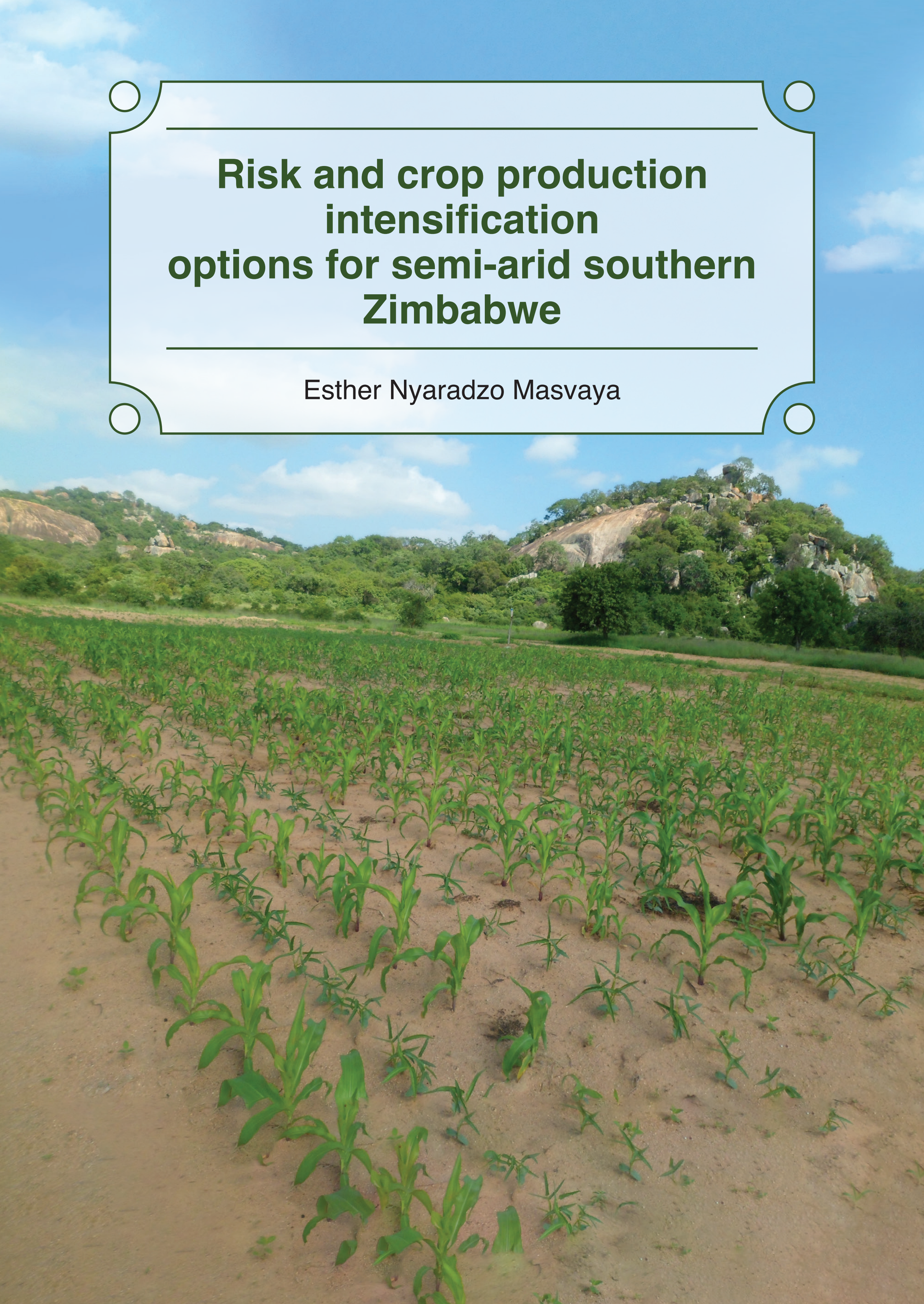

Risk and crop production intensification options for semi-arid southern Zimbabwe

Esther Nyaradzo Masvaya

Propositions

1. The rooting patterns explain above-ground yields of species in crop mixtures
   (this thesis).
2. The balance between the positive and negative effects of residue retention in maize cropping systems can be managed with nitrogen fertilisers
   (this thesis).
3. Thinking of moving beyond technologies before fully exploring if, when, where and how these technologies work serves no purpose.
4. Efforts to deliberately enhance adaptability can, unintentionally, lead to loss of resilience.
5. Approaches to address climate change need to engage with socioeconomic and spatial inequalities to be effective.
6. Research should build on prior knowledge of best practices and new methods, not mimic fashion trends.
7. A PhD study should be driven by contributions to society not by ambitions for academic kudos.

Propositions belonging to the thesis entitled:

"Risk and crop production intensification options for semi-arid southern Zimbabwe"

Esther Nyaradzo Masvaya

Wageningen, 27 May 2019

Risk and crop production intensification options for semi-arid southern Zimbabwe

Esther Nyaradzo Masvaya

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This research was conducted under the auspices of the C.T. de Wit Graduate School of Production Ecology and Resource Conservation

Risk and crop production intensification options for semi-arid southern Zimbabwe

Esther Nyaradzo Masvaya

Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Monday 27 May 2019
at 4 p.m. in the Aula.

Esther Nyaradzo Masvaya
Risk and crop production intensification options for semi-arid southern Zimbabwe,
191 pages.

PhD thesis, Wageningen University, Wageningen, the Netherlands (2019)
With references, with summaries in English

ISBN: 978-94-6343-437-9
DOI: https://doi.org/10.18174/471607

Although rainfed cropping in semi-arid areas is risky due to frequent droughts and dry spells, climate smart agriculture (CSA) and sustainable intensification (SI) technologies have a role to play in ensuring smallholder farmers in semi-arid sub-Saharan Africa (SSA) are food self-sufficient. Conservation agriculture (CA) and cereal-legume intercropping were identified as cropping systems that have potential to produce food in risky environments. The objective of this study was to determine the potential of CA and intercropping to contribute to SI and CSA by quantifying crop productivity and soil N dynamics using field and modelling approaches.

An on-farm field experiment was set up in Matobo where the effects of two principles of CA (reduced tillage and mulch application) in combination with soil fertility amendments on soil mineral N release, plant N uptake and maize yields were assessed in comparison with the plough tillage. Ploughing stimulated N mineralisation and maize N uptake more than the ripper tillage. However, mulching reduced mineralisation and subsequently lowered crop N uptake compared with no mulch application under the plough tillage. Ripping combined with mulch application resulted in mineral N values and maize yields comparable to the plough only treatment. Planting early (1 Nov to 15 Nov) and with the first rains, especially with the ripper + mulch treatment, resulted in exceeding the food self-sufficiency threshold of 1080 kg ha^{-1} if fertility amendments were applied, as well as in a low probability of complete crop failure, ranging from 0–40%. The field experiment was complimented with a modelling exercise using APSIM to investigate the effects of different planting date, tillage and soil fertility management strategies on crop yields over a larger range of climate and risk related issues. APSIM simulated the occurrence of the mineral N flush with the first rains. Its coincidence with planting resulted in average yield benefits in the range of 200-800 kg ha^{-1}.

Maize-cowpea intercropping experiments were established covering several seasons to determine effects on soil chemical variables, root dynamics and yield of intercrops. With the addition of 40 kg N ha^{-1}, maize grain yields were increased significantly by 500–1100 kg ha^{-1} in a normal season. However, cowpea yields were compromised attributed to the lack of below-ground niche differentiation in root distribution between maize and cowpea. Most intercrops had a land equivalent ratio >1 showing that there was generally greater productivity and over-yielding in the intercrops proving intercropping a robust option across seasons and soil types.

Modelling the maize-cowpea intercrop with APSIM showed that maize yields were reduced by 3–25% with intecropping in comparison with sole maize. For cowpea, a week's delay in planting resulted in significant reductions in yields. Planting maize and cowpea at populations of 37 000 and 74 000 plants ha^{-1} respectively on the same date and with 40 kg N ha^{-1} scenario maximised the probability of meeting household energy and protein requirements on sandy soils. On the clay, the relay intercropping scenarios where cowpea was planted 2–4 weeks after maize met household nutrition needs. Maize-cowpea intercropping was better than growing sole crops as it is a more efficient system to achieving food security in smallholder farms.

The CA and intercropping technologies proved climate-smart to some extent by improving productivity under an uncertain climate. Other than productivity, both CA and intercropping were shown to contribute significantly towards soil fertility environmental sustainability and food self-sufficiency and therefore sustainable intensification. These technologies will need to be accompanied by the application of N containing fertility amendments as these proved critical to reducing the risk of crop failure and achieving the best possible yields.

Key words: APSIM; Climate smart agriculture; Conservation agriculture; Maize-cowpea intercropping; N mineralisation; Risk management; Semi-arid; Smallholder; Sustainable intensification

Contents

CHAPTER 1

GENERAL INTRODUCTION

1.1. Background

Farming in semi-arid sub-Saharan Africa (SSA) takes place under harsh agro-ecological conditions: low and unpredictable rainfall, high temperatures, high climatic variability, low soil fertility, land degradation, attacks of pests, and diseases and weed infestation (Arslan et al., 2014; Rurinda et al., 2015). Whilst global agricultural production will need to increase by about 70–100% by 2050 to feed the increasing population, van Ittersum et al. (2016) suggested that in the case of SSA the average cereal demand will increase by about 335%. This means that if SSA is to be food self-sufficient in the future, drastic measures must be taken to heighten production, by increasing the yields on existing cropland and/or by expanding the area of land under cultivation where possible (Chamberlin et al., 2014). In Southern Africa, climate change is predicted to have a negative impact on agriculture. More frequent and prolonged droughts and higher temperatures threaten the region's crop production, potentially adding to the vulnerability of smallholder farming households (Serdeczny et al., 2017). It is therefore important to explore the production potentials of cropping options proposed for risky semi-arid environments on low-fertility soils, with a view to ensuring the food self-sufficiency of smallholder farm households.

The problem of low soil fertility and land degradation is exacerbated by the fact that farmers tend to use little external nutrient inputs. Nitrogen (N) is inherently deficient in the soils in the region; therefore its management is key for achieving food security and safeguarding the sustainability of any cropping system (Sanchez, 2002; Morris, 2007). Repeated efforts to increase input use (especially of fertiliser) in SSA have met with little success. The main impediments are (a combination of) climate variability, farmers' risk perception, and limited on-farm investment (Cooper et al., 2008). Access to nutrients is also a problem for smallholders in SSA (Mupangwa et al., 2013). Owing to poor crop management practices and unbalanced blanket fertiliser recommendations, that do not address the complexity of smallholder farming systems (Giller et al., 2011; Chikowo et al., 2015; Njoroge et al., 2017), the efficiency of the fertilisers that are being used is generally low. This makes it even harder to convince farmers to use them.

1.2. Climate-smart agriculture and sustainable intensification approaches

In order to meet the challenge of ensuring sustainable global food and nutrition security in the face of climate change, two approaches have been proposed in recent times: climate-smart agriculture (CSA) and sustainable intensification (SI). CSA interventions are defined by their ability to deliver on three fundamental dimensions: a) adaptation to the effects of climate change, thereby building resilience into the system; b) provision of mitigation benefits in terms of greenhouse gas emission reduction and building carbon (C) stocks (both above and below ground) and c) improved reliability, sustainability, productivity and profitability of agricultural production systems (Campbell et al., 2014; Lipper et al., 2014). SI approaches aim to increase food production on existing farmland in ways that have a lower environmental impact and which do not undermine the capacity to continue producing food in the future (Godfray et al., 2010). The two approaches, SI and CSA, can be fruitfully combined. CSA focuses on improving risk management, information flows and local institutions to support adaptive capacity to provide the fundamentals for spurring and enabling intensification (Campbell et al., 2014), while SI is crucial to both adaptation and mitigation.

Conservation agriculture (CA) and legume technologies such as intercropping have been put forward as promising options to achieve both CSA and SI (Pretty et al., 2011; Campbell et al., 2014; Ollenburger and Snapp, 2014; Vanlauwe et al., 2014a; Falconnier et al., 2016; Droppelmann et al., 2017; Thierfelder et al., 2017). The effective application of these cropping system options, as reported in these studies, results in increased food production per unit land, while maintaining or rebuilding soil fertility.

1.2.1. The case of conservation agriculture in Southern Africa

Conservation agriculture (CA) is a technology promoted to cushion smallholder farmers in SSA against the adverse effects of soil fertility decline; it would allow a stabilisation of crop yields and increase drought resilience (Hobbs et al., 2008). It is based on three principles: a) minimum or no tillage, b) mixing and rotating crops and, c) maintaining semi-permanent or permanent soil cover (FAO, 2011). CA involves specific management practices, such as reduced tillage, residue retention, soil fertility amendment application and timely weed management (Mazvimavi and Twomlow, 2009). The benefits associated with CA include crop sequence intensification (Brouder and Gomez-Macpherson, 2014), a better use of the cropping season window permitted by an earlier field entry (Hobbs et al., 2008; Nyagumbo et al., 2017), an increase of soil organic carbon (Rusinamhodzi, 2015), and soil moisture retention, owing to a reduction of run-off, soil erosion, and lower surface soil temperatures (Mupangwa et al., 2007; Thierfelder and Wall, 2009; Nyamadzawo et al., 2012). The long-term effects of CA when practiced comprehensively include improved crop yields and a reduction of the production costs (Rusinamhodzi et al., 2011; Sithole et al., 2016). There is, however, no consensus that these benefits occur and when or where they occur (Gowing and Palmer, 2008; Giller et al., 2009; Giller et al., 2011; Giller et al., 2015; Pittelkow et al., 2015).

Although CA is promoted as a soil fertility-enhancing technology, application of crop residues poor in N, such as cereal stover, may result in prolonged immobilisation of mineral N (Giller et al., 1997). In CA, reduced N availability has also been attributed to slow residue decomposition and N losses from leaching and denitrification (Angás et al., 2006; Verachtert et al., 2009). To offset the reduced N availability caused by the use of poor quality residues and other N losses, Nyamangara et al. (2014b) recommended larger N inputs. In a similar vein, Vanlauwe et al. (2014b) proposed that an appropriate use of fertiliser be added as a fourth principle in defining CA. Thereby, crop productivity would be enhanced, and sufficient crop residues would be produced to ensure soil cover.

