et al. (1996) reported that continuous maize production under no-tillage is most successful on well-drained soil, rather than on either imperfectly or poorly drained soil, especially under wet soil conditions. It has also been suggested that maize monocropping has drastic adverse effects on soil quality and crop yield especially under conditions of low traffic and no-tillage with mulching (Lal, 1997). Most soils in southern Africa have biophysical limitations (poor nutrient concentrations, acidity, coarse texture), that limit biomass accumulation therefore combinations of legume rotations and mineral nitrogen fertilisation is the most viable option for sustainable agriculture in this region (Chikowo et al., 2004).

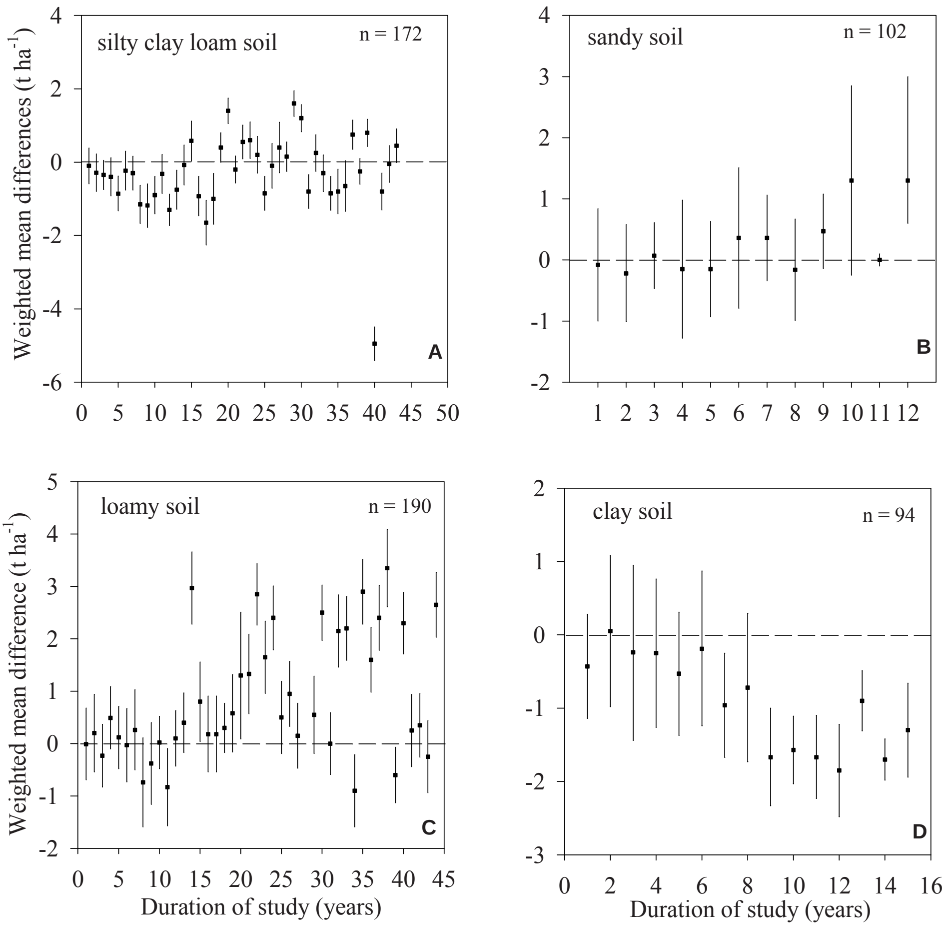

Fig. 2.8. Weighted mean differences between conservation agriculture practice (NT, NTR and NTM) and conventional tillage over time as affected soil texture. A, effect sizes do not show any increase in yield over time in silt clay loam soils. B, effect sizes do not show any increase in yield over time in sandy soils. C, effect sizes show substantial increases in yield over time in loam soils. D, effect sizes show loss in yield over time in clay soils.

2.3.7 Effect of nitrogen fertiliser input

Nitrogen is often the most limiting nutrient for maize produced in the tropics (Osmond and Riha, 1996)(Osmond and Riha, 1996). At nitrogen fertiliser applications of below 100 kg N ha^{-1} there were fewer yield advantages of conservation agriculture over conventional tillage but more yield benefits were obtained with high applications of above 100 kg N per hectare

(Fig. 2.9). The results agree with Díaz-Zorita et al. (2002) who reported in a review that maize yields were increased more by nitrogen fertilisation than tillage under sub-humid and semi-arid regions of Argentina. These results show that conservation agriculture practices are input intensive therefore improved crop yields under conservation agriculture depend on the ability of farmers to use fertiliser in sufficient quantities and correct proportions. The current average fertiliser use by smallholder farmers in Africa is at 8 kg ha^{-1} (Groot, 2009) and considerable effort is required to improve its use (Sanginga and Woomer, 2009). While the fertiliser rates categories considered are quite high and most farmers in southern Africa cannot afford such rates, fertiliser remains important to alleviate nutrient constraints.

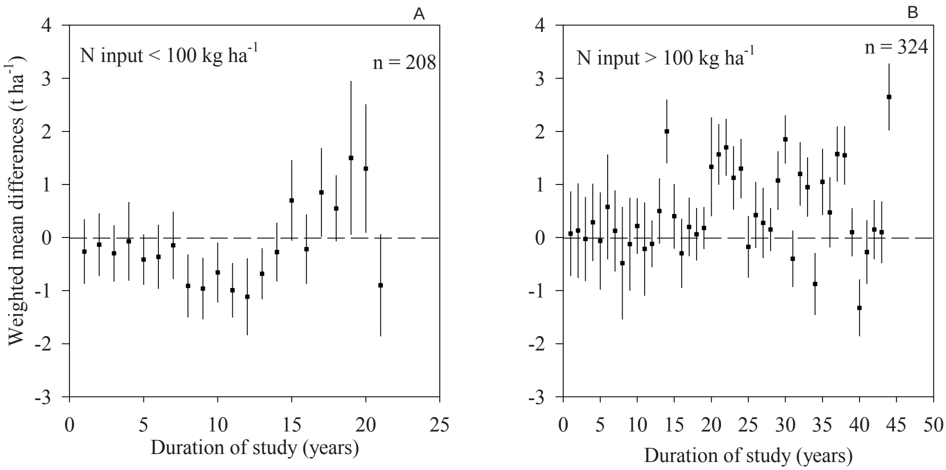

Fig. 2.9. Effect of nitrogen input on the weighted mean differences between conservation agriculture (NT, NTR and NTM) and conventional tillage over time. Effect sizes show yield increases when nitrogen input is above 100 kg ha^{-1}.

Most crop residues in semi-arid areas are derived from maize, millets and sorghum, which are traditionally known for their poor quality due to high C:N ratios, generally greater than 60 (Cadisch and Giller, 1997; Handayanto et al., 1997). Although crop residues are often on the soil surface, there is a greater chance of partial incorporation and decomposition as the season progresses (Parker, 1962). The wide C:N ratio and the relatively large amounts of readily decomposable carbon compounds leads to prolonged nitrogen immobilisation by micro-organisms, rendering the nitrogen unavailable for crop growth in the short term (Giller et al., 1997) thus high nitrogen inputs are required when poor quality crop residues are used as mulch.

2.3.8 Yield stability analysis

There was no treatment effect on stability as a regression between environmental and treatment mean for soil texture (Table 2.3 and Fig. 2.10) and for duration of experiment (Table 2.4 and Fig. 2.11) with regression coefficients ranging from 0.94 to 1.06 and r^2 values ranging between 0.92 and 0.99. The regression analysis for no-tillage with mulch practice had a smaller regression coefficient in sandy soils showing an advantage of mulch based systems to optimise moisture availability in soils of poor drainage. Our hypothesis that reduced tillage and residue retention leads to more stable yields was not supported by the data.

Table 2.3**.** Linear regression equations and r^2 values for tillage practice maize grain yield means for clay and sandy soils. $P > |t|$ is the probability of a greater absolute value of the slope (/t/)

Soil texture	Tillage treatment	Regression equation	r^2	Slope P > /t/
Clay	Conventional	$y = 0.49 + 1.01x$	0.94	<0.0001
	No-till	$y = -0.246 + 1.01x$	0.93	<0.0001
	No-till + mulch	$y = 0.045 + 1.06x$	0.92	<0.0001
Sand	Conventional	$y = -0.005 + 1.001x$	0.99	<0.0001
	No-till	$y = -0.180 + 1.045x$	0.98	<0.0001
	No-till + mulch	$y = 0.259 + 0.942x$	0.99	<0.0001

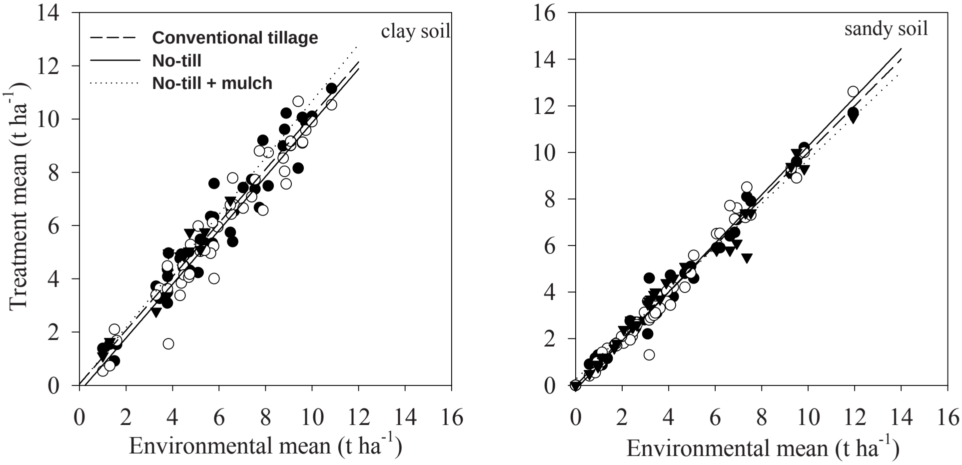

Fig. 2.10. Linear regressions for tillage practice maize grain yield means on the environmental maize grain yield means for clay and sandy soils. Slopes were compared among treatments at $P < 0.05$.

Table 2.4. Linear regression equations and r^2 values for the tillage system maize grain yield means on the environmental maize grain yield means for short-term and long-term trials. $P >$ $|t|$ is the probability of a greater absolute value of the slope (/t/)

Duration	Tillage treatment	Regression equation	r^2	Slope P > /t/
< 10 years	Conventional	$y = -0.132 + 1.03x$	0.97	<0.0001
	No-till	$y = -0.043 + 0.99x$	0.96	<0.0001
	No-till + mulch	$y = 0.496 + 0.953x$	0.95	<0.0001
> 10 years	Conventional	$y = -0.060 + 0.99x$	0.91	<0.0001
	No-till	$y = 0.0393 + 1.009x$	0.91	<0.0001
	No-till + mulch	$y = 0.236 + 0.970x$	0.82	<0.0001

2.3.9 Lessons for southern Africa

Competition for crop residue use, low fertiliser use, non-use of herbicides, labour shortage, erratic rainfall, lack of crop rotations and poor soils combine to offer many challenges for the practice of conservation agriculture among smallholder farmers in southern Africa (Siziba, 2007; Giller et al., 2009). It is clear from the meta-analysis that the success of conservation agriculture in improving crop yields depends on appropriate targeting to climatic and edaphic conditions with adequate inputs (fertiliser and herbicides). Farmers are unlikely to adopt all the conservation agriculture practices and success will not come from the pre-packed technologies alone but from how farmers adapt and apply them depending on resources availability, production objectives (benefits) and biophysical circumstances (Ojiem et al., 2006). In situations of crop-livestock integration where competition for crop residue uses is strong, intercropping with grain legumes can be a viable strategy to achieve surface cover because the legume will cover the area between rows of the main crop and help conserve moisture (Scott et al., 1987). In cases were linkages to markets for grain legumes can be secured, legume production can be an excellent opportunity for farmers to increase land size allocated for legumes and improve rotation with main cereal crops. Alternatively planting basins can be an efficient method of moisture conservation if they can be maintained after weeding operations (Mupangwa et al., 2007; Mupangwa et al., 2008).

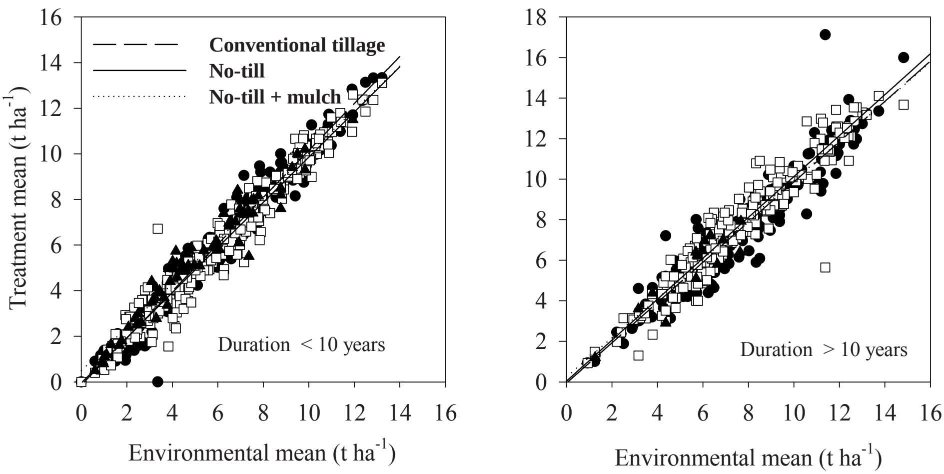

Fig. 2.11. Linear regressions for the tillage practice maize grain yield means on the environmental maize grain yield means for short-term (< 10 years) and long-term (> 10 years). Slopes were compared among treatments at $P < 0.05$.

2.3.10 Challenges with long-term experiments

Long-term trials are designed to help identify and recommend production systems with beneficial effects on the environment as well as crop productivity across variable environments over time. However, in long-term trials when the cropping system has approached a new equilibrium, it is difficult to attribute effects to particular factors as the interactions between the factors (tillage, mulch, rotation, soil texture and rainfall) involved are so subtle and site-specific that proper experimental designs are required. Sources of variations where crop residues are retained increase as yield varies across seasons to the extent that the effect of mulch will not be explicitly identified. Results from this meta-analysis suggest that yields decline due to continuous monoculture effects and this is more pronounced on sandy soils of low inherent fertility (Lal, 1997). These monoculture effects will become more pronounced with time, diminishing the influence of tillage practices on maize yield. Reduction in maize grain yield with continuous maize and no-tillage have been recorded and attributed to unknown underground effects which need further research (Wolfe and Eckert, 1999; Fischer et al., 2002). Well-designed long-term experiments are still desirable across different agro-ecological conditions to unravel the effects of mulch, tillage and rotation on maize grain yield. We propose a simple experimental design (Fig. 2.12) that we expect can be used to identify the effects of different components. We also propose that the analysis of studies across seasons should take into consideration variability in rainfall to avoid overestimating treatment effects.

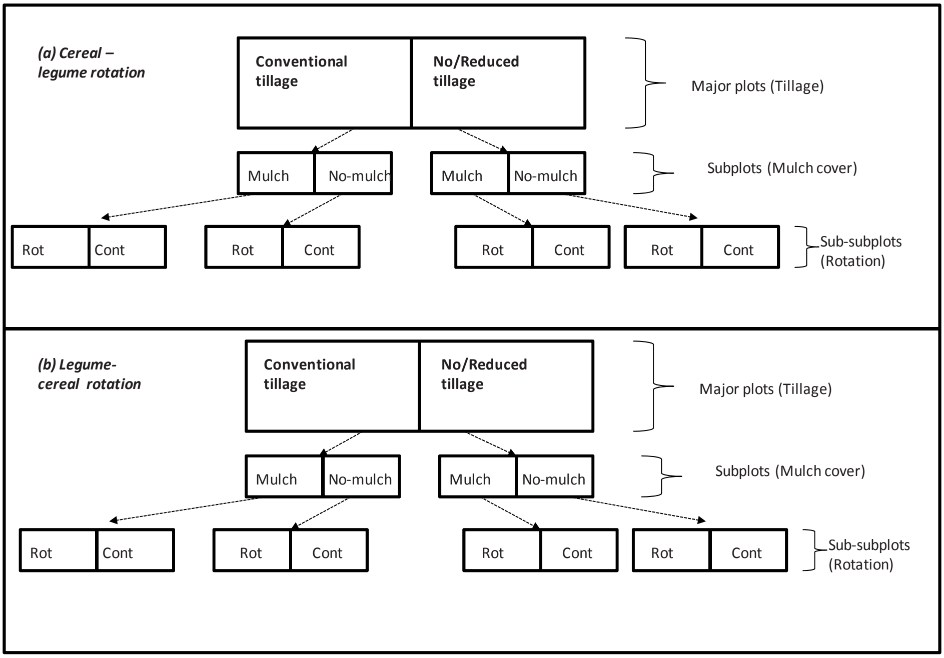

Fig. 2.12. Simple factorial design to unravel the effects of tillage, mulch and rotation on crop yields. Major plots should be established side by side with one being for cereal-legume rotation and the other being for legume-cereal rotation, this allows the study of both cereal or legume continuous monocropping effects.

2.4 Conclusions

The factors considered in our analysis covered most of the environments where rain-fed agriculture is practiced and gives us a basis to draw the following conclusions. Positive impacts of moisture conservation on crop yield in soils of poor drainage are likely to occur in low rainfall environments, and maize yield was lower in no-tillage without rotation compared with conventional tillage but higher when rotation was practised. Results clearly showed that the successful practice of conservation agriculture required high inputs, especially nitrogen fertiliser. Under rain-fed agricultural conditions where total rainfall and its distribution is important for crop production, yield stability analysis results showed that under drought or too much rainfall, no treatments can offset the effects of these extreme conditions. Incentives for abandoning the plough still exist through savings in fuel, labour, and wear and tear of farm implements however this need to be quantified in a separate analysis. Very few studies if any can disaggregate the effects of the three principles (reduced tillage, mulch cover and crop rotation) on maize grain yield and thus well designed long-term experiments are still desirable across different agro-ecological conditions to unravel the effects of mulch, tillage and rotation on maize grain yield. Improving maize yields under conservation agriculture in southern Africa depends on the ability of farmers to practice crop rotation and given that on average they plant legumes on 5% of the land, we propose that conservation agriculture be repackaged to reflect the diversity of farming systems and other biophysical and socio-economic considerations for improved impact. Our analyses have shown that success of conservation agriculture in southern Africa depends on the promotion of other good agronomic practices such as targeted fertiliser application, timely weeding and crop rotation.

Chapter 3

Maize-grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique

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Abstract

Many farmers in central Mozambique intercrop maize with grain legumes as a means to improve food security and income. The objective of this study was to understand the farming system, and to evaluate the suitability of maize-legume intercropping to alleviate the biophysical and socio-economic constraints faced by smallholder farmers in central Mozambique. To achieve this we characterised the farming systems and measured grain yields, rainfall infiltration, economic returns and acceptability of maize-legume intercrops under different N and P application levels. Two intercropping strategies were tested: (a) an additive design of within-row intercropping in which legume was intercropped with alternating hills of maize within the same row; maize plant population was the same as sole crop maize, and (b) a substitutive design with distinct alternating rows of maize and legume (local practice). Fertiliser treatments imposed on all treatments were: (i) no fertiliser, (ii) 20 kg P ha^{-1}, (iii) 20 kg P ha^{-1} + 30 kg N ha^{-1}, and (iv) 20 kg P ha^{-1} + 60 kg N ha^{-1}. Intercrops were relatively more productive than the corresponding sole crops; land equivalent ratios (LER) for within-row intercropping ranged between 1.1 and 2.4, and between 1.0 and 1.9 for distinct-row intercropping. Average maize yield penalty for intercropping maize and pigeonpea in the within-row was small (8%) compared with 50% in the distinct-row, design; average (season × fertiliser) sole maize yield was 3.2 t ha^{-1}. Intercropping maize and cowpea in within-row led to maize yield loss of only 6%, whereas distinct-row intercropping reduced maize yield by 25% from 2.1 t ha^{-1} of sole maize (season × fertiliser). Cowpea yield was less affected by intercropping: sole cowpea had an average yield of 0.9 t ha^{-1}, distinct-row intercropping (0.8 t ha^{-1}) and the within-row intercropping yielded 0.9 t ha^{-1}. Legumes were comparatively less affected by the long dry spells which were prevalent during the study period. Response to N and P fertiliser was weak due to poor rainfall distribution. In the third season, maize in rotation with pigeonpea and without N fertiliser application yielded 5.6 t ha-

^{1}, eight times more than continuous maize which was severely infested by striga *(Striga asiatica*) and yielded only 0.7 t ha^{-1}. Rainfall infiltration increased from 6 mm h^{-1} to 22 mm hr^{-1} with long-term maize-legume intercropping due to a combination of good quality biomass production which provided mulch combined with no tillage. Intercropping maize and pigeonpea was profitable with a rate of return of at least 343% over sole maize cropping. Farmers preferred the within-row maize-legume intercropping with an acceptability score of 84% because of good yields for both maize and legume. Intercropping increased the labour required for weeding by 36% compared with the sole crops. Farmers in Ruaca faced labour constraints due to extensification thus maize-pigeonpea intercropping may improve productivity and help reduce the area cultivated. In Vunduzi, land limitation was a major problem and intensification through legumes is among the few feasible options to increase both production and productivity. The late maturity of pigeonpea means that free-grazing of cattle has to be delayed, which allows farmers to retain crop residues in the fields as mulch if they choose to; this allows the use of no-tillage practises. We conclude that maize-legume intercropping has potential to: (a) reduce the risk of crop failure, (b) improve productivity and income, and (c) increase food security in vulnerable production systems, and is a feasible entry point to ecological intensification.

Keywords: maize grain-legume intercropping, intensification, extensification, crop productivity, profitability, climatic risk

3.1. Introduction

Legumes provide an important pathway to alleviate the constraints related to nitrogen (N) limitations in the soil and improve crop productivity. They can quickly cover the soil surface and reduce soil erosion (Giller and Cadisch, 1995), suppress weeds (Liebman and Dyck, 1993), fix atmospheric N_2 (Giller et al., 1994), reduce pests and diseases (van der Pol, 1992; Trenbath, 1993), spread labour needs (van der Pol, 1992) and improve the efficiency of land use (Morris and Garrity, 1993b, 1993a). Grain legumes are generally preferred by smallholder farmers in the tropics above green manures and cover crops because they ensure food security, improved diet and income (Giller, 2001). When intercropped with cereals, larger quantities of better quality organic matter inputs are produced leading to greater productivity benefits compared with continuous maize monocrops (Hartwig and Ammon, 2002; Schmidt et al., 2003; Rochester, 2011). Multi-purpose grain legumes such as pigeonpea (*Cajanus cajan* (L.) Millsp.) have shown potential to be included in cereal-legume rotations in the tropics (Giller et al., 2009; Baudron et al., 2012). Due to these attributes, legumes are regarded as a critical component of conservation agriculture (Meyer, 2010), and results of a recent meta-analysis confirmed this suggestion (Rusinamhodzi et al., 2011). The contribution to the soil N-budget through biological N_2-fixation is especially important in low-input farming systems such as those that prevail in central Mozambique. Thus cereal legume intercropping appears to be a useful component of ecological intensification (Doré et al., 2011), an approach to produce more food per unit resource to achieve positive social outcomes without negative effects on the environment (Cassman, 1999; Hochman et al., 2011).

Despite the many benefits, the importance of legumes in the farming systems of the tropics is hampered by lack of information, seed costs, and poor market infrastructure (Graham and Vance, 2003). As a result the contribution of legumes to many smallholder farming systems remains small (Giller, 2001). When legumes are intercropped, the planting of two or more crops either simultaneously or in relay increases the labour requirements compared with cereal monocropping which may limit the widespread use of legumes (Waddington et al., 2007). In the field, deficiencies of phosphorus (P), potassium (K), sulphur (S), and micronutrients such as zinc (Zn), molybdenum (Mo) and boron (B) may limit legume growth and N_2-fixation (O'Hara et al., 1988). Phosphorus availability is often regarded as the most limiting factor (Giller and Cadisch, 1995). At the farm level, it is important that grain legumes provide multiple benefits and are acceptable to farmers; farmer evaluations provides a basis for assessing the suitability of production options to their needs and local environment (Ashby, 1991; Rusinamhodzi and Delve, 2011). Thus we hypothesized that if maize-legume intercropping is more productive, economically viable, and is acceptable to the majority of farmers then it is a low cost pathway to remove the binding constraints of poor soils, unreliable rainfall and drought that are characteristic of central Mozambique.

Central Mozambique is sparsely populated (Folmer et al., 1998) and characterised by extensive farming systems in which slash and burn, limited fertiliser use and continuous monocropping are common, and there is little crop-livestock integration. Soils are infertile (Maria and Yost, 2006) and the poor soil productivity is compounded by limited capital resource endowments, poverty and limited market participation. A major challenge in central Mozambique is to improve soil and crop productivity to meet the food security and cash needs of smallholder farmers without creating new constraints (Mafongoya et al., 2006). Grain legume crops provide a good starting point as intensification and diversification options due to their multi-purpose nature (food, fodder and soil fertility) and the small initial capital investment required. Development agencies in central Mozambique worked with the government extension department to introduce new varieties of grain legumes, particularly improved pigeonpea and cowpea varieties, in the mid-2000s. They encouraged farmers to intercrop these legumes with maize as a way of improving soil productivity, food security and income. The initiative was based on known benefits of introducing legumes in maize-dominated cropping systems of southern Africa (Jeranyama et al., 2000; Giller, 2001; Snapp et al., 2003; Waddington et al., 2007). Although the initiative was targeted at overcoming prevailing soil fertility problems, there were no best practice guidelines and intercropping had not been systematically studied to develop site-specific recommendations for farmers interested in the new cropping systems.

Inclusion of legumes as intercrops requires rearrangement of the planting patterns through substitutive or additive designs to maintain the productivity of the main crop (Liebman and Dyck, 1993; Giller, 2001). Competition can also be reduced by staggering the planting dates of the companion crops in the intercropped system (Francis et al., 1982). Staggered planting is also used for reducing risk of total crop failure when expected rainfall is uncertain and within-season fluctuations are common (Cooper et al., 2008). In central Mozambique, the promoted intercropping strategy was a substitutive design where two rows of maize alternate with a row of the legume reducing the plant population for both maize and legume compared with sole crops. Yet in southern Malawi, maize is intercropped with pigeonpea in the same row in an additive design. The space lost to the pigeonpea is compensated by sowing three maize seeds per planting station thus maintaining the plant population of maize which results in no substantial yield loss (Sakala et al., 2000).

Intercropping systems have not been studied in central Mozambique; we studied maize-pigeonpea and maize-cowpea intercropping under farmers' conditions for three years from 2008 to 2011 in the Ruaca and Vunduzi communities in central Mozambique. The central objective of this study was to understand the farming system, and to evaluate the suitability of maize-legume intercropping to alleviate the biophysical and socio-economic constraints faced by smallholder farmers in central Mozambique. In Ruaca, grain yields, rainfall infiltration, economic returns and acceptability of maize-pigeonpea intercropping were compared for two intercrop combinations and sole crops under different N and P application levels. In Vunduzi, grain yields of maize-cowpea intercrops were compared for two intercrop combinations and sole crops under different N and P application levels. In addition, we assessed the proportion of farmers practising maize-pigeonpea intercropping each season.

3.2. Materials and Methods

3.2.1 Study areas

The experiments were conducted in the Ruaca (18^{o}50'S, 33^{o}11'E; 700 masl; mean seasonal rainfall of 900 mm) and Vunduzi (18^{o}46'S, 34^{o}20'E; 300 masl; mean seasonal rainfall of 700 mm) villages in central Mozambique. Rainfall occurs between October and April in a unimodal distribution pattern. Soils in both sites are predominantly sandy of extreme poor fertility (Table 3.1) classified as Haplic Lixisols (FAO). The extensive farming systems are characterized by slash and burn and no mineral fertilisers are used. Farmers traditionally grow food crops such as maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R.Br.) (Rohrbach and Kiala, 2007). Local varieties of pigeonpea are grown on the edges of fields, and cowpea (*Vigna unguiculata* (L.) Walp.) in mixtures of more than three crops in fields close to the homestead. Fewer farmers grow groundnuts (*Arachis hypogaea* L.) as a sole crop often on small pieces of land. Maize is an important food and cash crop which is often intercropped with pigeonpea or cowpea in both sites. Cultivation on mountain slopes is common in Vunduzi whereas fields in Ruaca are fairly level. Labour shortages often lead to severe weed pressure which is only controlled by burning the entire field before seeding of the next crop.

Table 3.1. Selected top-soil (0-20 cm) properties of representative soil profiles in (a) Ruaca and Vunduzi, and (b) fields used in the rainfall simulation experiment in Ruaca village, central Mozambique.

(a)

Site	Bulk density ($Mg\ m^{-3}$)	pH	Organic C (%)	Total N (%)	Available P ($mg\ P\ kg^{-1}$)	Exchangeable K ($cmol_c\ kg^{-1}$)	Exchangeable Ca ($cmol_c\ kg^{-1}$)	Particle size (%)		
								Clay	Silt	Sand
Ruaca	1.5	6.0	0.6	0.04	3.0	0.2	2.2	9	11	80
Vunduzi	1.6	5.9	0.9	0.08	4.0	0.4	2.8	10	13	77

(b)

Rainfall simulation experimental fields

Field										
0 year, continuous maize	1.5	5.9	0.2	0.02	0.7	0.1	0.5	11	9	80
1 year, maize-pigeonpea	1.4	6.0	0.6	0.04	2.8	0.2	2.2	14	12	74
3 years, maize-pigeonpea	1.4	5.9	1.2	0.08	6.9	0.3	3.6	6	5	89
5 years, maize-pigeonpea	1.3	6.0	1.4	0.09	8.4	0.3	3.8	14	11	75

3.2.2 On-farm trials

Experiments in which maize was intercropped with pigeonpea were established on four farms with four replications per farm in Ruaca, and maize intercropped with cowpea was established on six farms with two replications per farm in Vunduzi. Replications were reduced in Vunduzi due to the relatively smaller fields compared to Ruaca. In Ruaca, pigeonpea was a priority cash crop because of a ready outside market, whereas in Vunduzi farmers preferred cowpea because their primary concern was food security. To reduce variability, all selected experimental fields were previously under continuous maize monocropping for at least five years prior to the establishment of the trials. In Ruaca, the treatments tested over three seasons (2008 to 2011) were: (a) maize sole crop (37 000 plants per ha), (b) pigeonpea sole crop (37 000 plants per ha) for the first two seasons followed by a maize sole crop, (c) within-row intercropping where maize and pigeonpea were planted within the same row (0.9 m between rows and 0.45 m between maize and pigeonpea plants within the row, three plants per station to give a population of 37 000 maize plants and 37 000 pigeonpea plants), and (d) distinct-row intercropping where two maize rows alternated with a single row of pigeonpea (2 m between rows of pigeonpea and 0.9 m between rows of maize to give a population of 24 667 plants of maize and 16 667 pigeonpea plants). The distinct-row intercropping treatment was considered local as farmers were practising it whereas the within-row treatment was adapted from southern Malawi (Sakala, 1994). Due to practical considerations we did not increase the plant population of the distinct-row intercrop option; it would be impossible to get between the rows and weed if normal population density of crops was maintained and the rows were separate.

The experimental design was split-plot; major plots (6 m wide × 80 m long) were for crop arrangement and split into 16 sub-plots (6 m wide × 5 m long) for fertiliser treatments. Fertiliser treatments imposed on all sole and intercrop treatments were: (i) no fertiliser, (ii) 20 kg P ha^{-1}, (iii) 20 kg P ha^{-1} +30 kg N ha^{-1}, and (iv) 20 kg P ha^{-1}+ 60 kg N ha^{-1}. The plots for distinct-row intercropping treatment were wider (10 m wide x 80 m long) to accommodate more rows of pigeonpea. Maize and pigeonpea were planted simultaneously because pigeonpea grows slowly and offers little competition to maize. In the third season (2010-2011), the residual benefits of pigeonpea were measured by planting maize in plots previously with sole pigeonpea. To maintain a sole crop of pigeonpea in the last season, continuous maize plots were split into two; continuous maize was planted in eight plots and sole pigeonpea was planted in the remaining eight plots.

In Vunduzi, the treatments tested for the same period were: (a) maize sole crop (37 000 plants per ha), (b) cowpea sole crop (111 000 plants per ha), (c) within-row intercropping where maize and cowpea were intercropped within the same row (0.9 m between rows and 0.45 m between maize and cowpea plants within the row, three plants per station to give a population of 37 000 maize plants and 37 000 cowpea plants), and (d) distinct-row, intercropping with two maize rows alternated with a single row of cowpea (0.9 m between rows of maize to give a population of 24 690 plants of maize and 18 500 cowpea plants). The experimental design was split-plot with the major plots (6 m wide × 40 m long) being for crop arrangement were split into 8 sub-plots of 6 m width × 5 m length for fertiliser treatments. The plots for distinct-row intercropping treatment were wider (10 m wide × 40 m long) to accommodate more rows of cowpea. Cowpea was planted 6 weeks after maize to reduce competition to maize (Shumba et al., 1990), and it was the standard local practice. Fertiliser treatments in Vunduzi were the same as in Ruaca. Phosphorus was applied in the planting holes for both maize and legumes but N was spot applied as a top dressing on maize at four and eight weeks after planting. It was not possible to quantify the residual benefits of cowpea in Vunduzi because maize failed totally the preceding season.

The experiments were established without tillage in both sites: planting and weeding was done with minimal soil disturbance using hand hoes. In Ruaca, fewer than 20% of the farmers own livestock and tillage implements, and the majority use hand hoes for land preparation and planting. In Vunduzi, farmers do not own cattle and only use hand hoes for land preparation and planting. Cattle were decimated in this area due a combination of the long civil war and livestock diseases, and tsetse fly (*Glossina* spp.) is still prevalent in the area. Previous crop residues were retained *in-situ* but soil cover at planting was less than 10% in all seasons mainly due to termite attacks. The seeds of maize hybrid SC513 (137 days to maturity), improved pigeonpea ICEAP00040 and cowpea (erect type short season, 75 days to maturity variety derived from IT18) were planted into moist soil.

3.2.3 Soil sampling and analysis

In 2008, soil was sampled in experimental fields from 0-20 cm depth, air-dried, sieved and stored prior to analysis. Bulk density was calculated as mass of oven dry soil core divided by volume of the core; undisturbed soil cores were taken using metal rings of 8 cm internal diameter and height of 5 cm. Soil texture analysis was done through the hydrometer method, pH was measured with a digital pH metre in a 1:2.5 (w/v) soil: deionised water suspension. Total C and N were analysed through dry combustion using a carbon/hydrogen/nitrogen Analyzer (Leco-CNS2000). The K and Ca concentrations were determined by flame photometry, and plant available P using the Bray method (Anderson and Ingram, 1993). Data from a selected soil profile most representative of the soil in each site is presented in Table 1.

3.2.4 Crop yield and rainfall measurements

Daily rainfall was measured with a rainfall gauge in the experimental fields. Grain and above-ground biomass yield measurements were estimated from 3 rows × 2 m sub-plots in the centre of each plot after physiological maturity. Pigeonpea and cowpea pods were harvested when they turned brown, dried and shelled by hand. Maize and legume grain yield was calculated at 12% moisture content and stover on dry weight basis. Sub-samples for stover were taken and dried at 70°C for moisture correction. Maize was harvested in mid-April and pigeonpea in mid-August. Cowpea was harvested three weeks after maize harvest.