1.2.2. Intercropping in SSA

Incorporation of legumes into cereal-based cropping systems is an inexpensive means to achieve crop diversification whilst rebuilding soil fertility (Snapp et al., 1998; Thierfelder et al., 2012). Biological N fixation (BNF) from a legume-rhizobia association increases soil N in the soil profile, thereby allowing for sustainable and continued productivity even in low-input cropping systems (Droppelmann et al., 2017). However, in SSA farmers favour the production of cereal crops. They allocate relatively small areas to legumes (Mapfumo and Giller, 2001; Nhemachena et al., 2003), and therefore reap only small benefits from the legume associations (Ncube, 2007). A poor availability of legume seed and dysfunctional markets for produce hinder legume production (Ncube, 2007; Mazvimavi and Twomlow, 2009). Further, farmers are reluctant to devote land to a rotational crop instead of to maize, which is the main food crop in subsistence households in Southern Africa (Thierfelder et al., 2012; Sithole et al., 2016). On the one hand, intercropping cereals with legumes offers potential benefits: it can help to achieve food security and increase cash income for smallholder farmers, whilst enhancing soil fertility and avoiding the perceived area loss entailed by rotation (Ngwira et al., 2012; Rusinamhodzi et al., 2012). On the other hand, intercropping may result in strong interspecies competition, which may lead to crop failure, as reported in earlier studies in southern Zimbabwe (Shumba et al., 1990; Jeranyama et al., 2000). Smallholder farmers appreciate grain legumes for providing both food and soil fertility benefits, but the input of fixed N from grain legumes may only be significant in sustaining the productivity of other crops if substantial amounts of harvest residues are retained *in situ* (Giller, 2001; Sanginga, 2003).

In intercropping systems, two or more crop species or genotypes are grown together and coexist for a time (Brooker et al., 2014). This allows for an intensification of the cropping system. The complementary utilisation of nutrients, water and solar radiation (Rusinamhodzi et al., 2012; Li et al., 2014) enhances the efficiency of land use whilst reducing the risk of complete crop failure (Carlson, 2008). This cropping system therefore provides a high level of production stability compared with monocropping. Intercrops produce more biomass than monocrops, and therefore can help mitigate climate change through C capture in biomass and soils. The performance of intercrop systems depends on the interaction between the crop species (interspecific relations) and the interaction between the crops and the soil environment. Each of these interactions is influenced by management and the local climate (Gou et al., 2016). Ideal intercrops are characterised by a complementary resource use and niche differentiation in space and time, ensuring an optimal resource use efficiency as well as optimal crop yields (Li et al., 2014). In semi-arid SSA poor cowpea yields in intercrops have been attributed to shading by maize, occurring when both crops are planted at the same time (Jeranyama et al., 2000). In semi-arid Zimbabwe, the companion cowpea shaded out the maize in seasons when the rainfall was plentiful (Shumba et al., 1990). It has been suggested that the competition between crops in intercrops can be managed by rearranging the plant populations of the crop species (Vandermeer, 1992) or by staggering the planting dates of the different crop species in relay cropping (Rusinamhodzi et al., 2012). There is, however, limited experimental evidence on the mechanisms that lead to benefits or risks in intercropping systems. In particular, the below-ground processes in intercropping systems remain largely unstudied in the semi-arid areas in SSA, although work that has been done in arid China may offer some clues (Mao et al., 2012). It is important to understand intercropping systems on poor fertility soils in SSA in order to determine strategies that can increase resource use efficiency and give the best returns to investments.

1.3. Study setting

The study was carried out in semi-arid southern Zimbabwe. Semi-arid areas in Southern Africa (Figure 1.1) are characterised by seasonal and highly variable rainfall (inter-annually and intra-seasonally), frequent droughts and flash floods (Spear et al., 2018). Temperatures are predicted to increase in the semi-arid areas in Southern Africa by between 1 and 4 ºC by 2050 and substantial multi-decadal variability in rainfall is predicted to continue, without certainty in the direction of the change in any area (Bhatasara, 2015). The study area lies in Zimbabwe's agro-ecological regions III and IV, which receive 450–800 mm rainfall per annum. Extended mid-season droughts, which affect yields, are common (Vincent et al., 1960). The dominant farming system is of a semi-extensive type, in which crop production is strongly integrated with livestock production. The livestock are kept for supporting crop production through the provision of draught power and manure; they also serve as a capital asset and diversify household income. Most smallholder farmers in the semi-arid areas in Zimbabwe prefer to grow maize rather than other cereals such as sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R. Br.). Maize accounts for more than half of the total cropped area (Twomlow et al., 2006). Minor crops include cowpea (*Vigna unguiculata* (L.) Walp.), groundnut (*Arachis hypogaea* L.) and Bambara nut (*Vigna subterranea* (L.) Verdc.) (Ncube et al., 2009b). The dominant soils are sandy soils which have a limited capacity to store soil organic matter and nutrients (Ncube, 2007). There are some pockets of clay soils in the region (Moyo, 2001). In the smallholder areas of Zimbabwe, the arable fields are individually owned following allocation by headmen. The fields are communally grazed during the dry season, except for securely fenced fields.

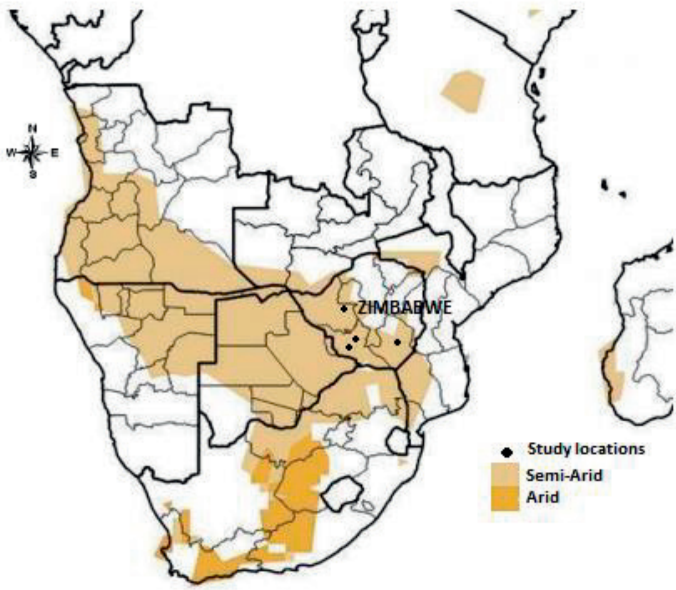


Figure 1.1: Map showing the extent of semi-arid regions of Southern Africa and the study locations in southern Zimbabwe (adapted from Spear et al., 2018)

1.4. Rationale of the study

From 2004 on, CA was promoted in the smallholder areas of Zimbabwe through various donor-funded relief and recovery programmes (Mazvimavi and Twomlow, 2009). Despite a mass outreach, there has been low and selective adoption of CA principles. In some cases, CA technologies were completely abandoned (Pedzisa et al., 2015). Intercropping, though widely practised in the region, is not strategically planned, which accounts for the very low yields from the component crops. A common observation is that the benefits and risks of any soil fertility-enhancing option which includes CA and legume technologies are very context-specific, depending upon, among other factors, location and seasonal variability (Erenstein et al., 2012; Arslan et al., 2014; Giller et al., 2015). It is therefore important to tailor options to contexts in which they perform best, as this improves the options' efficacy and the likelihood of adoption (Descheemaeker et al., 2016b). In matching options such as CA and intercropping to specific contexts, the heterogeneity of farmer households should also be taken into account. The motivation for the adoption of any crop-management option will inevitably be pragmatic and influenced by resource endowments. The impact of climate change and the feasibility of options are also likely to differ among farmers (Traore et al., 2017). Farmers will adopt or adapt options that will give them the maximum utility in terms of resources – labour, land and capital investments (Mazvimavi and Twomlow, 2009). It is also necessary to determine whether cropping systems like CA and intercropping will lead to food security and are resilient to climate change.

Several studies have quantified productivity and resource use efficiencies in CA and intercropping systems in the region (for example, Rusinamhodzi et al. (2011); Rusinamhodzi et al. (2012); Thierfelder et al. (2012); Thierfelder et al. (2013); Nyamangara et al. (2014b)). There is a scarcity of data, however, on the performance of different cropping systems in the long term. In order to assess the suitability and viability of management options and practices, systematic efforts that employ both field and modelling approaches are needed. Such efforts will provide scientists with a better ex ante understanding of CA and intercropping systems and their impacts in the short and long term. This understanding can then be translated into information allowing the implementation of feasible and effective SI and CSA options relevant for smallholder farmers in their contexts. Crop models have facilitated a quantitative understanding of the effects of crop growth and agronomic management factors on crop development and productivity (Chimonyo et al., 2015). The use of these models offers a cost-effective and fast alternative to field trials for exploring cropping scenarios and estimating their productivity under a range of management and environmental conditions. For the crop models to effectively simulate the cropping systems, a lot of data need to be generated and synthesised from field trials. Because of a dearth of relevant data, it has so far been difficult to assess the potential of CA and intercropping systems in semi-arid Southern Africa.

1.5. Objectives of the study

The aim of this study is to determine the potential of CA and intercropping to contribute to sustainable intensification and climate-smart agriculture by quantifying crop productivity and soil N dynamics using field and modelling approaches in semi-arid southern Zimbabwe.

1.5.1. Specific objectives:

In the thesis I aim to:

(i) determine if and how tillage, mulching, manure and fertiliser application and their interactions improve soil mineral N release, plant N uptake and ultimately maize yields through on-farm experimentation;

(ii) calibrate and evaluate the APSIM model and apply it to assess different management scenarios;

(iii) explore the maize-cowpea intercropping above- and below-ground dynamics and the resultant effect of the intercropping system on chemical soil fertility and crop yields;

(iv) use the APSIM model evaluated for maize-cowpea intercropping to identify best management intercropping practises that offer the least risk of failure and lead to improved productivity and food self-sufficiency in the region.

1.6. Thesis outline

In this thesis I quantify selected chemical soil fertility variables and crop yields in maize only and maize-cowpea intercrops following different tillage and fertility amendment applications in the study area (semi-arid southern Zimbabwe). This thesis consists of six chapters: an introductory chapter, four research chapters and a discussion chapter. Each of the research chapters covers one of the four objectives. Figure 1.2 gives an overview of the research objectives and the relationships between the different components of this thesis.

Chapter 2 addresses objective (i). It offers the results of the testing, through field experimentation, of the hypothesis that in cropping systems in semi-arid climates and on poor fertility soils, the benefits of CA and added mulch are in immobilising N, thereby preventing it from being lost from the system and ensuring its availability for later crop growth. The effects of tillage, mulching, manure and fertiliser application and their interactions are determined, by specifying how they affect soil mineral N release, plant N uptake, and maize yields.

Chapter 2 records the response of crops to different management options during the seasons in which the trials were conducted. The results therefore have a limited applicability. In Chapter 3, addressing objective (ii), a crop growth model is applied to understand the processes and the performance of different management options studied in Chapter 2 over a longer period. Here, after model calibration and evaluation, the APSIM model is used to assess the benefits and risks of selected planting dates and their interaction with tillage treatments and mulch and fertility amendment applications in maize cropping systems in the study area.

The hypothesis that maize-cowpea intercropping systems result in overyielding and therefore robust crop production in risky environments is tested in Chapter 4, which addresses objective (iii). The overyielding in intercropping systems will be assumed to result from below-ground root distribution complementarity; therefore, the root length density will be determined. Relay intercropping is proposed to result in temporal niche differentiation leading to improved land-use efficiency. Land equivalent ratios of the maize-cowpea intercrops are also calculated and used as an indicator of land-use efficiency.

Chapter 5 will address objective (iv); here the hypothesis is tested that maize-cowpea intercropping is a low-risk option, furthering household food self-sufficiency. The APSIM model is calibrated and tested, using experimental intercropping data. The results enable the assessment of the cropping option's potential to improve productivity in a predominantly maize-based cropping system and to consistently ensure food self-sufficiency in smallholder households regardless of seasonal variability.

Chapter 6 will synthesise the findings from the previous chapters. The implications of the CA and intercropping systems are discussed, considering the different farm types in semi-arid Zimbabwe. I discuss the question to what extent the cropping systems can be seen as climate-smart and as allowing sustainable intensification. The chapter concludes by discussing the possible strengths and limitations of the approaches used in this study and providing recommendations for further research.