3.2.5 Infiltration measurements

In 2010, water infiltration measurements were carried out in selected farmers' fields using a portable rainfall simulator described by (Amezquita et al., 1999). A chronosequence of continuous maize-pigeonpea intercropping was established through farmer interviews and soil sampling; fields for the rainfall simulation experiment were selected based on similarity in soil properties (Table 3.1b). Durations of intercropping compared were: zero, one, three and five years; zero duration corresponded to continuous maize monocropping. Simulated rainfall with intensity of 70 mm hr^{-1} was applied for two hours on an area measuring 0.13 m^2 (0.325 m × 0.4 m) surrounded by a 4 cm buffer zone (Thierfelder and Wall, 2009). An intensity of 70mm hr^{-1} was chosen because it is a typical intensity for tropical and semi-arid rainfall (Hudson, 1993), and ensured uniformity of raindrop size. The small plots were confined using metal sheets leaving a single outlet leading into a small gutter where runoff was collected. Rainfall simulations were performed when the soil was close to field capacity (we allowed 2 days after rainfall events) in February 2010 when maize was at grain filling and pigeonpea was still in vegetative growth. Horton's equation, which describes water infiltration as a continuous function in which infiltration rate decreases asymptotically from an initial value, was fitted to the infiltration data for the short duration fields (< 3 years of intercropping): $f = f_c + (f_0 - f_c)e^{-kt}$, where f is the maximum infiltration rate (mm hr^{-1}) at time t, f_c is the saturated soil infiltration rate (mm hr^{-1}), f_0 is the initial infiltration rate (mm hr^{-1}) at time zero, k is a constant that defines function f, and t is time (Horton, 1940).

Infiltration characteristics in the longer duration fields (3 and 5 years of continuous intercropping) were well described by a sigmoidal decay curve characterized by a lag-phase of decrease of initial infiltration with four parameters: $i_t = i_f + \frac{i_i - i_f}{1-\left(t/t_0\right)^x}$ where

t_0 is time at $i_t/2$.

3.2.6 Farm surveys

Focus group discussions were conducted in the study sites to identify local criteria used by farmers to categorise themselves into different resource groups (RG). The indicators of resource ownership were prioritised, and based on these; all farmers in the village were allocated to one of the identified resource groups. A total of 52 and 42 farmers were interviewed in Ruaca and Vunduzi respectively. Initial selection of farmers was random but some of the selected farmers were not willing to be interviewed and we had to select from those initially omitted. The interviews were conducted at the farmer's homestead with the assistance of local extension officers to understand landholdings, crop types, typical crop rotations, nutrient inputs, and tillage and crop residue management. Socio-economic characteristics included family size, labour availability, months of food security, sources of income, proportion of off-farm income and production orientation. Land to labour ratio was calculated by dividing the land size and available labour per farm. Comparing households, small values of land: labour ratio indicate land limitation, larger values suggest labour limitation. A specific question was asked to ascertain the number of farmers who had planted the intercrops, this data was verified through transect walks and fields visits.

A matrix scoring method on a scale of 1-20 was used to evaluate the maize-pigeonpea intercrops and the corresponding sole crops treatments in the 2009/2010 season using the criteria of food security, cash income, input costs, ease of weeding and time to maturity. A group of 23 farmers (14 women and 9 men) participated in the evaluation using a combination of visual assessments, ranking and scoring procedures. Final scores were obtained by multiplying the scores given by farmers and the appropriate weight of each criterion (Pimbert, 1991), assigned through pairwise ranking. Acceptability of a treatment was calculated as the percentage of total score to the maximum possible score for each treatment. The full scoring procedure is described by (Rusinamhodzi and Delve, 2011).

3.2.7 Labour data collection

We estimated labour requirements by direct observation for each treatment from the experimental plots (480 and 800 m^2). A regular team of farmers performed required activities on each plot at similar times of the day; the farmers were not informed that their activities were being timed. Important recordings were: activity, start time, number of people, treatment, plot size and end time. The average labour times for each task for each treatment were calculated and converted to person-days units (8 hours) per hectare. Weeding was done three times at three, six and nine weeks after crop emergence; reported data is total time for the three weeding stages. Data from "farmers' recall" were not used because there were many confounding factors mainly related to planting densities, not having all treatments and the irregular nature at which farmers carried out their activities.

3.2.8 Calculations and statistical analysis

Intercrop productivity was analysed using the land equivalency ratio (LER) method (de Wit and van Den Bergh, 1965), computed using the following formula: $LER = \left[\frac{intercrop\ maize\ yield}{sole\ maize\ yield}\right] + \left[\frac{intercrop\ legume\ yield}{sole\ legume\ yield}\right]$ where all yields are expressed in t ha^{-1}. LER is relative land requirements for intercrops compared to monocrops. LER values greater than 1.0 show that intercropping is more productive and those less than 1.0 show that monocropping is more efficient. Competition was evaluated by computing the competitive ratio (CR) using the formula described by (Willey and Rao, 1980):

$$CR_{crop\,x} = \left(\frac{LER_{crop\,x}}{LER_{crop\,y}}\right)\left(\frac{Z_y}{Z_x}\right)$$

where Z_x and Z_y are the sown proportion of each crop in the mixture. The CR value gives the exact degree of competition by indicating the number of times one crop is more competitive than the other. Yield penalty was calculated as the percentage difference in yield between sole crop maize and intercropped maize; data reported for each intercrop treatment was calculated as an average for three seasons across fertiliser treatments.

A principal components analysis was performed to determine the household characteristics that were most important for explaining variability between the identified farmer resource groups (McLachlan, 2005) in both Ruaca and Vunduzi. A partial budget analysis was done at farm level to understand the impact of moving from maize monocropping to maize-pigeonpea intercropping in Ruaca. The marginal rate of return (MRR) was calculated by expressing the difference between the net benefit of the treatments under comparison as a percentage of the difference of the total variable costs (Evans, 2005). Different price scenarios were used for both crops as significant price changes were observed; prices were often subdued soon after harvest but rose sharply as supply of produce diminishes especially in November and December.

The generalized linear model (GLM) in SAS 9.2 (TS2MO) of the SAS System for Windows © 2002-2008 was used to test the individual and interactive effects of intercropping treatment, fertiliser application and season on crop yield. The interactions tested were intercrop treatment × fertiliser, and season × arrangement × fertiliser. In the analysis, intercropping treatments and fertiliser application were considered fixed factors while season was considered as a random factor. The standard error of difference between means was calculated using the procedure described by Saville (2003).

3.3. Results

3.3.1 Rainfall distribution

More rainfall was received in Vunduzi (mean of 947 mm and coefficient of variation of 15%) than in Ruaca (mean of 729 mm and coefficient of variation of 9%). Rainfall distribution was erratic and variable between sites and seasons (Fig. 3.1). Severe mid-season drought spells were common with only the 2008/09 season having well-distributed rainfall. There was a severe dry spell in the first half of the 200/10 season followed by excessive rainfall. By contrast there was heavy rainfall early in the 2010/11season until January and then a severe long dry spell in February and March.

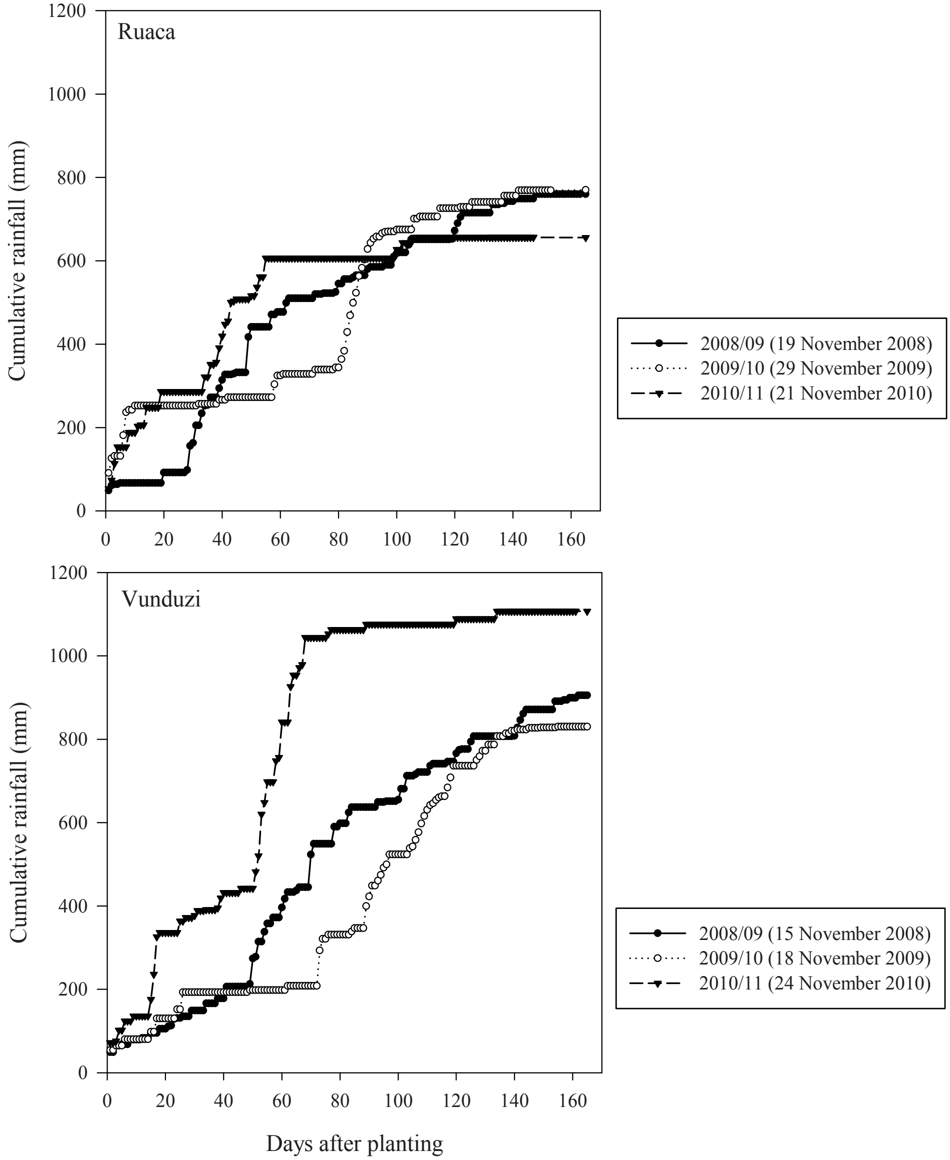

Fig. 3.1. Cumulative rainfall distribution at the two experimental sites (Ruaca and Vunduzi) for three consecutive seasons. The rainfall pattern is unimodal and occurs between October and April, dates in parenthesis are the maize planting dates for each season.

3.2 Grain yields and intercrop productivity in Ruaca

Season (through rainfall distribution) and crop arrangement had a significant effect ($p < 0.001$) on maize and pigeonpea grain yield, and intercrop productivity in Ruaca (Table 2 and

Fig.3.2); the interactions between fertiliser and intercrop treatments were weak. Maize yield in the within-row intercropping treatments was larger than in sole crop in both the 2009/10 and 2010/11 seasons whereas the distinct-row intercropping resulted in significantly less yield than the sole crop in both the 2008/09 and 2009/10 seasons. The largest yield in sole maize was 2.3, 2.6 and 0.8 t ha^{-1} for 2008/09, 2009/10 and 2010/11 respectively; in the distinct-row intercropping treatment it was 0.8, 1.6 and 2.8 t ha^{-1} and in the within-row intercropping treatment 1.6, 2.8 and 5.8 t ha^{-1} (Fig.3.2). In the 2008/09 season, the response of maize to N and P fertilisation was significant; 20 kg ha^{-1} P and 60 kg ha^{-1}N increased maize yields in the sole crop by 1.4 t ha^{-1}, in the within-row intercrop by 0.4 t ha^{-1}, and by 0.3 t ha^{-1} in the distinct-row intercropping treatment compared to no fertiliser application. Pigeonpea responded better to fertiliser application in the second and third season but not in all treatments (Fig.3.2b). Pigeonpea grain yield was 1.2 t ha^{-1} in sole crop, 0.8 t ha^{-1} in distinct-row intercrop and 1.0 t ha^{-1} in within-row intercrop in 2008/09 season and there was no response to fertiliser application (Fig.3.2b). In 2009/10, intercropping reduced significantly the yield of pigeonpea, the largest yield was 1.5 t ha^{-1} in sole crop, 0.7 t ha^{-1} in distinct-row and 0.9 t ha^{-1} in within-row intercropping. The yield penalty of intercropping maize was compensated for by yield of the companion pigeonpea crop leading to LERs of at least one for all treatments across all seasons (Table 3.2). The yield penalty for intercropping maize and pigeonpea within the same row was small (8%) compared with the distinct-row option (50%). LERs for within-row intercropping were significantly larger than for distinct-rows in all years. In the third year, sole maize yields in Ruaca were strongly suppressed (<0.8 t ha^{-1}) by heavy infestation with striga (*Striga asiatica* (L.) Kuntze) that was not observed in the intercrops or the sole pigeonpea plots. Yields of maize grown as a sole crop after two previous years of sole pigeonpea yielded 4.8 t ha^{-1} without fertilizer and 5.9 t ha^{-1} with addition of only 20 kg P ha^{-1} (Fig. 3.3) and there was no response to N fertiliser application.

Competitive ratios (CR) were larger for maize (0.9 - 1.4) than for pigeonpea (0.7-1.1) in maize-pigeonpea intercropping.

Table 3.2. Effect of intercropping, fertiliser application and season on the land equivalence ratios (LER) of maize-legume intercropping in Ruaca and Vunduzi.

Treatment	Fertiliser	Maize-pigeonpea intercropping (Ruaca)			Maize-cowpea intercropping (Vunduzi) [a,b]
		2008/09	2009/10	2010/11	2010/11
Distinct-row	No fertiliser	1.1	1.1	1.4	1.4
	20 kg P ha^{-1}	1.0	1.1	1.2	1.8
	30 kg N + 20 kg P ha^{-1}	1.1	1.0	1.2	1.7
	60 kg N + 20 kg P ha^{-1}	1.0	1.2	1.3	1.9
Within-row	No fertiliser	2.2	1.7	2.0	2.4
	20 kg P ha^{-1}	1.4	1.7	2.4	2.0
	30 kg N + 20 kg P ha^{-1}	1.4	2.0	2.0	2.2
	60 kg N + 20 kg P ha^{-1}	1.5	1.9	2.1	2.0
*SED		0.1	0.1	0.2	0.2

[a]In the 2008/09 season, farmers consumed the cowpea before the experiment could be harvested, LER not calculated
[b]In the 2009/10 season, the maize crop failed completely due to a prolonged mid-season dry spell, LER not calculated
*Combined SED for treatment means

3.3.3 Grain yields and intercrop productivity in Vunduzi

Season (through rainfall distribution) and crop arrangement had a significant effect ($p <$ 0.001) on maize and cowpea grain yield in Vunduzi; fertiliser application had a significant effect on cowpea and not maize yield (Table 3.2 and Fig.3.2). In Vunduzi, the within-row intercropping strategy was more productive than the farmers' two rows of maize alternating with a row of cowpea in 2010/11 when both crops yielded (Table 3.2). In the maize-cowpea intercrops, the poor productivity of maize due to long dry spells reduced competition, which led to relatively greater cowpea productivity. The intercropping treatments were at least equal to or more productive than the sole crop, as shown by the LERs (Table 3.2). In the first year

(2008/09), no cowpea yields were recorded in Vunduzi because farmers started consuming it due to their severe food insecurity before measurements could be made. In the 2009/10 season, maize completely failed due to a prolonged dry spell lasting more than 55 days, yet cowpea survived and gave a significant harvest especially in plots where N and P fertiliser was applied (Fig 3.2a). We also observed that maize was affected more by the dry spells in plots that received N than plots that received only P fertiliser. Cowpea yield responded better to fertiliser application than maize. In Vunduzi, the yield penalty of intercropping maize and cowpea was 6% in the within-row treatment and 25% with distinct-rows. In the maize-cowpea intercrop, the CRs for maize ranged from 1.2 to 1.8 and for cowpea 0.6 to 0.8.

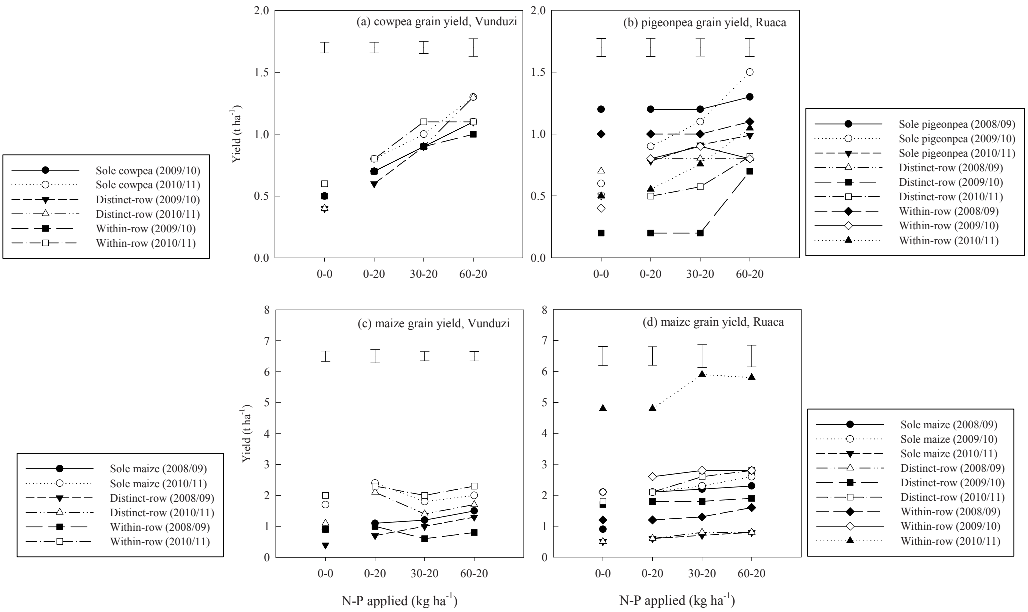

Fig.3.2. Effect of intercropping, N and P fertilization, and season on grain yield of (a) cowpea, (b) pigeonpea, (c) maize in Vunduzi, and (d) maize in Ruaca. Maize and legume yields plotted at different scales to allow easier visualization of effects. Error bars indicate the standard error of difference between means (SED).

3.3.4 Rainfall infiltration

Intercropping maize and pigeonpea continuously for five years increased steady state rainfall infiltration from 6 mm hr^{-1} to 22 mm hr^{-1} compared with continuous maize monocropping (Fig. 3.4). There was more surface water run-off (94%) on plots that were under continuous maize than on plots that were intercropped since one year (88%), or three years (68%), and least (42%) run-off was recorded on plots that were since five years under intercropping. Infiltration characteristics in the sole maize field and the field that was intercropped since only one year, followed an exponential decrease whereas in the fields that had been intercropped since 3-5 years, the pattern followed a sigmoidal decay curve characterized by a lag-phase in decrease of infiltration.

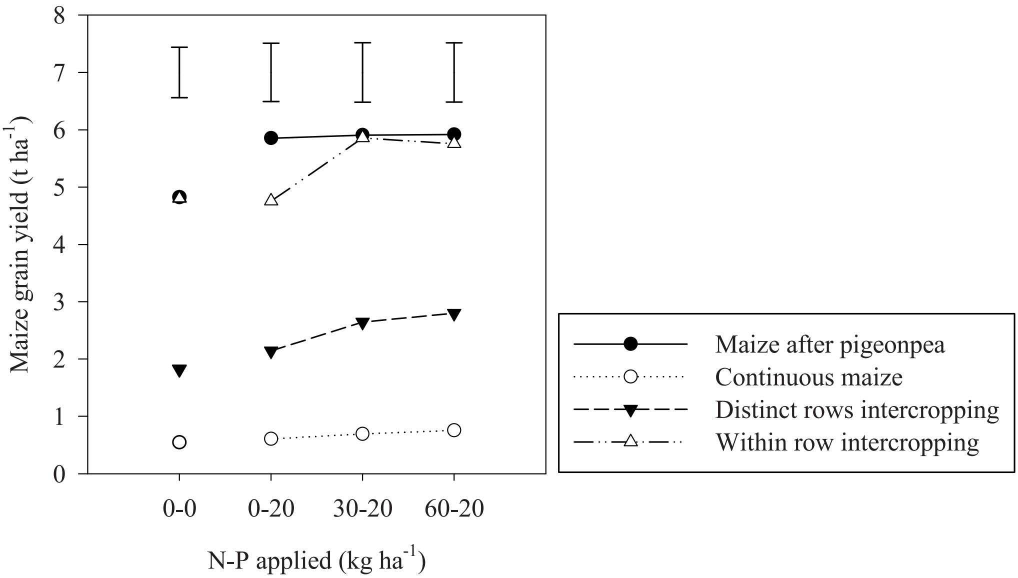

Fig. 3.3. Effect of intercropping, rotation, and N and P fertilization on maize grain yield in Ruaca in the third (2010/11) season.

3.3.5 Economic analysis

Weeding in sole maize required a total of 17.6 man days per hectare, in sole pigeonpea it increased to 18.2, to 22.3 in within-row intercrops, and to 26.4 man days per hectare in the distinct-row intercrops. On average, intercropping maize and pigeonpea increased weeding time by 36%. The analysis of benefits versus variable costs showed that integrating legumes into maize-based cropping systems increased profitability at all price scenarios for the crop grain sales with a minimum of 343% MRR (Table 3.3a). The MRR was greater without than with fertiliser mainly because the sole maize crop responded better to fertiliser than when intercropped. Farmers generally sold their produce immediately after harvest when prices were low; later in the year, maize prices increased by up to 140% and pigeonpea by up to 50% of the initial price. Under these price scenarios, farmers' earnings increase by 67% without fertiliser and 35% with fertiliser for the within-row intercropping treatment and, 36% without fertiliser and 61% with fertiliser for the distinct-row treatment (Table 3a).

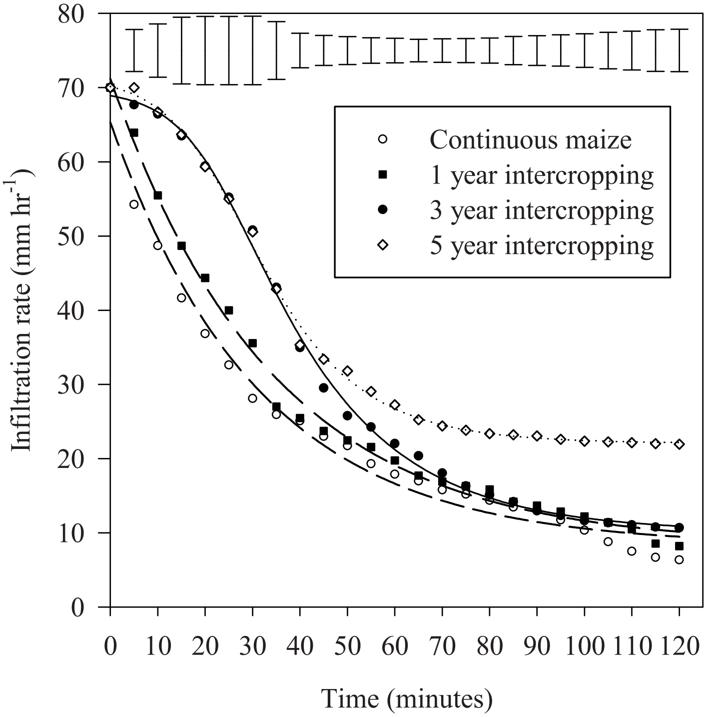

Fig. 3.4. Simulated rainfall infiltration as affected by duration of intercropping in a sandy soil in Ruaca village, central Mozambique. Error bars indicate the standard error of difference between means (SED).

3.3.6 Farmer evaluation of maize-pigeonpea intercrops in Ruaca

Food security and cash income were identified by farmers as priority production objectives. Input costs, ease of weeding and time to maturity, in that order, were also important for evaluating maize-pigeonpea intercrops. Overall, farmers preferred intercrops over sole crops; although not currently practised, the within-row intercropping strategy was found to be the most acceptable to farmers (84%) followed by distinct-row intercropping, and sole maize was more acceptable than sole pigeonpea (Table 3.3b). Farmers in the richest and poorest resource group (see section 3.6) did not attend these evaluation meetings as a result the acceptability scores were for the middle resource group and did not differ between men and women.

Table 3.3. (a) The marginal rate of return of sole pigeonpea and maize-pigeonpea intercropping compared with sole maize cropping with and without fertiliser at variable prices of both maize and pigeonpea, (b) acceptability of maize-pigeonpea intercrops to farmers' production orientation and objectives in Ruaca village, numbers in parenthesis are the weighted scores (score × weight).

(a)

Fertiliser	Production option	MRR (%) at given price condition			
		Normal price	Peak maize price (+140%)	Peak pigeonpea price (+50%)	Peak price for both crops
No fertiliser	Sole pigeonpea	3729	437	6819	3528
	Within-row	667	1361	1112	1639
	Distinct-row	343	621	465	743
Fertiliser (20 kg P and 30 kg N ha^{-1})	Sole pigeonpea	759	93	1326	660
	Within-row	500	791	673	963
	Distinct-row	472	472	758	758

(b)

Evaluation criteria	Treatment (scoring scale 1-20)			
	Sole maize	Sole pigeonpea	Distinct row intercrop	Within row intercrop
Food security (weight =5)	14 (70)	8 (40)	19 (95)	20 (100)
Cash income (weight =4)	6 (24)	18 (72)	16 (64)	20 (80)
Input costs (weight =3)	15 (45)	9 (27)	12 (36)	10 (30)
Ease of mechanical weeding (weight =2)	15 (30)	14 (28)	6 (12)	15 (30)
Time to maturity (weight =1)	14 (14)	4 (4)	12 (12)	12 (12)
Total score	183	171	219	252
Acceptability (%)	61	57	73	84

3.3.7 Diversity of farmers in the study areas in relation to the practise of maize-legume intercropping

Four resource groups were identified in Ruaca using the size of cropped land, the number of cattle owned, the farmers' production orientation and the characteristics of the main house (Table 3.4). Farmers in category RG1 were under-resourced and frequently worked as casual labourers for wealthier farmers in the village. Farmers in category RG4 depended on off-farm activities for most their livelihoods, provided an important link with traders and employed labourers. Only farmers in RG2 and RG3 were already practising maize-pigeonpea intercropping. In Vunduzi, field size and household characteristics were important as indicators of wealth status and three resource group categories were identified. Farmers in the best resourced group (RG3) regularly hired casual labourers because they cropped large areas and used the produce to pay for the labour. Only better-resourced farmers in RG2 and RG3 practised maize-legume intercropping. Principal components analysis showed that more than 97% of the variability in households in Ruaca was explained by the first three principal components, PC1 (89%), PC2 (6.7%) and PC3 (1.9%). In Ruaca, PC1 was strongly related to livestock ownership and PC2 was related to land size owned and area of land cropped. The variability in households in Vunduzi was explained by more factors as compared with Ruaca, the first three principal components accounted for only 74% of the variability, PC1 (42.3%), PC2 (20.3%) and PC3 (11.7%). In Vunduzi, PC1 was related to the area of land cropped and PC2 to the number of goats and pigs.

The land: labour ratio was greater in Ruaca (1.6 ha person^{-1}) than Vunduzi (0.6 ha person^{-1}), however land utilization was greater in Ruaca (76%) than in Vunduzi (62%). In Vunduzi only 2% of the farms were self-sufficient in food for 12 months whereas in Ruaca, 46% of the farmers were self-sufficient in food for 12 months. The proportion of farmers practicing maize-pigeonpea in Ruaca decreased from 85% in the 2007/08 season to 78% in 2008/09, 52% in 2009/10 and finally to 37% in the 2010/11 season. In Vunduzi, the proportion increased from 25% in 2007/08 to 32% in 2008/09, it was 34% in 2009/10 and finally to 66% in the 2010/11 season.

3.4. Discussion

3.4.1 Maize-legume intercrop productivity

Our results suggest that maize-legume intercropping fits well within the biophysical and socio-economic conditions of smallholder farmers in central Mozambique and is a suitable starting point for ecological intensification. The maize-legume intercrop options studied were relatively more productive than the corresponding sole crops despite a strong response to seasonal variation in rainfall. Thus, grain yield results across seasons suggest that crop production in the two sites was water-limited (Harmsen, 2000). In a similar study spanning over 12 years in a loamy sand soil under sub-humid conditions in Zimbabwe, Waddington et al. (2007) reported that yield variations between seasons was mainly caused by rainfall fluctuations; maize yield was reduced when rainfall was below 600 mm with or without fertiliser application.

Well-designed maize-legume intercrops in both time and space have been found to be highly productive (LER $\geq$ 1) and efficient in resource utilization under sub-humid conditions resulting in maintenance or improvement of the yield of the main crop (Baldé et al., 2011). The small yield penalty in within-row maize-pigeonpea intercropping showed that pigeonpea can provide an additional yield benefit without negatively affecting maize as has been reported previously (Sakala, 1994; Waddington et al., 2007). Intercropping cowpea with a non-legume has also been shown to increase the efficiency of the biological N fixation process and reduces the reliance of the legume on applied N (Rusinamhodzi et al., 2006). Cowpea was harvested when maize totally failed in Vunduzi in 2009/10 season suggesting that relay planted intercropping with short duration crops such as cowpea can reduce risk of crop failure under erratic rainfall. Other authors have demonstrated that intercropping can reduce the risk of low yields or crop failure associated with drought or unpredictable rainfall (e.g. Ghosh et al., 2006). On the other hand, the failure of maize crop was beneficial to cowpea as there was no shading; Ofori and Stern (1987) suggested that cowpea yields are likely to be depressed due to shading by the companion maize crop. In 2010/11season, cowpea yields were not reduced even though maize yields were large (Table 3) suggesting reduced competition for resources. Jeranyama et al. (2000) reported that companion maize grain yields were not reduced when cowpea was relay planted because peak nutrient demands where temporally different.

Effect of fertiliser application on maize yield was poor in both sites due the effects of dry spells which coincided with critical crop growth stages such as tasseling and silking. Pigeonpea yield responded significantly to the largest N input of 60 kg ha^{-1}, Ghosh et al. (2006) reported that N is a limiting factor for growth of pigeonpea intercrop during the first half of the season, thus N fertiliser is necessary to improve productivity. Cowpea responded significantly to the application of N and P fertiliser in the seasons when it was harvested. The good response to fertiliser in cowpea was due to staggered planting; its maturity coincided with favourable moisture conditions later in the season. However, Ofori and Stern (1987) reported larger yield loss of cowpea with addition of N fertiliser in a silt loam soil under Mediterranean-type climate.

Rotational effects of pigeonpea in sole and in intercrop were significant; the initial effect was through the reduction of Striga infestation. Continuous maize was heavily infested with Striga in the third season of the experiment leading to yield loss of up to 88% compared to maize after pigeonpea. Other studies have reported that Striga infestations can reduce maize yields by up to 80% (e.g. Ransom et al., 1990); both rotation and maize-legume intercropping are effective to overcome this challenge (Oswald and Ransom, 2001; Oswald et al., 2002). A second effect was the residual N effect from pigeon pea. In our experiments, maize after pigeonpea did not respond to added N but only to P because pigeonpea has been found to contribute as much as 90 kg N ha^{-1} to the N nutrition of the next maize crop (Sakala et al., 2000), which might have been sufficient under these conditions.

3.4.2. Rainfall infiltration

Rainfall infiltration improved significantly with duration of maize-pigeonpea intercropping. The infiltration curves were also different with long-term intercropping causing a lag-phase in infiltration rate, which was attributed to the high accumulation of biomass covering the soil surface and the concomitant increase in soil carbon (C) (Roth et al., 1988). Vachon and Oelbermann (2011) observed that the integration of N-rich legumes in maize-based systems leads to sequestration of C compared with sole crops. Pigeonpea was harvested two months before the start of the succeeding season which ensured crop residues retention and substantial soil C input. Myaka et al. 2006 reported that increased circulation of organic matter due to pigeonpea had a likely long-term effect on soil quality. The undisturbed continuous pore system and the absence of a hardpan due to no-till also contributed to the observed high infiltration (Thierfelder and Wall, 2009). The deep-rooting characteristic of pigeonpea is also thought to contribute significantly to improved infiltration (Godoy et al., 2009). Our results suggest that maize-pigeonpea intercropping in the long-term may lead to greater rainfall infiltration resulting in more water being available for crop growth and offset the effects of dry spells.

3.4.3 Labour demand, profitability and acceptability

Weeding time was increased by 36% in intercrops although the increase was not related to weed intensity but to the need to take care of pigeonpea which grows slowly compared to maize as well as difficulty in navigating through the crop mixtures. Our results are similar to Mucheru-Muna et al.(2009) who reported an increase in requirement for careful weeding operations in intercropping compared with sole cropping. However, other authors have reported lower weeding requirements in maize-legume intercropping systems due to weed suppression (Banik et al., 2006) caused by more crop biomass and better soil cover (Chamango, 2001). Given that in the study sites labour is normally priced on the basis of area worked than the amount of time spent weeding, it is likely that the variation in weeding costs is small between the treatments tested.

The MRR showed that legume monocropping or intercropping with maize was far much more profitable than maize monocropping; profitability was directly related to the proportion of pigeonpea in the intercrop. However, Waddington et al. (2007) reported that low input sole maize was more profitable than when intercropped with pigeonpea or cowpea; low input sole maize was more attractive due to low costs and the a higher selling price than the legumes between 1994 and 2006 in Zimbabwe. In our study area, although maize was commonly sold, it was often sold only when the household food requirements have been achieved while pigeonpea could be sold immediately after harvest. Although farmers can increase their earnings if they delay selling their produce at harvest, investments in post-harvest storage and pest control strategies are required. Shifting from sole maize to maize-pigeonpea intercropping can achieve the objectives of improved cash income.

Farmers' evaluation of the intercrops was primarily based on the ability of the options to achieve food security and cash income while reducing input costs. Food security was related to yield of maize and cash income to the yield of pigeonpea. On input costs, sole maize scored more than sole pigeonpea and the intercrops. Time to maturity was important because crops should mature early and close the food insecurity gap. Pigeonpea matures late thus the sole pigeonpea crop was scored below maize. This also means that cultivars of pigeon pea that mature early are most suitable for the farmers. Overall, the within-row intercropping strategy was preferred and farmers were willing to shift from the commonly practiced distinct-row intercrop due to its ability to maintain the yield of maize and the relatively high yield of the legume. In general, matching technological performance to farmers' preferences is critical for widespread adoption as farmers prefer technologies that fit within their resources such as labour, capital and management demands ((Fujisaka, 1989; Chianu et al., 2006).

Table 3.4. Perception of wealth and the resource groups identified by farmers in Ruaca and Vunduzi villages in central Mozambique. Numbers in parenthesis are the farmers in that particular resource group.