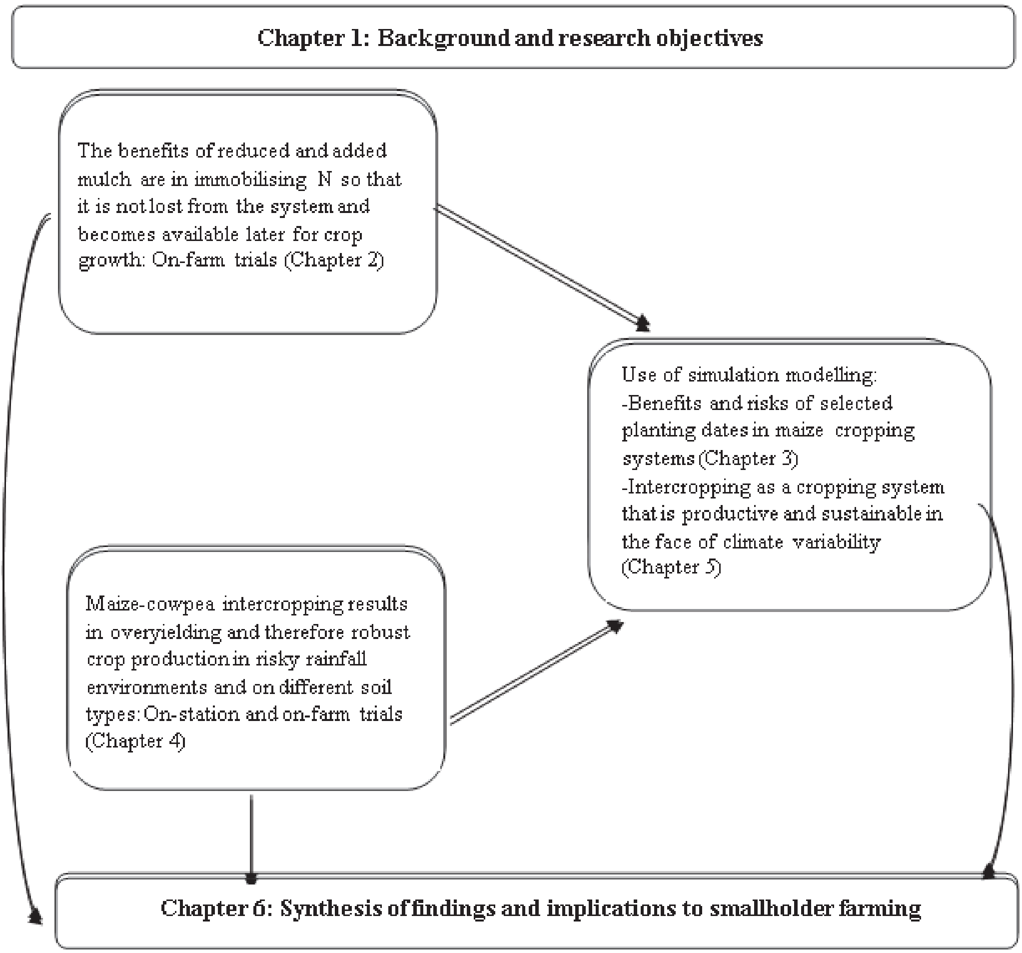


Figure 1.2: Overview of the thesis chapters

CHAPTER 2

Tillage, mulch and fertiliser impacts on soil nitrogen availability and maize production in semi-arid Zimbabwe

This chapter is published as:

Masvaya, E.N., Nyamangara, J., Descheemaeker, K., Giller, K.E., 2017. Tillage, mulch and fertiliser impacts on soil nitrogen availability and maize production in semi-arid Zimbabwe. Soil Tillage Res 168, 125-132.

Abstract

Conservation agriculture has been promoted widely in sub-Saharan African to cushion smallholder farmers against the adverse effects of soil fertility decline, stabilize crop yields and increase resilience to climate change and variability. Our study aimed to determine if aspects of CA, namely tillage and mulching with manure and fertiliser application, improved soil mineral N release, plant N uptake and maize yields in cropping systems on poor soils in semi-arid Matobo, Zimbabwe. The experiment, run for three seasons (2012/13–2014/15), was a split-split plot design with three replicates. Tillage (animal drawn ploughing and ripping) was the main plot treatment and residue application was the sub plot treatment with two levels (100% residues removed or retained after harvest). Five fertility amendments (mineral fertiliser at 0, 20 and 40 kg N ha^{-1}, 5 t ha^{-1} manure only and 5 t ha^{-1} manure + 20 kg N ha^{-1}) were sub-sub plot treatments. Plough tillage stimulated N mineralisation by 4–19 kg N ha^{-1} and maize N uptake 13–23% more than the ripper tillage. When mulch was added to the plough tillage, mineralisation was slowed resulting in less crop N uptake (by 5–19%) compared with no mulch application. N uptake was highest in the manure treatments. N recovery and agronomic N efficiency by maize were highly variable over the three seasons, reflecting the uncertainty complicating farmers' decision making. Nitrogen recovery in the manure treatments was generally poor in the first season resulting in low grain yields in the range 100–260 kg ha^{-1} regardless of tillage, though higher in subsequent seasons. In the second season manure application gave the largest grain yields under the ripper tillage, both with and without mulch averaging 1850 and 2228 kg ha^{-1} respectively. Under the plough tillage, the 40 kg N ha^{-1} treatment gave the highest grain yields of 1985 kg ha^{-1}. In the third season yields were generally poor under all treatments due to low and poorly-distributed rainfall. The CA principles of minimum soil disturbance and maintenance of a permanent mulch cover resulted in reduced soil mineral N availability for crop uptake and poor maize yields. Nutrient inputs through mineral fertilisers and manure are key to ensuring production in such infertile, sandy soils which predominate in semi-arid regions of southern Africa.

Key words: Agronomic efficiency; apparent N recovery; crop residue retention; N mineralisation

2.1. Introduction

Smallholder farmers practicing rainfed agriculture in sub-Saharan Africa (SSA) face a myriad of challenges; these include poor soil fertility, low incomes, labour and land constraints, and are further exacerbated by climate variability (Mupangwa et al., 2012; Rurinda et al., 2013a; Ngoma et al., 2015). Different approaches to improve soil fertility have been proposed including biological nitrogen fixation, soil surface residue management, fertiliser use, enhanced recycling of animal manure and conservation agriculture (Nyamangara et al., 2005; Hobbs, 2007; Ncube et al., 2009a; Mupangwa et al., 2012).

Conservation agriculture (CA) has been promoted throughout sub-humid and semi-arid areas of SSA to cushion smallholder farmers against the adverse effects of soil fertility decline, crop yield decline, and climate change and variability (Hobbs et al., 2008; Ngoma et al., 2015). CA is based on three principles: (i) minimum or no tillage to minimise soil disturbance, (ii) diversification of crop species (often with legumes) grown in rotation and/or association, and (iii) maintaining semi-permanent or permanent soil cover, for example by leaving at least 30% of crop residues (FAO, 2011; Stevenson et al., 2014). This three-pronged approach is reported to have the potential to improve farm resource use efficiency and crop yields especially where moisture is limiting (Hobbs et al., 2008).

Although CA is promoted as a soil-fertility enhancing technology, application of crop residues poor in N, such as cereal stover, may result in prolonged immobilisation of mineral N (Giller et al., 1997). In CA systems, reduced N availability has been attributed to slow residue decomposition and N losses from leaching and denitrification (Angás et al., 2006; Verachtert et al., 2009). Nyamangara et al. (2014b) proposed that larger N inputs may be required under CA to offset the N immobilisation caused by cereal stover. A combination of high quality manure combined with low quality crop residue may reduce N leakage and increase nutrient use efficiency (Kihara et al., 2011). Qin et al. (2015) found that larger N inputs resulted in a positive effect of straw mulch on maize yields. In sub-humid west Africa, maize grain yield in a no-till system was only increased by mulch when fertiliser was also applied (Lal, 1995). However, smallholder farmers in SSA typically apply only small amounts of N which may not be adequate. Vanlauwe et al. (2014b) argue that appropriate fertiliser use should be considered a fourth principle of CA as fertiliser is required to enhance both crop productivity and produce sufficient crop residues to ensure soil cover.

In the current smallholder farming system, the perturbation by tillage stimulates a flush of mineral N (the "Birch effect") with the start of the rains (Chikowo et al., 2004; Giller et al., 2011), whereas soil organic matter may have otherwise been protected from degradation. This "Birch effect" is reported to be short-lived and the decomposition rates may fall back to rates similar to that of an undisturbed soil (Andersson and Giller, 2012). Minimum tillage promoted in smallholder areas in SSA under CA is mainly focused on the hand hoe planting basins (Giller et al., 2011; Nyakudya and Stroosnijder, 2015). Farmers with limited access to draught power and using hand hoes prepare their fields in the dry season in order to spread labour requirements for land preparation, allowing for early planting (Nyamadzawo et al., 2012). However, the use of animal drawn conservation tillage methods such as the ripper and direct seeder provide an opportunity to reduce the labour demand associated with land preparation using hand hoes. Mechanisation can increase productivity per unit area by improving timeliness of farm operations including planting. Early planting may coincide with the "Birch effect" which is beneficial to the crop (Chikowo et al., 2004). Minimum soil disturbance in CA systems, however, results in slower mineralisation compared with conventional tillage because of the minimum disturbance (Chivenge et al., 2007) leading to preservation of soil organic matter from decomposition. Due to this slow mineralisation, (Lal, 2007) suggested that resource poor farmers would be better off ploughing their sandy soils to enhance mineralisation of whatever soil organic matter present to enhance nutrient supply in the short term. There are, however, no detailed studies on seasonal mineral N availability in the semi-arid areas under CA practices such as minimum tillage and crop residue retention particularly on soils of poor fertility that are typical in smallholder agriculture in SSA.

We hypothesise that for cropping systems in semi-arid climates and on poor fertility soils, the benefits of CA and added mulch are in immobilising N so that it is not lost from the system and becomes available later for crop growth. The study specifically aimed at determining if and how tillage, mulching, manure and fertiliser application and their interactions improved soil mineral N release, plant N uptake and ultimately maize yields.

2.2. Materials and methods

2.2.1. Site description

The study was carried out in Nqindi ward, Matobo district, Matabeleland South, Zimbabwe (20 39.58′S, 28 15.58′ E; 900 masl). Matobo district lies in Agroecological Zone IV, characterised by semi-arid climate typical of south west Zimbabwe. Rainfall is unimodal with a distinct wet (November – March) and dry (April - October) season. The wet season receives 450-650 mm annual rainfall with a long term average annual rainfall of 580 mm. Droughts are frequent as are severe dry spells during the wet season. There is only a 45-65% probability of rainfall between October and April exceeding 500 mm (Vincent et al., 1960). The dominant soils are Eutric Arenosols derived from granite (WRB, 2006). These sandy soils constitute >15% of the total land area in Zimbabwe (Hartemink and Huting, 2008). The smallholder farming system in Matabeleland is characterised by privately managed arable fields and communally-managed grazing lands. The arable fields are also communally grazed during the dry season unless if securely fenced off. Matobo district is largely rural (99.4%) with Nqindi ward having a total population of 3507 persons (ZIMSTAT, 2012).

2.2.2. *Trial layout and treatments*

A field experiment was set up in December 2012 on a slightly sloping (< 2%) farmer's field and run for three seasons. The experiment was set up as a split-split plot with plots arranged in a randomised complete block design with three replicates. The tillage system was the main plot treatment with two levels (ox-drawn ploughing and animal drawn ripping) and the mulch management was the sub plot treatment with two levels (100% residue removed, and 100% residues retained after harvest). The mulch sub-treatment was not applied in the 2012/13 season as this was the first season. Five fertility amendments (mineral fertiliser at 0, 20 and 40 kg N ha^{-1}, 5 t ha^{-1} manure only and 5 t ha^{-1} manure + 20 kg N ha^{-1}) were randomised as the sub-sub plot treatment. Plots measured 35 m x 12 m with borders measuring 5 m x 15 m. The third CA principle, crop rotation, was not included in the study because of the short duration of the experiment.

2.2.3. *Trial management*

A basal application of compound D fertiliser (14 kg N ha^{-1}, 12 kg P ha^{-1} and 12 kg K ha^{-1}) or manure was applied in planting furrows. The 0N fertility treatment received a basal application of single super phosphate (12 kg P ha^{-1}) and muriate of potash (12 kg K ha^{-1}). All plots were planted to a short season maize variety (SC403) at 0.9 m x 0.3 m spacing to achieve a plant population of 37 000 plants ha^{-1}. The remainder of the N requirement (6, 20, 26 kg N ha^{-1} for the 20 kg N ha^{-1}, manure + 20 kg N ha^{-1} and 40 kg N ha^{-1} treatments respectively) was applied as a top dressing, using ammonium nitrate (which contained 34.5 % N) at six weeks after planting and when there was enough soil moisture for top dressing. In the second season incessant rains caused waterlogging such that top dressing application was delayed until nine weeks after planting which coincided with the crop flowering stage. The plots were kept weed free by an initial application of glyphosate [N-(phosphono-methyl) glycine] herbicide soon after planting and thereafter by hand hoeing when required. At harvest, in plots where mulch was to be applied, the stover was left on the soil surface. The amount of mulch retained on the surface was dependent on the biomass produced in the previous seasons and ranged from 1–2 t ha^{-1} after the 2012/13 season and 2–4 t ha^{-1} after the 2013/14 season which translated to approximately 10–20 % and 20–30% surface cover at planting respectively (based on visual assessment of ground cover). In the plough tillage treatment, the mulch was ploughed in at land preparation. The plots were located in a fenced off section of the farm and thus no livestock could feed on crop residues during the dry months.

2.2.4. Rainfall data

The farmer hosting the trial was provided with a rain gauge and record book to record daily rainfall for the 2012/13 to 2014/15 seasons. The rainfall records were compared and verified with records from the nearby Matopos Research Institute weather station.

2.2.5. Soil, manure and plant samples

a. Soil sampling and analyses

Initial soil samples were collected from each block at incremental depths of 0.10 m up to 1 m. The samples for each depth were bulked, mixed and analysed separately. Soils were air dried and sieved through a 2 mm sieve and analysed for pH, texture, total and mineral N, Olsen P and organic C (Table 1.1). Aerobically composted manure was collected from one source (Matopos Research Institute's Beef Production Section) to avoid variability. The manure was dug out from the kraals two months prior to application. Manure samples were analysed for total C, N and P using the modified Walkley-Black method with external heating, micro-Kjeldahl and the modified Olsen methods respectively (Anderson and Ingram, 1993). The manure contained 199.0 g C kg^{-1}, 9.8 g N kg^{-1} and 2.6 g P kg^{-1} of manure in 2012/13; 201.1 g C kg^{-1}, 9.5 g N kg^{-1} and 2.7 g P kg^{-1} of manure in 2013/14 and 196.0 g C kg^{-1}, 10.0 g N kg^{-1} and 2.6 g P kg^{-1} of manure in 2014/15.

Table 1.1: Selected soil characteristics of the study site in in Nqindi ward, Matobo district, south-west Zimbabwe

Depth (cm)	pH ($CaCl_2$)	Total N (g kg^{-1})	Organic Carbon (g kg^{-1})	C:N ratio	Mineral N (kg ha^{-1})	Olsen P (mg kg^{-1})	Particle size analysis		
							% Sand	%Silt	%Clay
0 – 10	4.7	0.51	6.6	13.2	23.3	11.1	84	16	0
10 – 20	4.7	0.40	4.2	10.5	26.4	5.5	90	10	0
20 – 30	4.6	0.30	3.5	11.7	33.9	2.6	90	10	0
30 – 40	4.8	0.30	2.5	8.3	15.7	1.3	88	10	2
40 – 50	4.8	0.20	1.4	7.0	6.9	ND*	90	10	0
50 – 60	4.8	0.30	1.1	3.7	11.3	ND	94	6	0
60 – 70	4.9	0.20	0.7	3.5	15.0	ND	90	10	0
70 – 80	5.0	0.18	0.5	3.1	21.4	ND	92	8	0
80 – 90	5.1	0.08	0.3	3.8	11.3	ND	92	8	0
90 – 100	5.0	0.08	0.3	3.8	16.9	ND	86	14	0

ND – not detected

b. *N mineralisation measurements*

Detailed field measurements of inorganic N dynamics were made using *in situ* incubation of undisturbed soil cores (Raison et al., 1987; Anderson and Ingram, 1993; Murwira and Kirchmann, 1993) throughout the 2013/14 growing season. Six tubes (0.35 m long with an internal diameter of 5 cm) were inserted randomly in each plot, soon after land preparation, to a depth of 0.30 m. Three of the tubes were removed immediately and the soil bulked for each plot. Initial mineral N (NH_4^+ and NO_3^-) was determined from these samples. At the surface, the tubes were covered with a polyethylene sheet to prevent water from entering. The polythene sheets were removed every morning for aeration. These tubes were removed and replaced at four-week intervals (days 28, 56, 84 and 112 after planting) until harvesting. N was extracted from the soil samples by shaking the field fresh sample in 0.5 M K_2SO_4 and the NH_4^+-N and NO_3^--N content was determined using methods described in Anderson and Ingram (1993). The net amount of mineralised N was calculated as the difference in mineral N between two points in time ($time_{i+1} - time_i$).

c. *Plant samples and crop yield*

At harvesting maize grain and stover (above-ground biomass minus grain) yields were determined from net plots measuring 4.5 m x 3 m. Grain and stover samples were subsampled and grain yields were adjusted to 12% moisture content. Plant samples were collected at four-week intervals (28 days) from planting until harvest in the 2013/14 season and at harvest at the end of every season. The plant samples were dried at 70 °C for 48 hours and analysed for total N content (Bremner and Mulvaney, 1982) to calculate aboveground N uptake. The apparent N recovery (ANR) was calculated as follows:

$$ANR = \frac{N\ uptake_F - N\ uptake_C}{Fertilizer\ N\ applied}\ X\ 100\%$$

The grain yields were used to calculate agronomic N efficiency (AE) as follows:

$$AE = \frac{Grain\ yield_F - Grain\ yield_C}{Fertilizer\ N\ applied}\ kg\ grain\ kg^{-1} N$$

where F and C denote "fertilised crop" and "unfertilised control" respectively (Mengel et al., 2001)

2.2.6. *Statistical analysis*

All parameters were tested for normality and found to be normally distributed using the Shapiro–Wilk W test (Shapiro and Wilk, 1965). Soil chemical characteristics were square root transformed to homogenise variances (Gomez and Gomez, 1984). Analysis of variance was conducted on the soil N mineralisation, N uptake, ANR, AE, grain and stover yield. The means of the treatments were separated by least significant difference (LSD) at 5% level of significance. All analyses were conducted using Genstat 14th Edition (VSN, 2011).

2.3. Results

2.3.1. *Rainfall distribution*

Rainfall amount, distribution and intensity were erratic and highly variable across the three seasons (Figure 2.1). Severe mid-season dry spells characterised the first (2012/13) and third (2014/15) seasons. The first and third seasons received rainfall totals of 272 and 432 mm that were 54 and 27 % lower than the long term average for the site (590 mm) respectively and were also below the lower limit (450 mm per annum) for the agro-ecological region. Both seasons were classified as droughts and the water-limited crop yield potential was negatively affected. In the second season (2013/14), the rainfall total of 872 mm exceeded the site average by 48 % and several high intensity storms resulted in intermittent waterlogging at the study site.

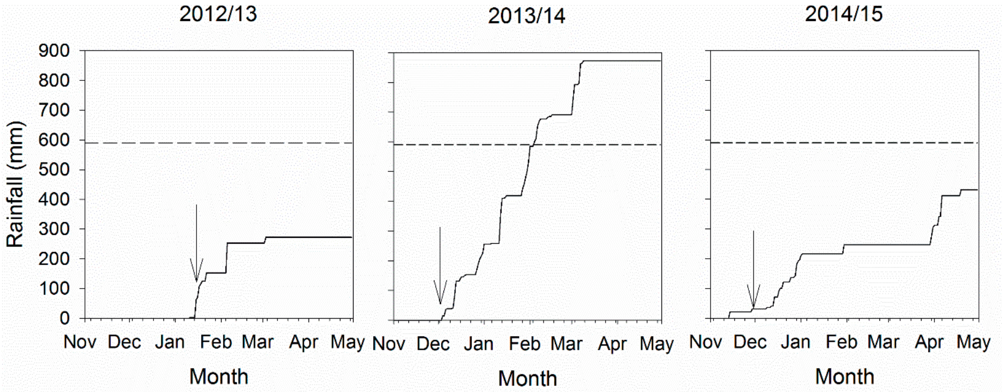


Figure 2.1: Cumulative rainfall (a – c) in Nqindi ward, Matobo district, Zimbabwe from the 2012/13 - 2014/15. The dashed line (a – c) is the long term seasonal average for the region. The solid arrows show the planting date for maize.

2.3.2. Mineral N, N uptake, apparent N recovery and agronomic N efficiency

a. Seasonal Mineral N dynamics and N uptake

There was an initial increase in mineral N in the first 28 days after planting, mineralisation then stabilized until day 84 (vegetative and reproductive stages) and then increased until harvesting (maturity stage) (Figure 2.2). N mineralised during the growing season represented 0.71–2.3% of the total N pool in the 0–0.3 m soil depth. Tillage and fertility amendments had a significant effect on N mineralisation ($P < 0.05$) throughout the season. The plough tillage resulted in more N mineralisation than the ripper tillage by 4–19 kg N ha^{-1}. There was also more mineralisation where N was applied either as mineral fertiliser or cattle manure compared with the control (0N) which generally had the lowest cumulative N mineralisation. Except when ploughing and mulching were applied, the highest cumulative N mineralisation was obtained with the 40N treatment. Mulching on its own generally had no significant effect ($P > 0.05$) on N mineralisation but its interactions with tillage and fertility amendments significantly influenced

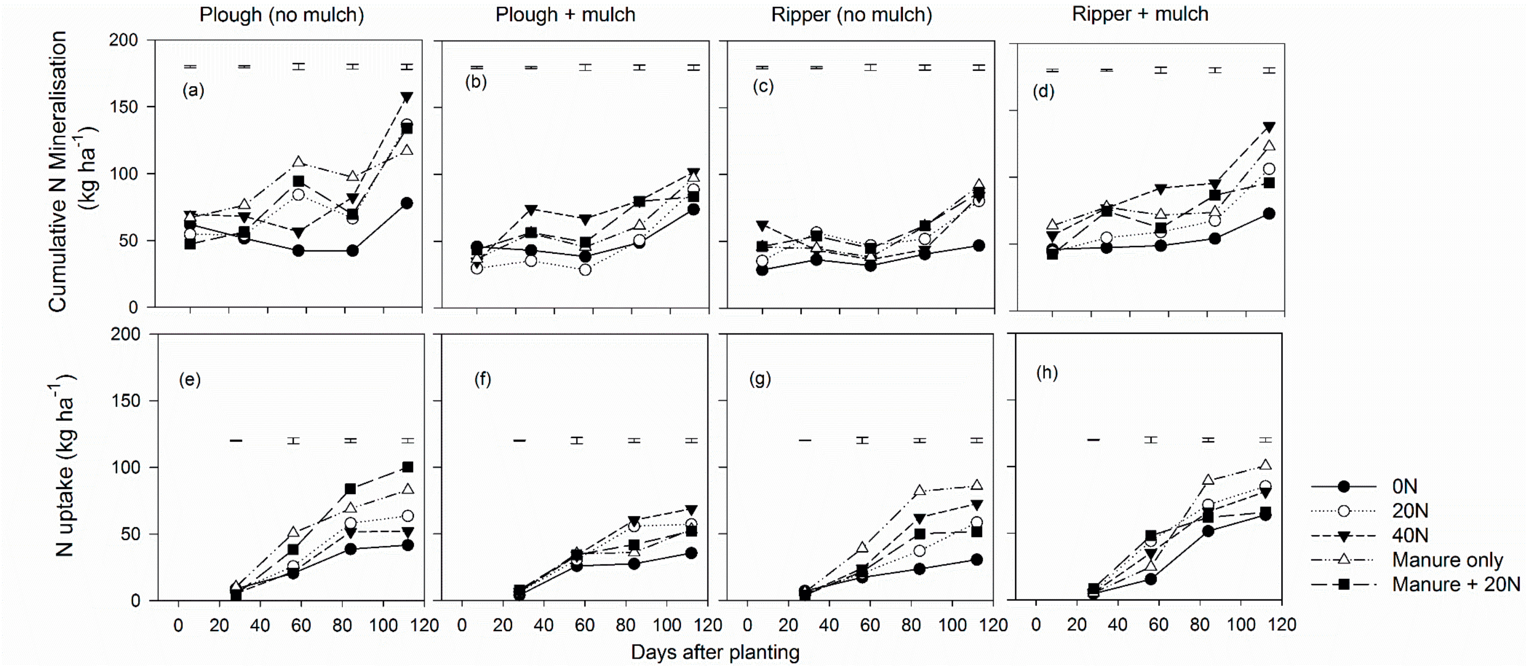


Figure 2.2: Cumulative N Mineralisation estimated from the *in situ* incubation technique (0–30 cm) (a – d) and Net N uptake by maize (above ground parts) (e – h) in the 2013/14 season influenced by soil fertility amendments under plough only (a and e), plough + mulch (b and f), ripper only (c and g) and ripper + mulch (d and h) on a sandy soil in Nqindi ward, Matobo district, south-west Zimbabwe. Bars represent standard errors of the difference of the means for the effect of the interaction of tillage, mulch and fertility amendment on cumulative N mineralisation and N uptake on days 28, 56, 84 and 112.

N mineralisation. When mulch was ploughed in, there was a decrease in mineralisation compared with ploughing without mulch by 8–15 kg N ha^{-1} (13–40%) across fertility amendment treatments, indicating N immobilisation. Under the ripper tillage, however, mulching resulted in a 16–100% higher mineralisation compared to no mulching. N mineralisation followed the trend plough (no mulch) > ripper + mulch > plough + mulch > ripper (no mulch) regardless of fertility amendment.

N uptake generally increased until day 84 when total plant N levelled off. Maize that received N fertility amendments had significantly greater N uptake ($P < 0.05$) throughout the season than the 0N control (Figure 2.2). Except for the plough + mulch treatment, N uptake was highest in the manure treatments. Tillage had a significant effect ($P < 0.05$) on total N uptake at day 84 and day 112. Maize N uptake under the ripper tillage was 13–23 % lower than the plough tillage. Mulching had a significant effect on N uptake by maize ($P < 0.05$). Incorporation of mulch under the plough tillage resulted in significantly lower N uptake ($P < 0.05$) by 5–19 % when compared with plough without mulch. N uptake and followed the trend plough (no mulch) > ripper + mulch > ripper (no mulch) > plough + mulch. The effect of the top dressing N fertiliser, applied at 48 days after planting, was not apparent in both the cumulative N mineralisation and the N uptake.

b. Apparent N recovery (ANR) and agronomic N efficiency (AE)

The ANR and AE were very variable across the three seasons and treatments (Table 2.2). Only fertility amendments had a significant effect ($P < 0.05$) on both the ANR and AE in the first season and on ANR in the second season. In the second season, fertility amendment significantly affected ANR with recovery highest under the 20N treatment regardless of tillage and mulch application. Tillage and mulching had no significant effect on both ANR and AE in all three seasons. The interactions of mulch and fertility amendments and of all three treatments

Table 2.2: Effect of tillage, mulching and fertility amendment on apparent N recovery and agronomic N use efficiency over three seasons (2012/13 – 2014/15) in Nqindi ward, Matobo district, south-west Zimbabwe

Tillage	Mulch treatment	Fertility treatment	% Apparent N recovery			Agronomic N efficiency (kg grain kg^{-1} N)		
			2012/13	2013/14	2014/15	2012/13	2013/14	2014/15
Plough	No mulch	20N	67.3	109.2	12.2	19.9	19.2	0.5
		40N	19.4	26.1	15.1	5.7	2.0	0.7
		Manure only	22.0	83.6	14.2	-1.1	27.9	1.1
		Manure + 20N	16.6	83.4	11.5	-1.9	21.6	-0.6
	Mulch	20N	-	107.7	7.8	-	21.3	-4.7
		40N	-	82.8	7.1	-	25.5	2.1
		Manure only	-	35.4	36.4	-	27.7	-1.6
		Manure + 20N	-	23.4	14.7	-	8.6	-0.7
Ripping	No mulch	20N	42.9	136.1	5.6	8.9	3.6	-1.7
		40N	8.3	104.8	5.9	8.7	4.8	0.5
		Manure only	13.9	110.1	18.9	2.9	12.4	-0.2
		Manure + 20N	12.2	59.9	16.2	-0.2	13.2	-0.7
	Mulch	20N	-	107.2	2.6	-	8.4	0.3
		40N	-	43.6	26.7	-	44.2	0.7
		Manure only	-	73.7	23.8	-	18.8	1.3
		Manure + 20N	-	2.4	8.0	-	18.1	0.4

Factor	P value	SED	P value	SED	P value	SED	P value	SED	P value	SED	P value	SED
Tillage type	0.463	13.37	0.199	2.34	0.534	8.49	0.90	3.96	0.804	3.61	0.574	0.72
Mulch	-	-	0.348	18.19	0.776	4.55	-	-	0.305	11.28	0.881	1.53
Fertility amendment	**0.007***	10.95	**0.014**	16.21	0.165	5.95	**<0.01**	2.72	0.181	8.53	0.041	0.79
Tillage x Mulch	-	-	0.945	18.33	0.271	9.63	-	-	0.962	11.85	0.404	1.69
Tillage x Fertility amendment	0.813	18.93	0.496	19.99	0.095	11.19	0.056	5.25	0.588	11.38	0.569	1.24
Mulch x Fertility	-	-	**<0.001**	26.92	**0.031**	8.59	-	-	0.159	15.62	0.441	1.83
Tillage x Mulch x Fertility	-	-	**<0.001**	33.54	**0.015**	14.11	-	-	0.378	19.32	0.074	2.21

(tillage, mulch and fertility amendments) had significant effects on ANR in the second and third seasons although these did not follow similar trends between the two seasons. ANR was highest under the ripper (no mulch) + 20N fertility treatment in the second season whilst in the third season, ANR was highest the plough + mulch + manure only. The third season had the poorest and highly variable ANR and AE. All treatments had ANR in the range 7.0–40.4 % and averaged 15%. This season had the least AE that ranged (-4.7)–1.3 kg grain kg^{-1} N and averaged (-0.16) kg grain kg^{-1} N. There were, however, no individual treatment effects but interaction effects of mulch and fertility amendments and tillage, mulch and fertility amendments on N recovered by the maize crop in the third season. There were no significant effects of tillage, mulch, fertility amendments and their interactions on AE in the second and third seasons.