Ruaca				Vunduzi		
RG1 (14)	RG2 (19)	RG3 (13)	RG4 (6)	RG1(5)	RG2 (33)	RG3 (5)
Land size: 0.5-1 ha, small compound, sells labour, and consistently food insecure. They are mostly heavy drinkers and children do not go to school. Lack of blankets, utensils and clothes.	Land size: 2-5 ha, cattle owned: < 5, goats: < 3, medium compound, occasionally sell labour, production is just enough to feed the family, Own a vegetable garden.	Land size: ≥ 10 ha, cattle: 5-10, goats: > 10, permanent house and farm workers, transport: ox-cart and bicycle. Consistently food secure, more off-farm activities and income. Access to clean water and good sanitation. Children go to school.	Land size: ≥ 10 ha, cattle: >10, goats: > 10, permanent house and farm workers, transport: car, bicycle, ox-cart. Have jobs in the city. Main house has bricks walls and iron sheets. Own a car, clean water and good sanitation. Access to credit and loans.	Land size: < 0.5 ha, one small house in the compound. Food insecure, sell labour, heavy beer drinkers. Always have many children	Land size: 0.5-1 ha, small and few houses. Goats: <5, chickens: <10, Food production is slightly below consumption. Own a bicycle for transport, and a radio.	Land size: ≥ 5 ha. Main houses with iron sheets in a large. Goats ≥ 20 compound. Hire farm labourers. Own at least 1bicycles for transport, at least 4 radios. Produce a variety of crops (beans, pigeonpea, groundnuts) Sell crop produce.

3.4.4 The socio-ecological environment and potential for maize-legume intercropping

Our results suggest that erratic rainfall distribution limited crop responses to added fertiliser despite the low fertility status of the soils (Maria and Yost, 2006). The low N status of the soils is favourable to stimulate legume N_2-fixation but deficiencies of P and K potentially limit the process. Crops such as pigeonpea increase recycling of organic matter, N and other nutrients which is likely to have a long-term beneficial effect on soil fertility (Myaka et al., 2006). The relatively high biomass productivity and late maturity of pigeonpea may delay free-grazing and enable *in situ* crop residue retention, combined with the weed-suppression ability (Gooding, 1962) may facilitate integration with no-tillage practises. Cowpea can also access sparingly soluble P and make it available for uptake by companion or succeeding crop (Vanlauwe et al., 2000). The deep rooted and long duration nature of pigeonpea means that it is suitable for anchoring the soil and preventing soil loss on the steep slopes that are found in Vunduzi and some parts of Ruaca. It may also induce a hydraulic lift, a redistribution of soil water from deeper in the soil profile to dry surface horizons by the root system (Sekiya and Yano, 2004), which may make more moisture available for the companion crop.

Cowpea matures early which is critical to alleviate the food security constraints but had a significantly lower price because it was only sold locally to fellow villagers compared to maize and pigeonpea which had external markets. The high selling price for pigeonpea was particularly attractive to farmers as it was four times that of maize; pigeonpea grain prices ranged between 0.6 and 1.0 US$ per kg while that of maize ranged between 0.14 and 0.3 US$ per kg. The attractive market price for pigeonpea in Ruaca was similar to that in Ntcheu district, Malawi as reported by Ngwira et al. (2012). The number of farmers practicing intercropping in a season in Ruaca suggested that market opportunities for crops were important. Late maturity of pigeonpea coincided with free roaming livestock that destroyed fields in Ruaca and often caused a significant drop in number of farmers growing it the following season. On the other hand, the absence of cattle alone was not enough in Vunduzi to stimulate widespread production of pigeonpea; the sudden jump in proportion of farmers practicing intercropping in 2009/10 was explained by the emergence of a market for pigeonpea.

Although farmers were diverse and distinct resource groups were identified, they all had similar expectations from their field crop production activities. Farming systems analysis suggested that labour shortage was a greater constraint in Ruaca than in Vunduzi. Land limitation in Vunduzi is an increasing problem because expansion of cropped area is limited by the neighbouring Gorongosa National Park. Despite a larger land: labour ratio in Ruaca, there was significantly greater land utilization compared with Vunduzi which contributed to more farmers being food self-sufficient. Land utilization in Vunduzi was limited by the steep slopes and rugged terrain which is less common in Ruaca. Our results showed that maize-legume intercropping required extra labour compared with sole crops; in Vunduzi land sizes were small and farmers were more likely to meet the labour requirements of intercropping than farmers in Ruaca. In Ruaca, farmers needed to reduce the land cultivated per season to be able to manage the intercropping systems or to hire extra labour. However, the loss in production due to reduction in land area could be compensated by the greater productivity of the intercrops.

3.5. Conclusion

The relatively high crop productivity and economic benefits of the maize-legume intercropping systems 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. The within-row intercropping strategy maintained the yield of the main maize crop and was a more acceptable crop production option for farmers. Maize-legume intercropping could be more profitable if farmers can delay selling their produce immediately after harvest. In situations of land limitation and insufficient fertiliser inputs, legume intercropping may provide a pathway for ecological intensification. In extensive farming systems, labour saved by reducing land area may offset the increased labour demand for intercropping. Maize-pigeonpea intercropping significantly increased rainfall infiltration in the long-term due to a better soil cover with residues, more C inputs and no-tillage, and possibly improved soil structure. The relatively high biomass productivity and late maturity of pigeonpea delays free-grazing and enables *in situ* crop harvest residue retention which matches well with no-tillage practises. Maize-legume intercropping reduces the risk of crop failure, improves productivity per unit area, improves profitability and can provide a pathway to food security in vulnerable production systems.

Chapter 4

Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe

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Abstract

Soil fertility decline is a major constraint to crop productivity on smallholder farms in Africa. The objective of this study was to evaluate the long-term (up to nine years) impacts of nutrient management strategies and their local feasibility on crop productivity, soil fertility status and rainfall infiltration on two contrasting soil types and different prior management regimes in Murehwa, Zimbabwe. The nutrient management strategies employed in the study were: a control with no fertiliser, amendments of 100 kg N ha^{-1}, 100 kg N + lime, three rates of manure application (5t, 15t and 25 t ha^{-1}) in combination with 100 kg N ha^{-1}, and three rates of P fertiliser (10, 30 and 50 kg P ha^{-1}) in combination with 100 kg N, 20 kg Ca, 5 kg Zn and 10 kg Mn ha^{-1}. Maize grain yields in sandy soils did not respond to the sole application of 100 kg N ha^{-1}; manure application had immediate and incremental benefits on crop yields in the sandy soils. A combination of 25 t ha^{-1} manure and 100 kg N gave the largest treatment yield of 9.3 t ha^{-1} on the homefield clay soils, 6.1 t ha^{-1} on clay outfield, 7.6 t ha^{-1} on sandy homefield and 3.4 t ha^{-1} in the eighth season. Yields of the largest manure application in the outfields were comparable to yields with 100 kg N in combination with 30 kg P, 20 kg Ca, 5 kg Zn and 10 kg Mn ha^{-1} in the homefields suggesting the need to target nutrients differently to different fields. Manure application improved rainfall infiltration in the clay soils from 21 to 31 mm hr^{-1} but on the sandy soils the manure effect on infiltration was not significant. Despite the large manure applications, crop productivity and SOC build-up in the outfield sandy soils was small highlighting the difficulty to recover the fertility of degraded soils. The major cause of poor crop productivity on the degraded sandy soils despite the large additions of manure could not be ascertained. The current practice of allocating manure and fertiliser to fields closest to homesteads exacerbates land degradation in the sandy outfields 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.

Farmers who owned cattle in the study site can achieve high manure application rates on smaller plots, and manure application can be rotated according to crop sequences. Consistent application of manure in combination with mineral fertilisers can be an effective option to improve crop yield, SOC and moisture conservation under smallholder farming conditions. Combined manure and mineral fertiliser application can be adapted locally as a feasible entry point for ecological intensification in mixed crop-livestock systems.

Key words: cattle manure, maize production, crop-livestock systems, degraded soils, nutrient gradients, integrated soil fertility management (ISFM), ecological intensification (EI).

4.1 Introduction

Farming systems in southern Africa exhibit a close integration between crops and livestock. Crop residues are used as livestock feed during the dry season (de Leeuw, 1996), and manure is an important source of nutrients for crop production (Murwira et al., 1995; Zingore et al., 2008). This synergistic relationship is widespread in farming systems, but varied in its ecological and economic complexity (McCown et al., 1979). In the maize-based farming systems of southern Africa, cattle are the main livestock and are grazed in a communal system during the day and kept in kraals close to homesteads at night. Cattle are herded in the communal rangelands during the rainy season and graze freely both rangelands and crop fields during the dry season. Benefits in these mixed crop-livestock systems are skewed towards cattle owners because they have access to crop residues from non-livestock owners; non-livestock owners only benefit if cattle deposit significant amounts of manure whilst grazing in their fields (Rufino et al., 2007). Manure availability is critical in these smallholder systems because mineral fertiliser use, as in the whole of sub-Saharan Africa, has remained far below the amounts required to sustain crop production (Sanchez, 2002; Bekunda et al., 2010). On the other hand household manure production is often insufficient for optimum application to all fields of the farm (Zingore et al., 2007a, 2007b; Rufino et al., 2011).

A combination of shortages of labour, fertiliser and manure often leads to preferential allocation of nutrients to fields close to the homestead resulting in highly nutrient deficient outfields (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007a). The outfields on sandy soils are typically characterized by deficiencies of N, P and S, high acidity, low soil organic carbon (SOC) and low water holding capacity (Zingore et al., 2007a). These multiple nutrient deficiencies in combination with low organic matter content render these soils non-responsive to application of NPK fertiliser. The differences in soil fertility resulting from variable farmer management practices require adapted nutrient management strategies to improve nutrient use efficiencies (Zingore et al., 2007b; Tittonell and Giller, 2013). A combination of mineral fertiliser and manure has shown promise to improve crop productivity of the nutrient depleted outfields (Dunjana et al., 2012). However restoration of the fertility of degraded soils is likely to be hampered by the need to maximise returns to limited nutrient resources which is assured in homefields compared with the degraded outfields (Zingore et al., 2007a).

Large quantities of good quality manure are necessary to achieve and sustain high crop productivity (Powell and Mohamed-Saleem, 1987; Snapp et al., 1998). Good quality manure should be anaerobically composted with added plant material, contain N greater than 1.8% and to be free of sand (Murwira et al., 1995; Rufino et al., 2007; Tittonell et al., 2010b). Applications of about 17 t ha^{-1} manure have been found to be effective in the short term in improving SOC, P, pH, base saturation and the restoration of crop productivity of a degraded sandy soil in north-east Zimbabwe (Zingore et al., 2008). In a similar study, annual applications of three or six tons of manure for five years on a sandy soil at Grasslands Research Station, Zimbabwe raised the fertility of the soils by progressively increasing the cation exchange capacity, the exchangeable bases and pH (Grant, 1967). Nyamangara et al. (2001) demonstrated that manure application of 12.5 t ha^{-1} per year or 37.5 t ha^{-1} once in three years significantly improved the structural stability and water retention capacity of sandy soils with low organic matter content. However, such application rates are only possible on small fields (< 0.5 ha) or for farmers who own many livestock. Both of the former studies reported results of three year investigations; the long-term recovery of degraded soils and their ability to support sustainable high crop productivity are not fully understood. Our major hypothesis is that long-term application of manure and mineral fertiliser can restore fertility of degraded soils and offset the yield and SOC differences between homefields and outfields which could be a sustainable and feasible entry point for ecological intensification. We also hypothesised that the rate of recovery of degraded soil depends on soil type.

In this paper the results of a 9-year agronomic experiment conducted in north–east Zimbabwe are described and discussed. The first three years results of this experiment were reported earlier by Zingore et al. (2007b). The overall objective of the experiment was to improve nutrient use efficiency through strategic application of limiting nutrients, and to identify a pathway to restore soil fertility of degraded outfields using a combination of mineral fertilisers and manure. We measured crop grain yield as it is the basis for household food security and income (Jayne and Jones, 1997), and SOC as it is an important determinant of soil fertility and sustainability (Körschens et al., 1998; Lal, 2006). In addition we measured rainfall infiltration as affected by long-term manure application using simulated rainfall. Water infiltration into the soil is an important soil quality indicator that is strongly affected by land management practices such as organic matter inputs (Lal, 1990; Franzluebbers, 2002), and is especially important under water-limited crop production. Manure avaialbility is a great constraint at farm the scale, thus we quantified feasible manure quantities and the corresponding current manure application rates to various plots across the farm.

4.2. Materials and methods

4.2.1 Site description

Manjonjo (17°49'S; 31°33' E, 1300 metres above sea level - m.a.s.l.) and Ruzvidzo (17°51'S; 31°34'E, 1300 m m.a.s.l.) villages are located in Murehwa smallholder farming area, 80 km north east of Harare. Murehwa is located in agro-ecological region II (Vincent and Thomas, 1960) which receives annual rainfall of between 750 and 1000 mm in a unimodal pattern. Mid-season dry spells are common. The soils in the area are predominantly granitic sandy soils (Lixisols: FAO, 1998) of low inherent fertility with intrusions of dolerite derived clay soils (Luvisols; FAO, 1998) that are relatively more fertile (Nyamapfene, 1991). Cattle ownership varies widely among households (Zingore et al., 2007a). Other small livestock such as goats and local chickens are also important. Farmers who own cattle use manure together with small amounts of mineral fertiliser they can afford on small areas of the farm resulting in improved crop productivity. Maize (*Zea mays* L.) is the dominant staple crop while groundnut (*Arachis hypogaea* L.), sweet potato (*Ipomoea batatas* (L.) Lam.) and sunflower (*Helianthus annuus* L.) are important crops.

The communal grazing area is characterised by the Miombo woodland dominated by *Julbernardia globiflora* (Benth.) Troupin*, Brachystegia boehmii* Taub. and *Brachystegia spiciformis* Benth. (Mapaure, 2001). Grass species of the genus *Hyparrhenia* are predominant, and *Andropogon, Digitaria*, and *Heteropogon* spp. are also common species. *Sporobolus pyramidalis* P. Beauv., a grass of poor grazing quality often dominates in overgrazed areas and perennially wet 'vlei' areas of the veld.

Table 4.1. Initial and final soil chemical properties after nine seasons of manure and mineral fertiliser application on fields with different previous management (homefield and outfields) on sandy and clay soils at Murehwa, Zimbabwe. The treatments 5TM, 5TM and 25TM refer to manure application rates of 5, 15 and 25 t ha^{-1}.

Soil	Field type	Treatments	C (%)	N (%)	pH	Available P	CEC	Ca	Mg	K ($cmol_c$	BS%
Sandy	Homefield	Initial	0.50	0.04	5.10	7.20	2.20	0.91	0.32	0.21	73.00
		Control	0.40	0.03	5.38	6.62	2.53	1.46	0.45	0.17	57.91
		100N	0.29	0.03	5.26	8.91	2.83	1.06	0.35	0.15	57.84
		100N + 5TM	0.59	0.05	5.43	7.47	5.27	2.29	0.72	0.32	64.77
		100N + 15TM	0.50	0.04	5.29	8.40	4.78	1.90	0.65	0.31	61.52
		100N + 25TM	0.68	0.06	5.47	9.38	6.51	2.91	0.95	0.40	66.83
	Outfield	Initial	0.30	0.03	4.90	2.40	1.60	0.26	0.19	0.11	37.00
		Control	0.34	0.03	5.00	2.01	3.30	0.94	0.36	0.10	45.84
		100N	0.30	0.03	5.08	4.33	2.84	0.92	0.34	0.12	51.74
		100N + 5TM	0.34	0.03	5.05	8.12	3.16	0.98	0.37	0.16	51.16
		100N + 15TM	0.39	0.03	5.12	8.47	3.94	1.29	0.49	0.21	53.21
		100N + 25TM	0.49	0.04	5.26	9.00	4.59	1.72	0.64	0.25	58.24
Clay	Homefield	Initial	1.40	0.08	5.60	12.10	24.20	11.50	6.20	0.80	78.00
		Control	1.38	0.05	6.44	10.39	19.63	10.32	5.38	0.67	83.06
		100N	1.37	0.05	6.47	10.87	22.75	11.53	8.76	0.58	87.76
		100N + 5TM	1.53	0.09	6.50	15.43	22.63	11.66	7.23	1.30	89.41
		100N + 15TM	1.63	0.08	6.52	15.45	24.32	12.86	7.94	1.24	90.52
		100N + 25TM	1.84	0.09	6.50	16.70	25.58	13.68	8.53	1.60	93.47
	Outfield	Initial	0.80	0.05	5.40	3.90	22.00	8.40	6.30	0.30	68.60
		Control	0.67	0.05	6.46	3.83	20.33	8.10	6.07	0.51	72.98
		100N	0.76	0.06	6.52	4.30	27.92	14.69	10.52	0.49	90.53
		100N + 5TM	0.82	0.06	6.51	9.81	30.73	15.71	10.94	0.63	88.19
		100N + 15TM	0.87	0.06	6.51	10.04	28.11	14.62	10.33	0.82	88.98
		100N + 25TM	0.97	0.06	6.44	10.80	23.68	12.23	8.70	0.98	89.51
	SEM		0.11	0.00	0.14	0.84	2.51	1.28	0.92	0.09	3.82

4.2.2 Experimental design

Initial farming system and field characterization revealed the occurrence of soil fertility gradients due to previous soil fertility management on both clay and sandy soils (Zingore et al., 2007a). Fields close to the homestead (i.e. 0-50 m) were relatively more fertile and called *homefields*, and those far away from the homestead (i.e. 100-500 m) were relatively less fertile and called *outfields* (Table 4.1). Thus the experiment was established on fields with contrasting soil types (Manjonjo- sandy soil, Ruzvidzo - red clay soil) and previous nutrient management intensity. The sand plus silt content of clay homefield was 56%, clay outfield 58%, sandy homefield 15% and sandy outfield 12%. Initial characterisation showed that both soils were deficient in N and P, confirming that they were the most limiting nutrients across soil types; whereas K was deficient only in the sandy soils (Table 4.1). Experimental fields were tilled using an ox-drawn mouldboard plough at the start of the rainy season. All previous crop harvest residues were grazed by cattle during the dry season. The experiment was located on four fields (clay homefield, clay outfield, sandy homefield, and sandy outfield) on two farms, one on each soil type. Experimental treatments were laid out in a randomized complete block design (RCBD) with three replications on 6 m × 4.5 m plots in each field. The experiment was run for nine seasons starting with the 2002/2003 season. No crops were sown in the fourth season (2005/2006) and the seventh season (2008/2009) due to logistical problems, fields had been tilled but weeds were allowed to grow. The initial treatments were:

i. Control (no amendment added)
ii. 100 kg N ha^{-1}
iii. 100 kg N ha^{-1} + 10 kg P ha^{-1} (i.e. 5 tons manure ha^{-1}),
iv. 100 kg N ha^{-1} + 30 kg P ha^{-1} (i.e. 15 tons manure ha^{-1}),

v. 100 kg N ha^{-1} + 30 kg P ha^{-1}, (i.e. 15 tons manure ha^{-1}), dolomitic lime (500 kg ha^{-1})

vi. 100 kg N ha^{-1} + 10 kg P ha^{-1},

vii. 100 kg N ha^{-1} + 30 kg P ha^{-1},

viii. 100 kg N ha^{-1} + 30 kg P ha^{-1}, dolomitic lime (500 kg ha^{-1})

ix. 100 kg N ha^{-1} + dolomitic lime (500 kg ha^{-1})

Mineral fertiliser N was applied as ammonium nitrate (AN, 34.5% N) and P as single super-phosphate (SSP), 20% P_2O_5). After the first season, the following treatments were modified: treatment (v) was modified to manure equivalent of 50 kg P ha^{-1} plus 100 kg N ha^{-1}, and treatment (viii) was modified to 50 kg P ha^{-1} (SSP) plus 100 kg N ha^{-1}. Application of dolomitic lime was discontinued because it had small effects on maize yield. Results from the initial four years showed no significant grain yield response to addition of N and P alone (Zingore et al., 2007b), and results from a pot experiment suggested that Ca and micronutrient deficiencies limited the response of maize to N and P (Zingore et al., 2008). Treatments that received mineral fertilisers only (AN and SSP) were modified in the 6^{th} season (2006/2007) to include Ca, Mn and Zn. This allowed assessment of the potential to increase maize yields and P use efficiency with Ca and micronutrient additions to mineral fertiliser treatments especially on degraded sandy soils compared with manure treatments. Potassium (K) was not included in the fertiliser treatments which in retrospect was an oversight in the design. From the sixth season, the treatments were:

i. Control (no amendment added)

ii. 100 kg N ha^{-1}

iii. 100 kg N ha^{-1} + 10 kg P ha^{-1} (i.e. 5 tons manure ha^{-1})

iv. 100 kg N ha^{-1} + 30 kg P ha^{-1} (i.e. 15 tons manure ha^{-1})

v. 100 kg N ha^{-1} + 50 kg P ha^{-1} (i.e. 25 tons manure ha^{-1})

vi. 100 kg N ha^{-1} + 10 kg P ha^{-1} + 20 kg Ca ha^{-1} + 5 kg Zn ha^{-1} + 10 kg Mn ha^{-1}

vii. 100 kg N ha^{-1} + 30 kg P ha^{-1} + 20 kg Ca ha^{-1} + 5 kg Zn ha^{-1} + 10 kg Mn ha^{-1}

viii. 100 kg N ha^{-1} + 50 kg P ha^{-1} + 20 kg Ca ha^{-1} + 5 kg Zn ha^{-1} + 10 kg Mn ha^{-1}

ix. 100 kg N ha^{-1} + 500 kg lime ha^{-1}

Aerobically composted solid cattle manure was applied annually on a dry-weight basis. Manure was dug and heaped without cover for two months before application to the fields, mimicking local management. To reduce variability, cattle manure was collected from the same farm every year and contained 20% C, 1.1% N, 0.18% P, 0.20% Ca, 0.08% Mg, 0.64% K, 800 mg kg^{-1} Fe, 22 mg kg^{-1} Cu, 280 mg kg^{-1} Mn, 112 mg kg^{-1} Zn (Zingore et al., 2008). Manure was spread evenly on the surface covering the whole plot and incorporated (0-10 cm) into the soil using hand hoes before planting. Basal and top-dressing fertiliser was spot-applied at each planting hill. Ammonium nitrate fertiliser was applied as top-dressing in two 50 kg N ha^{-1} amounts at three and six weeks after crop emergence in all plots except the control. A medium maturity, drought tolerant hybrid maize variety SC525 was planted at a spacing of 90 cm between rows and 25 cm within the row to give a plant population of 44444 plants ha^{-1}. All plots were weeded manually four times during each season.

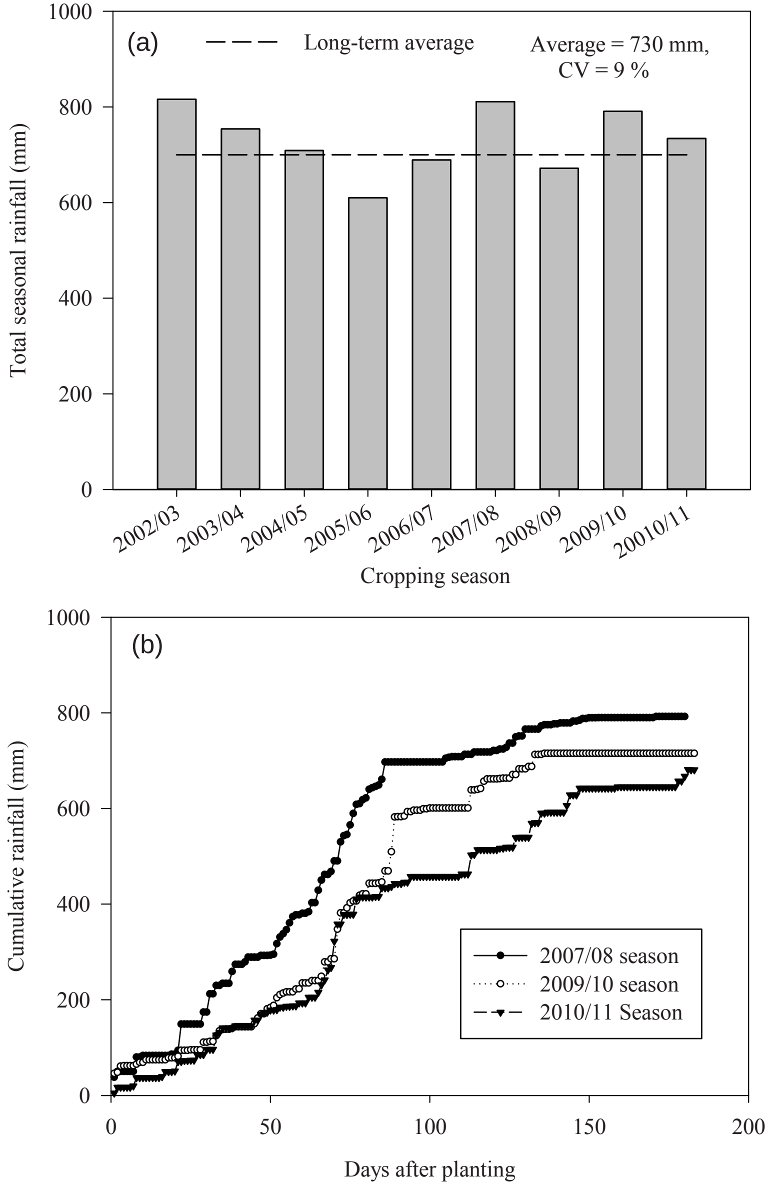

Fig. 4.1. (a) Measured total seasonal (October-May) rainfall received during the experimental period in Murehwa, (b) seasonal rainfall distribution in the last three seasons standardised by days after planting

4.2.3 Soil and manure sampling and analysis

In 2002 (baseline) and in 2011 (after nine seasons), soil samples were taken from the experimental fields using an auger (0-20 cm depth), air-dried and, sieved prior to analysis. Total C and N in soil and manure were analysed through dry combustion using a carbon/hydrogen/nitrogen analyzer (Leco-CNS2000). Available P was measured by the Olsen method (Olsen et al., 1954). Soil pH was measured with a digital pH metre in a 1:2.5 (w/v) soil: deionised water suspension, Ca and Mg were determined by atomic absorption spectroscopy and K by flame photometry after extraction in ammonium acetate, and cation exchange capacity (CEC) by the ammonium acetate method as described by Anderson and Ingram (1993).

4.2.4 Rainfall infiltration measurement

Artificial rainfall was generated by a portable rainfall simulator based on single full cone nozzle principle and calibrated following the procedure of Panini *et al.* (1993) and Nyamadzawo *et al.* (2003). Simulated rainfall with intensity of 35 mm h^{-1} was supplied from a height of 5 m on a surface area of 2.25 m^2 (1.5 m × 1.5 m). Uniformity of size and distribution of raindrops was achieved at this rainfall intensity. Measurements were taken from the central 1 m^2 confined using metal sheets leaving a single outlet leading into a small gutter where runoff was collected. The nozzle was checked and adjusted; three rain gauges were installed in the wetted buffer area to check the uniformity of rainfall distribution. Water for the simulation experiment was collected from the communal borehole closest to the experimental field. The rainfall simulations were carried out in October 2009 under dry conditions (less than 5% soil moisture); simulations continued until steady state runoff was attained on the clay soils. On the sandy soils, rainfall simulations continued for more than 5 hours because it was not possible to reach steady state infiltration. Infiltration was estimated by calculating the difference between applied rain and runoff. The irregular infiltration patterns in sandy soils meant the data could not be modelled. A sigmoidal decay curve characterized by a lag-phase of decrease of initial infiltration was used to describe the clay soil infiltration data. The model had four parameters: $i_t = i_f + \frac{i_i - i_f}{1-\left(t/t_0\right)^K}$ where i_i is initial infiltration rate, i_f is final infiltration rate, t_0 is time at $i_i/2$, K is the infiltration rate decay coefficient.

4.2.5 Crop yield measurement

Maize was harvested after physiological maturity; yield was estimated from a net plot of 5.4 m^2 (2.7 m × 2 m) in the centre of the plot to avoid border effects. Grain was shelled from the cob by hand and separated from stover (leaves stalk and core). Grain weight was measured using a digital scale, and moisture content taken immediately to correct yields to 12.5% moisture. Stover sub-samples were dried in the oven at 70 ºC until constant mass to convert fresh stover yields measured in the field to dry matter.

4.2.6 Manure collection estimates

An on-farm survey was carried out in September 2011 to estimate the amount of manure that households (who owned cattle) collected from their kraal in Manjonjo village. We also estimated the manure application rates for the various plots to which manure was applied. Twenty five farmers were interviewed, a specific question was asked on the number of carts collected from the kraal per farm. The mass of manure contained in a local standard cart (1 m^3) was measured using a digital scale. Total amount of manure collected was obtained by multiplying the number of carts collected by the standard mass of manure in a cart per farm.

Sub-samples of manure were collected, oven dried and moisture content used to express manure on a dry weight basis.

A boundary line was fitted to establish the relationship between amount of manure collected and number of cattle owned per farm. Boundary lines were fitted through boundary points that corresponded to the largest manure quantity (y) at each value of the number of cattle (x) using the model: $y = ax + b$. The most suitable boundary line model was obtained by minimizing the root mean squared error (RMSE) between the fitted boundary line and the boundary points using the Solver function in MS Excel.

4.2.7 Statistical analysis

The generalized linear mixed model (GLMM) in GenStat 14th Edition (VSN, 2011) was used to test the effects of nutrient management treatment, soil and field type, season and their interaction on crop yield. Maize grain yields data were tested for normality and found to be normally distributed using the Shapiro-Wilk W test (Shapiro and Wilk, 1965). Three models were used in the analyses: Model 1 (combined model) was used to describe maize yield across both clay and sandy soils, Model 2 (clay soil) to describe maize yield under clay soil and Model 3 (sandy soil) to describe maize yield under sandy soils. Model 1 aimed at testing the general effect of the factor 'soil type' on maize yields. In Model 2 and Model 3, the effect of 'nutrient management' and 'field type' was further specified for the two soil types in order to test their specific effects on maize yield. In the analysis, nutrient management treatments, soil and field type were considered fixed factors while season was considered a random factor. Nutrient management, soil and field types were considered fixed factors because these were specifically determined and their effects on yield were of major interest. The fixed effects were tested by sequentially adding terms to the fixed model. Season was considered a random factor due to the fact that the effect of season under rainfed conditions is nested in the interaction of amount × distribution of rainfall, and cannot be determined experimentally. It is also unlikely that the duration of the experiment covered all the possible combinations of amount × distribution of rainfall. The major interest on the seasonal effect was also on the variation among them rather than the specific effects of each on crop yield in each treatment. A multiple correlation analysis was performed to understand the relationship between maize grain yield and other measured variables such as bulk density, SOC and rainfall infiltration using data from the 2009/2010 season.

Table 4.2. Output of the GLMM procedures for explaining variability of maize grain yields in the long-term trial in Murehwa (2002–2011). Model 1 (combined model) was used to test the general effect of the factor 'soil type' on maize yields. The effect of 'nutrient management' and 'field type' was further specified for the two soil types in order to test their specific effects on maize yield in Models 2 (clay soil) and 3 (sandy soil).

Model	DF	F Value	Pr > F
COMBINED MODEL	231	10.41	<.0001
season	6	35.32	<.0001
soil	1	426.27	<.0001
field	1	298.06	<.0001
treatment	8	95.03	<.0001
field*treatment	8	3.54	0.0006
soil*treatment	8	6.42	<.0001
season*treatment	43	3.96	<.0001
soil*field	1	2.22	0.137
soil*field*treatment	8	0.78	0.6165
season* soil*field*treatment	147	1.67	<.0001
CLAY SOIL	115	7.43	<.0001
season	6	21.32	<.0001
field	1	90.02	<.0001
treatment	8	47.62	<.0001
field*treatment	8	1.46	0.172
season*field*treatment	92	2	<.0001
SANDY SOIL	115	11.12	<.0001
season	6	19.43	<.0001
field	1	294.46	<.0001
treatment	8	59.84	<.0001
field*treatment	8	3.88	0.0003
season* field*treatment	92	2.29	<.0001

4.3. Results

4.3.1 Experimental factors on maize grain yield

Total seasonal rainfall did not vary strongly among the seasons with the 2005/06 season recording the least rainfall (Fig. 4.1a). However, intra-seasonal rainfall distribution varied strongly (Fig.4.1b); there were large differences in rainfall received during the critical grain filling stage, ca. day 80 after planting. Treatment (nutrient management), soil type, field type and season all had significant (P<0.0001) effects on crop grain yield (Table 4.2). The interaction of all the four factors was also significant on crop grain yield. Analysis of residual variances showed that soil type had the strongest (F = 426) effect on yield followed by field type and nutrient management, and lastly season (Model 1). Under each soil type (Models 2 and 3), field type, cropping season and nutrient management were significant on crop grain yield (P<0.001). On sandy soils (Model 3), field type had a stronger effect on crop yield than on clay soils. As a result, the interactions between field type and nutrient management were weak on clay soils (P=0.172) and stronger in sandy soils (P=0.0003) (Table 4.2). The strong effects of field type on grain yield suggest that targeting of nutrients to homefields and outfields is important for efficient use of limited nutrient resources at the farm-scale.

A multiple correlation analysis between maize grain yield, soil bulk density, SOC measured in the 8th season and final water infiltration rate showed that maize grain yield was strongly (P<0.05) correlated with SOC and negatively correlated with soil bulk density (Table 4.3). Final infiltration was positively correlated to SOC but negatively correlated with soil bulk density.

Table 4.3. Correlations between maize grain yield and other measured parameters using data obtained in 2009/2010 season.

Variable	by variable	Correlation	Significance
Bulk density	Grain yield	-0.3881	0.3421
SOC	Grain yield	0.9079	0.0018
SOC	Bulk density	-0.5921	0.122
Infiltration	Grain yield	0.155	0.714
Infiltration	Bulk density	-0.845	0.0083
Infiltration	SOC	0.4843	0.2239

4.3.2 Short term (≤ 3 years) maize grain yields

On the sandy soils, the effects of nutrient management strategies in the first season on maize grain yield were apparent in the homefield but not in the outfield (Fig. 4.2a &4.2b). The smallest (<0.1 t ha^{-1}) yields on control plots for the first three seasons were observed on the outfield sandy soil (Fig. 4.2a). Application of manure had a cumulative effect on crop yield; application of 100 kg N + 25 t ha^{-1} manure in the sandy outfield increased yield from 0.5 t ha^{-1} in the first season to 2.7 t ha^{-1} in the third season. In the sandy homefield, the largest yield was 4.4 t ha^{-1} obtained with 100 kg N + 25 t ha^{-1} manure but decreased to 3.4 t ha^{-1} in the third season although it was still the largest yield among all the treatments (Fig. 4.2b). In the third season, application of 100 kg N ha^{-1}alone did not increase crop yield significantly in both outfield and homefield sandy soils. In most cases, the yields of NP fertiliser treatments were in between the yields of 100 kg N and 100 kg N + manure treatments.