2.1.1. Maize yields in response to tillage, mulch and fertility amendment application

Grain yields in the first season were low and in the range 105–720 kg ha^{-1} under both tillage treatments and across all fertility amendments (Figure 2.3). In this season, ploughing gave higher grain (200–720 kg ha^{-1}) and stover yields (1500–2100 kg ha^{-1}) compared with ripping (105–454 kg ha^{-1} grain and 860–1500 kg ha^{-1} stover) although not significant for grain ($P < 0.05$). The harvest indices, although not significant, were generally higher under the plough tillage compared with ripping by 1–10%. There were significant differences in grain yields resulting from the application of different fertility amendments. Both manure treatments resulted in low grain yields under both tillage treatments. The highest grain yields were obtained when mineral N fertiliser was added (both the 20N and 40N treatments). The effects of tillage, mulch, fertility amendments and their interactions on stover yields and the harvest indices were no significant.

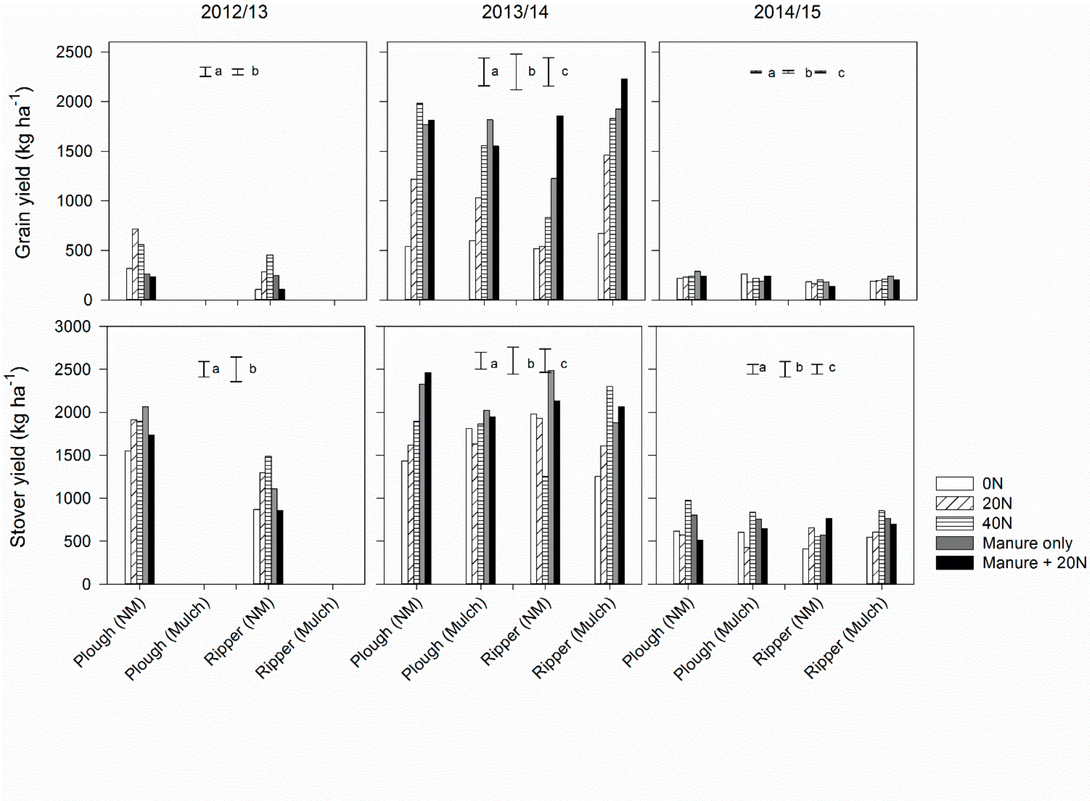


Figure 2.3: Maize grain and stover yields in Nqindi ward, Matobo district (2012/13-2014/15 season). Bars represent standard errors of the difference of the means for factors (a) Tillage, (b) Fertility amendment and (c) Mulching.

Although there were no significant differences in grain and stover yields resulting from tillage, ripping, in general, significantly depressed grain yields by 4–60% in the second season when compared with ploughing. The effect of mulch only on grain and stover yields was not significant ($P < 0.05$). Mulching significantly increased grain yields in all fertility treatments under the ripper tillage except for the 0N and manure only treatments. However, mulching reduced grain yields when combined with ploughing under the 20N, 40N and manure + 20N fertility treatments by between 2 and 60%. In the second season, fertility amendments alone had a significant effect on grain and stover yields. Manure application gave the highest grain yields under the ripper tillage, both with and without mulch (averaging 1850 and 2228 kg ha^{-1} respectively). Under the plough tillage, the 40N treatment gave the highest grain yields of 1985 kg ha^{-1} on average whilst the manure treatments resulted in the highest stover yields. The harvest indices were not significant for tillage, mulch, fertility amendments and their interactions

In the third season, the effects of tillage, mulch and fertility amendment treatment on grain and stover yields and harvest indices were not significant. Grain and stover yields were generally poor due to low and poorly distributed rainfall. Grain yields were in the range 200–270 kg ha^{-1}, whilst stover yields 400–900 kg ha^{-1}. The grain yields followed the same trends as in the previous seasons.

2.2.Discussion

2.2.1. N mineralisation patterns, uptake and recovery

In general, the Conservation Agriculture principles of minimum soil disturbance and maintenance of a permanent soil cover (mulch) resulted in reduced soil mineral N availability for crop uptake and ultimately low yields from a poor fertility soil in semi-arid Zimbabwe. Ploughing enhances the mineralisation of organic matter in the soil by exposing previously unexposed soil surfaces to attack by microbes and by providing the latter with new sources of energy (Peigné et al., 2007). Compared with ploughing, ripper tillage causes less soil disturbance and exposes the soil organic matter less to the climatic elements and soil microbes, with slower mineralisation as a result. Our results concur with studies that reported slower mineralisation of organic matter under reduced tillage compared with conventional tillage because of less topsoil disturbance (Bationo et al., 2007; Chivenge et al., 2007). This low mineralisation associated with the ripper tillage resulted in low N uptake and consequently decreased grain yields (in the second season) when compared with the plough tillage when no mulch was applied under both tillage treatments.

When mulch was ploughed in, mineralisation was slowed compared with no mulch application. Soil inorganic N may have been immobilised during the decomposition of the applied mulch with a large C:N ratio averaging 53:1 whilst the soil's C:N ratio averaged 12:1. The C:N ratio of crop residues is a good indicator of whether mineralisation or immobilisation will dominate during decomposition. N release patterns are regulated by the initial composition of the crop residues and the stoichiometric requirements of the decomposers (Palm et al., 2001; Manzoni et al., 2008). Mineral fertilisers provide a ready source of nutrients and may stimulate decomposition of cereal stover (Sakala et al., 2000).

We observed substantial N mineralisation at the end of the season, which produced a pool of mineral N that may be held in the soil over the dry season due to the absence of leaching and reduced N uptake by plants (Rasouli et al., 2014). Perturbation by tillage further stimulates a flush of N mineralisation with the start of the rains. Crops are not able to store surplus N to improve yields and grain quality in later vegetative stages (Verhulst et al., 2014). This implies that the N mineralised at the end of the season, as well as that which becomes available through the "Birch effect", may well be lost due to the first rains ahead of planting or before the next crop is established and growing actively. In their study, (Chikowo et al., 2003) concluded that there is an inherent problem in managing N originating from mineralisation as it accumulates at the beginning of the season, well ahead of peak demand and root development by crops, and is susceptible to leaching.

There was a decrease in observed mineralisation in the critical vegetative stage. For semi-arid regions, (Piha, 1993) suggested split applications of N fertiliser at rates based on future expected rainfall to maximise fertiliser use and recovery efficiency. In our experiment, we applied fertiliser at planting and at 48 days after planting. The second N application did not result in a significant observed increase in N availability. It may have been because at the start of the incubation experiment, the mineral N was increased by the basal fertiliser application such that a further addition in mineral N later on in the season may not have been apparent. The success of split N application may depend on the number of fertiliser applications and their timing and quantities, on weather conditions and on the amount of available soil mineral N (Piha, 1993; Verhulst et al., 2014). In our experiment, the timing of the second application in the second season was affected by waterlogging. We had to wait until all the water had infiltrated before we could apply the top dressing fertiliser. The second application coincided with the maize flowering stage, a critical growth stage, which may have contributed to the higher yields observed in this season in conjunction with the higher rainfall.

The N recovery and agronomic N efficiency by maize were highly variable over the three seasons, which reflects the uncertainty complicating farmers' decision making. Nitrogen recovery by maize in the manure treatments was generally poor in the first season, though greater in subsequent seasons, as reported earlier (Nyamangara et al., 2004). The authors attributed the slow N mineralisation from manure to the C and N stabilisation which occurred during aerobic decomposition of the manure during storage. N recovery from the manure +

20N treatment was very high in the second season, which is attributed to residual fertility from the previous season, which was very dry. Farmers should use resources available to them as fertility amendments to supply N to the maize cropping system, either as organic manures or as mineral fertilisers. However, manure application is a preserve of cattle owners and mineral fertilisers remain unaffordable to most smallholder farmers in SSA including Zimbabwe (Mtambanengwe and Mapfumo, 2005; Mazvimavi and Twomlow, 2009; Chianu et al., 2012).

Maize grain and stover yields were affected by the quality of the seasons in terms of rainfall amount and seasonal distribution. Two of the three seasons (the first and third) in which the experiment was conducted were classified as droughts, negatively affecting yields. Low rainfall and poor rainfall distribution are a characteristic of and major challenges to crop production in semi-arid areas of southern Africa (Nyamangara et al., 2014b). Thierfelder et al. (2013) reported that CA systems showed great potential in mitigating the effects of seasonal dry-spells, as the high infiltration rates in CA would lead to greater soil moisture availability for crops. This was, however, not the case in our experiment (with a mulch cover of 0 and 2-4 t ha^{-1} in the first and third seasons respectively) as the two seasons were characterised by long dry spells midway through the season lasting more than 21 days.

2.2.2. Methodological limitations of the in situ incubation method

One limitation of the *in situ* method in estimating N mineralisation is that in replacing soil cores into the soil, maize roots may have been severed and retained within the tubes. These roots may have immobilised N during their decay leading to an underestimation of N mineralisation (Raison et al., 1987). Conversely N may have been released during their decomposition leading to an overestimation of N mineralisation (Khanna and Raison, 2013). Furthermore, *in situ* core methods promote the accumulation of NH_4^+-N (by preventing uptake). The NH_4^+-N may be nitrified leading to accumulation of NO_3^--N which may increase denitrification (Raison et al., 1987). We measured mineralisation in the top 0.3 m which is the plough layer although maize roots explore deeper soil horizons. Hence our N mineralisation results may not account for all of the N available to the crop. Nevertheless, the *in situ* incubation method gave useful insights into the differences among treatments (Figure 2.2).

2.2.3. Input access: drawbacks of smallholder farmers

The principles of CA minimum soil disturbance and maintenance of a mulch resulted in reduced mineralisation (Figure 2.2) resulting in low yields whilst a combination of the principles resulted in high mineralisation and yields comparable to conventional plough minus mulch (Figure 2.3). Fertiliser application resulted in yield benefits regardless of tillage or mulch application particularly when moisture was not limiting. The potential benefits of the tillage, mulch application and fertility amendment application on crop productivity and soil N dynamics are related to the management intensity individual farmers can achieve. The use of mineral fertilisers is key to production yet their widespread use by smallholder farmers remains low as availability in rural areas remains a key constraint to their use as well as their cost remains prohibitive. With over 40% of households in semi-arid Zimbabwe having access to draught animals (ZimVac, 2012), the use of the ripper may provide a solution to curb the chronic labour demand associated with land preparation in manual forms of in smallholder communities. However, only a few equipment manufacturers have been producing ripper tine attachments for the mouldboard plough and these require pre-financing for production. There are poor market linkages between smallholder farmers market linkages between smallholder farmers and local agro-dealers, and agro-dealers and input suppliers. At present, input producers are unwilling to provide fertilisers or equipment such as rippers on credit to local farmers in dry areas as risks of crop failure from the erratic rainfall pattern are high. The high likelihood of crop failure from the poor rainfall in the semi-arid areas is in itself a disincentive for farmers to the purchase and use of fertilisers. Access to inputs still remains a challenge especially to poor farmers who are often concerned with meeting the immediate household food requirements over the improvement and maintenance of soil fertility on these sandy soils important in the long term.