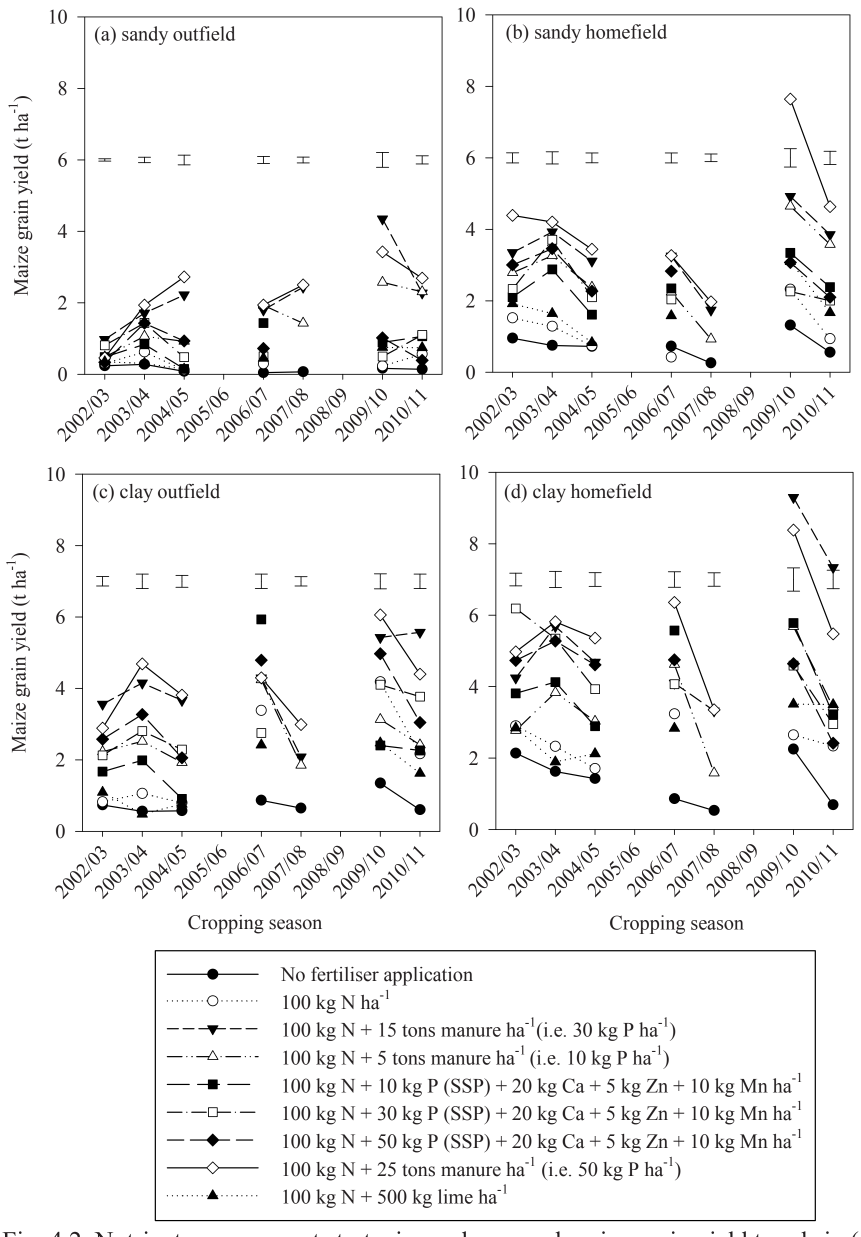

Fig. 4.2. Nutrient management strategies and seasonal maize grain yield trends in (a) sandy outfield, (b) sandy homefield, (c) clay outfield and, (d) clay homefield in Murehwa. Treatments receiving mineral fertilisers only (AN and SSP) were modified in the 6th season (2006/2007) to include Ca, Mn and Zn. Error bars are the standard error of differences (treatment × season)

On the clay soils, there were no significant yield differences between control and application of 100 kg N ha^{-1} in the first three seasons on both field types (Fig. 4.2c &4.2d). In general, in the first year, control yields in the clay outfields were less than half those in the clay homefields (Fig. 4.2c & 4.2d). The largest control yield of 2.1 t ha^{-1} was recorded in the first season in the homefield but decreased in the two successive seasons. The yield of the control on the outfield was 0.8 t ha^{-1} in the first season and did not change significantly in the second and third seasons. The largest yield (4.3 t ha^{-1}) in the first three seasons on the clay outfield was obtained with 100 kg N + 25 t ha^{-1} manure in the second season, however, yield declined after the second season, as for all treatments. In the first season, yields attained with manure were less than with N+P fertiliser, but by the third season yields attained with manure were larger than with N+P fertiliser in the clay homefield. On the clay outfield, yields from manure treatments were consistently greater than from N and P treatments.

4.3.3 Long term maize (> 3 years) grain yields

After the third season, significant yield benefits were recorded in treatments that combined fertiliser and manure, and showed incremental benefits in successive seasons (Fig. 4.2). The largest yields for the experimental period were recorded in the eighth season (a season that had good rainfall distribution); on the homefield sandy soils application of 100 kg N + 25 t ha^{-1} of manure resulted in the largest grain yield of 7.6 t ha^{-1} for the experimental period. The corresponding treatment in the outfield sandy soils yielded only 3.4 t ha^{-1} and was not significantly different from the application of 100 kg N + 15 t $ha^{-1}$of manure in all seasons. The largest yield in the clay outfield was obtained with application of 100 kg N + 25 t ha^{-1} manure; top yields were 6.1 t ha^{-1} for the outfield and 9.3 t ha^{-1} for the homefield. The largest yield of 6.1 t ha^{-1} in the outfield in the 8th season obtained with the application of 25 t ha^{-1}

manure, was the same as yield obtained in the homefield with the application of 100 kg N ha^{-1} + 50 kg P ha^{-1} + 20 kg Ca ha^{-1} + 5 kg Zn ha^{-1} + 10 kg Mn ha^{-1}. In the ninth season, maize grain yields were smaller relative to the eighth season, however, manure based treatments out yielded the fertiliser-based treatments on all fields. The ninth season received less rainfall than the eighth season.

4.3.4 Comparison of initial and final seasons

In the sandy outfield maize grain yield declined by 50% from 0.2 t ha^{-1} in the first season to 0.1 t ha^{-1} (Fig. 4.3a) in the final season. In the sandy homefield, a loss of 0.4 t ha^{-1} between the first and final season due to lack of inputs was significant (Fig. 4.3b). In the clay outfields, the yield decline due to lack of inputs was small compared with the other three fields (Fig.4.3c). In the clay homefield, lack of nutrients reduced yield significantly from 2.1 t ha^{-1} in the first season to 0.7 t ha^{-1} in the final season (Fig. 3d). On clay soils, in both field types, long-term application of 100 kg N ha^{-1} maintained yields around 2 t ha^{-1}. In sandy soils, long-term application of 100 kg N ha^{-1} maintained yields below 1 t ha^{-1} and approached zero in sandy outfields.

Additions of Ca and micronutrients increased yield in the long term in the outfields for both sandy and clay soils (Fig. 4a & 4c) compared with the first season. However, the opposite results were recorded in the corresponding homefields, yields declined in the final season with respect to the first (Fig. 4b & 4d). The restoration of crop productivity in the degraded sandy soils was only relevant when a combination of mineral fertiliser and manure were used (Fig. 4.3). In the final season, maize grain yields with N + manure application in the outfields were comparable to yield with the equivalent P fertiliser treatment the homefields. The difference in yield between mineral fertilisers, and a mixture of N fertiliser and manure was largest in the sandy outfields (Fig. 4.3). Yields of corresponding nutrient management treatments on outfields were significantly smaller than on homefields after nine seasons for both soil types.

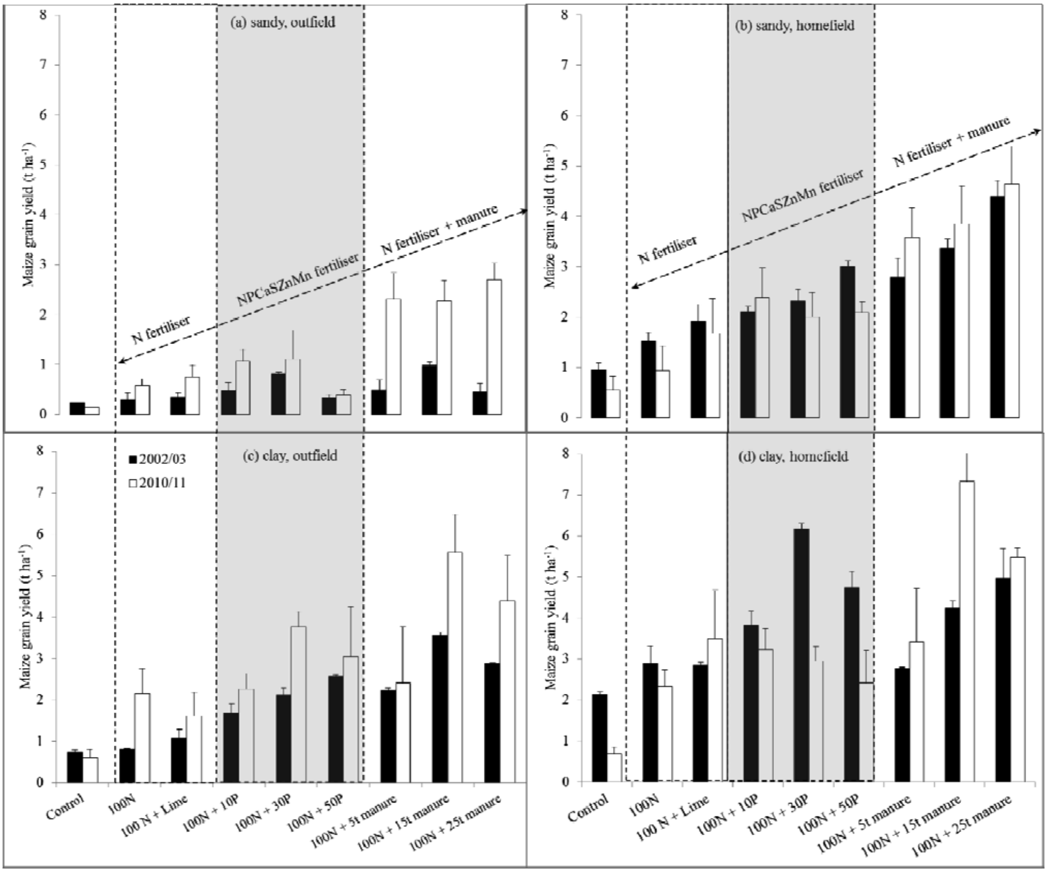

Fig. 4.3. Maize grain yield gaps in (a) sandy outfield, (b) sandy homefield, (c) clay outfield, and (d) clay homefield under different nutrient management strategies at the start (2002) and end (2011) of the experiment in Murehwa. NPCaSZnMn refer to the treatments which received N, P, Ca, S, Zn and Mn in the form of inorganic fertiliser, error bars are the standard error of mean.

4.3.5 Comparative yield advantage of manure

On the sandy soils, manure treatments often yielded better than the equivalent mineral fertiliser treatments, even with Ca and micronutrients (from the sixth season onwards), for the entire experimental period (Fig.4.4a & 4.4b). The superiority of manure treatments was especially apparent in the long-term. On the clay soils the trend was different to that obtained on the sandy soils (Fig. 4.4c & 4.4d). On the homefield clay soils yields from treatments with application of manure were not significantly different from those from treatments with the equivalent mineral fertiliser treatments in the first three seasons. Application of 100 kg N + 5 t ha^{-1} manure resulted in similar grain yields as those from the treatments with the mineral fertiliser equivalent (10 kg P ha^{-1}) for the whole experimental period, whilst the larger manure applications showed larger yields than the equivalent P fertiliser treatments in the eight and nine seasons. In the clay outfields, yields from manure treatments were superior to those from the equivalent mineral P fertiliser treatments but the magnitude of the difference was fairly constant during the experimental period.

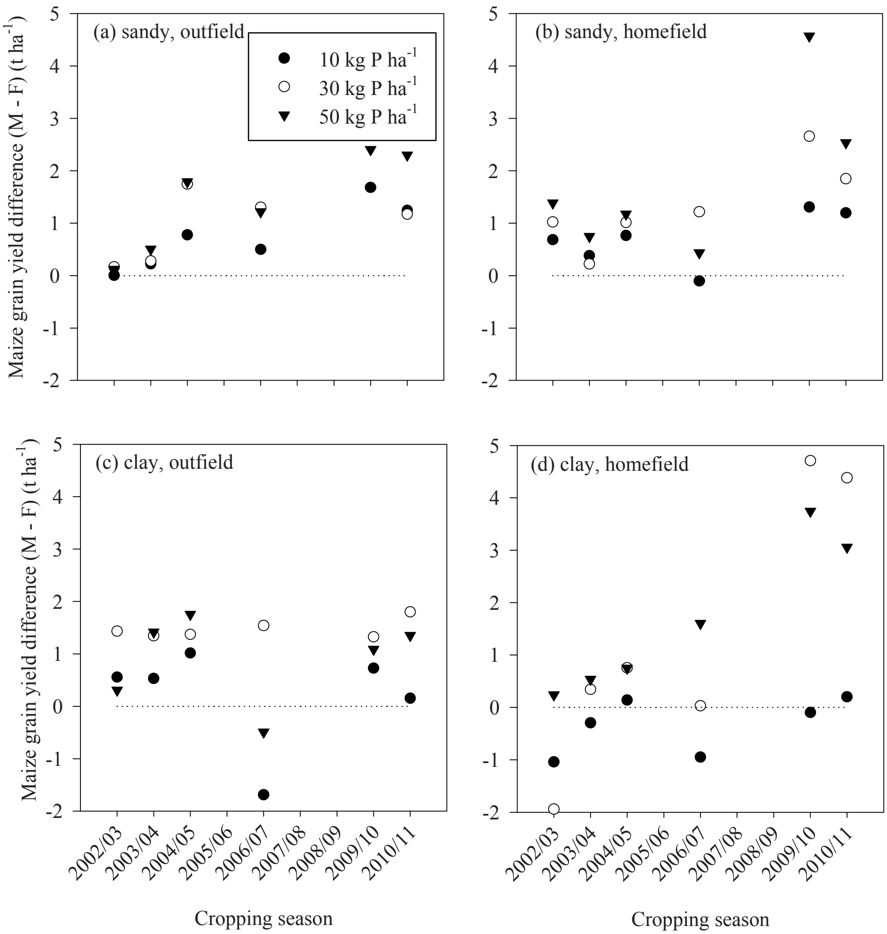

Fig. 4.4. Seasonal effect on maize grain yield differences between manure (M) and fertiliser (F) treatments at equivalent amount of phosphorus application in (a) sandy outfield, (b) sandy homefield, (c) clay outfield, (d) clay homefield in Murehwa, dotted line is line of no yield difference.

4.3.6 Maize response to incremental manure and P applications

Maize grain yield generally increased with increased amounts of manure and P applied. In the sandy outfield, response to manure application was poor in the first season; maize yield of 0.3 t ha^{-1} without manure application was only increased to 1.0 t ha^{-1} with application of 15 t manure ha^{-1}, and was 0.5 t ha^{-1} with application of 25 t manure ha^{-1} (Fig. 4.5a). Response in the homefield was significant; in the first season, application of 5 t manure ha^{-1} doubled maize grain yield compared with where manure was not applied. Manure applications beyond 5 t ha^{-1} did not result in significant yield increase in either the initial or final season on outfield sandy soils. On clay soils, maize grain yield increased significantly with increasing manure application up to 15 t ha^{-1} manure, beyond which yield declined (Fig. 4.5b). Application of 5 t ha^{-1} manure on clay homefield depressed yields in the first seasons relative to 100 kg N ha^{-1} only. Generally maize grain yield response to incremental additions of manure in the final season was superior to the response in the first season.

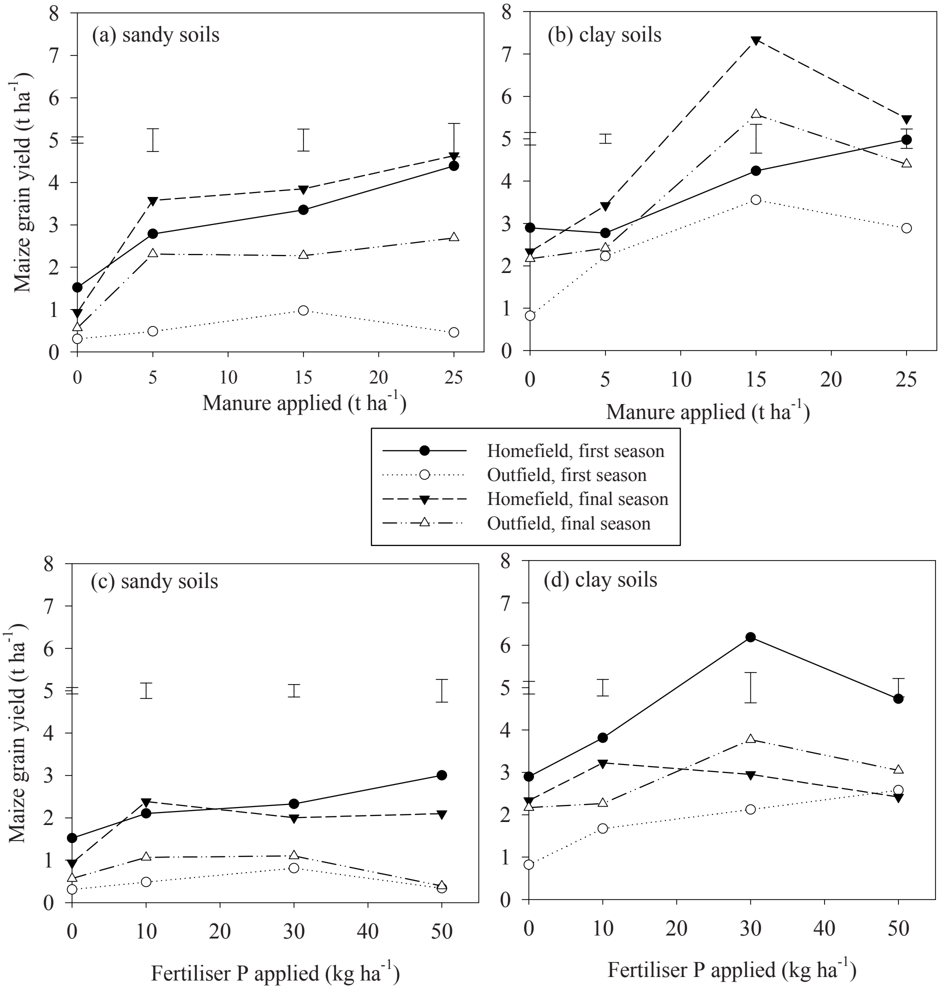

Fig. 4.5. Maize grain yield response to increasing manure application rates (a) in sandy and (b) clay soil, maize grain yield response to increasing P application rates in (c) sandy soil and (d) clay soil in the first and final season as affected by field type in Murehwa. Error bars are the standard error of differences (s.e.d).

Maize grain yield responses to incremental additions of P fertiliser were similar to the pattern observed with incremental manure additions (Fig. 4.5c & 4.5d). The application of 30 kg P ha^{-1} fertiliser seemed to be the maximum amount of P required to achieve the largest maize grain yield on both clay and sandy soils, field types and first and final season. For example, application of 30 kg P ha^{-1} increased yield from 2.9 t ha^{-1} to 6.2 t ha^{-1}, but declined to 4.7 t ha^{-1} in the clay homefield in the first season. Surprisingly, yield response to P application was poor in the final season compared with the first season in both sandy and clay homefields.

4.3.7 Comparison of initial and final soil fertility statuses

Compared with the initial values, most soil properties changed during the experimental period widening the gap between the soil fertility statuses of the fields and soil types than closing them. Long-term application of manure increased the N concentration in the soils although the changes were not significant relative to the initial status and also to the control treatment across the four fields (Table 4.1). The pH results were rather inconsistent, pH was larger than the initial years across all treatments although treatment differences were not significant. Available P increased significantly with the application of 100 kg N + 25 t ha^{-1} manure on both soils in all field types while it decreased or remained unchanged in the control and the 100 kg N ha^{-1} treatment. The largest increase in P with application of 100 kg N + 25 t ha^{-1} manure was observed in the outfields, P increased from 3.9 to 10.8 and 2.4 to 9.0 mg kg^{-1} for sandy outfield and clay outfield respectively. Cation exchange capacity increased significantly in sandy soils but increases in clay soils were not significant. Manure application also led to significant increases in base cations and base saturation.

The change in SOC concentration in the soil (0-20 cm) over time was proportional to the amount of C added in manure. SOC increased significantly with the application of 100 kg N + 25 t ha^{-1} manure on both soils in all field types while it decreased or remained unchanged in the control and the 100 kg N ha^{-1} treatment (Table 4.1). At the end of the experiment, the treatment with the lowest application of manure (100 kg N ha^{-1} + 5 t manure ha^{-1}) in combination with 100 kg N ha^{-1} resulted in an increase in SOC from 0.5% to 0.8% in sandy homefield, 0.3% to 0.5% in sandy outfield, from 1.4% to 1.53% in clay homefield, and from

0.8 to 0.82% in clay outfield. The largest manure application of 100 kg N + 25 t ha^{-1} increased SOC from 0.50% to 0.86% in sandy homefield, 0.30 to 0.49% in sandy outfield, 1.40% to 1.84% in clay homefields and 0.8% to 0.97% in clay outfield (Table 4.1).

4.3.8 Effect of manure application on rainfall infiltration

Water infiltration was difficult to determine on the sandy soils due to excessive drainage and suspected water repellence (Fig. 4.6a). On the outfield sandy soils, application of 100 kg N + 25 t ha^{-1} manure significantly increased time to run-off from 89 minutes (control) to 210 minutes. In the homefield, there was no difference in time to run-off as well as the infiltration patterns between control and application of 100 kg N + 25 t ha^{-1} manure (Fig. 4.6a). The simulations continued for five hours, final infiltration was very small (5 mm hr^{-1}) and there was no difference in final infiltration between treatments and between fields.

Application of 100 kg N + 25 t ha^{-1} manure on the homefield clay soils led to a final infiltration of 31 mm hr^{-1} after 3 hours compared with 27 mm hr^{-1} for the control. On the outfield clay soils with application of 100 kg N + 25 t ha^{-1} manure, runoff started after 48 minutes and final infiltration was 29 mm hr^{-1} after 2.5 hours (Fig. 4.6b). The difference in infiltration between clay field types was larger for the control treatments but smaller with application of 100 kg N + 25 t ha^{-1} manure.

The irregular infiltration patterns in sandy soils meant the data could not be modelled. On clay soils, the reduction in infiltration rate was not instantaneous resulting in a sigmoidal decay curve (Fig. 4.6b).

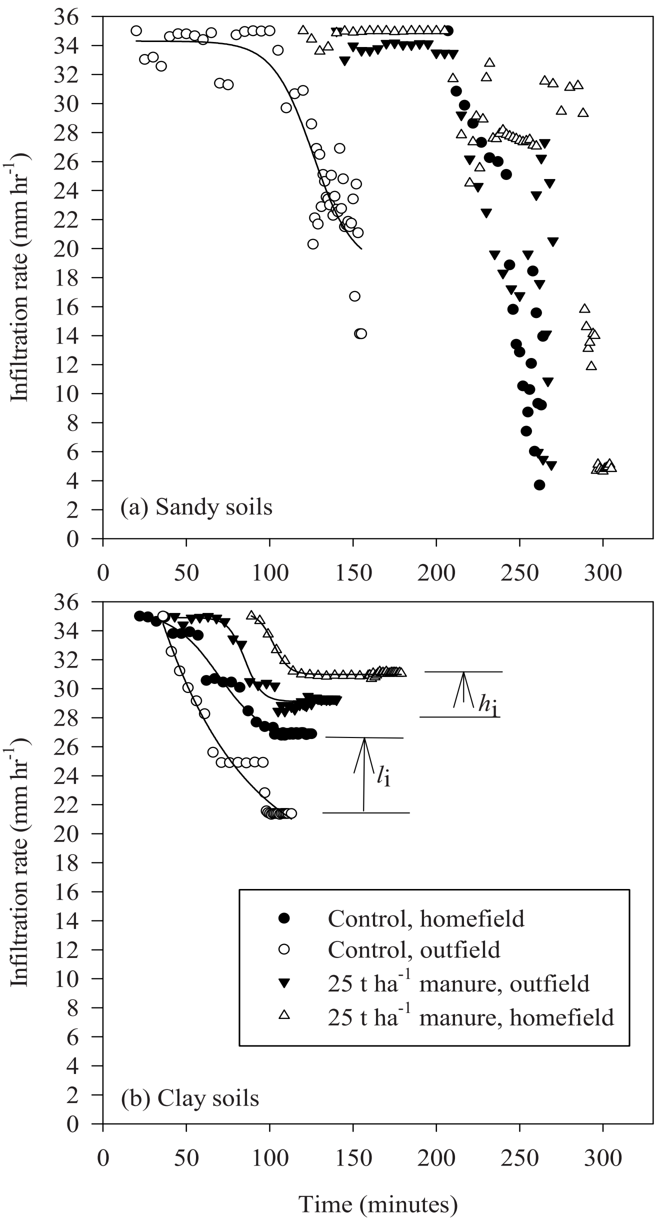

Fig.4.6. Rainfall infiltration in a sandy soil (a) and clay soil (b) as affected field type and manure application in Murehwa. Degradation caused by previous management diminishes at larger organic inputs (h_i) and worsen without organic inputs (l_i). The sigmoidal model with four parameters: $i_t = i_f + \frac{i_i - i_f}{1-\left(t/t_0\right)^K}$ where i_i is initial infiltration rate, i_f is final infiltration rate, t_0 is time at $i_i/2$, K is the infiltration rate decay coefficient was used to describe infiltration in clay soils.

4.3.9 Farm-level feasible manure quantities

In Manjonjo village, only 38% of farmers owned cattle. Cattle numbers ranged from one to 13 with an average of five per farm for the farmers who owned cattle. Cattle ownership was a major determinant of manure availability. The upper boundary line of the relationship between the amount of manure measured and number of cattle owned per farm was linear: $manure\ (t\ year^{-1})\ = 0.94\ \times\ number\ of\ cattle$ (Fig. 4.7a). Results suggest that at least six heads of cattle were required to achieve the minimum application of 5 t ha^{-1} used in the experiment if the target on the farm is a hectare each year. The lower boundary line showed that the amount of manure collected under poor management is sometimes very small despite relatively large cattle numbers. Thus the amount of manure available per farm varied across households even with the same number of cattle. Beyond cattle ownership, manure application rates varied greatly between fields mainly due to management decisions and availability of mineral fertilisers. A greater proportion of the cultivated land in the village was subdivided into plots of sizes of between 0.1 and 0.5 ha (Fig. 4.7b). It was estimated that on average 30% of the cultivated plots of cattle owners received manure every season at an average application rate of 4.1 t ha^{-1} with a range of 0.4 - 17.5 t ha^{-1} (Fig. 4.7b). The application rates achieved by farmers suggest that the yield improvements we have reported especially related to effects of 5 t ha^{-1} manure are possible on some fields for farmers who own cattle.

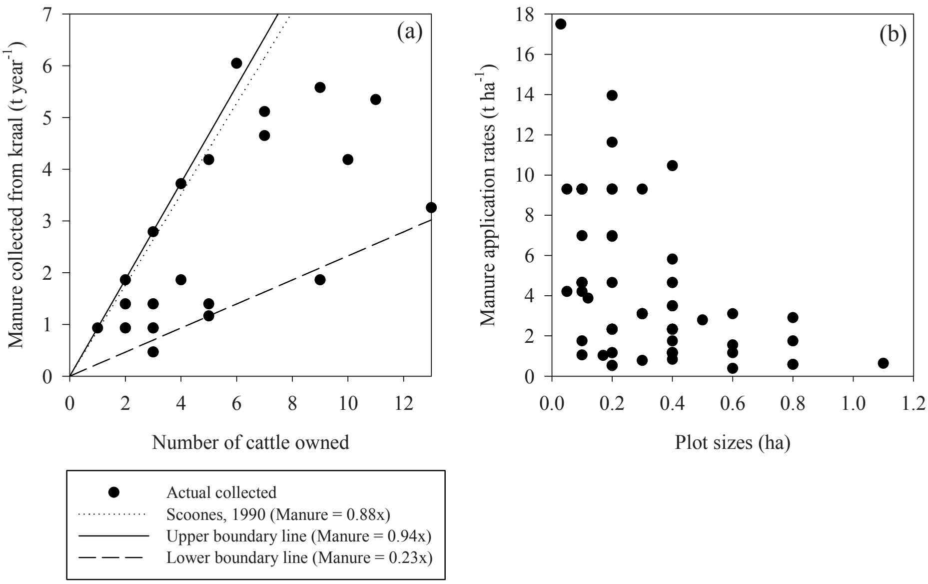

Fig. 4.7. (a) The relation between livestock ownership and manure collected from the kraal, (b) variations in cultivated field sizes and manure application rates, only for fields where manure was applied in Manjonjo village, Murehwa.

4.4. Discussion

4.4.1 Management and biophysical factors

The variability in fertility status of fields due to previous management and its effects on crop productivity were apparent on both clay and sandy soils. Cropping season, nutrient management strategies and their combinations also had significant effects on maize grain yield (Table. 4.2). The variability in total rainfall between seasons was small (Fig. 4.1), which suggested that the effect of season on crop yield could have been due to differences in intra-seasonal rainfall distribution. Rainfall in the study region is often poorly distributed over the season with periods of both low and high rainfall which result in yield fluctuations across seasons (Challinor et al., 2007). The yield data reported here were recorded in trials that were generally well managed, planting was with the first effective rains each season, plots were kept weed free and fertilisers were applied at the right time. Nitrogen fertiliser was split applied to avoid losses and improve nutrient use efficiency which is critical especially in the sandy soils characterised by rapid drainage.

Crop productivity differed strongly between soil types as expected because the sandy soils had very low nutrients and organic matter content compared with clay soils that were inherently more fertile (Table 1; Nyamapfene, 1991). On the other hand, soil fertility gradients (homefields vs. outfields) are known to influence the response of crops to added nutrients (Vanlauwe et al., 2006; Zingore et al., 2007a); thus homefields had larger yields than outfields. The differences in crop responses were due to differences in soil organic matter, base cations and micronutrient inputs. In the long term, the history of management as well as the seasonal management and soil type were critical in determining yields agreeing with previous findings on short-term crop responses (Zingore et al., 2007b).

4.2 Response of crop yields to manure versus fertiliser applications

Although fertiliser is considered critical for sustainable crop production, the potential of fertiliser alone to restore soil fertility on the depleted sandy soils was very poor. The delayed response to nutrients often act as disincentive to smallholder farmers because the building of soil fertility takes much more time than is required to deplete it (Tittonell et al., 2012). The delayed increase in crop yields was more pronounced on the outfield sandy soils due to a combination of previous inadequate nutrient management and inherent infertility. The four field types we studied clearly followed different pathways in rebuilding soil fertility as shown by the maize grain yield. It appeared possible to restore soil fertility for the red clay soils in a reasonably short time while it requires much more time to recover degraded sandy soils.

Our results showed the importance of supplementary manure addition on crop productivity, especially on the degraded and non-responsive sandy soils; the core of integrated soil fertility management (Vanlauwe et al., 2010). There was an increase over time in the yield difference between mineral, and combined organic and mineral nutrient management strategies. The long-term relative yield increases of combining manure with mineral fertiliser were much greater on the more degraded outfield sandy soils than fertiliser alone. Results agree with Chivenge (2011) who observed after a meta-analysis a significant yield increases when fertiliser was used in combination with organic matter. Crop yields with manure treatments were always larger than with mineral fertiliser at equivalent P application rate in sandy soils (Fig. 4.5). This could have been due to potassium (K) deficiencies. Potassium availability was especially poor in the sandy soils (Table 1) but was not included in the treatments; deficiency of K often leads to slow growth and lower yields due to poor water use efficiency and poor N uptake (Leigh and Jones, 1984; Ashley et al., 2006). Results suggest that manure was superior to mineral fertiliser due to increase in soil organic carbon and possibly the supply of K, Mg and micronutrients. The high permeability of sandy soils suggests that there was also a risk of nutrient leaching resulting in small crop yields (Nyamangara et al., 2003; Dempster et al., 2012). Manure allows synchrony between nutrient release and crop uptake in sandy soils of excessive drainage (Murwira and Kirchmann, 1993). The value of manure in conjunction with mineral fertiliser on sandy soils in Zimbabwe has also been noted by other authors (Mugwira, 1984, 1985; Mugwira and Shumba, 1986).

Maize grain yield response to incremental manure inputs was characterised by an exponential rise to the maximum when the amount of manure approached sufficiency for both first and final year yields. Maximum yield was observed to occur at manure application rates of 15 t ha^{-1} yr^{-1}. These results were similar to those reported by Nyamangara et al. (2003) who observed that annual application of 12.5 t ha^{-1} of manure in combination with 60 kg N ha^{-1}

was the best strategy to ensure large crop yields and small leaching risk on sandy soils. On very sandy soils such as those we studied, the first and last increments of fertiliser inputs were often poorly utilized for increasing growth leading to a sigmoidal response pattern (cf. Mathews and Hopkins, 1999).

4.3 Soil organic carbon

Soil organic carbon increased in plots that received manure and was proportional to C input. SOC increases were greater in the clay soil than in the sandy soil. Soil with high clay content has a higher SOC stabilisation rate than soils with low clay content (Zhang et al., 2010). In soils of high clay content, SOC is protected from decomposition through macro- and micro-aggregation and physicochemical binding with silt and clay particles (Six et al., 2002). In general, soil organic matter increases are therefore primarily related to amount of C input in sandy soils and to soil disturbance in clay soils (Chivenge et al., 2007). In a review of long-term experiments, Edmeades (2003) found that manure led to stronger increases in organic matter than inorganic fertiliser application.

We observed a high correlation (r = 0.91, Table 4.3) between SOC and maize grain yield i.e. plots with large SOC had the largest maize yields especially in the long term. Soil organic carbon increases crop yield by increasing available soil water capacity in sandy soils, improving supply of nutrients and by enhancing soil structure and other physical properties (Lal, 2006). We conclude that in mixed crop-livestock systems where crop residues are not retained *in situ*, routine manure application provides one of the most locally adapted pathways to restoring soil organic matter and consequently soil fertility.

4.4 Rainfall infiltration

Water infiltration was significantly greater on clay soils than on sandy soils. Differences can mainly be attributed to the structural characteristics of the soils in each field. Time to pond and run-off was shorter on clay than on sandy soils; larger pores in sandy soils allowed water to drain easily. The irregular infiltration pattern on the sandy soil appeared to suggest preferential flow and the rapid drainage characteristics of the soil meant that the soil continuum was not uniformly wet and thus was characterised by uneven water infiltration (Ritsema et al., 1993). The sudden decrease in infiltration on sandy soils could have been caused by some entrapped air which would lower the hydraulic conductivity (Wang et al., 1998), and repellence in the sandy soils (Dekker and Ritsema, 1994). Water repellence is the retardation of surface water infiltration due to the hydrophobicity of organic matter in sandy soils (Brandt, 1969). Low pH which is characteristic of the sandy soils of our study sites has been found to increase soil water repellence (Woche et al., 2005). The water supply at a rate of 35 mm hr^{-1} coupled with the initial dry conditions (less that 5% soil moisture) was not sufficient to cause immediate surface ponding and run-off. In the end, infiltration decreased substantially which could be a result of surface compaction caused by raindrop impact. The lack of significant difference in final infiltration between homefields and outfields on sandy soils could have been due to the extremely high sand content of 85% and 87% respectively (Table 4.1).

On clay soils, plots receiving manure had a larger steady state water infiltration rate showing the importance of organic matter inputs in improvement of soil physical properties (Chivenge et al., 2007; Dunjana et al., 2012). Organic matter is important for soil aggregate stability and good soil structure which improve water infiltration (Franzluebbers, 2002). The decrease in infiltration rate was more consistent on the clay soils than on sandy soils; the relatively high

SOC content and uniformity of pores ensured that steady-state infiltration could be established within a relatively short time from dry conditions. The significantly different infiltration rates between homefields and outfields in clay soils could have been due to differences in SOC. Nyamadzawo et al. (2003) observed that the amount of C in the top 0-5 cm soil was the single largest determinant of variation in steady state infiltration rates, suggesting that soil C was an important factor in soil properties. Annual application and residual effects of manure have been observed to reduce runoff significantly by between 2 and 62%; a strong relationship was observed between amount of manure application and run-off (Gilley and Risse, 2000).

The correlation coefficient between maize yield and water infiltration was small ($r = 0.15$, Table 4.3) mainly due to lack of significant difference in infiltration rates between plots on sandy soils yet large differences in grain yield. Large infiltration rates may also lead to small yields as they may lead to waterlogging especially on shallow soils and leaching of crop nutrients beyond the root zone. However, in this agro-ecological zone, large rainfall infiltration is desirable to store moisture in the soil and offset the negative effects of poor rainfall distribution on crop yields.

4.5 Applicability and limitation of results

We sought to explore the potential to recover degraded soils using cattle manure i.e. "pushing the envelope" - what options are available to facilitate innovations around manure use and go beyond current crop productivity. The results after 9 years of substantial (minimum 5 t manure yr^{-1}) organic inputs did not show a breakthrough. The fertility of the outfields still could not be brought equal to the homefields (Table 4.1). In most cases, the initial soil fertility differences were maintained between fertile homefields and degraded outfields. Potassium concentration remained small and could have been limiting crop productivity in the fertiliser treatments especially on the sandy soils. However, in the combination of manure and N treatments, sufficient K was applied through manure but yields remained much smaller on the outfields compared with homefields. The sandy soils were deeper (ca. 150 cm) than the clay soils (ca. 68 cm), and not susceptible to waterlogging, thus it appears that the failure to recover crop productivity was not linked to soil depth. The initial SOC in the sandy outfields may have been too small to achieve large yields: Kay and Angers (1999) suggested that irrespective of soil type, if SOC contents are below 1%, it may not be possible to achieve maximum yields. The SOC on sandy soils and clay outfields were below this value and maize grain yield and SOC were correlated (Table 3). However a comprehensive review of literature by Loveland and Webb (2003) suggested that a threshold SOC value for maximum crop production is elusive as it depends on management and other biophysical limitations such as rainfall and soil type.

The clay soils maintained a larger potential for sustaining crop productivity than sandy soils. Considering the relevance of the results, the sandy soils are of great importance in the study site because they occupy approximately 75% of the land area. Moving from 1 t ha^{-1} of maize grain yield in the first year to 2.7 t ha^{-1} in the ninth season represented a 170% increase in crop productivity for the sandy outfield for the best performing treatment. However, 2.7 t ha^{-1}was significantly smaller than yields obtained in other fields e.g. 4.6 t ha^{-1} in the sandy homefield, 5.6 t ha^{-1} in the clay outfield or 7.3 t ha^{-1} in the clay homefield. Results suggest recovery of severely degraded sandy soils may be beyond the reach of the majority of smallholders who face resource constraints.

Manure availability is the critical factor that determines how the results we reported here can be deployed by the majority of smallholder farmers in mixed crop-livestock systems (Rufino et al., 2011). In one of the villages of the study, about 38% of the farmers owned cattle, and roughly 30% of the fields received manure every season. Cattle ownership is locally considered among farmers as an epitome of development thus the integration of crop and livestock is important to these farming systems. Roughly close to a tonne (0.94 tons) of manure per animal per year can be generated for recycling under current management (Fig. 4.7a). Our estimates of manure collected per animal were similar to that reported by Scoones (1990), who obtained a relationship of 0.88 tons per animal per year. Cattle spend much of the time during the day in non-arable areas where excretion of more than half of the manure takes place reducing the amount of manure available (Rufino et al., 2011). The combination of manure availability and average farm size suggest that there is insufficient manure for all fields every season. Improved crop productivity with manure use will depend on how much mineral fertiliser individual farmers can access, and on farm and field specific management related to application rates and crop sequences.

The central question remains: where can farmers' best allocate manure on the farm, in outfields or homefields to maximize benefits? Recommended figures of 10 tons ha^{-1} yr^{-1} (Grant, 1981) are only possible on small areas of land. Farmers in our study site demarcated their fields into manageable plots of about 0.1- 0.5 ha (Fig. 4.7b) in which larger manure rates were applied every other year. On smaller plots, larger and more effective manure application rates are feasible (Zingore et al., 2008). Our results suggest that crop productivity was greater in the homefields than outfields after nine years of applying manure which shows a constraint to recovery of degraded soils. Farmers already target manure to fields close to the household to ensure food self-sufficiency (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007a). Thus the limited quantities of manure available can be targeted to small plots and not the whole farm to improve its effectiveness on crop productivity.

Beyond crop yields, we have seen that manure increased rainfall infiltration in clay soils and C sequestration. This aligns the paradigm of ecological intensification (Cassman, 1999), where crop production systems need to go beyond increasing crop productivity to address undesirable environmental consequences. The integrated nature of most smallholder production systems (Thornton and Herrero, 2001), suggest that the results reported here are widely relevant to the majority of smallholder farming systems, and it is imperative to find locally adapted strategies to improve manure use.

4.5 Conclusions

Manure application in combination with mineral fertilisers resulted in larger yields on clay than on sandy soils both in the short and long term. The potential for soil fertility restoration was poor if only mineral fertilisers were added. Yields of the largest manure application in the outfields were comparable with yields with the largest fertiliser P application in the homefields. Yields on sandy outfields remained significantly smaller than on the other field types despite the substantial manure inputs. Our results suggest that at farm scale, manure is used more efficiently in the homefields. Increase SOC resulted in improved rainfall infiltration in the clay soils; the SOC increase in sandy soils did not increase infiltration. Application rates we used are feasible in Murehwa because farmers manage small (0.1-0.5 ha) fields, but the amounts of manure available are insufficient for the area of cropland at village scale. We conclude that consistent application of manure in combination with mineral fertiliser improves crop productivity in both short and long term and is a sustainable locally adapted option for ecological intensification in mixed crop-livestock systems of smallholder farmers.

Chapter 5

Crop residue use and trade-offs on smallholder crop-livestock farms in southern Africa: implications for intensification

To be submitted to Agricultural Systems as:

Leonard Rusinamhodzi, Mark T. van Wijk, Marc Corbeels, Mariana C. Rufino, Ken E. Giller. Crop residue scarcity and intensity of trade-offs on smallholder mixed crop-livestock farms in southern Africa: implications for intensification options.

Abstract

Decisions to use crop residues as soil cover for conservation agriculture create trade-offs for farmers who own cattle in crop-livestock systems. Trade-off analyses among soil C, crop and animal and crop productivity were analysed using NUANCES-FARMSIM (FArm-scale Resource Management SIMulator) model. The model simulates crop and livestock production including feedbacks between systems' components by linking the sub-models FIELD (Field-scale Interactions, use Efficiencies and Long-Term soil fertility Development) and LIVSIM (livestock simulator). Manure decomposition, manure C and N dynamics were simulated using the HEAPSIM sub-model. Retention on topsoil the soil of 0, 25 50, 75 and 100% of the maize stover yield produced per farm, and use of the remainder as animal feed in the dry season were compared. The impact of the crop residue allocations on crop and animal productivity as well as SOC dynamics over a 12 year period in Murehwa, Zimbabwe was quantified for two farm types. Retaining 100% maize residues in the field led to an annual loss of on average 68 kg body weight per animal and 93 kg body weight for cattle on farms of the relatively wealthiest farmers (Resource Group 1) who had most land and cattle and RG2 respectively, and is therefore unsustainable for livestock production. The effect on crop yield was an increase in farm yield of 1.6 t farm^{-1} yr^{-1} and 0.7 t farm^{-1} yr^{-1} for RG1 and RG2 respectively. Farmers who did not own cattle (RG3 and RG4) have a greater scope of retaining their crop residues if they invest in more labour to keep the residues during the dry season. Farmers in RG3 can obtain an extra 1 t farm^{-1} yr^{-1} of maize if they retain all residues and apply the same rate of fertiliser currently applied by RG1 farmers, whereas RG3 farmers will improve by 0.7 t farm^{-1} yr^{-1}. However, improved crop productivity for RG3 and RG4 is limited by lack of access to fertiliser. We conclude that at current productivity, farmers who own cattle have limited scope to allocate crop residues for soil cover as it leads to significant loss in animal productivity and economic value.

Keywords: maize residues, mixed crop-livestock systems, tradeoff analysis

5.1 Introduction

Conservation agriculture (CA) based on crop residue retention in combination with minimum tillage and crop rotations or intercrops actively promoted in many parts of the tropics (cf. FAO, 2008) including southern Africa (Giller et al., 2009). Smallholder agriculture in southern Africa is often characterized by mixed crop-livestock systems (Thornton and Herrero, 2001) in which livestock traction for tillage and feeding of crop harvest residues to livestock are common practices (Lal, 1991; Erenstein, 2002; Rao and Hall, 2003). Livestock are an important source of food and income, and can be used as a kind of insurance with which food can be bought when crops fail to generate cash (Stroebel et al., 2008). In particular, cattle support crop production through the provision of draught power and manure, Cattle manure is important as fertiliser and in some instances, the only resource to sustain soil fertility (Murwira, 1995). These multiple roles suggest that the sustenance of livestock is critical for whole farm productivity. In this study, the costs and benefits of feeding livestock with crop harvest residues are assessed.

It is doubtful whether smallholder farmers in general can produce sufficient crop residues to satisfy the dual objectives of improved crop production through CA and of sustained livestock production (Giller et al., 2009). Promotion of CA therefore could potentially reduce the amount of feed and threaten the integration of crop and livestock production on smallholder farms. Yet integration of crop and livestock production is considered to be a key pathway to improve productivity, efficiency and sustainability of smallholder agriculture (Bationo and Mokwunye, 2002; Franzluebbers, 2007; Rufino, 2008).

For example in Zimbabwe, supplementary feed sources in the form of crop residues are needed to feed livestock during the dry season when the quality of the feed of the communal grazing areas is insufficient (de Leeuw, 1996). It is estimated that crop harvest residues (stover) in the dry savanna zones of Sub Saharan Africa contribute to between 40 and 60% of the total dry matter intake of cattle during the dry season (Standford, 1989; de Leeuw, 1996). The use of crop residues as livestock feed combined with uncontrolled grazing during the dry season suggest that maintaining a permanent mulch of crop residues in the field throughout the year is not feasible. Thus the introduction of CA leads to trade-offs on cattle body weight and crop yield because of reduced feed intake in the dry season after allocating the crop residues for soil cover (Naudin et al., 2012).

Competition for the available crop residues also exists across different farm types. Cattle-owners have free access to the crop residues of non-cattle owners, thereby limiting the options available for carbon input into the soils of the latter. Denying access to crop residues by livestock would impact negatively on animal productivity and reduces the amount of manure available for crop fertilisation (Rufino et al., 2011).

The poor crop productivity in combination with the importance attached to cattle intensifies the trade-offs for crop harvest residue uses but quantification of these trade-offs in terms of crop and livestock production is still lacking. The objective of this study was to quantify the farm level benefits related to the allocation of maize harvest crop residues for livestock feed or for soil fertility management. The farming system and cattle management at Murehwa, Zimbabwe was studied. In this farming community, ruminant production traditionally depends on natural pastures (Jingura et al., 2001) supplemented by crop harvest residues. Our hypotheses were that under the smallholder crop-livestock systems, non-livestock owners can rebuild 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.

5.2 Materials and methods

5.2.1 Study site

Murehwa smallholder farming area is located about 80 km east of Harare and lies between 17° and 18° S latitude, and 31° and 32° E longitude, at an altitude of about 1 300 m. The population density is about 104 people km^{-2}. The climate is sub-humid with average annual rainfall of 750 mm distributed in a unimodal pattern between December and April. The soils are mostly granitic sandy soils (Lixisols) of poor fertility with infrequent intrusions of more fertile dolerite-derived clay soils (Luvisols) (Nyamapfene, 1991). The farming system is a mixed crop-livestock system with maize (*Zea mays* L.) as the dominant staple crop, although some farmers do not own cattle. Other crops commonly cultivated include groundnut (*Arachis hypogaea* L.), sweet potato (*Ipomoea batatas* (L.) Lam.), sunflower (*Helianthus annuus* L.) and a variety of vegetables, mostly brassicas. Cattle are the main livestock and are grazed in a communal system where they graze freely in the rangeland during the day and are kept in kraals close to the homesteads at night. Cattle are important for traction, manure production, as well as for fulfilling other economic and social requirements. The communal grazing area is characterised by the natural miombo woodland of *Julbernardia globiflora* (Benth.) Troupin*, Brachystegia boehmii* Taub. and *Brachystegia spiciformis* Benth. trees (Mapaure, 2001). Grass species of the genus *Hyparrhenia* are predominant, and *Andropogon, Digitaria* and *Heteropogon* spp. are also common species. *Sporobolus pyramidalis* P. Beauv often dominates in the overgrazed areas and perennially wet areas of the veld. In the dry season, most crop fields are used for cattle grazing, and cattle eat crop residues to complement the poor quality grazing that remains.

5.2.2 Farm diversity

A total of 80 farmers were interviewed in Manjonjo village, Murehwa in August 2011. We aimed to interview all farmers in the village, but 6 farmers were absent at the time of the interviews. The interviews were conducted at the farmer's homestead with the assistance of local extension officers to understand landholdings, crop types, typical crop rotations, fertiliser and manure inputs, tillage and crop residue management, and cattle management. Focus group discussions were conducted and the indicators of resource ownership were prioritised according to Zingore (2007a), and based on these, all farmers in the village were allocated to one of the previously identified four resource groups (RG1, RG2, RG3 and RG4, Table 5.1a). Socio-economic characteristics included family size, labour availability, months of food security, sources of income, proportion of off-farm income and production orientation.

5.2.3 Modeling framework

We used the NUANCES-FARMSIM model (van Wijk et al., 2009) to simulate and understand the trade-offs in the use of crop residues in relation to the biophysical conditions under which production takes place. The sub-model FIELD simulates crop production and the dynamics of C and nutrients in the soils, and LIVSIM 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 P dynamics of manure were simulated using the HEAPSIM sub-model (Rufino et al., 2007). The total amounts of manure on the heap at the start of the season represented the manure input into the fields.

Table 5.1: (a) Characteristics of farm types and resource groups used in the model simulations classified according to the typology for the communal area of Murehwa, and (b) soil analysis of different field types belonging to the different farmer resource groups from Zingore *et al., (2007a)*.

(a) Farm characteristics

Resource group	Wealthier	Medium-wealthier	Medium-poor	Poor
	RG1	RG2	RG3	RG4
Household size	7	5	6	5
Proportion in the village (%)	6	35	26	33
Livestock owned	ca. 10 cattle	<10 cattle	No cattle	No cattle
Farm size (ha)	2.2	1.6	1	0.7
Homefield (ha)	1.2	0.8	0.6	0.4
Outfield (ha)	1	0.8	0.4	0.3
Cattle heads (#)	10	5	0	0
		Fertiliser use		
Fertiliser N per farm (kg)	120	60	35	15
Homefields (kg N ha^{-1})	67	50	33	20
Outfields (kg N ha^{-1})	40	25	38	0
Fertiliser P (kg P $farm^{-1}$)	17	10	4	1
Homefields (kg P ha^{-1})	10	10	5	0
Outfields (kg P ha^{-1})	4	2	1	0
Resource exchanges	Hire labour and share draught power	Do not sell or hire labour, share draught power	Sometimes sell labour or exchange it for draught power	Sell labour and/or exchange it for draught power
Land holding (ha)	>3	2-30	<2	<1
Food self-sufficiency	Self-sufficient, able to sell grain and vegetables	Self-sufficient, able to sell grain and vegetables	Purchase grain and sell vegetables	Purchase food or receive food aid

(b) *Soil characteristics*

Field type	Homefield	Outfield	Homefield	Outfield	Homefield	Outfield	Homefield	Outfield
Clay + silt (%)	12	15	9	8	13	15	12	14
Bulk density (kg dm^{-3})	1.42	1.51	1.43	1.52	1.48	1.43	1.56	1.49
SOC (g kg^{-1})	5.6	4.1	6	2.2	4	3.3	3.8	3
TSN (g kg^{-1})	0.6	0.41	0.62	0.22	0.45	0.31	0.36	0.29
CEC ($cmol_c$ kg^{-1})	4.5	1.5	3	2	3	2	2	3
Ext. P (mg kg^{-1})	8	4	9	4	4	3	5	3
pH (1:2.5 water)	5.2	4.7	5.4	4.2	5	4.1	4.7	3.9

5.2.4 Simulation of crop production and soil organic matter and nutrient dynamics

Crop production is calculated as the product of resource availabilities and efficiencies (Tittonell et al., 2010a). FIELD calculates yields on a seasonal basis using resource interactions to predict light-determined, water- and nutrient-limited crop yields (N, P and K). Seasonal availability of soil nutrients is calculated following the QUEFTS approach (Smaling and Janssen, 1993) and soil organic matter dynamics with a 4-pool soil C model following first-order kinetics. The FIELD model was modified to incorporate soil texture effects on the rate of decomposition of the active soil organic matter pool, and also to the incorporate soil C saturation based on soil texture (Hassink, 1997). Detailed explanations of the model structure were provided by Tittonell *et al*. (2008; 2010a).

The cropping system considered in the simulated scenarios was continuous maize production in line with current farmers' practice. A 12 year rainfall dataset for the site was used to represent the climatic/rainfall variability in the simulations. Manure application was based on the manure production calculated by LIVSIM, taking into account losses due to manure partition between grazing areas and the kraal as well as manure decomposition and losses on the heap, storage and application, calculated by HEAPSIM. The manure applied to the fields was targeted to the homefields for RG1 and RG2 in line with current farmer practices. Homefields in Murehwa refer to fields close to the homestead which have historically received more nutrients than fields far away resulting in better soil fertility.

The FIELD model was previously parameterized to simulate long-term changes in SOC in a chronosequence of land use in Zimbabwe as well as against long-term data on maize responses to manure, and N and P application in Murehwa (Zingore et al., 2011). A mulch of crop residues improves water use efficiency (WUE) by improving available moisture in drier periods through increased rainfall infiltration and reduced soil evaporation. WUE is the product of water capture and conversion efficiency. The water capture efficiency was allowed to increase by 10% with mulching (Wang et al., 2011) during the drier years, when rainfall was below the long-term average of 750 mm per season. The major assumption was that the impact of mulch is relevant to the water capture efficiency and not the water conversion efficiency. To simulate the effect of CA on crop yields, FIELD was parameterized against long-term maize yield data from a tillage and residue management experiment on a sandy soil at Domboshawa, Zimbabwe (Vogel, 1993; Nehanda, 2000).

5.2.5 Simulation of livestock production

The sub-model LIVSIM was used to simulate cattle production in time (Rufino et al., 2011). The LIVSIM model was parameterized and tested previously for the same location by Rufino et al. (2009; 2011). LIVSIM also simulates manure excreted. Livestock productivity of individual animals is determined by the genetic potential of the breed and the feed available. At herd level, decision rules for herd management such as weaning age, management of reproduction, lactation, and feeding groups are incorporated into the model. Reproduction is simulated stochastically using probabilities associated with bodyweight and age combinations. Maximum and minimum bodyweights are calculated by interpolation from the upper and lower estimated boundaries of animal growth (Rufino et al., 2011).

The amount of feed from pastures available for livestock was based on total biomass estimations in the field (Dury, 2007). During the rainy season (from December, to May) the quantity of grass biomass available from rangelands was assumed to be non-limiting; only quality effects were taken into account for livestock productivity. In the dry season (from June, to November) the quantity of pasture biomass was only a third of that available in the rainy season, and both quality and quantity of the grasses limited livestock productivity. Feeding with crop harvest residues is then an important option to maintain productivity. In southern Africa, animals may lose up to 30% of their maximum summer body weight during the dry winter period without supplementary feeding (Van Niekerk, 1974). Feeding of concentrates was not considered in the analyses, following current farmers' practices. Herd size was restricted to a maximum of 10 for RG1 and five for RG2. Only a maximum of one bull was allowed to remain in the herd and other bulls were sold when they reached an age of two years. The cows were allowed a maximum of five lactations before they were replaced. LIVSIM is a stochastic model whose outcomes differ with every run; the results presented are average model outcomes of 500 runs. LIVSIM was parameterised for the dominant cattle breed in the region, the Mashona.

5.2.6 Trade off analyses: description of scenarios

For RG1 and RG2 farmers, five different scenarios of crop residue retention for soil surface cover were analysed: 0, 25, 50, 75 or 100% of the total crop harvest residues left on the field, and the effect of these practices on crop yields and animal productivity were evaluated: The rest of the crop residues were used as livestock feed in the dry season. The 0% crop residue retention represented current farmer's management where all crop residues are grazed by cattle. The crop residues available per month per animal was calculated as the total maize stover harvested per farm divided by the product of number of cattle × months of dry season. In open grazing systems, significant quantities of manure are deposited in the grazing areas or in fields of other farmers, and manure that accumulates in the kraal decomposes, resulting in significant losses in manure, and relatively small quantities being available for application to the fields (Rufino et al., 2007). A manure collection efficiency of 40% was assumed for the proportion of the manure that is collected in the kraal. The manure on the heap (40% of total) is further reduced in quantity via decomposition which was simulated through HEAPSIM. Because management decisions such as changing the time spend in the kraal can affect the amount of manure that ends up in the kraal, we also performed a sensitivity analysis with respectively higher and lower values (20 and 60%) for manure collection efficiencies of and the impact of these on crop productivity where quantified. With the above simulated scenarios, we assumed that cattle did not access crop residues from non-cattle farmers (RG3 and RG4). For RG3 and RG4 farmers, two scenarios were analysed: 0 or 100% of crop harvest residues left on the field. On top of these, also two levels of fertilisation were assessed, a baseline fertilizer (Table 5.1) based on current practices of RG3 and RG4 farmers, and one fertilization rate as used by RG1 farmers, assuming under this scenario that RG3 and RG4 farmers could afford this amount of fertiliser.

Besides farm types, we also used field types (homefields, outfields) to distinguish observed differences in soil fertility and responses to inputs. The field types used and their distribution over the farm types (Table 5.1) were based on detailed field classification over the resource groups reported previously by Zingore et al., (2007a). The field characteristics used in the simulations are summarised in Table 5.1b.

5.2.7 Crop residues cover

The amounts of crop residues corresponding to 0, 25, 50, 75 and 100% retention were assessed with respect to providing soil cover using the equation proposed by Gregory (1982). Percentage cover for randomly distributed flat residue elements is calculated as: $cover = 1 - \exp^{(-A_m \times M)}$, where M is residue biomass (g), and A_m is a cover coefficient ($m^2\ kg^{-1}$). The biomass-to-cover relationship reaches a plateau at high rates of biomass additions, so considerable residue decomposition may occur before cover decreases. The value of A_m reported in literature can be as small as 0.114 to as large as 0.40 for decomposed and relatively undecomposed crop residues respectively (Gregory, 1982). We used the value of 0.114 and 0.27 for A_m to calculate the percentage cover of crop residues retained in the scenarios for non-decomposed maize residues composed of stalks and leaves, and residues that underwent decomposition composed mainly of stalks; the leaves being decomposed.

5.2.8 Farm economic returns and food supply

A partial budget analysis was used at farm level to assess the expected gains or losses on farm income, food supply and energy balance, in relation to retaining various proportions of crop residues in the field. In the analysis both crop and animal production components were considered for RG1 and RG2 while only the crop production component was considered for RG3 and RG4 farmers. Costs for animal production included cattle herding as farmers often hire herd boys throughout the season. Other costs included vaccination or pest control often paid per month and livestock tax. Crop production costs were for fertilisers, maize seed, and external labour for carrying crop residues to the kraal and manure from the kraal and applying in the fields. The value of manure was estimated based on arrangements in the village where manure is exchanged for chemical fertiliser. Costs of inputs and producer prices of maize were collected from the relevant service suppliers. The energy and protein supply was estimated using the content of these in milk and maize. Milk energy values for the Mashona cattle used in the simulations were based on the values reported by Mandibaya et al.(2000).

Data is presented and reported for individual years as well as means calculated from model outcomes over the 12-year period. The capacity of farm production to meet the dietary (energy and protein) needs was calculated based on the guidelines of the World Health Organisation (WHO and FAO, 1995). The protein and energy balance was calculated as the difference between the family needs and their production on a per capita basis in each resource group.

5.3. Results

5.3.1 Maize productivity

The initial effects of crop residues retention on simulated maize grain yields were small but by the 12th year the gap between the crop retention scenarios widened (Fig. 5.1). The effects of mulch were larger on the more fertile homefields than the outfields. The initial simulated maize productivity for the RG1 homefield was 2.7 t ha^{-1} and increased to 3.8 t ha^{-1} after 12 years with 100% crop residue retention but declined to 2.1 t ha^{-1} without crop residue retention (Fig. 5.1a). Retaining 50% of the crop residues produced did not increase maize yields with respect to the initial year whereas 75% and 100% retention led to substantial increases. In the RG1 outfield, the simulated effect was smaller, retaining 0 and 25% crop residues did not change crop yields after 12 years but retention of 50, 75 and 100% led to yield gains of 0.14, 0.3 and 0.5 t ha^{-1} respectively (Fig. 5.1b). In the RG2 homefield, all but 100% crop residue retention led to loss in maize productivity in the final year compared to the first. Retaining 0, 25, 50 and 75% residues led to simulated yield reductions of 1.0, 0.7, 0.4 and 0.2 t ha^{-1} respectively, while 100% had a marginal yield advantage of only 0.03 t ha^{-1} (Fig. 5.1c). In the RG2 outfield, retaining 50% crop residues had a neutral effect on crop yields (Fig. 5.1d). Retaining 0 or 25% crop residues reduced simulated productivity by 0.03 t ha^{-1}, 75% and 100% led to increases of 0.04 t ha^{-1} in each case.

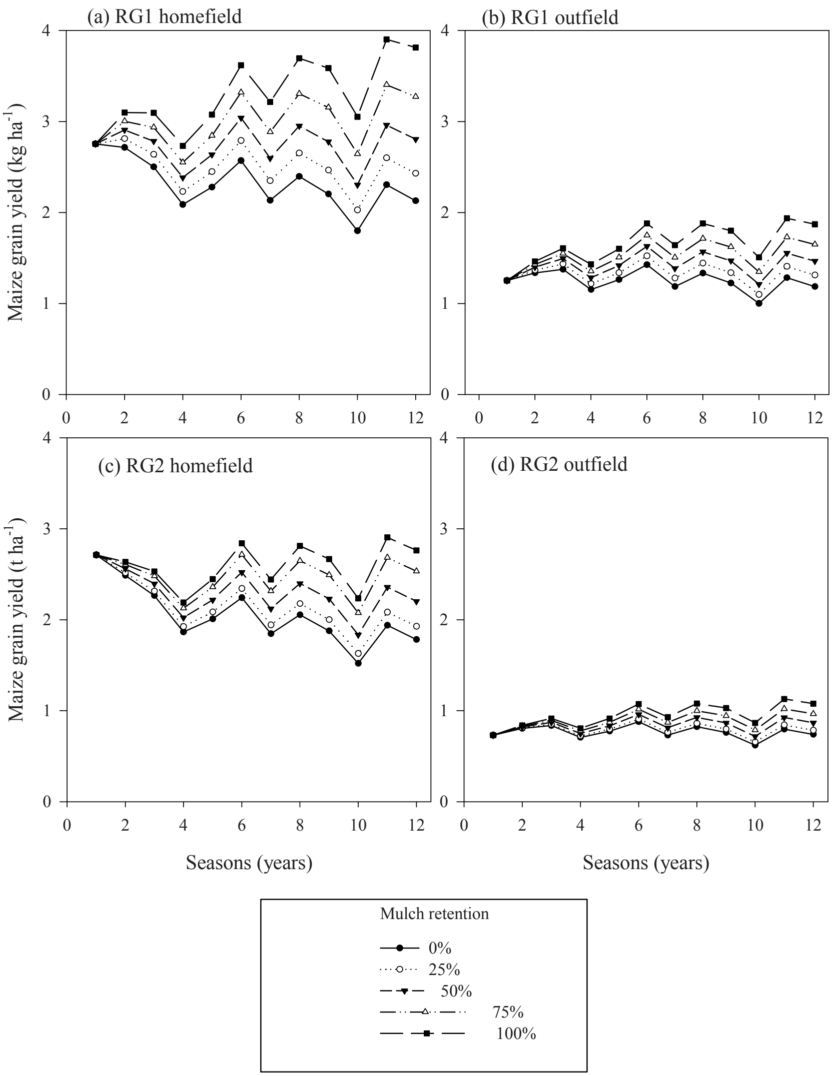

Fig. 5.1. Simulated maize productivity in homefield and outfields of farmers in RG1 and RG2 at different rates of crop residues retention, 0% CR corresponds to current practice of feeding all crop residues to livestock. Data points are the averages of the 500 simulation runs.

According to the model simulations, farmers belonging to RG3 and RG4 harvested small yields that continued to decline at current management practices, especially for the homefields (Fig. 5.2a). Simulated maize grain yield in R3 homefield declined from 1.4 t ha^{-1} to 1.1 t ha^{-1} after 12 years, in the RG3 homefield the decline was from 1.1 t ha^{-1} to 0.7 t ha^{-1} (Fig. 5.2a). Simulations showed that the current poor productivity (0.1-1.4 t ha^{-1}) of maize cannot be increased by crop residue retention alone even if all the crop residues were retained (Fig. 5.2a & Fig. 5.2b), partly because the amounts of crop residue produced are too small. Crop residues stabilised yields in the absence of fertiliser. The fields are in a low productivity trap, of which they can only escape through external input of nutrients. The model outcomes suggested that long term retention of crop residues with application of 60 kg N and 10 kg P ha^{-1} has a potential to double the current yields (Fig. 5.2c). RG3 and RG4 are the farm categories most constrained by resource limitations with little opportunities to improve nutrient input use. According to the model simulations application of fertiliser and crop residue retention can increase yield from 0.8 t ha^{-1} for RG4 to about 1.4 t ha^{-1} after 12 years. For the RG3 farmers, maize yields can be improved from about 1.4 t ha^{-1} to 1.9 t ha^{-1} after 12 years if they can retain all previous crop residues (Fig. 5.2c).

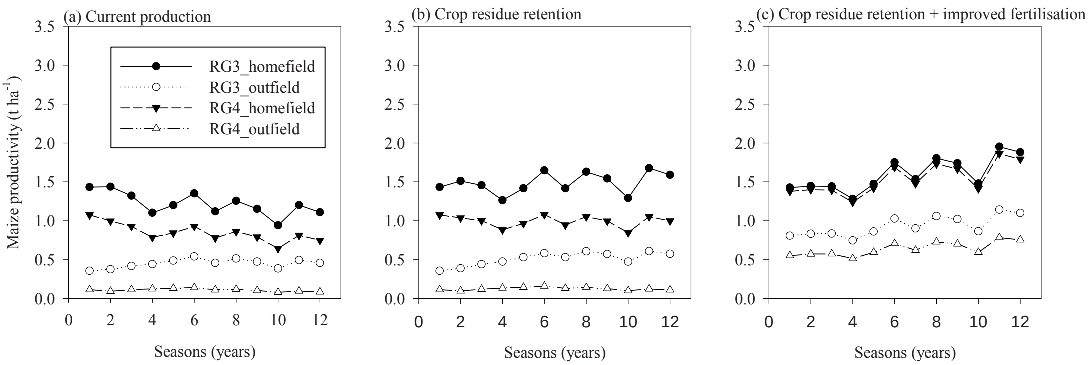

Fig. 5.2. Simulated maize productivity at current management, with crop residue retention, and with crop residue retention and improved fertilization for non-cattle owners. All crop residues produced are retained *in situ* for farmers in resource groups, RG3 and RG4, improved fertilisation refers to 67 kg N and 10 kg P ha^{-1}.

Maize production harvest at the farm level can be improved from 0.84 to 1.82 t farm^{-1} yr^{-1} for RG3 farmers, and from 0.32 to 1.24 t farm^{-1} yr^{-1} if they can retain crop residues and apply 67 kg N and 10 kg P ha^{-1} (Table 5.2).

Table 5.2. Simulated maize production by farmers from RG3 and RG4 farmers under the baseline scenario, crop residue retention and crop residue retention with improved fertiliser application scenarios. Improved fertiliser is 67 kg N ha^{-1} and 10 kg P ha^{-1} used by RG1 farmers.

Scenario and resource group	Grain yield (t farm^{-1})	Stover yield (t farm^{-1})	Stover returned to soil (t farm^{-1})	SOC (t farm^{-1})
Current production				
RG3	0.84 ± 0.05	1.26 ± 0.10	0.14 ± 0.01	4.76 ± 1.70
RG4	0.32 ± 0.04	0.48 ± 0.08	0.06 ± 0.01	4.62 ± 1.31
Crop residue retention (100%)				
RG3	1.08 ± 0.10	1.68 ± 0.13	1.46 ± 0.02	7.44 ± 0.89
RG4	0.44 ± 0.06	0.66 ± 0.08	0.59 ± 0.00	5.13 ± 0.97
Crop residue retention plus improved fertiliser				
RG3	1.82 ± 0.18	2.73 ± 0.37	2.46 ± 0.05	11.70 ± 0.56
RG4	1.24 ± 0.14	1.86 ± 0.22	1.71 ± 0.02	7.12 ± 0.50

5.3.2 Animal productivity

Substantial body weight increases were observed in the model simulations in response to the increasing proportion of crop residues offered to animals and due to the dry season cycles. As expected, largest body weights were simulated when animals were offered 75 or 100% of the crop residues available, withholding crop residues always resulted in the lowest simulated body weight. Offering 100% of the residues to animals led to an average simulated body weight of 4066 kg per farm (or 407 kg per animal in a herd of both young and adult animals) which was reduced to 3394 kg (or 339 kg per animal) when all residues were retained in the field for RG1 farmers (Table 5.3). Similar trends were simulated for RG2 farmers, the largest body weight of 2187 kg (or 437 kg per animal) was simulated with all residues fed to livestock and was reduced to 1772 kg (or 354 kg per animal) when all residues were retained in the field. Simulated milk production as well as excreted N followed similar trends (Table 5.3). The simulated amount of produced manure was directly related to dry matter intake as expected.

5.3.3 Soil organic matter dynamics

Model simulations showed clearly that retention of crop residues in combination with manure increased SOC (0-20 cm) especially in the long-term. The retention of all (100%) or 75% crop residues produced appeared to increase SOC in the long term (Fig. 5.3). Compared with the current practise of removing crop residues from the field, retention of crop residues was beneficial especially in the homefields characterised by high crop productivity. Without residues in the RG1 homefield, simulated SOC declined from 16 t ha^{-1} to 10 t ha^{-1} over 12 years (Fig.5.3a) but increased substantially to 23 t ha^{-1} when all the crop residues were retained in the field. Simulated SOC for the other crop residues proportions were in between with 50% crop residues maintaining the initial SOC content. In the outfield, retention of all crop residues increased SOC above the initial 12 t ha^{-1} while 75% crop residues maintained SOC at the baseline content after 12 years (Fig. 5.3b). In the RG2 homefield, the largest crop residues retention and 75% retention arrested SOC decline but declined with all other treatments (Fig. 5.3c). In the RG2 outfield, all crop residue retention rates led to SOC loss although it was slowed with 100% crop residues (Fig. 5.3d).