2.3. Conclusions

We observed that mineralisation, N uptake and crop yields were stimulated under plough tillage compared with the ripper tillage. When mulch was added together with plough tillage, the mineralisation of N, crop N uptake and maize yields were decreased compared with no mulch application under the same tillage. When combined together, following two principles of CA, the ripper tillage and mulch application did not reduce mineralisation and resulted in yields comparable to those obtained under the plough tillage without mulch. Nitrogen containing fertiliser and manure resulted in more available N for the crop and increased grain yields. We conclude that nutrient inputs are key to ensuring production in the infertile, sandy soils predominant in semi-arid regions of southern Africa.

Acknowledgements

We thank the Netherlands Organization for International Cooperation in Higher Education (NUFFIC) for funding.

CHAPTER 3

Risk management options in maize cropping systems in semi-arid areas of Southern Africa

This chapter is published as:

Masvaya, E.N., Nyamangara, J., Giller, K.E., Descheemaeker, K., 2018. Risk management options in maize cropping systems in semi-arid areas of Southern Africa. Field Crop Res 228, 110-121**.**

Abstract

Although rainfed cropping in semi-arid areas is risky due to frequent droughts and dry spells, planting early with the first rains is often expected to result in yield benefits. We hypothesised that planting early leads to yield benefits if the planting coincides with a mineral N flush at the start of the season but leads to crop failure if there is a false start to the cropping season. The effects of different management options, including tillage (ploughing and ripping), mulch (two levels 0 and 2 t ha^{-1}) and fertility amendments (five treatments: 0; 20 and 40 kg N ha^{-1}; 5 t manure and 5 t manure + 20 kg N ha^{-1}) on grain yields were simulated using the calibrated and tested APSIM model over a 30-year period (1984 – 2015). Yields were simulated and compared across seven planting date scenarios (1 November, 15 November, 30 November, 15 December, 31 December, 15 January and planting when cumulative rainfall of 20 mm was received in three consecutive days). The best yielding scenario (planting on 15-Nov) had an average yield of 755 kg ha^{-1} whereas very late planting (15 January) gave the worst yield of 550 kg ha^{-1} averaged over 30 seasons. Early planting (1-Nov to 15-Nov) resulted in exceeding the food self-sufficiency threshold of 720 kg ha^{-1} in 50 – 90 % of the cases, as well as a low probability of crop failure, ranging from 0 to 40 %. Grain yield penalties due to a false start followed the trend: ripper + mulch > plough + mulch > ripper (no mulch) averaging 256, 190 and 182 kg ha^{-1} respectively across all the fertility treatments. The model simulated the occurrence of the mineral N flush with the first rains in 15 – 27 of 30 seasons, depending on the mulch and fertility amendment. Its coincidence with planting resulted in average yield benefits of 712, 452, 382 and 210 kg ha^{-1} for the following respective planting dates: 1Nov, 15Nov, 30 Nov, variable date when >20 mm rainfall received. The study provided insights to inform strategic, tactical, and operational farm management in a risky environment. Strategic application of different agronomic management practices such as early planting in combination with reduced tillage, mulch and N containing fertility amendments is critical to reduce risk of crop failure in the smallholder cropping systems of semi-arid areas of southern Africa and achieve the best yields possible.

Key words: False season start; Household maize grain requirement; N mineralisation; N stress; Planting date strategy; Semi-arid

3.1. Introduction

Smallholder farmers in sub-Saharan Africa (SSA) face many production constraints that are exacerbated by climate variability and change. Droughts and dry spells are frequently experienced in semi-arid Zimbabwe during the growing season, making rain-fed cropping risky (Baudron et al., 2012b; Rurinda et al., 2013b). The climate in Zimbabwe is controlled by global atmospheric circulation patterns, chief amongst them the movement of the inter-tropical convergence zone (ITCZ) in the north and the tropical temperate troughs (TTTs) further south which determine the annual seasonality of precipitation across tropical Africa (Tadross et al., 2007; Mavhura et al., 2015). Mid-season dry spells of 10–20 days commonly occur around late December/early January following the movements of these systems (Tadross et al., 2007) and are disastrous for crop production if the air systems migrate too far such that the dry spells become extremely long. The inter-seasonal rainfall variability in semi-arid Zimbabwe is characterised by early rains in some seasons whilst the rain may arrive late in others (Mupangwa et al., 2011a). Also, at the end of the growing season rains may stop early, which happens regularly in semi-arid parts of Zimbabwe (Mupangwa et al., 2011a). This rainfall variability makes the selection of crop types and varieties, and the planning of planting dates critical for successful cropping in rain-fed systems.

The impact of planting date on crop production has been evaluated in Zimbabwe with a focus on escaping dry spells that typically occur in January (Spear, 1968). It has been recommended that farmers plant with the first effective rains to minimise reduction in maize grain yield of up to 32% associated with delayed planting attributed to the shorter day-lengths as the season progresses (Shumba et al., 1992). However, in a crop modelling study in semi-arid Zimbabwe, Rurinda et al. (2015) found that planting in current and future climates (up to 2099) can be delayed to some extent without any yield penalties. Nevertheless, in the current farming systems, the shortage of animal traction for land preparation often leads to delays in planting time, resulting in serious yield penalties if the short window of the first rains when the soil is wet enough to be tilled is missed.

Farmers use a range of planting dates and plant at almost any opportunity because of the rainfall pattern, input access, and the availability of draught power and labour (Milgroom and Giller, 2013; Rurinda et al., 2013b; Nyagumbo et al., 2017). Conservation agriculture (CA) can provide a major benefit by reducing the tillage requirement, thus allowing farmers to plant on time at the start of the season. Nyagumbo (2008) indicated that in Zimbabwean cropping systems, the major benefit of CA for crop yields comes from timely planting and not from the specific tillage employed. The onset of the first rains stimulates soil microbial activity resulting in a peak of soil N mineralisation (Birch, 1960). The mineral N flush (Birch effect) is usually of short duration due to losses through leaching, denitrification, volatilisation and plant uptake (Chikowo et al., 2003; Bognonkpe and Becker, 2009). The magnitude of the mineral N flush is dependent on a number of factors which include the quantity and quality of organic matter (Franzluebbers et al., 1995), the duration of the dry spell at the onset of the rainy season and rainfall variables such as the intensity and quantity of rainfall (Bognonkpe and Becker, 2009). Planting early with the first rains may be beneficial to crops if the planting coincides with this mineral N flush or risky if these first rains appear to be a false start to the cropping season. Such false starts are not uncommon in semi-arid areas, as early-season rains are commonly followed by a dry spell, which is detrimental to crop establishment (Chikowo, 2011).

Several approaches from simple functional approaches to predict net N mineralisation (Stanford and Smith, 1972; Cabrera, 1993) to mechanistic approaches for simulating mineralisation-immobilisation turnover in soils have been used to model and thus describe N mineralisation kinetics in soils (Benbi and Richter, 2002; Mohanty et al., 2011). The

Agricultural Production Simulator Model (APSIM) is a crop growth simulation model that can be used to predict N dynamics in soils. APSIM has been calibrated and validated for Zimbabwean conditions and crop cultivars. The model has been used previously to simulate maize response to N application (Shamudzarira and Robertson, 2002) and manure inputs in humid and dry regions (Chivenge et al., 2007), N and water stress dynamics in cereal-legume rotations (Ncube et al., 2009a), the effects of mulch on crop yields and soil water dynamics under different tillage systems (Mupangwa et al., 2011b) and as a climate risk assessment tool (Chikowo, 2011; Rurinda et al., 2015). Experimental data on the effects of tillage systems on mineralisation and crop yields in the variable climates of SSA are not readily available thus calibrated and tested models such as APSIM can potentially be used as tools for strategic, tactical and operational decision support in crop management on-farm (Matthews et al., 2002).

It is important to know which management options in terms of planting dates, tillage and fertility amendments offer the greatest pay offs in terms of crop yields in different types of seasons, and in terms of reducing the risk of crop failure. Such information can enable farmers to plan on how to optimise resources available to improve crop production by being able to synchronise nutrient supply with crop demands. We hypothesised that under the current climate of semi-arid southern Africa, planting early is risky, as it: (1) leads to yield benefits to crops if the planting coincides with a mineral N flush at the start of the season, but (2) leads to crop failure if there is a false start to the cropping season. The specific objectives of this study were to (a) calibrate and test the APSIM model for maize production and N mineralisation in semi-arid Zimbabwe (b) to simulate the effects of tillage system and fertilisation on seasonal N mineralisation and crop yields and (c) apply the model to determine the effect of different planting date, tillage and soil fertility management strategies on the probabilities of experiencing complete crop failure and achieving maize grain yields that ensure household food self-sufficiency under the current climate.

3.2. Materials and methods

3.2.1. Study site

The site chosen for this study was Nqindi ward, Matobo district, Matabeleland South, Zimbabwe (20 39.58′S, 28 15.58′ E; 900 masl). The district lies in Agroecological Zone IV, characterised by semi-arid climate. Rainfall is unimodal with a distinct wet (November – March) and dry (April - October) season. The long-term average rainfall in the district is 580 mm. Droughts are frequent as are severe dry spells during the wet season (Vincent et al., 1960). The dominant soils are Eutric Arenosols derived from granite (WRB, 2006).

3.2.2. Field experiment set up for model calibration and testing

Maize growth and development data for the model calibration and testing were collected from an on-farm field trial carried out in Nqindi ward for three seasons 2012/13–2014/15. The field trial was set up as a split-split plot with plots arranged in a randomised complete block design with three replicates. The tillage system was the main plot treatment with two levels (ox-drawn ploughing and animal drawn ripping, both to a plough depth of 0.15 m) and the mulch management was the sub plot treatment with two levels (100% residue removed, and 100% residues retained after harvest). The mulch sub-treatment was not applied in the 2012/13 season as this was the first season. In subsequent seasons, the mulch retained averaged 2 t ha^{-1}. With tillage, a fraction of the retained residues was incorporated, approximating 20 and 80 % under the ripper and plough tillage respectively. Five fertility amendments (mineral fertiliser at 0, 20 and 40 kg N ha^{-1}, 5 t ha^{-1} manure only and 5 t ha^{-1} manure + 20 kg N ha^{-1}) were randomised as the sub-sub plot treatment. The mineral fertiliser was applied at planting at a rate of 14 kg N ha^{-1}, the difference in N for the 20 and 40 kg N ha^{-1} treatment was applied six weeks after planting as top dressing. With the manure treatments, the manure was applied at planting, in the manure + 20 kg N ha^{-1} treatment, the mineral fertiliser was applied at six weeks after planting as top dressing. A short duration hybrid maize variety SC403 was planted in the trial (Masvaya et al., 2017b). Plant (at harvesting) and manure samples were analysed for total C and N content (Bremner and Mulvaney, 1982; Anderson and Ingram, 1993) to determine the C:N ratios which were 80 and 20 respectively.

Initial soil samples were collected from each block at incremental depths of 0.10 m up to 1 m, the soil depth. The samples for each depth were bulked, mixed and analysed separately. Soils were air dried, passed through a 2 mm sieve and analysed for pH, texture, total and mineral N, Olsen P and organic C (Anderson and Ingram, 1993). Bulk density measurements were also derived from field measurements.

Nitrogen mineralisation in the field trial was estimated by an *in situ* incubation technique. Detailed field measurements of inorganic N dynamics were made using *in situ* incubation of undisturbed soil cores throughout the 2013/14 growing season (Masvaya et al., 2017b). Mineral N (NH_4^+ and NO_3^-) was determined from the soil samples from the cores removed and replaced at four-week intervals from planting until harvesting (days 28, 56, 84 and 112 after planting). N was extracted from the soil samples by shaking the field fresh sample in 0.5 M K_2SO_4 and the NH_4^+-N and NO_3^--N content was determined using methods described in Anderson and Ingram (1993). The net amount of mineralised N was calculated as the difference in mineral N between two points in time ($time_{i+1} – time_i$).

3.2.3. Climate data

Long term daily maximum and minimum temperature, radiation and rainfall data (1984–2015) was obtained from the national weather station at Matopos Research Institute. The average seasonal rainfall for the 30-year period was 567 mm; the average maximum and minimum temperatures were 26.2 ºC and 11.6 ºC respectively whilst the solar radiation averaged 21.7 MJm^{-2}. Daily rainfall measurements were also collected from the farms hosting the trial between October 2012 and December 2014. The long-term rainfall data was used to determine seasons with a false start.

For semi-arid Zimbabwe, the start of the season has been defined as the first day after 1 October when the rainfall accumulated over 1 or 2 days is at least 20 mm and not followed by a period of more than 10 consecutive dry days in the following 30 days (Stern et al., 2006; Mupangwa et al., 2011a). A false start to the season would therefore occur when 20 mm of rainfall or more is received in 1 to 2 days then followed by a dry spell of more than 10 consecutive dry days.

3.2.4. Model description

In this study, APSIM version 7.8 (available at www.apsim.info) was used to simulate the crop system. The system was represented by four modules which require several parameters: the soil water (SOILWAT2), soil N and fertiliser module (SOILN2), surface organic matter for crop residue dynamics (surfaceOM) and the maize module. The APSIM crop module contains a short duration hybrid maize variety SC401 which was used to represent the SC403 used in the field trials.

Description of N mineralisation in the APSIM SoilN2 module

In APSIM, the SoilN2 module simulates the transformations of C and N in the soil which include fresh organic matter decomposition, N mineralisation and immobilisation, urea hydrolysis, ammonification, nitrification and denitrification (Gaydon et al., 2012). It operates on a daily time step, and decomposition of the fresh organic matter pool (FOM) occurs simultaneously in the two soil organic matter pools (BIOM and HUM) (Mohanty et al., 2011). The flows between the different pools are calculated in terms of carbon, with the corresponding nitrogen flows depending on the C:N ratio of the receiving pool (www.apsim.info). A constant C:N is assumed for BIOM; C:N for HUM is derived from the C:N ratio of the soil which is an input. Mineralisation in APSIM is also driven by soil moisture and temperature. Decomposition of BIOM and HUM pools are calculated as first-order processes (Probert et al., 1998), as proposed in empirical models (Stanford and Smith, 1972; Cabrera and Kissel, 1988). APSIM also assumes that part of the HUM pool is stable and the decomposition rate of the HUM pool is calculated with the equation of Bartholomew and Kirkham (1960) which follows the two-pool exponential mineralisation model (Probert et al., 1998; Probert et al., 2005).

3.2.5. APSIM model parameterisation

The soil parameters (Table 3.1) were partly derived from the soil analysis described in section 2.2). For the SOILWAT2 module, the soil characteristics of drained upper limit (DUL), saturation (SAT) and lower limit (LL15) (Table 3.1) were adopted from the sandy soils at Lucydale farm, Matopos Research Station (Masikati, 2006), which are similar in terms of parent material and texture to those at the study site in Nqindi, Matobo district. The U and CONA were set at 8.0 mm day^{-1} and 3.5 mm day^{-1} respectively, values suitable for tropical conditions and a value of 0.7 was used for the SWCON, a coefficient that specifies the proportion of the water in excess of field capacity that drains to the next layer in one day (Chikowo, 2011; Rurinda, 2014).

The bare runoff curve number was set at 85 and 55 for the plough and ripper tillage respectively. These curve numbers were chosen to account for the high runoff and low infiltration associated with excessive ploughing of sandy soils (plough treatment), and for high infiltration rates and low runoff under conservation tillage (ripper treatment) (USDA-SCS, 1986; Mupangwa, 2010). In addition to the difference in curve number, the user defined fraction of surface residues to incorporate under the plough and ripper tillage was set at 0.8 and 0.2 respectively.

The two mulch levels of the experiment (Section 3.2.1) were mimicked in the surfaceOM module where the initial surface residue was defined: 0 or 2 000 kg ha^{-1} for the 0 and 100%

Table 3.1: Soil physical and chemical properties used for the APSIM simulations

Soil depth (m)	Bulk density (Mgm^{-3})	pH (H_2O)	OC (%)	LL15 (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	NO_3-N (kg ha^{-1})	NH_4-N (kg ha^{-1})
0.00-0.15	1.43	5.69	0.66	0.04	0.14	0.44	0.51	0.42
0.15-0.30	1.42	5.68	0.42	0.07	0.15	0.45	0.84	0.62
0.30-0.45	1.42	5.76	0.35	0.13	0.20	0.45	1.18	0.62
0.45-0.60	1.55	5.77	0.25	0.13	0.20	0.40	0.55	0.67
0.60-0.75	1.55	5.91	0.14	0.18	0.22	0.40	0.37	0.68
0.75-1.00	1.61	5.99	0.11	0.22	0.24	0.38	0.32	1.17

mulch retained treatments respectively and applied at the start of each simulation run. The C:N ratios of the maize residue and manure were set at the measured values of 80 and 20 respectively. The manure and fertiliser application rates as defined in the five fertility amendment treatments in Section 2.1. were specified in the APSIM manager.

3.2.6. *Model testing*

The model set up as described above was used as the baseline scenario which reflects the actual conditions at the site where the field experiments were set up. The APSIM model was used to simulate maize grain and stover yields at harvesting and daily N mineralisation from the two seasons in which the field experiment was run 2012/13 and 2013/14. Model outputs were compared with observed field data from the field experiment. The statistical expressions used to compare the observed and simulated data are root mean square error (RMSE) and the modelling efficiency (EF). The EF (equation 2) compares the deviation of the observed and predicted values to the variance of the observed values (Moriasi et al., 2007) :

$$Root\ Mean\ Square\ Error\ (RMSE) = \left[\frac{1}{n}\sum_{i=1}^{n}\left(P_i - O_i\right)^2\right]^{0.5} \quad (1)$$

$$Modelling\ Efficiency\ (EF) = \frac{\left[\sum_{i=1}^{n}(O_i - O_m)^2 - \sum_{i=1}^{n}\left(P_i - O_i\right)^2\right]}{\sum_{i=1}^{n}(P_i - O_i)^2} \quad (2)$$

Where P_i is simulated values; O_i is measured values; O_m is mean of measured values, and n is number of the observations.

Model simulations

Following model testing, the model was used to simulate the effects of different management options reflecting the field trial treatments combining tillage (plough and ripper), mulch (two levels 0% and 100%) and fertility amendments (five treatments: 0; 20 and 40 kg N ha^{-1}; 5 t manure and 5 t manure + 20 kg N ha^{-1}) on crop yields and their intermediary effects on cumulative infiltration, runoff, water stress and N stress. Rain water infiltration and N stress were investigated for three "typical" season types in terms of the rainfall amount relative to the long-term average and the frequency of dry spells longer than 14 days: normal (2000/01), wet (2005/06) and dry (2012/13). In this study, we defined a dry season by the occurrence of dry spells longer than 14 days in addition to receiving rainfall that was more than 25% below the average rainfall, whilst a wet season did not have long dry spells and received at least 25% above average rainfall. A normal season also did not have the long dry spells and received rainfall in the range 450 – 600 mm. Soil water stress was investigated throughout each season. When the simulated water and N stress value was 1, the crop experienced no stress and when the value was 0, the crop was under severe stress.

The calibrated and tested APSIM model was further used to explore the riskiness of maize production. Different planting rules were compared (Table 3.2): (i) planting on a fixed date irrespective of the rainfall received and (ii) planting using a variable rule based on the rainfall amount received. For each of the scenarios, annual grain yields and the daily net N mineralised over the 30-year period (1 September 1984 to 30 June 2015) were simulated. The model was reset every 1 July to initial water, N, surface OM and phosphorus to remove the year-to-year effects. The riskiness of the planting date strategy was evaluated with the 30-years simulated yield data based on (i) the probability of complete crop failure and (ii) the probability of achieving the annual maize grain requirement for an average family from a hectare. The daily energy requirement of a male adult equivalent is 2500 kcal (FAO, 2004). If this energy requirement is met by consuming maize, this translates to a per capita maize grain requirement of approximately 256 kg year^{-1} (FAO, 1995). An average family in Matobo district comprises a male adult equivalent of approximately 5.5 on an average farm size of 1.3 ha (Musiyiwa, 2014). Therefore, the annual maize threshold yield to meet the grain requirement for an average family is approximately 1080 kg ha^{-1}.

Table 3.2: Summary of the seven scenarios examined in the simulation experiment

Scenario	Planting rule	Name	Details
1	Fixed date	Very early planting	• Tillage on 1 November every year • Sow on 1 November every year
2	Fixed date	Early planting	• Tillage on 15 November every year • Sow on 15 November every year
3	Fixed date	Normal	• Tillage on 30 November every year • Sow on 30 November every year
4	Fixed date	Normal	• Tillage on 15 December every year • Sow on 15 December every year
5	Fixed date	Late planting	• Tillage on 31 December every year • Sow on 31 December every year
6	Fixed date	Very late planting	• Tillage on 15 January every year • Sow on 15 January every year
7	Variable date	First effective rains	• Amount of rainfall: 20mm • Number of days of rainfall: 3 • Minimum allowable soil water: 12 mm

From the daily N mineralisation output, the number of seasons in which the mineral N flush coincided with planting for each planting scenario. The yield gain was calculated as the difference between the mean yield when the mineral N flush coincided with planting and the mean yield when the planting missed the mineral N flush. Based on Chikowo et al. (2003), this "coincidence" is achieved when the N flush occurs within seven days before or after planting.

The variable planting date rule was used in the determination of false season starts following the definition in section 2.3. The yield penalty when planting coincided with a false season start was calculated as the difference in mean yields from seasons that experienced a false start and seasons without a false start.

3.2.7. Data analyses

Both single factor (planting date scenario, mulch, tillage, fertility treatments) and the interaction effects on simulated maize yields and net N mineralisation were estimated using ANOVA procedure (Tukey's test at $P \leq 0.05$) using Genstat 18th edition (VSN International Ltd., http://www.vsni.co.uk/). Correlation and linear regression analyses was performed to test the strength of the relationship between net N mineralised in-season and maize grain yield over the 30-year period. The significance of the model was tested with the F value and variables were included in the final model only if they were significant at $P < 0.05$.

3.3. Results

3.3.1. Model performance

The APSIM model performed well in terms of capturing the observed grain and stover yield response to tillage, mulch and fertility amendment application (Figure 3.1). The EF values were generally high (>50%) with good predictions for grain yields for the wet season 2013/14 and the dry seasons 2012/13 and 2014/15 which received below average rainfall (272 and 432 mm respectively). The predictions for the stover yields were satisfactory although the model tended to overestimate stover production.

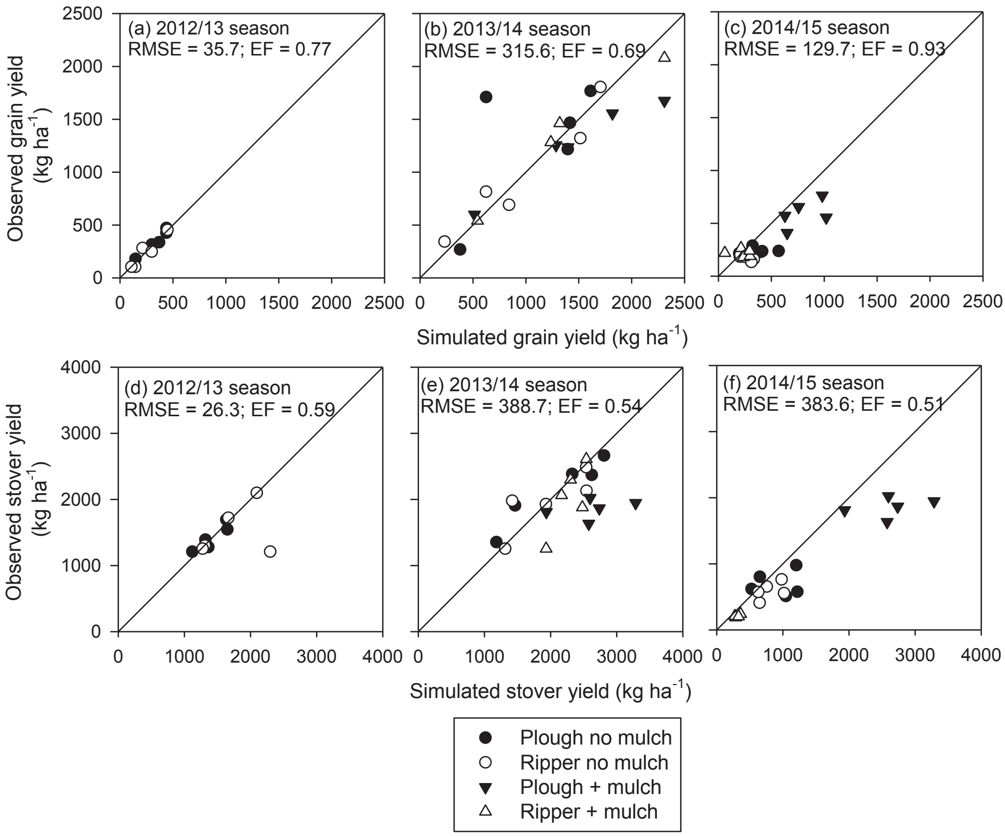


Figure 3.1: On-farm trials observed versus APSIM predicted maize grain and stover yields for the seasons 2012/13 – 2014/15

The model under-estimated both soil N mineralisation (EF = 0.58) and N uptake (EF = 0.40) (Figure 3.2) but the general pattern of the cumulative N mineralised agreed well with the measured data across the treatments (EF ranged between 0.91 and 0.96) (Figure 3.3). The model predicted a net immobilisation for all tillage, mulch and fertiliser treatments in the on-farm trial in the first 10 – 15 days after planting.

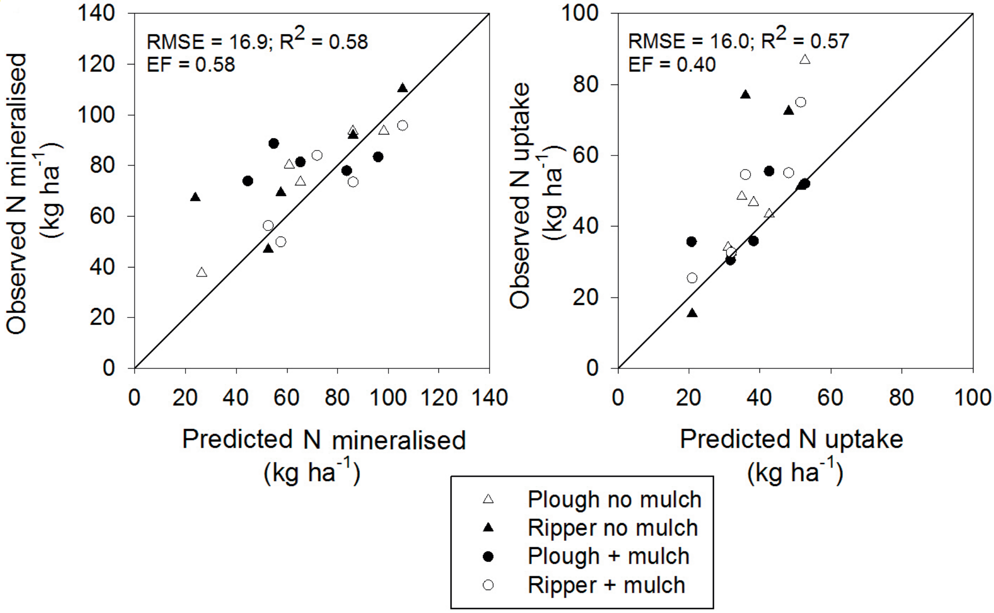


Figure 3.2: Observed vs. predicted seasonal N mineralised and maize N uptake in the 2013/14 season