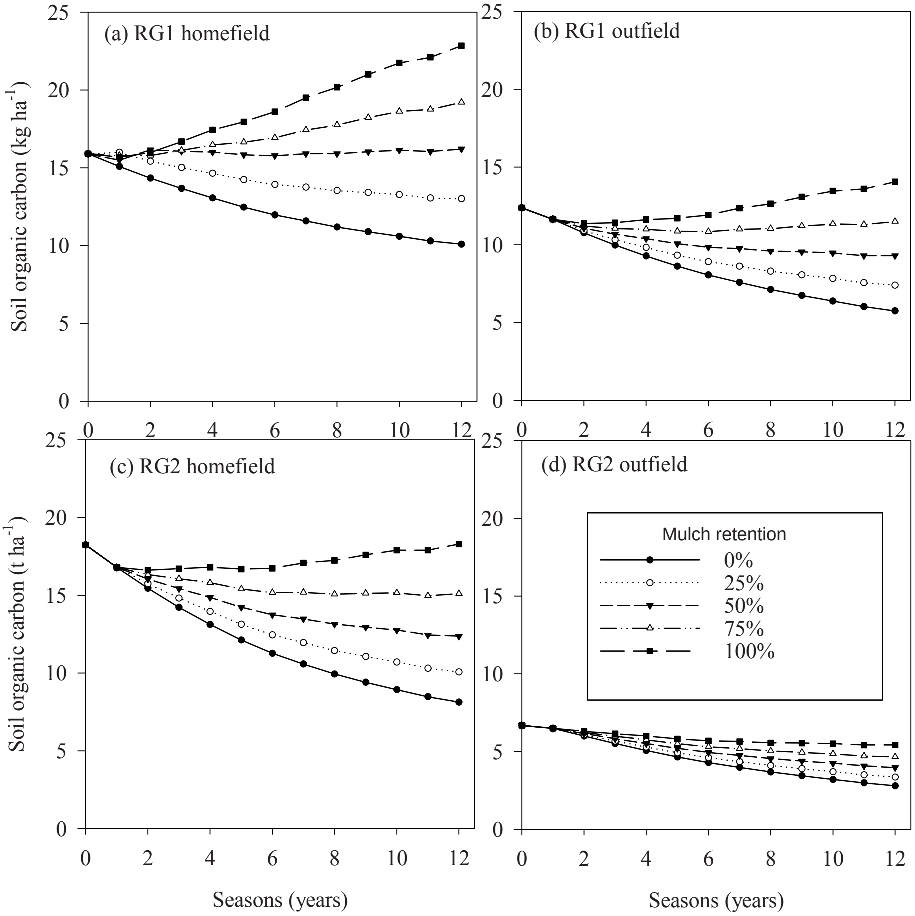

Fig. 5.3. Simulated soil organic carbon dynamics in the top 0-20 cm soil layer using different proportions of crop residue retention in the field. RG refer to resource groups.

At current practice, simulated SOC declined from 12 t ha^{-1} to 6 t ha^{-1} on RG3 farms and from 9 t ha^{-1} to 4 t ha^{-1} on RG4 farms over the 12-year simulations (Fig.5.4a). Crop residue retention slowed the decline to 9 and 8 t ha^{-1} for RG3 home and outfields respectively (Fig. 5.4b). The decline did not change for RG3 outfields but slowed down on the homefield where final SOC was 6 t ha^{-1} after 12 years, down from 9 t ha^{-1} in the first year (Fig 5.4b). When crop residues were combined with fertiliser inputs, simulated SOC after 12 years was larger than the initial value due to incremental amounts of crop residues retained on the soil surface

(Fig. 5.4c). The model results showed that crop residue retention offered no opportunity to rebuild SOC, especially when crop productivity was small, but in combination with fertiliser inputs, SOC increased (Fig. 5.4c).

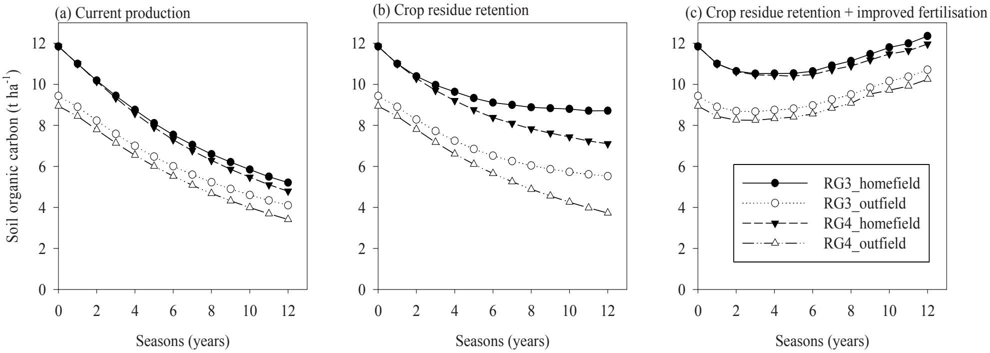

Fig. 5.4. Soil organic carbon dynamics for farmers in resource groups (RG3 and RG4) at (a) current production where crop residues are removed, (b) crop residue are retained but at current fertiliser application rates, and (c) crop residue retention with improved fertiliser application. In the scenario of crop residue retention, all produced crop residues are retained because farmers in RG3 and RG4 do not own cattle.

5.3.4 Feedbacks between crop and livestock production

Model simulations showed that crop residue retention was positively correlated with crop productivity but negatively correlated with animal productivity (Fig. 5.5). The model predicted that retaining all crop residues in the field led to losses of about 70 kg live weight per animal, 0.7 t manure, 350 kg milk, and increases of 8 tons SOC, 1.6 t maize grain yield per farm for RG1 farmers per year (Table 5.3). For RG2 farmers, it led to a loss of 94 kg live weight per animal, 0.5 t manure, 300 kg milk, and increases of 6.5 t SOC and 0.7 t maize grain per year. Dry matter intake by cattle across the crop residue retention scenarios was directly proportional to the amount of crop residues offered as feed. Without additional crop residues as feed, animals of RG1 farmers consumed 15.1 t farm^{-1} yr^{-1} and it increased to 17.5 t farm^{-1} yr^{-1} when all crop residues were offered to animals (Table 5.3). Simulated manure availability decreased from 1.6 to 1.2 t farm^{-1} when crop residues were withheld from feeding the animals. For RG2, the model predicted that animals consume 8.8 t farm^{-1} yr^{-1} of dry matter with when crop residues were offered but only 7.6 t farm^{-1} yr^{-1} when all residues were kept for soil cover. The trade-off between crop yield and animal body weight was strong (2.4 kg maize grain per 1 kg body weight of livestock), but the shape of the curve depends on the efficiency with which manure is collected (Fig. 5.5). The amount of manure applied, and thus the collection efficiency of manure had a significant effect on simulated maize grain yield (Fig. 5.5a & 5.5b). Improving collection efficiency from 20 to 60% resulted in a simulated yield increase of 0.6 t farm^{-1} yr^{-1} at baseline (crop residue removal) scenario and this yield difference was maintained even when all residues were retained *in situ*. The efficiency of manure collection did not affect simulated livestock production, at 100% crop residue retention there was no difference in simulated body weight of animals for all manure collection efficiencies (Fig. 5.5b). Simulated milk yield was also directly related to the simulated body weight of animals and decreased with increases in crop residues retained, but not with manure collection efficiency.

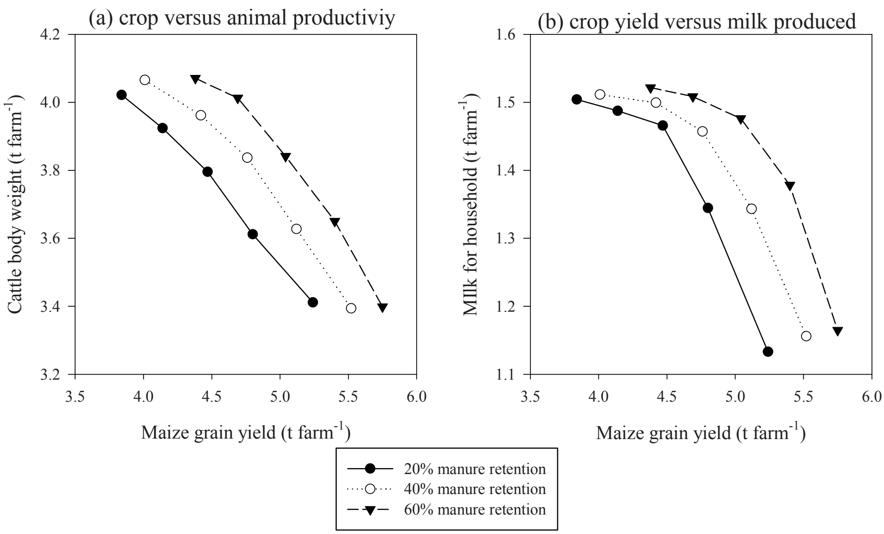

Fig.5.5. Trade off in animal or crop productivity, (a) crop productivity against animal live weight per farm and (b) crop productivity versus milk produced for the household. Three (20, 40 and 60%) manure recovery efficiencies were considered during the simulations. Manure

recovery efficiency is the % of manure accumulated in the kraal to total manure excreted by animals. The manure recovered in the kraal is further reduced due to losses during storage. Data shown are the average values for the 12-year of simulation

Table 5.3. Simulated effects of crop residue retention in the field on crop and animal productivity, and soil organic carbon for the two resource groups that own cattle (RG1 and RG2). The means and their standard deviations are for the 12 year period of the simulations, the standard deviations are “composite standard deviations” that takes into account the uncertainties to with the 12 year model run and the stochasticity of Livsim.

Resource group	Crop residues retained in field (%)	Target herd size (#)	BW (kg farm^{-1})	DMI intake (t farm^{-1} yr^{-1})	CR intake (t farm yr^{-1})	Manure produced (t farm yr^{-1})	Excreted N (kg yr^{-1})	Manure applied (kg farm yr^{-1})	Milk for household (kg farm yr^{-1})	Stover produced (t farm^{-1})	SOC (t farm^{-1})	Grain yield (t farm^{-1})
RG1	0	10	4066 ± 385	17.5 ± 2.5	5.4 ± 0.3	4.6 ± 0.5	129 ± 22	1.6 ± 0.3	1512 ± 107	6.0 ± 2.3	20.0 ± 5.7	4.0 ± 0.9
	25	10	3962 ± 432	17.3 ± 2.6	4.9 ± 0.2	4.5 ± 0.4	125 ± 23	1.6 ± 0.2	1492 ± 138	6.6 ± 2.5	22.4 ± 5.0	4.4 ± 0.9
	50	10	3837 ± 375	16.7 ± 2.5	3.6 ± 0.4	4.3 ± 0.1	122 ± 24	1.5 ± 0.3	1457 ± 148	7.1 ± 2.5	23.8 ± 1.2	4.8 ± 1.0
	75	10	3627 ± 416	15.9 ± 2.5	1.9 ± 0.2	4.1 ± 0.2	117 ± 19	1.3 ± 0.1	1343 ± 211	7.7 ± 2.4	25.7 ± 1.2	5.1 ± 1.1
	100	10	3394 ± 438	15.1 ± 0.6	0.00	3.9 ± 0.6	110 ± 18	1.2 ± 0.2	1156 ± 232	8.3 ± 2.7	28.0 ± 1.8	5.6 ± 1.1
RG2	0	5	2187 ± 204	8.8 ± 0.7	3.8 ± 0.5	3.0 ± 0.4	58 ± 3.2	1.2 ± 0.2	964 ± 98	4.2 ± 0.6	16.5 ± 4.6	2.8 ± 0.5
	25	5	2092 ± 175	8.4 ± 0.9	3.3 ± 0.4	2.8 ± 0.2	55 ± 4.0	1.1 ± 0.2	902 ± 102	4.4 ± 0.6	18.0 ± 3.7	2.9 ± 0.4
	50	5	1973 ± 242	8.1 ± 0.6	2.3 ± 0.3	2.7 ± 0.1	54 ± 4.1	0.9 ± 0.2	795 ± 86	4.7 ± 0.9	19.5 ± 2.7	3.1 ± 0.7
	75	5	1818 ± 214	7.8 ± 0.5	1.4 ± 0.2	2.6 ± 0.2	54 ± 3.1	0.8 ± 0.1	742 ± 81	5.1 ± 0.8	21.2 ± 1.6	3.4 ± 0.7
	100	5	1722 ± 237	7.6 ± 0.5	0.00	2.5 ± 0.3	48 ± 1.3	0.8 ± 0.2	688 ± 74	5.3 ± 1.1	23.1± 0.6	3.5 ± 0.9

5.3.6. Farm economic and energy balance analysis

Model outputs of crop yield and animal productivity at the farm level were used to calculate the economic and food status of the crop residue scenarios. The current practice of allocating all crop residues to animals results in the largest gross margin of US$7429 per year for RG1 and decreased to US$6497 when all crop residues were allocated to the crops (Table 5.4). For RG2 farmers, the decrease was from US$4037 to US$3299. Farmers in RG3 and RG4 can increase gross margin from US$67.00 and USD10 to US$250 and US$116 respectively if they retain crop residues and apply 67 kg N and 10 kg P ha^{-1} of fertiliser. The protein balance was positive for all crop residue retention scenarios for RG1 and RG2 farms, it increased from 23 g $capita^{-1}$ day^{-1} to 38 g $capita^{-1}$ day^{-1} if RG1 farmers retained 100% crop residues due to increased crop productivity. RG3 and RG4 farms experienced a negative protein balance with the largest deficit being 44 g $capita^{-1}$ day^{-1} at current farming practices which could be reduced to a negative 28 g $capita^{-1}$ day^{-1} with retention of crop residues in the field and crop fertilisation (Table 5.4). Both RG1 and RG2 farms had a positive balance on their energy production and consumption per capita at all crop residue retention scenarios and increased from 17 MJ $capita^{-1}$ day^{-1} to 26 MJ $capita^{-1}$ day^{-1} with 0% and 100% crop residue retention respectively due to increased crop productivity. For RG2 farms the increase was small, from 16 to 21 MJ $capita^{-1}$ day^{-1}. Positive changes in energy balances were simulated when crop residues were retained in the poorest resource groups, for RG3 farms from negative 3 to positive 4 MJ $capita^{-1}$ day^{-1} and from negative 6 to positive 2 MJ $capita^{-1}$ day^{-1} for RG4 farms.

Table 5.4. Total farm benefits, gross margin, energy and protein production, and energy and protein balances per farm for each of the resource groups in Murehwa, %CR refers to the percentage of crop residues retained in the field. Details and explanation of the calculation are shown in the appendix.

Production system	RG1					RG2					RG3		RG4	
	% CR					% CR					% CR		%CR	
	0	25	50	75	100	0	25	50	75	100	0	100	0	100
Livestock production														
Total costs (US\$ yr^{-1})	480	480	480	480	480	420	420	420	420	420	0	0	0	0
Total value of livestock (US\$)	7283	7110	6898	6426	5968	3981	3793	3554	3255	3077	0	0	0	0
Gross Margin (US\$)	6803	6630	6418	5946	5488	3561	3373	3134	2835	2657	0	0	0	0
Maize production														
Income (US\$ farm-1 yr^{-1})	1060	1166	1272	1352	1484	742	769	822	901	928	223	482	85	329
Total variable costs (US\$ yr^{-1})	434	444	454	467	475	266	269	274	280	285	156	232	75	217
Gross margin (maize production) (US\$ yr^{-1})	626	722	818	885	1009	476	499	547	621	642	67	250	10	112
Farm benefits														
Grand total costs (US\$ yr^{-1})	914	924	934	947	955	686	689	694	700	705	156	232	75	217
Total farm income (US\$ yr^{-1})	8343	8276	8170	7777	7452	4723	4562	4376	4156	4004	223	482	85	329
Gross margin (US\$ yr^{-1})	7429	7352	7235	6830	6497	4037	3873	3681	3456	3299	67	250	10	112
Food energy balance per capita (MJ day^{-1})	17	19	21	23	26	16	17	18	21	21	-3	4	-6	2
Protein balance per capita (g day^{-1})	23	27	33	35	38	20	20	22	26	27	-38	-23	-44	-28

5.4. Discussion

5.4.1 Intensity of trade-offs

The objective of this paper was to quantify the farm level benefits related to the allocation of maize harvest residues for livestock feed or for soil fertility management. Our results show that from an economic perspective it is logical that farmers prioritise the sustenance of livestock with crop residues over soil fertility management. Results showed that strong trade-offs between crop and livestock production exist in crop residue management (Fig. 5.5). It appears that due to the poor crop productivity in the system, there is no middle ground in crop residue use: livestock farmers need them as livestock feed and non-livestock farmers need them for soil cover and nutrient inputs. Results supported our hypothesis that livestock owners can derive the most benefits if they offer crop residues to livestock and use manure for soil fertility replenishment while non-livestock owners can rebuild soil fertility and crop productivity best by retaining crop residues in the fields.

Livestock are mostly kept as a store of wealth and income generation (Table 6) and the loss of body weight due to shortage of feed in the dry season is a threat to animal condition and survival. The simulated gross margin of US$7429 for livestock farmers is many times more than that of non-livestock farmers (Table 5.4). The single rainfall season exacerbates the competition for crop residues as farmers prioritise production of food crops and are unwilling to invest in fodder production due to labour and capital constraints.

Although farmers who do not own livestock do not have to feed animals, the crop residues of their fields are mostly eaten by the cattle of neighbouring cattle owners. As a result, their fields show a negative C balance resulting in declining soil fertility despite little manure droppings from the grazing animals. They could address this by keeping the crop residues on their fields. However, the opportunities to achieve this require investments either in labour to carry residues away or in fencing off their fields for protection from cattle. The first option appears feasible as the resource-poor farmers often have large households with sufficient labour (Table 5.1). However, removing crop residues from the field exposes the soil surface for long periods in the dry season and the full benefits of crop residue mulching on crop productivity might not be realised.

In much of southern Africa, crop and livestock production are closely integrated. A large herd of cattle can produce large amounts of manure which may lead to high crop productivity (Rufino et al., 2011). However, based on amounts of C input back to the soil, the livestock pathway is not the most efficient; crop residues add more C to the soil on a mass basis. In the open grazing systems such as those in this study site, 60-70% of the manure produced is lost in the rangelands as well as through handling and storage (Schleich, 1986). Heap composting of manure without cover which is common in the study area results in loss of N through volatilisation and leaching (as well as C through aerobic decomposition) (Kirchmann and Witter, 1989), reducing the nutrient content of manure. On the other hand, livestock facilitate nutrient concentration in manure which may have positive short-term effects on crop yield (Zingore et al., 2007b). With crop residues more C is kept in the cropping system although positive effects on crop yield mainly occur in the long-term as the high C:N ratios of cereal crop residues such as maize often lead to short-term nutrient immobilisation (Palm et al., 2001). Thus in the early years of crop residue retention, extra nutrient inputs are needed.

5.4.2 Options to alleviate trade-offs

Many authors have suggested that trade-offs can be alleviated through increased biomass production (cf. Giller et al., 2009; Naudin et al., 2012; Valbuena et al., 2012). However, previous work in Murehwa has shown that there is no simple pathway to increase crop biomass as the poor sandy soils often do not respond to added nutrients (Zingore et al., 2007b). Instead, it is manure in combination with fertiliser application that improves crop productivity (Rusinamhodzi et al., 2013). The erratic rainfall distribution patterns often characterised by long dry spells are another important barrier to increased crop productivity in southern Africa (e.g. Rusinamhodzi et al., 2012). Excessive as well as insufficient seasonal rainfall often lead to small yields as shown in a long-term trial in Zimbabwe (Rusinamhodzi et al., 2011). At present, options to increase biomass to overcome the trade-offs appear limited. Lessons from Lake Alaotra region in Madagascar have revealed that in mixed crop-livestock smallholder farming systems there is potential to achieve soil cover and feed if cover crops such as *Vicia villosa* Roth *and Stylosanthes guianensis* Aubl. are integrated into the cropping systems (Naudin et al., 2012). However, green manure cover crops are often not valued by farmers because they lack short-term benefits such as contribution to the household diet (Giller, 2001), and require substantial labour input.

5.4.3 Threshold crop residue cover for CA

A soil cover of 30% is often suggested as the minimum threshold to achieve the benefits of mulching, especially in relation to erosion control (Baker et al., 2002). In this study we considered a minimum soil cover of 30% although this value is rather arbitrary and larger levels of soil cover lead to greater reductions of soil erosion. On the other hand small amounts of cover (< 30%) may have beneficial effects (Findeling et al., 2003) as the relationship between runoff/erosion reduction and mulch cover is exponential. Estimates show that a minimum of 1.3 t of maize crop residues are required per hectare to cover at least 30% of the soil surface, but this value increases to 3.1 t when decomposition over time is considered (Fig. 5.6). Soil cover is also important under water limited conditions as it influences the soil water balance positively by increasing rainfall infiltration and reducing evaporation (Scopel et al., 2004b). The capacity of crop residues to provide sufficient cover is mainly dependent on the presence of leaves which have a larger area to mass ratio than straw yet the leaves are easily degraded on the soil surface. In the RG1 homefield, farmers can achieve 30% cover by retaining 25% of the crop residues produced if they can be preserved with all the leaves. In the RG1 outfield, 75% retention of crop residues with minimum leaf loss can achieve 30% soil cover; all residues cannot achieve 30% cover when partial decomposition is considered. In the RG2 homefield, 30% soil cover can be achieved by retaining 50% of crop residues produced when partially decomposed. By contrast, in the RG2 outfield, retention of all crop residues produced did not achieve the minimum threshold under all conditions. It appears that reducing the decomposition of crop residues by removing crop residues from the field might be useful for farmers to achieve the minimum amount of residues required, although the benefits of keeping the soil covered throughout the whole year such as protection against wind erosion and moisture conservation will be lost.

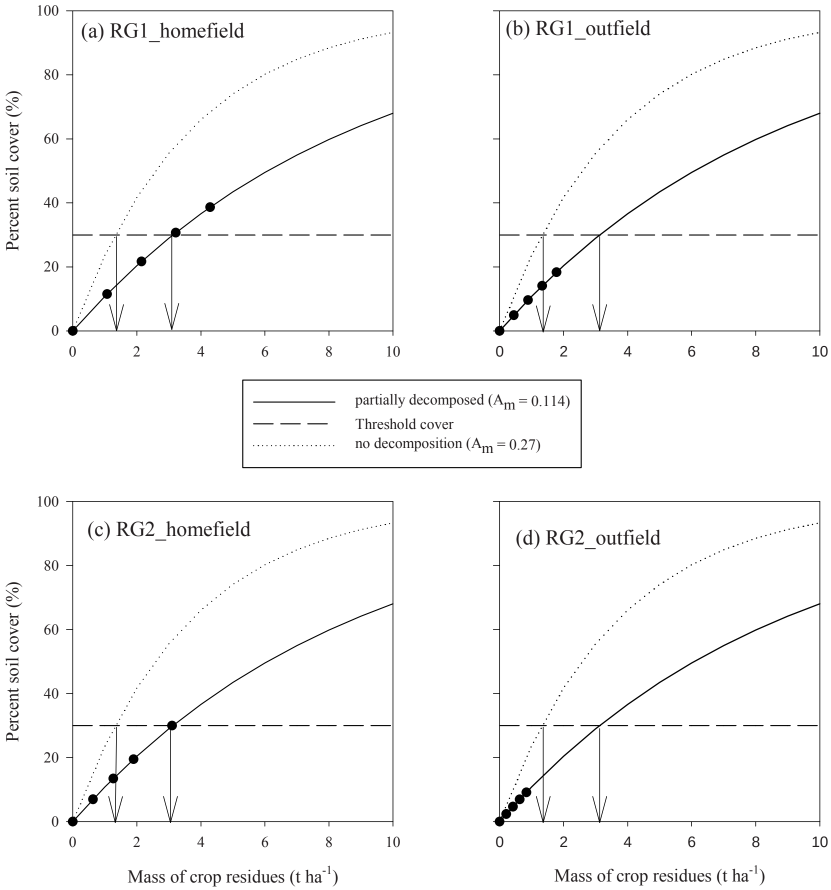

Fig.5.6. The relationship between mass and the corresponding soil cover provided by maize crop residues, dotted line represents the relationship when crop residues have leaves and solid line is mass cover relationship when crop residues have lost leaves. RG refers to resource groups, A_m is a cover coefficient (m^2 g^{-1}) of crop residues. The dashed lines show the threshold (%) needed for effective soil cover and the data points correspond to cover provided by 0, 25, 50, 75 and 100 % of crop residues based on current productivity for each field type in Murehwa, Zimbabwe.

5.4.4 Crop residue allocation and maize productivity

Model predictions showed that maize grain yield increased in the long-term when previous crop resides were retained but only on the more fertile fields or in combination with adequate nutrient inputs (Fig. 5.1 & 5.2). It appears that although RG3 and RG4 farmers could retain residues in the field they also need to provide adequate chemical fertiliser inputs for improved crop productivity. The need for extra inputs, especially N, to increase crop productivity in combination with crop residue retention has previously been confirmed in a meta-analysis (Rusinamhodzi et al., 2011) and also through a CA component omission study (Thierfelder et al., 2013). Relatively few farmers in the region are able to use much fertiliser. RG1 and RG2 Farmers are likely to derive the most benefits if they chose to retain some of their crop residues as they can afford to purchase fertiliser and apply it in combination with cattle manure. The residence time of RG1 and RG2 cattle grazing in the fields of RG3 RG4 farmers' is short because the crop residues produced there are often small and significant manure deposition might not occur.

Our simulations showed that crop yields with crop residues retention increased substantially in the long term but short-term benefits were small. Yield increases due to crop residue retention under sub-humid climate in the short term are mainly due to ability of mulch to increase rainfall infiltration, reduce evaporation losses especially during dry spells (Lal, 1995; Adekalu et al., 2007). In the long term, addition of SOC to the soil is more important (Chivenge et al., 2007). Crop residues retention may lead to N immobilisation requiring farmers to use large N inputs which they cannot afford (Giller et al., 2009). The short term needs of farmers may be a barrier to the realisation of the long-term benefits of improved crop production. The first two benefits can be instantaneous but are highly variable depending on soil and weather interactions; the latter needs time to develop as we have shown in this study.

5.4.5 Crop residue allocation and animal productivity

Animal productivity was negatively related to the proportion of maize crop residues retained in the field as soil cover (Table 5.3, Fig. 5.5). This underlined the importance of crop residues in providing feed during the critical dry season. Contribution of maize residues to dry matter intake by cattle per annum has been estimated to be approximately 25% in the dry season (Rufino et al., 2011). Maize stover is also considered to be the only important nutritious forage during the dry season where 75% of the feed still come from the dry pastures (Methu et al., 2001). In this study, herd size was restricted during the simulations to 10 animals for RG1 and 5 for RG2 in line with observations; thus total herd live weight was used as the most important indicator of productivity. Retention of up to 50% of crop residues produced appeared to have a relatively small effect on animal body weight. On average only 23 kg per animal was lost per year compared with 70 kg per animal if all crop residues were retained in the field. The loss in bodyweight also affected milk yield, 356 kg of milk was lost per year if RG1 farmers did not feed their crop residues to their animals. If farmers chose to keep 50% of their residues and use the other to feed animals, the loss in milk yield decreased to 155 kg per year. In contrast to crop productivity, allocation of crop residues to livestock feed has immediate positive effects on livestock production. This means that allocation of crop residues to livestock feed will remain attractive to farmers with livestock, and it will be difficult to convince them otherwise. If market conditions improve, it could also mean that a viable option for farmers is to aim for the short term gain in livestock productivity, and use the manure produced and money earned to buy mineral fertiliser with which crop production can be increased. These types of short and long- term interactions were beyond the scope of this study, but will be the focus of future work.

5.4.6 Crop residues allocation and soil organic carbon

Crop residue retention and manure inputs are possible options to build soil C under the conditions of smallholder farming. The model predicted that SOC the 0-20 cm top soil layer increases significantly when 75-100% of crop residues are retained in combination with manure, especially for RG1 and RG2 farmers. According to the model simulations SOC in fields of RG3 and RG4 farmers did not increase when crop residues were returned with baseline fertiliser application, but increased when fertiliser application was improved. These results support the hypothesis that SOC changes are directly linked to the amount of organic matter input to the soil up to a given level (saturation point) and that the inputs must exceed the amounts lost through decomposition (Rasmussen and Parton, 1994; Six and Jastrow, 2002). The soils in the study sites used for the simulation scenarios were coarse-textured sandy soils (Nyamapfene, 1991). Faster degradation of SOC by micro-organisms occurs in sandy soils than in clay soils due to less physical protection. Thus large inputs of organic matter are needed annually to compensate for the high losses (Chivenge et al., 2007).

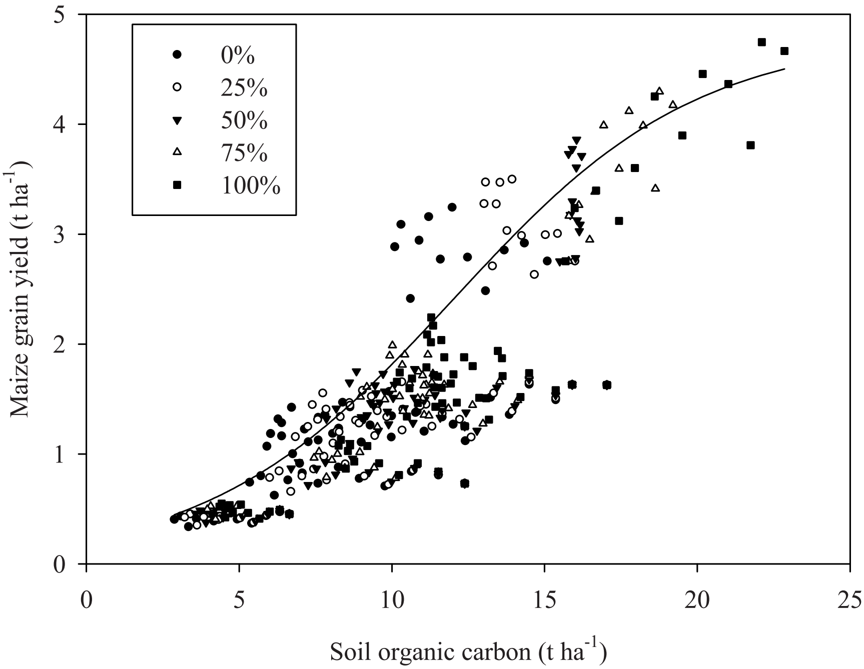

Fig.5.7. The relationship between simulated maize grain yield and simulated soil organic carbon was described by the ‘S’ shaped equation $Y_c = \frac{Y_{\max}}{1+K.e^{-bc}}$, where Y_c is maize grain yield at a given amount of SOC, Ymax is the maximum yield simulated under the conditions of the site, *K* is a constant, *b* is the relative rate of change of SOC and *c* is the amount of SOC. Data used are simulated yearly mean values for the 12 year simulation period for all the field types.

The relationship between simulated maize grain yield and SOC followed a sigmoidal pattern characterised by an initial lag phase in which increases in SOC did not result in significant maize grain yield (Fig. 5.7). The next phase was linear relationship up to a maximum yield. In most soils, the relationship between SOC and crop yield exhibit a linear relationship often up to a limit beyond which other factors limit crop yield (e.g. Loveland and Webb, 2003; Tittonell et al., 2008; Lal, 2010). Our results suggested that SOC needed to increase substantially before high yields can be achieved especially in the nutrient-depleted outfields. When fertiliser inputs are limited, crop nutrients have to be supplied from the breakdown of soil organic matter. Kay and Angers (1999) suggested that when SOC was smaller than 1%, it is difficult and may not be possible to obtain significant crop yields. However, our simulations suggested that in this site maize yield responses to added nutrients were possible even when SOC remains less than 1%.

5.4.7 Crop residue allocation and farm economic value

According to our model simulations, retention of all crop residues in the field reduced farm economic value by US$937 per year for RG1 farms and US$738 per year for RG2 farms (Table 5.4). The calculated loss in income was significantly larger for RG1 than for RG2 farms suggesting that there is a direct relationship between income and the number of cattle owned. The monetary value of the production systems of cattle owners and non-cattle owners were not comparable. The prices of meat products are determined by the market and are often competitive whereas maize prices are set by the government and often very low. A comprehensive review by Barret (1991) revealed that cattle in the communal areas of Zimbabwe play a significant role in storage of wealth, most cash generated from cropping activities is often invested in buying animals for future use. Due to the relatively large crop productivity of cattle owners, it is likely that they can invest income from crops in building the cattle herd thus increasing their economic value more than non-cattle owners. The simulated quantities of milk produced per farm decreased when animal bodyweight decreased resulting in less income for farmers. The analysis also revealed a large dependence of farm profit on animal productivity, implying that maintenance of animal bodyweight is needed to for improved farm income. Livestock can be disposed of at any time when cash is needed especially when paying for school fees and other immediate cash needs, thus the use of crop residues for animal feed takes precedence. Although we analysed cattle production in terms of economic value of cattle, milk production and manure produced, the actual value of cattle is greater due to other uses such as insurance, security, asset protection and status display (Moll, 2005).

One of the key objectives of farmers is to be self-sufficient in food, especially in the staple crop maize. Decisions to allocate all crop residues to cattle resulted in the highest profit and the largest food supply for RG1 farmers. On the other hand, the protein balance was improved when crop residues were retained, mainly caused by improved maize production. The food energy deficit for RG3 and RG4 farms was large in the baseline scenario (no retention of crop residues on the field) but could be addressed if farmers improved their crop management by retaining crop residues and applying fertiliser. The absence of milk also created negative protein balances for RG3 and RG4 farmers. The model simulations suggest that the baseline scenario i.e. feeding crop residues to livestock maximises profits for livestock owners while retaining all crop residues in the field maximises profits for non-livestock owners.

5.4.8 Opportunities for intensification

Management decisions on crop residue uses are made at the farm level. Maize harvest residues play an important role in the smallholder farming systems in Murehwa as maize is planted on more than 60% of the cropped area and primarily used as stock feed for cattle owners. Due to refusals and trampling, a substantial part of the maize residues carried to the kraal are not consumed by cattle but serve as bedding material and improve manure quality (Nzuma and Murwira, 2000). There are opportunities to use sorghum (*Sorghum bicolor* (L.) Moench) and finger millet (*Eleusine coracana* (L.) Gaertn) residues for soil cover as they are generally left in the field and burnt before the next crop is planted.

Crop-livestock integration is considered the backbone of smallholder agricultural production in the tropics (Thornton and Herrero, 2001) because of benefits of manure application

(Murwira et al., 1995) and traction. Rufino et al. (2011) concluded from a simulation study that the best way for crop-livestock integration was achieved with small rates of fertiliser, partial retention of crop residues in combination with small rates of manure. It was apparent from our study that most manure production occurs without crop residues being offered to livestock (Table 4), thus manure will always be available to RG1 and RG2 even if they choose to retain crop residues in the field. However, crop residues are important in improving manure quality through reduced N losses (Kirchmann and Witter, 1989). The choice for tillage that farmers can use under these circumstances should allow the chance to apply manure while retaining crop residues on the surface. Planting basins are being promoted for this purpose albeit with more labour input.

The macro-economic conditions in Zimbabwe in the last decade have limited the options available for smallholder farmers to improve their production systems. For example, during the farming system survey and analysis we observed that all farmers who owned livestock could not afford to provide concentrates or supplementary feeding beyond crop residues. Such management decisions have implications on the quality of manure produced and the subsequent crop productivity. Small investments in forage legumes could be beneficial to the animal diet and help improve the conditions of livestock and quality of manure.

Farmers who do not own cattle (RG3 and RG4), have options to fence off their fields or to carry crop residues to the homestead after harvest and then bringing them back to the field at planting. Although substantial labour and capital is required for such activities, it is probably the best option for C input in their cropping systems. The challenge here is to encourage poor farmers who often have a range of short-term, simultaneous objectives such meeting their food demands that may or may not ensure the maintenance of soil fertility, which is important in the longer term.

5.5 Conclusions

The trade-offs in crop residue uses were strong for farmers who own cattle and where maize harvest residues are needed to sustain animal productivity in the dry season. There is little scope for crop residue retention in the field for RG1 and RG2 farmers as it will lead to loss in animal productivity. Retention of all crop residues reduced farm income by US$937 and US$738 per year for RG2 and RG3 farmers respectively. Although fields are converted to communal pastures during the dry season, individual farmers have the prerogative to fence-off their fields and protect their residues. The presence of trade-offs for 40% of farmers in a village who own cattle cannot be used to deny the opportunity for C input for 60% of farmers who do not own cattle. Crop residue retention is the only acknowledged opportunity for C input into the fields of non-cattle owners and our simulations showed the potential to improve crop productivity if adequate extra nutrients in the form of chemical fertiliser can be achieved. We conclude that to maintain productivity of animal and crops, more than half of the amount of the crop residues may be allocated for livestock feeding and less than half left on the field for farmers who own cattle. Non-livestock owners can improve productivity by investing more in labour to manage and protect their crop residues from cattle of neighbouring farmers and some chemical fertiliser inputs, but will result in reduced feed supply for cattle at the village scale.

Chapter 6

General discussion

6.1 Introduction

Poor soils, in combination with erratic rainfall, poorly functioning markets and fragmented policies, are a threat to food security on smallholder farms in Africa. Soil fertility decline continues unabated because rates of nutrient inputs remain far below optimum (Sanchez, 2002). Several initiatives have failed to address these challenges because they have been products of 'closed box innovations' by scientist and development practitioners with scant attention to farmers' needs and priorities. Where farmers have been involved, inadequate capital has limited the scope to expand or improve their current circumstances. Insufficient farm resources against multiple objectives and uses create trade-offs in resource allocation limiting the available options for improved resource use and increased productivity. Erratic rainfall and in some cases non-responsive poor soils reduce significantly the returns to investments (Zingore, 2006).

Attempts to address the problem of poor crop productivity on smallholder farms in Africa need to take a holistic approach for addressing the constraints from field scale to farm and beyond in both space and time. Thus, I combined several methodologies in pursuit of appropriate crop production intensification options for selected maize-based farming systems of southern Africa. The general purpose of this thesis was to identify appropriate crop production intensification options that are suitable to the socio-economic and biophysical conditions of selected smallholder maize-based farming systems in southern Africa with emphasis on building soil fertility. Soil fertility restoration is important because poor nutrient management in the past is one of the major underlying causes of current poor crop productivity on most smallholder farms in sub Saharan Africa (Buresh et al., 1997; Zingore et al., 2007b).

In this chapter I synthesize the main findings and draw relevant conclusions in the context of smallholder farming systems in southern Africa. This will be achieved by discussing the relevance (nuances) and lack of it (nuisances) for the tested intensification technologies across smallholder farms. In southern Africa, farming systems are dominated by mixed crop-livestock systems but vary in intensity of interaction between these production components. It is therefore quite obvious that there are no ‘silver bullet’ solutions to the constraints that the diverse populations of farmers face in each locality.

6.2 Extensification versus intensification systems

Crop production extensification is a means of increasing production by extending the area under cultivation while maintaining or reducing quantities of input per unit area (Erenstein, 2006). Intensification is the opposite, an increase in the productivity of existing land through increased inputs of external resources in the production of food and cash crops and livestock (Table 6.1). In central Mozambique and Zimbabwe both extensification and intensification of agricultural production takes place. A gradient from extensification to intensification can be established across the three sites of my study (Fig. 6.1). Extensification is often noted by the large labour input and relatively large land sizes (Erenstein, 2006) which are common in Ruaca and Vunduzi (Chapter 1, Table 1.1). In comparison, Murehwa characterised by high crop-livestock interactions (Chapter 4) maybe be considered to be more land constrained and thus intensification is needed to increase crop production. In Murehwa, the relatively strong crop and livestock integration provides manure and the supplementary N input through fertiliser allows farmers to achieve the largest crop productivity among the three sites. Land utilisation (proportion of cropped to land owned) was larger in Murehwa than the other sites (ca. 85%). In contrast, in central Mozambique farmers largely depend on shifting cultivation (bush fallowing) and in some instances grass fallowing for soil fertility restoration.

Table. 6.1. Contrasting characteristics between extensification and intensification of agricultural production systems. Adapted from Boserup (1965).

Characteristics	Extensive systems	Intensive systems
Fallow length	long	short
Productivity	low	high
Efficiency	high	variable but lower
Population density	low	high
Technology	simple	often complex
Fertilizing of soil	none or little	high
Land tenure	communal ownership	individual/family
Economic systems	usually subsistence	usually market
Socio-political complexity	generally less	generally greater

Although currently the population density is low in central Mozambique (Chapter 1, Table 1.1), population growth in the near future and a limited natural resource base require choices that use natural resources in a more intensive and sustainable way to meet current and future food needs. Population pressure is already evident in Ruaca where farmers are reducing fallow periods and shift to some form of intensification albeit with limited nutrient inputs. In Vunduzi and Ruaca, burning of crop residues is common as an easy option for land clearance especially due to the presence of wild mucuna (*Mucuna spp.* (L.) DC.) which causes intensely itchy dermatitis, and also farmers consider burning as important for soil fertility improvement. The burning of crop residue and cultivation on steep slopes is leading to a decline of soil organic matter, soil erosion and to soil degradation. Burning results in changes in soil physical, chemical and biological properties, and may have long term negative implications on sustainability (Davis and Condron, 2002). However, burning has short term benefits on crops as it leads to considerable enrichment of the soil with nutrients especially P, K, Ca, and an increase in pH (Kyuma et al., 1985). Substantial N fertiliser may be needed under such conditions to boost initial crop growth.

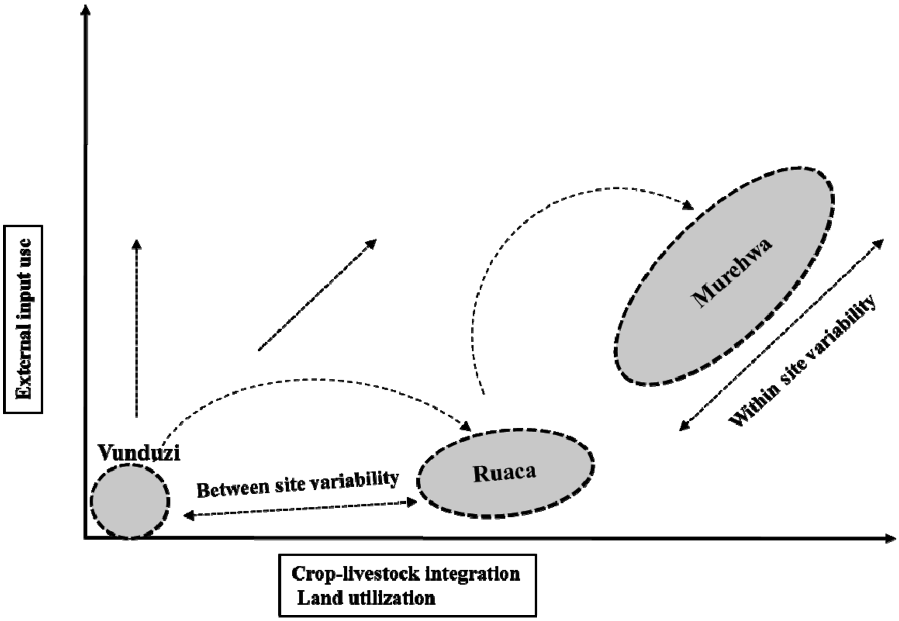

Fig.6.1. Relative differences in characteristics of the study sites, land utilization is the ratio of total land under crops to total land owned. Vunduzi is characterised by small input use, small land utilization and low intensity of crop-livestock integration. In Ruaca, input use is similar to Vunduzi but has larger land utilization and crop-livestock integration. In Murehwa, all attributes considered were relatively larger than in the other two sites. Variability in resource ownership among households was larger in Murehwa than in all the three sites. Arrows show possible development pathways.

6.3 Adequate fertiliser use is elusive

Chemical fertilisers are needed for improved crop productivity, but their use in southern Africa falls below crop requirements averaging about 16 kg ha^{-1} (Morris et al., 2007). Permanent cultivation often leads to deficiencies in N and P, and annual applications are required each year to improve crop productivity. The barriers to higher fertiliser use vary greatly between and within countries due to differences in socio-economic conditions of the farming communities. Locally, household and farm characteristics, social and human capital, and farmer perceived effects of fertilisers on soil fertility are important determinants (Mapila et al., 2012). Green and Ng'ong'ola (1993) identified crop type, farming system, credit access, off-farm income and regular labour in that order as important determinants of fertiliser use. Additionally, biophysical conditions such as amount of rainfall, and soil type determine amount and or type of fertiliser to be applied in a given situation (Nkonya et al., 1997). The risk of crop failure resulting from poor rainfall is a strong disincentive to the purchase and use of fertilizers on the subsistence crops (Probert et al., 1995). A combination of these factors and how they influence fertiliser use are summarised in Fig. 6.2; socio-economic conditions seem to have an overriding effect on fertiliser use and are likely to persist in the future. Crop production intensification requires some form of nutrient inputs as previously mentioned (Table 6.1) and their success in increasing productivity will depend on how much and what form of additional fertiliser farmers can afford to apply to their fields. Legumes have potential to add substantial amounts of N to cropping systems if crop residues are returned and if they have small harvest indices (Giller, 2001). However provision of N alone is not adequate, P is needed especially for effective biological nitrogen fixation (Vance et al., 2002). In mixed crop-livestock systems, manure can be a good source of P but is an unreliable source of N especially in the short term (Chapter 4) thus for such situations additional N is required.

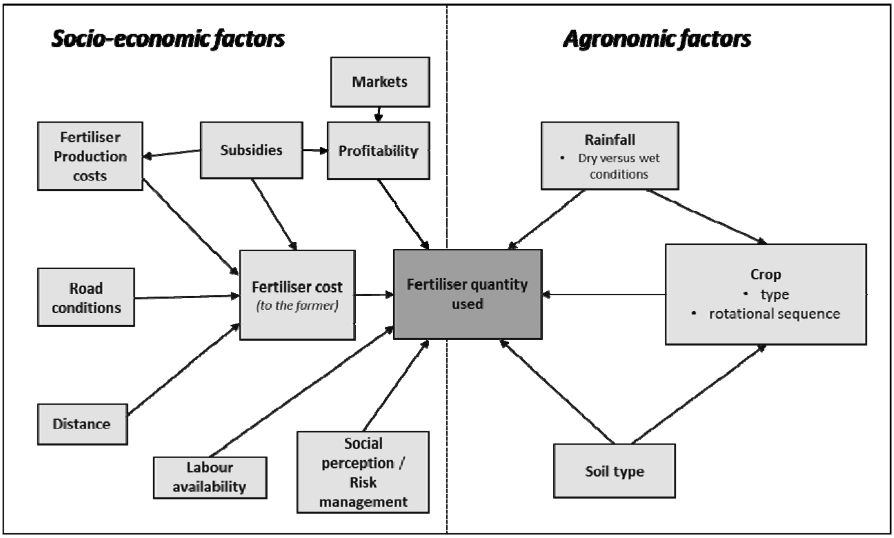

Fig.6.2. Summary of the determinants of fertiliser use, socio-economic factors play a major role in fertiliser use.

6.2 Crop intensification options

The short-term needs of farmers to provide for their families must be met in combination with long-term sustainability of agricultural production systems. The sites studied experience different challenges to improved crop productivity at all scales from plot, farm, village and beyond. The multi-scale analysis in the preceding chapters showed clearly the importance of targeting options for improving crop productivity to the conditions of farmers in agreement with other authors (Giller et al., 2009; Erenstein et al., 2012). The thesis followed the approach proposed by Ojiem et al. (2006) in analysing the suitability of crop production intensification in both space and time.

In the following subsections, the relevance of three crop production intensification options are discussed in relation to the biophysical and socio-economic conditions in the three study sites. Conservation agriculture (CA) based on minimum tillage, crop residue retention and crop rotation and associations is considered due to the prominence it has been given in recent years as the answer to the poor crop productivity on small farms in southern Africa. In southern Africa, moisture and nutrient conservation is needed to harness the erratic rainfall received. Maize-legume intercropping is revisited and analysed in the context of low input agriculture, the need for intensification and persistent dry spells prevalent in Mozambique and the rest of southern Africa. The role of manure in improving crop productivity in the context of mixed cop-livestock systems is considered because it is the C input most readily available for cattle owners.

a. What role for conservation agriculture?

When the study was initiated, CA was being promoted vigorously as the most appropriate crop production option for smallholder farmers in southern Africa. Despite lack of sufficient empirical evidence on the technical performance and relevance of CA in southern Africa before 2009, substantial global literature on CA existed that could be used to draw lessons on its suitability for this region. A global dataset was used to determine the biophysical environments where CA could be most successful and explain why it could fit in some places and not in others as described below. A meta-analysis of no-till and crop residue management (Chapter 2) showed clearly that potential positive effects of a technology cannot be assumed to be relevant in every place (Fig. 2.6). Positive impacts of CA on crop yield through moisture conservation were observed in low rainfall environments. It was apparent that improving maize yields under CA depended on the duration and promotion of good agronomic practices such as targeted fertiliser application, timely weeding and crop rotations. It has long been known that crop rotation is part of good agronomy under all tillage practices so these results are not peculiar to CA. Legume production as currently practised does not cover more than 10% of cultivated area (e.g. Mapfumo and Giller, 2001) under most smallholder farms in Zimbabwe, meaning that only 10% of the cultivated area may be rotated with legumes per year. For many years, most farmers in southern Africa have not been able to achieve sufficient fertilisation and crop rotations and it is unlikely that they will do so simply because CA has been introduced. It is also likely that farmers who can achieve the crop management required already have relatively high crop productivity and may not see major benefits of shifting from current practices. Conservation agriculture required more N fertiliser inputs especially in the short-term (Fig. 2.9b) together with a complete change of how crop and animal production components are integrated at the farm level (Chapter 5). The minimum requirements required for successful CA in much of southern Africa do not exist, and the technology thus faces impediments to its implementation.

Much of the research on CA has been conducted at the plot level, focusing on the effects of CA on soil quality, with little effort on how CA fits into the broader farming systems (Giller et al., 2009; Baudron et al., 2012). Retention of crop residues in the field as a mulch is not feasible for most farmers due to competition for livestock feed (Chapter 5). The need for investments in more fertiliser results in CA being unattractive for most farmers. Retention of crop residues will lead to depressed yields in the short term due to immobilization of N. This contrasts sharply with farmers' needs; the main objectives of farmers in the study sites were to achieve food security and cash income. Therefore the short term needs of farmers maybe a threat to the uptake of CA. Whilst short-term crop yield response to CA are highly variable, yields often improve in the long-term when continued accumulation of crop residues result in increased SOC and nutrients being available for crop growth.

In Murehwa I observed that sorghum and finger millet residues were not preferred by livestock and may have greater potential to be used as mulch. However, the land area allocated to these crops was significantly smaller than maize. There is a dearth of data to properly establish a mechanistic relationship of factors that affect crop residue decomposition on the soil surface to understand their persistence under the conditions of southern Africa. Termite activity results in a rapid removal of surface applied crop residues with potential to lose all the surface mulch before the expected benefits to crops are realised. Such information is important in devising proper post-harvest crop residue management. Currently farmers who are testing CA remove crop residues from the field (Fig. 6.3) and bring them back at time of planting, investing substantial labour in the process. Even though farmers can protect their residues *ex situ*; it appears that through this practice the important function of soil protection is lost.

Fig.6.3. Protection of maize residues in the dry season at Manjonjo village, Murehwa. The practice involved substantial labour input carrying crop residues to the makeshift structure and back to the fields at planting. Farmers invested substantial labour into this practice and indicated they did this to qualify for free fertiliser inputs.

b. Revisiting intercropping

Maize-pigeonpea intercropping showed promise to address the constraints of food security and income faced by farmers in central Mozambique. Farmers faced numerous constraints related to market access for inputs and outputs and lack of capital among a plethora of challenges. Extension support is weak, especially at the local level. The benefits of introducing legumes either in crop rotations or through intercropping to increase yields in cereal-dominated cropping system are well-known in Africa (e.g. Chikowo et al., 2006; Adjei-Nsiah et al., 2007; Ncube et al., 2007; Sileshi et al., 2008). Intercropping is the only feasible option to grow two or more crops per year because much of southern Africa is characterized by a unimodal rainfall pattern (Taljaard, 1986) that only permits a single cropping season each year. Intercropping provides the possibility of a greater total yield than would be obtained from either sole crop (Willey, 1979; Seran and Brintha, 2010). Grain legume intercrops are preferred because besides providing soil cover between the rows of the main crop, they are potential sources of plant nutrients that complement or supplement inorganic fertilisers and help to ensure food security. The substitutive design promoted by the local non-governmental development organisation where two rows of maize alternated with a row of pigeonpea reduced the plant population for both maize and legume and resulted in smaller yields. I showed in Chapter 3 that a simple innovation of rearranging crops to plant in an additive design reduced plant competition and led to substantial yield benefits even without added nutrient inputs. Although this knowledge was being used in some parts of Malawi, conveyance of that knowledge and the required best practice guidelines was missing.

Maize grain yield after pigeonpea was up to 6 t ha^{-1} (Chapter 3, Fig. 3.3) highlighting the potential of pigeonpea in improving productivity in low input systems. Although the relatively large crop productivity and economic benefits of the maize-legume intercropping systems that were attractive to farmers, intercropping increased labour required by 36% compared with monocropping of maize. In extensive farming systems, labour saved by reducing land area may offset the increased labour demand for intercropping. The intercrop treatments were under no-tillage which allowed the development of an undisturbed continuous pore system in the soil, accumulation of organic matter on the soil surface and increased water infiltration. The other major strength of intercropping is the reduction in risk of total crop failure. Intercropping maize and drought resistant legumes such as pigeonpea and cowpea showed great potential to cushion farmers against the devastating effects of prolonged dry spells in central Mozambique. Although crop productivity improved with legume intercropping, the marketing conditions remain fragmented and pose a serious threat to continued intercropping especially for pigeonpea. Delayed selling of produce increased profits for farmers but the critical need for cash income often forced farmers to sell their produce immediately after harvest. I also showed that results at the plot level were not the only consideration for the continued practice, the presence of an assured market and interactions with livestock were particularly key factors (Fig. 6.4). Roaming livestock early in the dry season prefer the growing pigeonpea plants than the dry maize crop residues resulting occasionally in total yield loss for farmers. Thus, intercropping maize with long duration pigeonpea is suitable in areas with small livestock densities and guaranteed market, whereas short duration grain legumes are needed in areas with perennial food shortages.

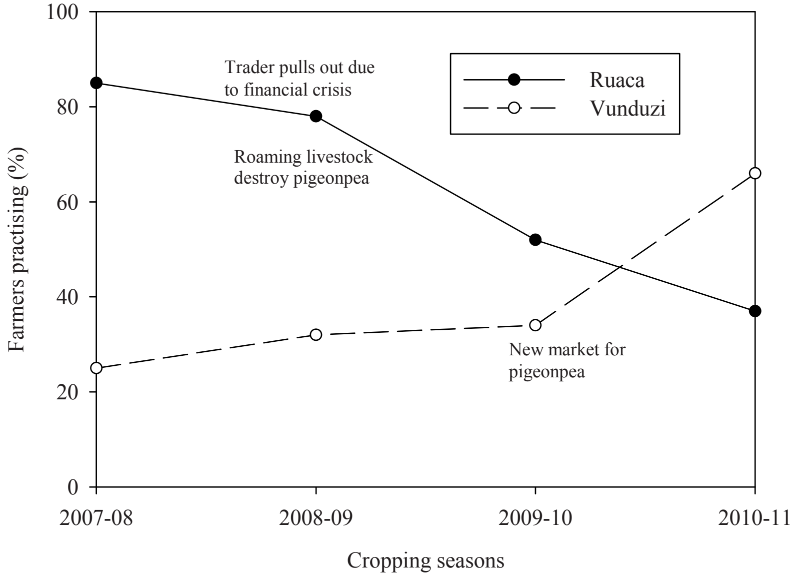

Fig.6.4. The proportion of farmers practicing maize-pigeonpea intercropping between 2007 and 2011 in the study sites in central Mozambique. Proportions are based on a total of 52 households in Ruaca and 43 households in Vunduzi that were tracked every season.

c. Where to apply manure?

In mixed crop-livestock systems of Murehwa, manure application has potential to improve crop productivity especially in the long term. Cattle do not generate organic matter or nutrients, but they are important in their transfer especially from grazing land to croplands. The passage of organic matter via their rumen systems in which the first degradation starts helps in the concentration of nutrients in manure. However, manure on the smallholder farms in southern Africa are often of poor quality containing significant quantities of sand and being stored in the open. This results in slow release of nutrients from the manure. An important dilemma in manure management and use under smallholder farm conditions is to determine where to apply given their limited quantities against multiple objectives of improving crop productivity versus restoration of degraded fields (Fig.6.5). In Murehwa, homefields refer to fields closest to the homestead that receive most of nutrient inputs and better crop management resulting in larger fertility than midfields and outfields. Fields that exhibit fast responses to nutrient inputs are often allocated the limited resources because they are considered by farmers less risky to investments (Tittonell et al., 2007). Results of a 9-year experiment on soil restoration reported in Chapter 4 supported this hypothesis and suggested that maximum yield benefits were realised if nutrients were targeted to responsive than degraded sandy soils.

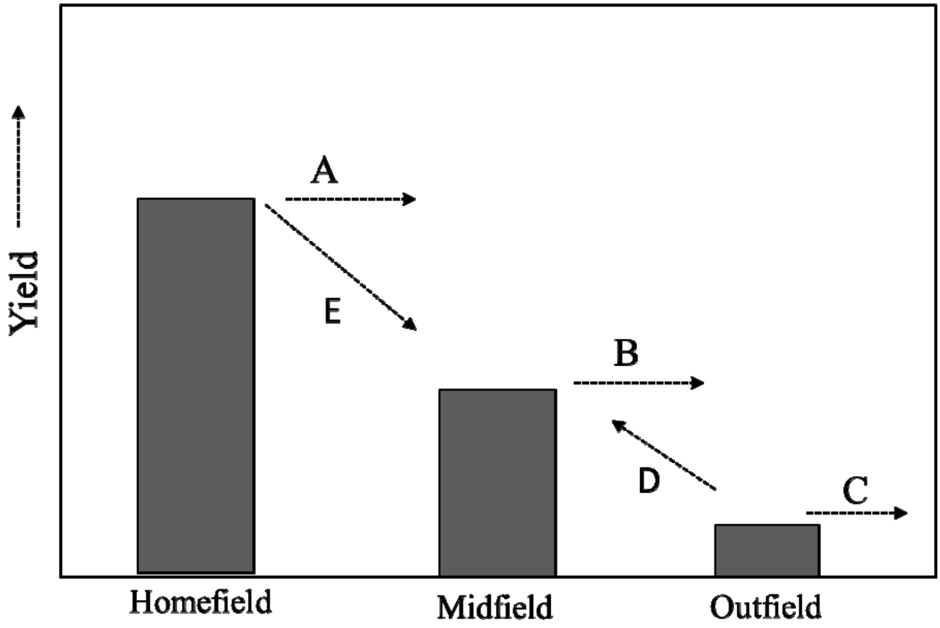

Fig.6.5. Dilemma of allocating limited manure quantities, restoration of soil fertility versus yield maximization on smallholder farms in mixed-crop livestock systems. Options include maintaining the different fields at their current fertility (A, B and C) or rebuilding fertility in degraded fields (D) at the expense of homefields (E) to achieve the soil fertility of midfields.

Chemical fertiliser used alone did not increase crop yields especially on sandy soils and there was no potential for soil fertility restoration, yields in sandy outfields remained significantly smaller than in the other field types. The largest yield in the clay outfield was obtained with application of 100 kg N + 25 t ha^{-1} manure; top yields were 6.1 t ha^{-1} for the outfield and 9.3 t ha^{-1} for the homefield (Chapter 4, Fig. 4.2). Manure application in degraded outfields has potential to rebuild soil fertility. Results, however, suggested that manure was used more efficiently for increased crop production in the more fertile homefields than the degraded outfields.

The demarcation of fields into small plots (0.1-0.5 ha) allows farmers to achieve large application rates of manure on some fields that improve crop yields. Best maize yield were obtained with combined manure and fertiliser application, which showed the importance of integrated soil fertility management (Vanlauwe et al., 2010).

6.3 Contribution to current debates

a. Ecological intensification

The paradigm of ecological intensification was first proposed by Cassman (1999), and is considered as a promising direction for crop production systems (Doré et al., 2011; Tittonell and Giller, 2013). This new pathway is premised on improving crop production by maximising resource capture and conversion efficiencies (de Wit, 1992; Giller et al., 2006), with emphasis on adaptation to local settings. In situations of land limitation and insufficient chemical fertiliser inputs, legume intercropping may provide a pathway for ecological intensification. The late maturity of pigeonpea forces farmers to exclude cattle from crop fields. This enables *in situ* crop harvest residue retention, combined with the relatively large biomass productivity builds soil carbon, improves rainfall infiltration and increases crop yields (Chapter 3). For mixed crop-livestock farming systems, I was able to show that consistent application of manure in combination with chemical fertiliser improves crop productivity in both short and long term and is a sustainable locally adapted option for ecological intensification (Chapter 4). When quantities of good quality manure are small, application can be targeted to small areas for efficient use. Good quality manure refers to manure that is anaerobically composted with added plant material, must contain N greater than 1.8% and to be free of sand (Chapter 4).

b. Trade-off analysis

In southern Africa poor crop productivity limits the availability of crop harvest residues especially in the dry season against multiple objectives creating trade-offs for their uses. The importance attached to livestock means that the little crop residues available on the farm are allocated for livestock feed restricting the potential for adoption of CA (Erenstein, 2002). Trade-off analysis with respect to crop residue retention and animal and crop productivity (Chapter 5) was done for a mixed crop-livestock systems in Murehwa, Zimbabwe using the NUANCES-FARMSIM model that simulates feedbacks between crop and livestock production systems by linking the sub-models of crop (FIELD, (Tittonell et al., 2010a) and animal production (LIVSIM (Rufino, 2008). The sub-models are linked by the manure management sub-model HEAPSIM (Rufino et al., 2007). The loss of an annual average of 67 and 93 kg per animal live weight for RG1 and RG2 respectively, and reduced manure production due to reduced biomass intake when residues were left in the field underlined the importance of choices that farmers make (Chapter 5). Retaining all maize residues in the field led to severe losses in animal productivity but significant gains in crop productivity in the long-term. However, the gains in crop productivity with crop residue retention appear too little to offset the loss in animal productivity. The poor selling price and a virtual absence of a market for maize during the last few years in the study area suggest that current management by farmers of feeding crop residues to cattle is the most appropriate. Traditionally farmers do not produce forages in this area despite legume, grass and agroforestry species being available for this purpose (Delve et al., 2001; Sumberg, 2002; Njarui and Mureithi, 2010), thus alternative sources of feed are limited.

Crop residue management decisions are made at the farm level and the choice of feeding animals or the soil only pertains to less that 40% of the farmers who own livestock in Manjonjo village, Murehwa. The remaining 60% of farmers have the prerogative to leave their residues on the field where they will be grazed by the cattle of neighbouring farmers or carried home for protection (Fig. 6.3). As shown in Chapter 5 crop residues retention is one opportunity for C input into the cropping system on non-livestock owners and these farmers should invest in keeping their crop residues for soil fertility amelioration. Cattle owners collect most of their crop residues from the field to use as feed during the critical dry season (Mtambanengwe and Mapfumo, 2005) and in turn use manure for C input. Non-livestock owners should therefore find a way of keeping their crop residues to improve soil fertility as there are no benefits of giving up their crop residues. The communal grazing rules allow cattle to access fields in the dry season for crop harvest residues but do not override individual farmers' decision on crop harvest residue use (Dore, 2001). The forestry resources are being degraded and quantities of leaf litter are inadequate to significantly contribute to C input. Green manures have faced resistance because they do not contribute to immediate family benefits such as food to the farm, yet they require substantial labour inputs. In some cases farmers are not aware of the existence of these green manure cover crops (Jama et al., 2000).

c. Farmer involvement in the research process

This thesis was aimed at targeting technologies to the needs of farmers by recognising the spatial and temporal variability due to differences in biophysical and socio-economic conditions i.e. creating so-called 'recommendation domains'. A key component of the research reported in this thesis was the involvement of farmers not only in extracting information from them but to discuss with them feasible opportunities for increased crop production (Chapter 3 and Chapter 4). Farmer participation in setting the research agenda in agricultural research and development is important as it allows exploration of options that are appropriate under their conditions (Johnson et al., 2003; Rusinamhodzi and Delve, 2011). Farmer evaluations especially in the intercropping treatments (Chapter 3) provided a basis for making recommendations about the relevance of the cropping system to their needs (e.g. Abeyasekera et al., 2002). The approach is necessary to reveal intrinsic farmer preferences for new technologies against established technologies, opportunities as well as constraints for their widespread use (Chianu et al., 2006). Farmers in Mozambique strongly believed that fertilizers kill the soil yet they also recognized that *mataka haana ndimu* (soils have lost fertility). They strongly rely on local methods to rebuild soil fertility and integration with legumes seems the most promising entry point. Efforts to improve fertiliser use may need to overcome this initial resistance.

6.4. Conclusions and future research needs

I have worked in Murehwa for the past 12 years and it is remarkable to notice the gradual decline in farm sizes. The standard farm sizes were originally three hectares but they are continuously being subdivided each time a male child starts a family. In some parts of Malawi and Zimbabwe, landholdings are already very small (below 1 ha) limiting the options available to diversify as farmers are often forced to dedicate most of their land to the staple food crops, mostly maize instead of legume crops (Thierfelder and Wall, 2010). Small farm sizes are particularly suited to intercropping to provide a chance to increase crop yields. The most critical question that remains is: can farmers derive the most benefits of emerging technologies with such very small land sizes? There is need to determine the minimum farm size for a defined resource group type of farmers that could derive the most benefits from a defined crop production option under a defined environment i.e. *how small is beautiful* (Giller, 2012).

I also had the opportunity to work in central Mozambique for the past five years; in Mozambique the situation is not of shrinking farm sizes but limitation for shifting cultivation and fallowing due to increasing population pressure in the sites I studied. Therefore, there is need for crop production intensification. In Ruaca there is need to demonstrate and convince farmers to use manure that is often left in the cattle pens. The lessons from Murehwa (Chapter 4) suggest that farmers in Ruaca could potentially use cattle manure to improve crop productivity especially in fields around the homesteads that are cultivated each year.

I have observed that for many years, farmers in Vunduzi who have been occupying land adjacent to the Gorongosa National Park have resisted to be moved and prefer co-habitation with the wild animals. It is clear that farmers are causing massive land degradation due to cultivation on the steep slopes of the mountain without soil and water conservation methods and urgent solutions are needed (Müller et al., 2012). It is unlikely though that they derive direct benefits from the park and the fact that they inherited ancestral land strengthens their position not to move. Current feasible options for these farmers revolve around intercropping to maximize crop yields and reduce soil loss. Pigeonpea is the most suitable for the conditions of erratic rainfall as the deep roots allows it to anchor the soil and access soil water from deeper horizons (Sekiya and Yano, 2004).

In conclusion, ecological intensification of crop production is needed to address the persistent food shortages in southern Africa. This thesis has revealed the occurrence of local opportunities to increase current crop productivity which in some cases do not need substantial capital inputs by the farmers, but more efficient use. My study also revealed that despite the large technical efficiency, some production options such as CA might not fit within the broader farming system as well as within the farmers' production orientation and resource capacities, thus "silver bullets" do not exist.

I hope that the findings reported in this thesis will be useful to scientists and development practitioners in formulating pathways for crop production intensification in southern Africa. I strongly believe that this thesis has provided ample evidence that local conditions of farmers are critical in defining the success of new interventions. Local opportunities exist to successfully *push the envelope* of crop production.

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Appendices

Appendix 1- Bias test for dataset used for meta-analysis

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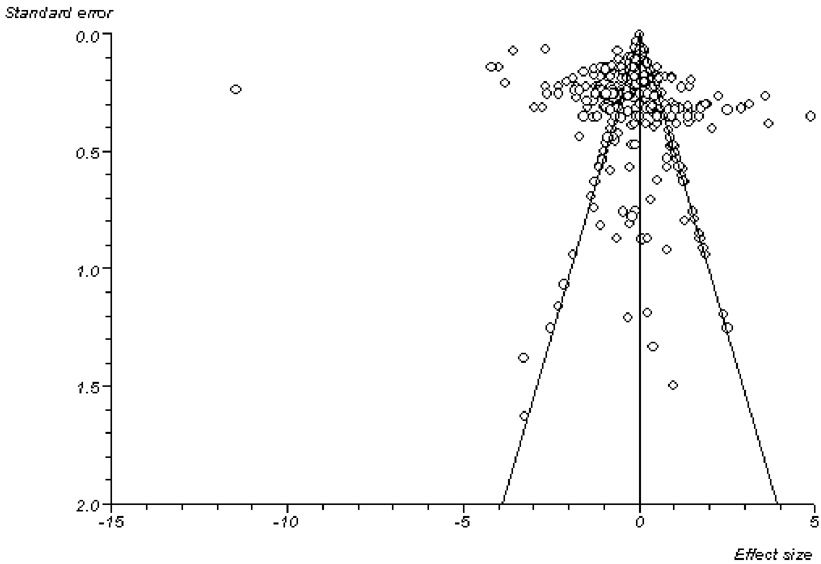
Appendix 6 – feed quality parameters for the feed stuffs used in the simulations

Appendix 1. Bias test for dataset used for meta-analysis



Appendix 2 – Data used for calculating economic value of farms

Production system	RG1					RG2					RG3		RG4	
	% CR					% CR					% CR		%CR	
	0	25	50	75	100	0	25	50	75	100	0	100	0	100
Livestock production														
Cost labour (herding) (US\$ yr^{-1})	300	300	300	300	300	300	300	300	300	300	0	0	0	0
Vaccinations/pest control (US\$ yr^{-1})	60	60	60	60	60	60	60	60	60	60	0	0	0	0
Livestock tax (USD yr^{-1})	120	120	120	120	120	60	60	60	60	60	0	0	0	0
Total costs (US\$ yr^{-1})	480	480	480	480	480	420	420	420	420	420	0	0	0	0
Value of manure (US\$)*	128	121	114	114	99	85	71	64	57	50	0	0	0	0
Average livestock sales (US\$ yr^{-1})	300	300	300	200	200	133	133	133	100	100	0	0	0	0
Value of livestock (US\$)	6099	5943	5756	5441	5091	3281	3138	2960	2727	2583	0	0	0	0
Milk production (kg yr^{-1})	1512	1492	1457	1343	1156	964	902	795	742	688	0	0	0	0
Protein (3.7% / kg)	56	55	54	50	43	36	33	29	27	25	0	0	0	0
Milk energy content (2.95 MJ kg^{-1})	4460	4401	4298	3962	3410	2844	2661	2345	2189	2030	0	0	0	0
Value of milk (US\$0.5 kg^{-1})	756	746	729	672	578	482	451	398	371	344	0	0	0	0
Total value of livestock (US\$)	7283	7110	6898	6426	5968	3981	3793	3554	3255	3077	0	0	0	0
Gross Margin (US\$)	6803	6630	6418	5946	5488	3561	3373	3134	2835	2657	0	0	0	0
Maize production														
Grain yield (t $farm^{-1}$)	4.00	4.40	4.80	5.10	5.60	2.80	2.90	3.10	3.40	3.50	0.84	1.82	0.32	1.24
Grain protein (3.27%)	131	144	157	167	183	92	95	101	111	114	27	60	10	41
Grain energy content (3.6 MJ kg^{-1})	60544	66598	72653	77194	84762	42381	43894	46922	51462	52976	12714	27548	4844	18769
Price (US\$ t^{-1})	265	265	265	265	265	265	265	265	265	265	265	265	265	265
Income (US\$ farm-1 yr^{-1})	1060	1166	1272	1352	1484	742	769	822	901	928	223	482	85	329
NPK (31 US\$ / 50kg bag) (US\$ yr^{-1})	62	62	62	62	62	31	31	31	31	31	20	62	0	62
Ammonium nitrate (31 US\$/ 50 kg bag)	198	198	198	198	198	99	99	99	99	99	66	100	20	100
Cost of maize seed	135	135	135	135	135	110	110	110	110	110	70	70	55	55
Labour (residues to kraal) (US\$ yr^{-1})	0	13	25	38	50	0	8	15	23	30	0	0	0	0
Cost of labour (manure) (US\$ yr^{-1})	39	37	34	34	30	26	22	19	17	15	0	0	0	0
Total variable costs (US\$ yr^{-1})	434	444	454	467	475	266	269	274	280	285	156	232	75	217
Gross margin (maize production) (US\$ yr^{-1})	626	722	818	885	1009	476	499	547	621	642	67	250	10	112
Farm benefits														
Grand total costs (US\$ yr^{-1})	914	924	934	947	955	686	689	694	700	705	156	232	75	217
Total farm income (US\$ yr^{-1})	8343	8276	8170	7777	7452	4723	4562	4376	4156	4004	223	482	85	329
Gross margin (US\$ yr^{-1})	7429	7352	7235	6830	6497	4037	3873	3681	3456	3299	67	250	10	112
Total proteins (kg yr^{-1})	187	199	211	216	226	127	128	131	139	140	27	60	10	41
Total energy (MJ yr^{-1})	65004	71000	76951	81155	88172	45225	46555	49267	53651	55006	12714	27548	4844	18769
Total protein needs (kg yr-1)	128	128	128	128	128	91	91	91	91	91	110	110	91	91
Farm food energy needs (MJ 1 yr^{-1})	22229	22229	22229	22229	22229	15878	15878	15878	15878	15878	19053	19053	15878	15878
Food energy balance (MJ yr-1)	42776	48771	54722	58927	65943	29347	30678	33389	37774	39128	-6339	8495	-11034	2891
Protein balance (kg yr-1)	59	71	83	89	98	36	37	40	47	49	-82	-50	-81	-51

Appendix 3 - Simulation of crop production

Here we illustrate in short how crop yields are calculated using the QUEFTS approach

Light determined yield: $LDY = PAR \times FRINT \times LCvE_p$

Where *PAR* is the amount of incident photosynthetically active radiation, FRINT is the fraction of *PAR* captured by plant, and $LCvE_p$ is the light or radiation conversion efficiency. The product $FRINT \times LCvE_p$ is the radiation use efficiency (RUE).

Water limited yield: $WLY = \text{Rainfall} \times FRCAP \times TCvE$

Where *FRCAP* is fraction of rainfall captured which varies depending on biophysical conditions, crop types and management. *TCvE* is the water conversion efficiency, the product of $FRCAP \times TCvE$ is the water conversion efficiency (WUE). Nutrient limited yields:

Example for N, $NLY = N\ availability \times NCtE \times NCvE$

The same approach is used for both P and K, *NCtE* is the capture efficiency of the mineral N available to the crop and *NCvE* is the conversion efficiency of the N taken up by the crop into biomass. Nitrogen uptake (Eq. 1.4) is taken as the minimum between N availability and target N uptake so that when N limits crop production N uptake approaches N availability and the value of *NCtE* approaches unity.

$$NUPT_{\text{target}} = \frac{Min(LDY, WLY)}{(NCvE_{\max} + NCvE_{\min}) \times \alpha}$$

NCvE is calculated as the maximum value between $NCvE_{min}$ and $NCvE_{max}$ corrected for the availability of water, P and K (Eq. 1.5).

$$NCvE = Max(NCVE_{\min}, NCVE_{\max} \times WRF \times PRF \times KRF)$$

WRF, *PRF* and *KRF* are reduction factors accounting for availability of water, P and K calculated as in Eqs. 1.6-1.8.

$$WRF = \left(\frac{\text{Rainfall} \times FRCAP}{WTRA_{\text{target}}} \right) \times \beta_W$$

$$PRF = \left(\frac{P_{\text{availability}}}{PUPT_{target}} \right) \times \beta_P$$

$$KRF = \left(\frac{K_{\text{availability}}}{KUPT_{\text{target}}} \right) \times \beta_K$$

Finally the resource-limited yield (*RLY*) is taken as the minimum between *NLY*, *PLY* and *KLY*.

Appendix 4 - Simulation of animal production

In LIVSIM, the difference (Difference Max W) between actual weights (Wt) to maximum weight (W max) is calculated by the following equation: $Difference\ Max\ W = W_{\max,t+1} - W_t$

$$Actual\ Growth_{t+1} = \min\left(AWG, Difference\ Max W\right)$$

where Actual Growth per month is the minimum of Difference Max W at the maximum growth allowed by the metabolisability of the feed (AWG) in kilograms per month.

The monthly probability of conception is calculated as:

$$\text{Prob Conception} = 1 - (1 - \text{Annual CalvingRate})^{1/12}$$

The attainable milk yield is calculated as:

$$Milk\ Yield = Potential\ Milk\ Yield \times Age\ Effect \times Condition\ Factor$$

Where condition index is calculated as:

$$Condition\ Index = \frac{W_t - W_{\min,t}}{W_{\max,t} - W_{\min,t}}$$

Manure production is calculated by:

$$FaecalDM = DMI \times \left(1 - DMD\right)$$

Where DMD is dry matter digestibility which is an input into the model.

Herbage intake is described by:

$$DMI_{a,z,g} = DMPI_g \times RI_z$$

Where $DMI_{a,z,g}$ is dry matter intake expressed in kg DM d^{-1}, $DMPI_g$ is the potential dry matter intake expressed in kg d^{-1}, and RI_z the relative intake (dimensionless). The potential intake (DMPI) is calculated by: $DMPI_{a,g} = 0.0107 \times \frac{BW_a}{(1 - DMD_g)}$

Where BW is bodyweight (kg), and DMD is dry matter digestible (g(kg DM)$^{-1}$).

$$RI_{z,g} = \frac{(Ba_{z,g} / K)^q}{1 + (Ba_{z,g} / K)^q}$$

Both q and K are dimensionless coefficients; K describes the capability of an animal to graze.

$$K = b \times BW^{0.36}$$

Where b is a dimensionless coefficient, this approach takes into account both herbage biomass and the animal's capability to harvest grasses.

Appendix 5 – Grazing units of the communal grassland of the Manjonjo village, NE Zimbabwe. Area and standing biomass and dead biomass (litter) and criteria used by herdsmen to distinguish grazing units (from Rufino et al. 2011)

Landscape units	Grazing units	Area (ha)	March		April		May		Most Abundant species
			Standing biomass (kg ha^{-1})	Litter (kg ha^{-1})	Standing biomass (kg ha^{-1})	Litter (kg ha^{-1})	Standing biomass (kg ha^{-1})	Litter (kg ha^{-1})	
Low Miombo Woodland	1	142	700	7	250	13	150	12	*Hyparrhenia dissoluta, sporobolus pyramidalis, aristada congesa*
	2	14	2400	288	2300	276	2100	441	*sporobolus pyramidalis, kyllinga erecta, Bulbostylis burchelli*
	3	11	3300	3	2450	74	1900	19	*Sporobolus, Cynodon dactylon, Eleusine indica*
Open	4	17	2500	25	2350	141	2300	184	*Sporobolus pyramidalis, Hyparrhenia dissoluta, Heteropogon contortus*
Grassland	5	39	3300	132	3100	31	2900	435	*Sporobolus pyramidalis, Scleria lageonsis, Kyllinga erecta*
	6	20	2000	0	1100	0	850	0	*Sporobolus pyramidalis, eragrostis heteromera, Cynodon dactylon,*
	7	8	1300	0	900	9	700	56	*Cynodon dactlon, sporobolus pyramidalis, Hyparrhenia dissoluta*
High Miombo Woodland	8	22	1550	78	1300	182	1200	288	*Hyparrhenia dissoluta, Andropogon gayanas, heteropogon contortus*
	9	154	1050	179	800	248	600	264	*Hyparrhenia filipendula, Andropogon gayanus, Aristida leusina*
	10	12	1350	95	1000	190	900	243	*Hyparrhenia dissoluta, andropogon gayanus, Themeda triandra*

Appendix 6 – feed quality parameters for the feed stuffs used in the simulations, (from Rufino et al. 2011)

Grass species	Early rainy season			Early dry season			Late dry season		
	ME (MJ kg DM^{-1})	DMD (g kg DM^{-1})	CP (g kg DM^{-1})	ME (MJ kg DM^{-1})	DMD (MJ kg DM^{-1})	CP (g kg DM^{-1})	ME (MJ kg DM^{-1})	DMD (g kg DM^{-1})	CP (g kg DM^{-1})
Hyparrhenia dissoluta	10.2	650	135	8	510	45	6.3	400	40
Sporobolus pyramidalis	9.8	620	125	7.9	400	43	5.2	330	30
Heteropogon contortus	10.5	670	110	7.5	410	32	5.8	370	24
Digitaria pazensiss	11.5	700	163	9.2	630	74	8.2	530	45
Andopogon gayanus	9.7	620	158	8	470	58	6.2	400	47
Cynodon dactlon	10.4	640	137	8.3	517	60	8	500	50
Aristida congesta	10	650	109	7.8	420	52	5.8	370	43
Supplementary feeding									
Zea mays leaves				8	520	72	7.6	500	50
Zea maize stems				6.8	500	54	6	450	45

Summary

Soil fertility decline and erratic rainfall are major constraints to crop productivity on smallholder farms in southern Africa. Crop production intensification along with efficient use of chemical fertiliser is required to produce more food per unit area of land, while rebuilding soil fertility. In Africa, the need to feed the hungry is most urgent yet farmers in this region experience some of the most brutal biophysical and socio-economic conditions. The objective of this thesis was to identify appropriate crop production intensification options that are suited to the socio-economic and biophysical conditions of selected smallholder maize-based farming systems in southern Africa. Three sites that formed a gradient of intensity of crop and livestock production were selected for the study. Murehwa in Zimbabwe is characterised by the largest intensity followed by Ruaca and lastly Vunduzi both in central Mozambique. In all three locations, maize is a key staple and cash crop.

Targeting of crop production options adapted to local conditions are needed to end perennial food shortages and poverty. The paradigm of ecological intensification is considered in identifying crop production systems that use inputs efficiently and lead to positive biophysical and socio-economic outcomes. Suggested feasible options include integration of crop and livestock production, increased crop diversification (intercropping), and conservation agriculture which promote nutrient and soil conservation.

A literature review, field methods based on participatory research, and modelling tools were combined in analysing potential crop production options across an agricultural intensification gradient. In addition a trade-off analysis was performed to provide insights into the consequences of allocating crop residues for animal feed or for soil fertility on total farm production and economic value.

A meta-analysis on maize grain yield under rain-fed conditions revealed that conservation agriculture required legume rotations and high nitrogen input use especially in the early years. The overall effect of NT without mulch depressed yields by 0.2 t ha^{-1} although the 95% CI of the WMD ranged between -1.8 and 1.8 t ha^{-1}) when compared to conventional tillage. No till with rotation had a positive WMD of 0.1 t ha^{-1} while no till without mulch had an overall WMD of -0.1 t ha^{-1} over conventional tillage. Reduced tillage with no mulch cover leads to lower yields than conventional tillage in low rainfall environments; mulch cover in high rainfall areas leads to lower yields due to waterlogging and improved yields under CA are likely on well drained soils. Generally higher yields were obtained in the long term especially when rotation was practised. The detrimental effects of rainfall variability in southern Africa are difficult to offset even with conservation agriculture. The analysis revealed that conservation agriculture needs to be targeted and adapted to specific bio-physical conditions for improved impact. Crop productivity under conservation agriculture in southern Africa will depend on the ability of farmers to achieve correct (amount and type) fertiliser application, timely weeding, and the availability of crop residues for mulching and systematic crop rotations which are currently lacking.

An additive design of within-row intercropping was compared to a substitutive design with distinct alternating rows of maize and legume (local practice) under no-till in the Ruaca and Vunduzi communities, central Mozambique. Intercropping increased productivity compared to the corresponding sole crops with land equivalent ratios (LER) of between 1.0 and 2.4. Maize yield loss was only 6-8% in within-row intercropping but 25-50% in the distinct-row option. Relay planting of maize and cowpea intercropping ensured cowpea yield when maize failed thus reduced the negative effects of dry spells. The residual benefits of maize-pigeonpea intercropping were large (5.6 t ha^{-1}) whereas continuous maize yielded only 0.7 t ha^{-1} and was severely infested by striga (*Striga asiatica*). The accumulation of biomass which provided mulch combined with no tillage increased rainfall infiltration. Intercropping was preferred by the majority of farmers due to increased farm harvest and profitability, even though the labour required for weeding increased by 36%. Where land limitation is a major problem as in Vunduzi, intensification through legume intercropping is a feasible option to increase crop productivity and farm income while reducing the risk of crop failure.

Nutrient management strategies that included manure in combination with chemical fertiliser that included N, P, Ca, Zn, Mn were evaluated for their potential to recover degraded soils and to support sustainable high crop productivity in Murehwa, Zimbabwe. The experiment was established on sandy and clay soils in two field types. Homefields were close to the homestead and relatively more fertile than the outfields due to previous preferential allocation of nutrients. Maize grain yields in sandy soils did not respond to the sole application of 100 kg N ha^{-1}; manure application had immediate and incremental benefits on crop yields in the sandy soils. A combination of 25 t ha^{-1} manure and 100 kg N gave the largest treatment yield of 9.3 t ha^{-1} on the homefield clay soils, 6.1 t ha^{-1} on clay outfield, 7.6 t ha^{-1} on sandy homefield and 3.4 t ha^{-1} in the eighth season. Yields of the largest manure application in the outfields were comparable to those with optimum fertiliser application in the homefields suggesting the need to target nutrients differently to different fields. Despite the large manure applications of up to 25 t ha^{-1}, crop productivity and soil organic carbon build-up in the outfield sandy soils was small highlighting the difficulty to recover the fertility of degraded soils. Manure can be used more efficiently if targeted to fields closest to homesteads but this exacerbates land degradation in the outfields and increases soil fertility gradients. Combined manure and mineral fertiliser application can be adapted locally for improved total farm productivity in mixed crop-livestock systems.

The NUANCES-FARMSIM model for simulating crop and animal productivity in mixed crop-livestock farming systems was used to perform trade-off analysis with respect to crop residue management, animal and crop productivity. The study site was Murehwa, Zimbabwe chosen among the three study sites because of the strong intensity of interaction crop and livestock production. Proportions (0, 25, 50, 75 and 100%) of maize stover produced per farm were allocated either to soil as mulch or animal feed during the dry season. Retaining all maize residues in the field led to severe losses in animal productivity but significant gains in crop productivity in the long-term. Yield increased 4 to 5.6 t farm^{-1} for RG1, and from 2.8 to 3.5 t farm^{-1} for RG2. Body weight loss was on average 67 kg per animal per year for RG1 and 93 kg per animal per year for RG2. Retention of all crop residues reduced farm income by US$937 and US$738 per year for RG1 and RG2 respectively. Non-livestock farmers (60% of the farmers) do not face trade-offs in crop residue allocation but have poor productivity compared to livestock owners. They have a greater scope of retaining their crop residues if they invest in more labour to keep their residues during the dry season. Farmers who own cattle cannot allocate crop residues for mulch at current productivity as it will lead to reduced animal productivity and farm economic value.

It is clear that intercropping maize and legumes is attractive to farmers for both nutrition and income although the existence of a market for the legume is crucial. Conservation agriculture conflicts with livestock and has large initial input demands such as nitrogen fertiliser which is beyond the reach of the majority of farmers in southern Africa. Manure use with supplementary nitrogen fertiliser improves crop productivity in mixed-crop livestock systems and is a good starting point to ecological intensification.

This study has revealed that crop production intensification options developed without considering the biophysical conditions as well as socio-economic circumstances of farmers are nuisances. External ideas should be used to stimulate local innovations to push the envelope of crop production without creating new constraints on resource use.

Samenvatting

De afname van de bodemvruchtbaarheid en onregelmatige regenval zijn belangrijke randvoorwaarden voor de productiviteit op kleinschalige landbouwbedrijven in zuidelijk Afrika. Intensivering van de gewasproductie door middel van efficiënt gebruik van kunstmest en het wederopbouwen van de bodemvruchtbaarheid is nodig om meer voedsel per oppervlakte-eenheid van land te produceren. De noodzaak om de hongerigen te voeden is hoogst dringend in Afrika, maar boeren daar ervaren een aantal van de meest acute biofysische en socio-economische omstandigheden. Het doel van dit proefschrift was het identificeren van geschikte opties voor intensivering van de gewasproductie, die functioneel zijn voor de sociaal-economische en biofysische omstandigheden van specifieke maïs productiesystemen van kleinschalige boeren in zuidelijk Afrika. Drie sites die een gradiënt van intensiteit van plantaardige en dierlijke productie vormden, werden geselecteerd voor de studie. Murehwa in Zimbabwe wordt gekenmerkt door de grootste intensiteit gevolgd door Ruaca en Vunduzi, beiden in centraal Mozambique. In alle drie locaties is maïs het belangrijkste voedsel- en marktgewas.

Het aanpassen van opties voor gewasproductie aan de plaatselijke omstandigheden is nodig om blijvende voedseltekorten en armoede te bestrijden. Bij het identificeren van plantaardige productiesystemen die inputs efficiënt gebruiken en leiden tot positieve biofysische en socio-economische resultaten, werd gebruik gemaakt van het paradigfma van ecologische intensivering. De gesuggereerde haalbare opties omvatten: de integratie van plantaardige en dierlijke productie, verhoogde diversificatie in de gewasteelt (mengteeltsystemen), en ‘Conservation Agriculture’ (CA), dat nutriënten en bodembescherming bevordert.

Een literatuurstudie, participatief veldonderzoek, en simulatiemodellen werden gecombineerd in het analyseren van de potentiële opties van gewasproductie over een gradiënt van intensiteit van landbouwbeoefening. Daarnaast werd er een 'trade-off' analyse uitgevoerd om inzicht te krijgen in de gevolgen van altertnatief gebruik van gewasresten op de totale productie en het economische rendement. De alternativen betroffen gebruik van gewasresten als veevoeder, en als bodembedekking ('mulch'), voor het verhogen van de bodemvruchtbaarheid.

Uit een meta-analyse van maïs opbrengsten in semi-aride en sub-humide streken bleek dat CA rotaties met vlinderbloemigen en hoge stikstofbemesting noodzakelijk maakt, vooral in de eerste jaren. Het algemene effect van het afschaffen van de grondbewerking zonder een 'mulch' van gewasresten is een afname van de maïs opbrengst van 0,2 t.ha^{-1} in vergelijking met conventionele grondbewerking. Echter, het 95% betrouwbaarheidsinterval van het gewogen gemiddelde verschil (WMD in het Engels) varieerde tussen -1,8 en 1,8 t ha^{-1}. Geen grondbewerking met rotatie had een positieve WMD van 0.1 t ha^{-1}, terwijl geen grondbewerking zonder een mulch van gewasresten een totale WMD had van -0,1 t ha^{-1} ten opzichte van conventionele grondbewerking. Verminderde grondbewerking zonder een mulch van gewasresten leidt tot lagere maïs opbrengsten dan conventionele grondbewerking in streken met weinig neerslag; in gebieden met hoge regenval leidt een mulch van gewasresten juist tot lagere maïs opbrengsten als gevolg van wateroverlast, tenzij er sprake is van goed gedraineerde gronden. Over het algemeen, werden hogere gewasopbrengsten pas verkregen op de lange termijn, en met name wanneer gewasrotaties werden toegepast. De nadelige gevolgen van varierende regenval in zuidelijk Afrika zijn moeilijk te compenseren, zelfs met CA. De analyse toonde aan dat voor een beter resultaat CA dient te worden aangepast aan de specifieke biofysische omstandigheden. In zuidelijk Afrika zullen de gewasopbrengsten met CA afhangen van het vermogen van de boeren om de juiste bemesting (hoeveelheid en soort) te gebruiken, tijdig te wieden, en van de beschikbaarheid van gewasresten voor het bedekken van de grond en het gebruik van systematische gewasrotaties. Momenteel ontbreekt het hier aan.

In een experimenteel ontwerp in de Ruaca en Vunduzi gemeenschappen in centraal Mozambique werd binnen-rij mengteelt vergeleken met afwisselende rijen van maïs en vlinderbloemigen (lokale praktijk) zonder grondbewerking. Mengteelt verhoogde gewasopbrengsten in vergelijking met de overeenkomstige monocultuur gewassen met land gelijkwaardige verhoudingen (LER in the Engels) tussen de 1,0 en 2,4. Het verlies aan maïs opbrengst was slechts 6-8% in binnen-rij mengteelt, maar bedroeg 25-50% in de optie met de afwisselende gewasrijen. Het zaaien van maïs en cowpea koeieboon (ook wel: oogjesboon) in mengteelt verzekerde een opbrengst met cowpea wanneer die van maïs mislukte, en dus verminderde het de negatieve effecten van droogte. De residuele effecten van de mengteelt met maïs en pigeonpea duivenerwt waren groot (5.6 t ha^{-1}) in vergelijking met continu maïs. Deze leverde slechts 0,7 t ha^{-1} op en was ernstig aangetast door striga (*Striga asiatica*). De accumulatie van biomassa voor gebruik als mulch, in combinatie met geen grondbewerking, verhoogde de infiltratie van regenval. De meerderheid van boeren geeft de voorkeur aan binnen-rij mengteelt vangwege de verhoogde gewasopbrengst en winstgevendheid, hoewel de arbeid die nodig is voor het wieden steeg met 36%. Waar landgebrek een groot probleem is zoals in Vunduzi, is intensivering door binnen-rij mengteelt met vlinderbloemigen een haalbare optie voor een hogere gewasproductie en een hoger bedrijfsinkomen. Tegelijkertijd vermindert het risico van misoogsten.

Strategieën voor het beheer van nutriënten die dierlijke mest combineren met kunstmest met N, P, Ca, Zn and, Mn, werden geëvalueerd op hun potentieel om gedegradeerde bodems te herstellen en om duurzame en hoge gewasproductie te bereiken in Murehwa, Zimbabwe. Het experiment werd uitgevoerd op zand- en kleigronden en in twee typen velden. Zogenoemde 'thuisvelden' waren dicht bij de boerehoeve gelegen en relatief vruchtbaarder dan de 'buitenvelden' als gevolg van historische preferentiële toewijzing van nutriënten. Op de zandgronden resulteerde bemesting met enkel 100 kg N.ha^{-1} niet in hogere maïsopbrengsten; dierlijke mest gaf echter onmiddellijke, en over de seizoenen toenemende, hogere gewasopbrengsten op de zandgronden. Een combinatie van 25 t ha^{-1} dierlijke mest en 100 kg N ha^{-1} als kunstmest gaf in het achtste seizoen de hoogste opbrengst (9,3 t ha^{-1}) op de kleigronden van het thuisveld, 6.1 t ha^{-1} op de kleigronden van het buitenveld, 7.6 t ha^{-1} op de zandgronden van het thuisveld en 3.4 t ha^{-1} op de zandgronden van het buitenveld. De opbrengsten met de hoogste gebruik van dierlijke mest in de buitenvelden waren vergelijkbaar met die van een optimale bemesting met kunstmest in de thuisvelden. Dit suggereert de noodzaak om de verschillende beschikbare bronnen van nutriënten te richten op verschillende velden. Ondanks de topassing van hogere dierlijke mest hoeveelheden (tot 25 ton ha^{-1}) was de gewasproductie en de opbouw van de organische stof op de zandgronden van de buitenvelden klein. Dit wijst op de moeilijkheid om de vruchtbaarheid van gedegradeerde gronden te herstellen. Dierlijke mest kan efficiënter worden gebruikt indien zij wordt gericht op velden die het dichtst bij de boerehoeve liggen. Dit dit verergert echter landdegradatie in de buitenvelden en verhoogt de bodemvruchtbaarheidsgradiënten. Gecombineerd gebruik van dierlijke mest en kunstmest kan lokaal worden aangepast voor een betere totale productiviteit in gemengde gewas-veehouderijsystemen.

Het NUANCES-FARMSIM model voor het simuleren van de productiviteit van gewassen en vee in gemengde gewas-veehouderijsystemen werd gebruikt om de trade-offs te analyseren tussen dierlijke en plantaardige productie met betrekking tot het beheer van gewasresten. Uit de drie locaties werd Murehwa in Zimbabwe gekozen simulatie locatie voor dit onderzoek vanwege de sterke interactie tussen de plantaardige en dierlijke productie. Verschillende verhoudingen (0, 25, 50, 75 en 100%) van maïs gewasresten geproduceerd op het bedrijf werden toegewezen hetzij aan de bodem als mulch, hetzij als veevoeder tijdens het droge seizoen. Behoud van alle maïs gewasresten in het veld leidde enerzijds tot ernstige verliezen in productiviteit van vee, anderzijds tot een aanzienlijke gewas productiviteitswinst in de lange termijn. De opbrengst steeg naar 4-5,6 t per bedrijf voor RG1 en 2,8-3,5 t per bedrijf voor RG2. Gewichtsverlies van vee bedroeg gemiddeld 67 kg per dier per jaar voor RG1 en 93 kg per dier per jaar voor RG2. Behoud van alle gewasresten verminderde landbouwinkomen met 937 en 738 US $ per jaar voor respectievelijk RG1 en RG2. Niet-veehouders (60% van de boeren) worden niet geconfronteerd met deze afwegingen in de toewijzing van gewasresten maar de productiviteit van hun land is reeds lager in vergelijking met dat van veehouders. Ze hebben meer mogelijkheden om hun gewasresten te behouden indien zij investeren om deze gedurende het droge seizoen te behouden. Met de huidige productiviteit kunnen boeren die vee bezitten hun gewasresten niet als mulch gebruiken, omdat dat zal leiden tot een verminderde productiviteit van het vee en een lager economisch rendement van de boerderij.

Het is duidelijk dat een mengteelt van maïs en vlinderbloemigen aantrekkelijk is voor boeren, zowel vanuit het voedings als een inkomensperpectivf. Voorwaarde is wel dat er een markt voor vlinderbloemigen is. CA conflicteert met veehouderij en vraagt om een grote initiële investering van o.a. stikstofbemesting, iets wat buiten het bereik ligt van de meerderheid van de boeren in zuidelijk Afrika. Het gebruik van dierlijke mest aangevuld met stikstofkunstmest verbetert de productiviteit van gewassen in de gemengde gewas- veehouderijsystemen en is een goed uitgangspunt voor ecologische intensivering.

Deze studie heeft aangetoond dat opties voor intensivering van de plantaardige productie die ontwikkeld zijn zonder rekening te houden met de biofysische en sociaal-economische omstandigheden van de boeren, uitsluitend een last voor hen zijn. Externe ideeën moeten worden gebruikt om lokale innovaties ter verhoging van de plantaardige productie te bevorderen, zonder dat deze nieuwe beperkingen creëren op het gebruik van de aanwezige hulpbronnen.

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As the building blocks of this thesis were coming together and the "end" in sight, it was clear certain individuals stood out and I take great pleasure in mentioning them in the paragraphs that follow. Some were special yet others were very special, and I hope to get away with my arbitrary decisions.

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There are many others I interacted with during this journey who contributed in some way to this work. I spend some worthy time with Dr. Sigrun Dahlin going up Mt Gorongosa in Mozambique, interviewing farmers, digging and sampling soils, buying fruits or fish at the market and engaging in some scientific discussions over dinner of breakfast. I also learned a lot from Professor Martin van Ittersum and Dr. Nico de Ridder. I also had the opportunity to sit with them for mouth-watering dishes at Martin's house and I am grateful for that. Nico, I still hope to get hold of that great recipe.

I worked briefly with Mrs. Colletah Chitsike in 2005 when I was completing my Masters degree while attached to CIAT. She taught me many things especially working with farmers across countries in southern Africa. She told me these words before she left: '*Leonard, I will definitely read about you in the future*". She declined to elaborate but I guess this is what she meant, thank you for the wisdom that you were so free to share and the belief. I am grateful to Dr. Bert Janssen, Dr. Jens Anderson, Dr. Shamie Zingore, Dr. Christian Thierfelder, Rennie Chioreso Munyai, Dr. Pauline Chivenge for some discussions and opportunities along the way.

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Curriculum vitae

Leonard Rusinamhodzi was born at Macheke clinic near Marondera, Zimbabwe on the 14th of September 1979. He did his primary and secondary school in Chiendambuya and Macheke before completing his Advanced-level studies at Allan Wilson High School in Harare in 1998 where he studied mathematics, biology and chemistry. He graduated successfully in 2002 at The University of Zimbabwe (UZ), with a BSc in Agriculture specializing in Soil Science. In 2003, he was offered a scholarship to study for a Masters by research based at CIAT-Harare while registered at the UZ which he completed in 2006. The Masters thesis was entitled *Effects of cotton-cowpea intercropping on crop yields and on soil nutrient status under Zimbabwean rain-fed conditions,* which produced two peer reviewed journal articles. From 2006 to 2008 he worked under Dr. Robert Delve as a Research Associate at CIAT-Harare on soil fertility management and linking farmers to markets for grain legumes. After the completion of this project, he was assigned to the Sub-Saharan Africa Challenge Program (SSA-CP) project which was primarily focussed on research and promotion of conservation agriculture. He gained invaluable experience working in an international organisation across diverse environments and cultures. This is when the idea of studying for a PhD was mooted. Links were established with Professor Ken Giller (who had previously taught him at undergraduate) and he started his PhD in January 2009 on targeting appropriate crop intensification options to selected farming systems of southern Africa. Leonard has extensive experience in participatory research in smallholder farming systems in southern Africa, with a deep understanding of the complex barriers to improved crop productivity in this region.

Leonard is married to Grace and have a beautiful son called Dalitso Thabo.

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List of publications

Peer reviewed journal articles

1. **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 147: 40-53.
2. **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.
3. **Rusinamhodzi L**, Corbeels M, van Wijk M, Nyamangara J, Rufino M and Giller KE (2011). A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agronomy for Sustainable Development 31: 657-673.
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5. **Rusinamhodzi L**., H.K. Murwira and J. Nyamangara (2006). Cotton–cowpea intercropping and its N2 fixation capacity improves yield of a subsequent maize crop under Zimbabwean rain-fed conditions. Plant and Soil Journal, 287:327–336.
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10. Thierfelder C, Cheesman S and **Rusinamhodzi, L** (2012) Benefits and challenges of crop rotations in maize-based conservation agriculture (CA) cropping systems of southern Africa. International Journal of Agricultural Sustainability: 1-17.

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1. **Rusinamhodzi L** and Delve R (2011) Participatory variety selection of pulses under different soil and pest management practices in Kadoma District, Zimbabwe. In Bationo A et al (eds) Innovations as key to the Green Revolution in Africa.

Oral presentations at international conferences

1. Labour burden and not crop productivity increased under planting basins in Murehwa District, Zimbabwe. ISFM2012 Conference, 22-26 October 2012, Safari Park Hotel, Nairobi, Kenya.
2. Maize-legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. AR4D Conference 26-27 September 2012, SLU, Uppsala, Sweden.

3. Effects of conservation agriculture and manure application on maize grain yield and soil organic carbon: a comparative analysis. 5th World Congress on Conservation Agriculture Incorporating 3rd Farming System Design, Brisbane, Australia, 24-29 September 2011.
4. Productivity of Maize-Legume Intercropping under No-till in central Mozambique: Challenges and Opportunities. FAO Regional Conservation Agriculture Symposium (8-11 February 2011, Emperors Hotel , Johannesburg)

Poster presentations at international conferences

1. Intensification options for the extensive farming systems of central Mozambique: Application of the NUANCES framework. CIALCA conference, 23-28 October 2011, Serena Hotel, Kigali, Rwanda.
2. Long-term maize-pigeonpea intercropping increases productivity and rainfall infiltration in a degraded sandy soil in central Mozambique. International workshop on Agroforestry: Ecological benefits of agroforestry (15-17 June 2011, Brandenburg University of Technology, Cottbus, Germany)
3. Long-term effects of conservation agriculture practices on maize yields under rain-fed conditions. Agro2010: International Scientific week around agrononomy (29 August to 3 September 2010, Montpellier, France).

PE&RC PhD Training Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (5.6 ECTS)

- Feasibility of conservation agriculture practices across farming systems: what fits where and when? (2009)

Writing of project proposal (4.5 ECTS)

- Feasibility of conservation agriculture practices across farming systems: what fits where and when? (2008)

Post-graduate courses (6.8 ECTS)

- Analysing farming systems and rural livelihoods in a changing world: vulnerability and adaption; PE&RC, UZ (2008)
- The art of modelling; PE&RC (2008)
- Working with dynamic models for agriculture – a short course; ESA, SupAgro, Agro2012 (2010)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Geordema: soil carbon, soil fertility (2012 / 2013)
- Agriculture, Ecosystems & Environment: conservation agriculture (2013)

Deficiency, refresh, brush-up courses (3 ECTS)

- Quantitative analysis of land use systems - QUALUS (2009)
- Systems analysis, simulation and systems management (2009)

Competence strengthening / skills courses (1.4 ECTS)

- The art of writing; WGS (2009)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)

- PE&RC Day (2012)
- PE&RC Weekend (2013)

Discussion groups / local seminars / other scientific meetings (6.6 ECTS)

- CIAT Meetings (2008-2012)
- WUR Discussion groups (2008-2012)

International symposia, workshops and conferences (9 ECTS)

- Agro2010; Montpellier (2010)
- FAO – CA Symposium; Johannesburg (2011)
- World Conservation Agriculture – WCA2011; Brisbane (2011)
- ISFM2012 – Microbes to markets; Nairobi (2012)

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Cover design
The pictures and the cover design by the author depict the range of crop production options across southern Africa as well as the constraints (poor soils, inadequate labour).