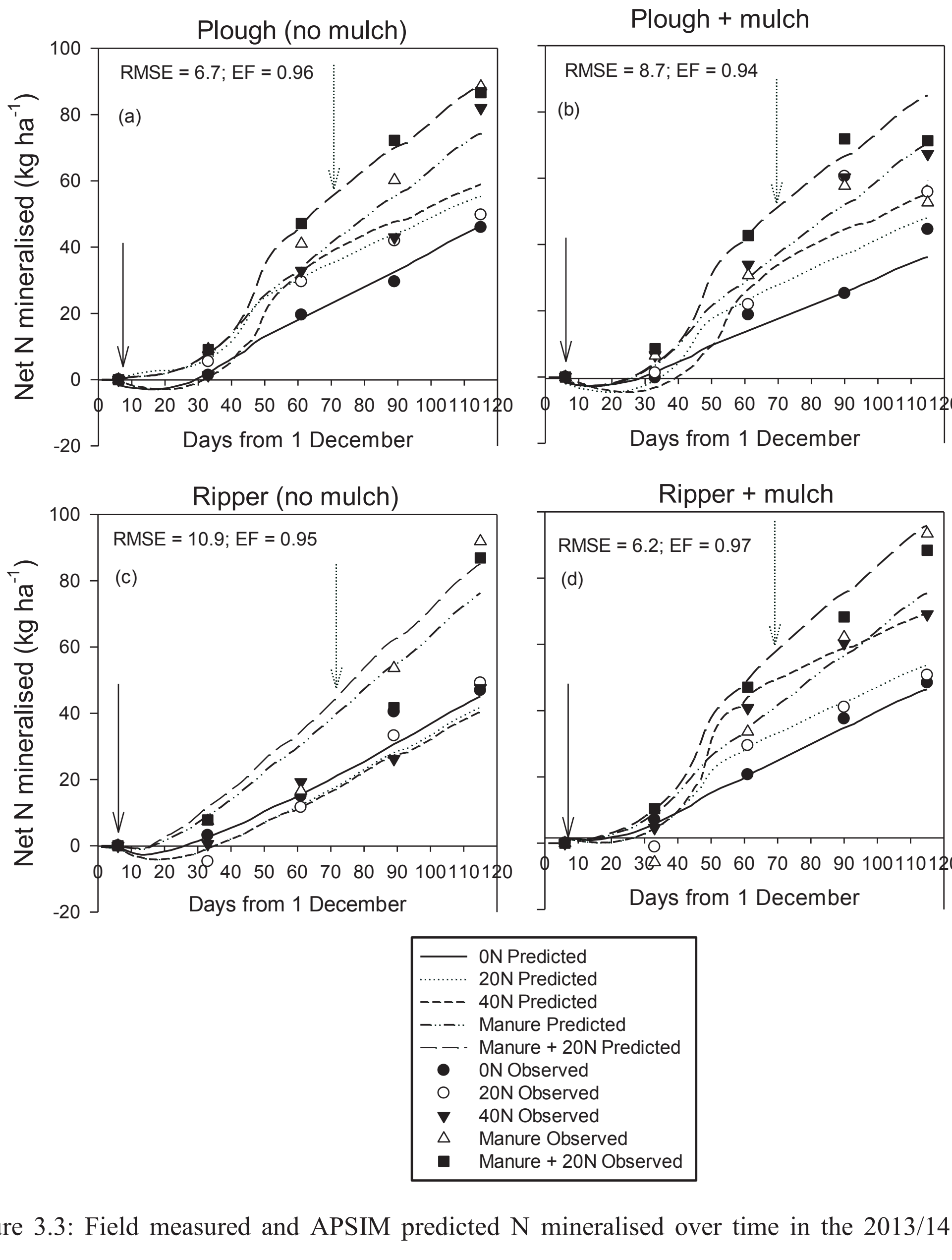


Figure 3.3: Field measured and APSIM predicted N mineralised over time in the 2013/14 season. The solid and dotted arrows indicate the date of planting and the start of flowering stage respectively

3.3.2. Tillage, mulch and soil fertility amendment effects on infiltration, runoff and N stress

The model predicted that most of the seasonal rainfall, 60–98 %, infiltrated for the 30-year simulation period. The proportion of rain that infiltrated was higher in the dry years, 90–98%, where rainfall was <450 mm compared with 60-88 % in the wetter years. Tillage and mulch application influenced runoff and infiltration. Cumulative infiltration (Figure 3.4) was highest under the ripper + mulch (93–97 %) and least with the plough - no mulch (60–67 %) regardless of the season. Infiltration was only marginally higher under the manure treatments than under the fertiliser only treatments (0N, 20N and 40N).

N stress was generally least severe in the first 30 days after planting across the three season types: normal, wet and dry (Figure 3.5). Under the 0N fertility treatment maize experienced the most severe stress from approximately 30 days after planting regardless of season type, tillage type and mulch application. For the other fertility treatments, differences in N stress depended on the season type. Firstly, in a normal season, the least N stress was experienced with the manure + 20N, although moderate N stress was experienced under this treatment at the end of the season under both tillage treatments with or without mulch. Secondly, in the wet season, there was generally severe N stress regardless of tillage and mulch. N stress transitioned from moderate < 30 days after planting to severe > 30 days after planting regardless of tillage or mulch from day 30 after planting to the end of the season. Finally, in the dry season, N stress was moderate from day 10 to day 50 after planting generally across all fertility treatments, thereafter N stress increased under the ripper tillage and under plough + mulch. The manure + 20N treatment also resulted in severe N stress from 60 days after planting until crop maturity under the ripper tillage.

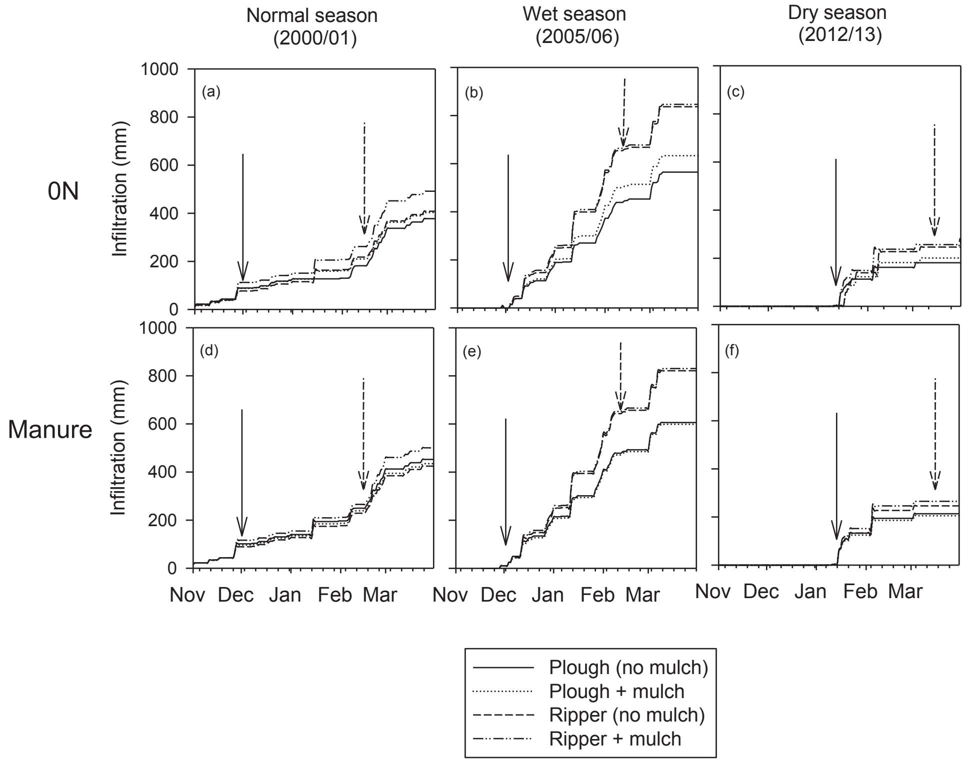


Figure 3.4: Simulated effect of tillage, mulch and fertility amendment on the cumulative infiltration on a sandy soil in semi-arid Zimbabwe for selected soil fertility management practices and in selected seasons representing normal (a and d), wet (b and e) and dry (c and f) years with respect to rainfall amount. The solid and dotted arrows indicate the date of planting and the start of flowering stage respectively

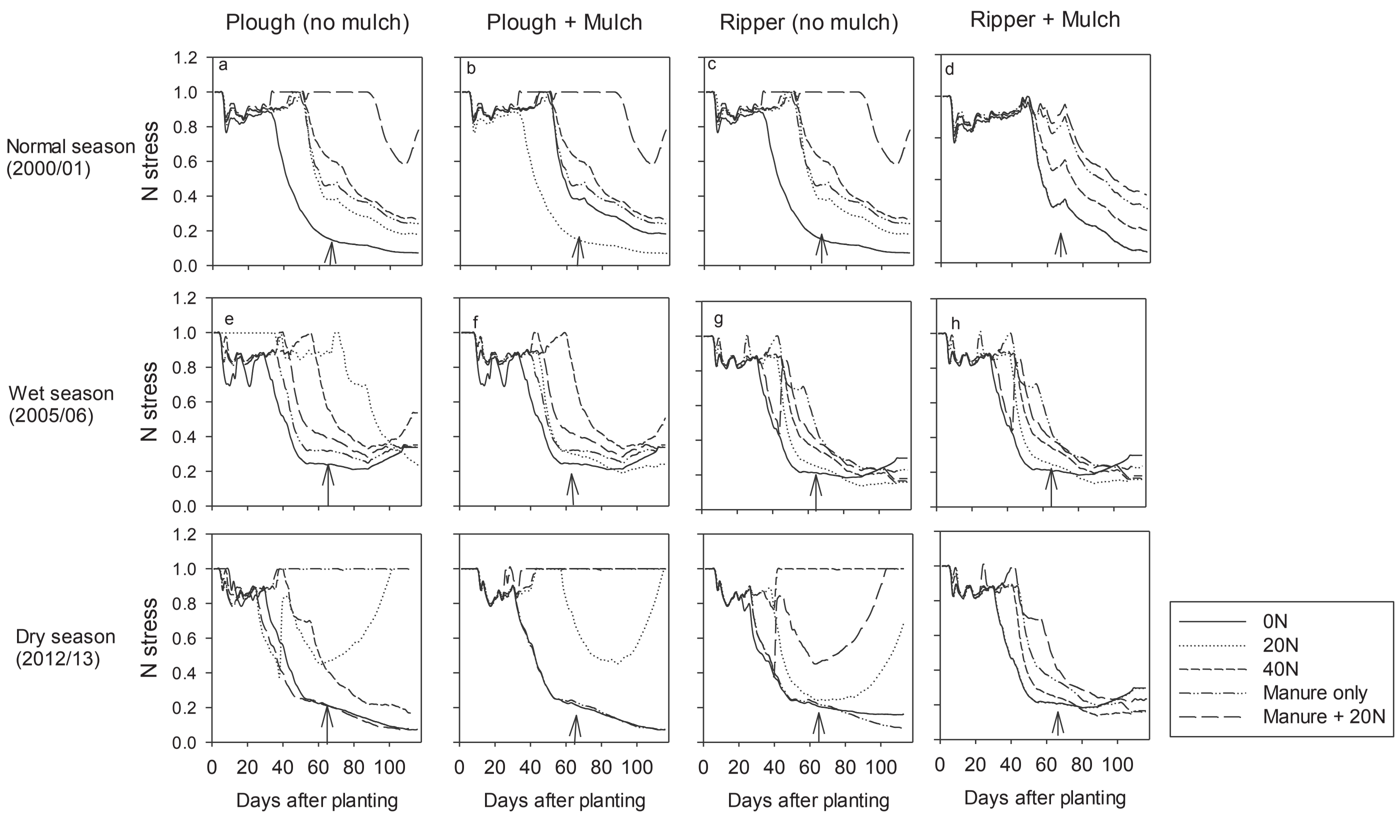


Figure 3.5: Simulated N stress factors (1 = no stress; 0 = extreme stress) in maize production from date of planting in response to different tillage fertility amendments under plough only (a, e and i), plough + mulch (b, f and j), ripper only (c, g and k) and ripper + mulch (d, h and l) on a sandy soil in semi-arid Zimbabwe in selected seasons representing normal (a - d), wet (e - h) and dry (i - l) years with respect to rainfall amount. The arrows indicate the start of the flowering stage

3.3.3. *Treatment effects on in-season N mineralisation*

Simulated nitrogen mineralised in season was significantly different between planting date strategies, fertility treatment, mulch application and tillage treatment and also the interactions between these factors were significant ($P < 0.05$) (Annex A). The earlier the planting the higher the net N mineralised in season because of a generally longer season compared with the later planting dates (Figure 3.6; Annex A). It followed the trend: planting after 20 mm rain > 15 Nov >1 Nov > 30 Nov > 15 Dec > 31 Dec > 15 January for the plough (no mulch), ripper (no mulch) and ripper + mulch regardless of fertiliser or manure input. Under the plough + mulch treatment however, N mineralised in season followed the trend 1 Nov > 20 mm rain > 15 Nov > 30 Nov > 15 Dec > 31 Dec > 15 Jan. The average amount of mineral N available (i.e. that available from mineral fertiliser plus net N mineralisation), over 30 years was highly variable but largely followed the trend: manure + 20N > manure only > 40N > 20N > 0N. With respect to tillage and mulch application, the amount of net mineral N followed the trend ripper + mulch > plough (no mulch) > plough + mulch > ripper (no mulch).

The chance that the mineral N flush coincided with planting varied depending on the planting strategy and was higher for the early (before 30 November and variable planting strategies, whereas the flush was always missed when planting after 15 December. The total amount of N released in the mineral flushes varied by season and fertility amendment and ranged from 0.3–30 kg N ha^{-1}. With respect to fertility treatment effects, the amount released followed the trend manure + 20N > manure only > 40N > 20N > 0N over the 30-year period. The mineral N flush with the start of the rains occurred more frequently with the manure + 20N (80–87 % of the seasons) followed by the 40 N treatment (60–80 %). The manure only and 0N treatments experienced the mineral N flush in 40–67 % of the 30 seasons.

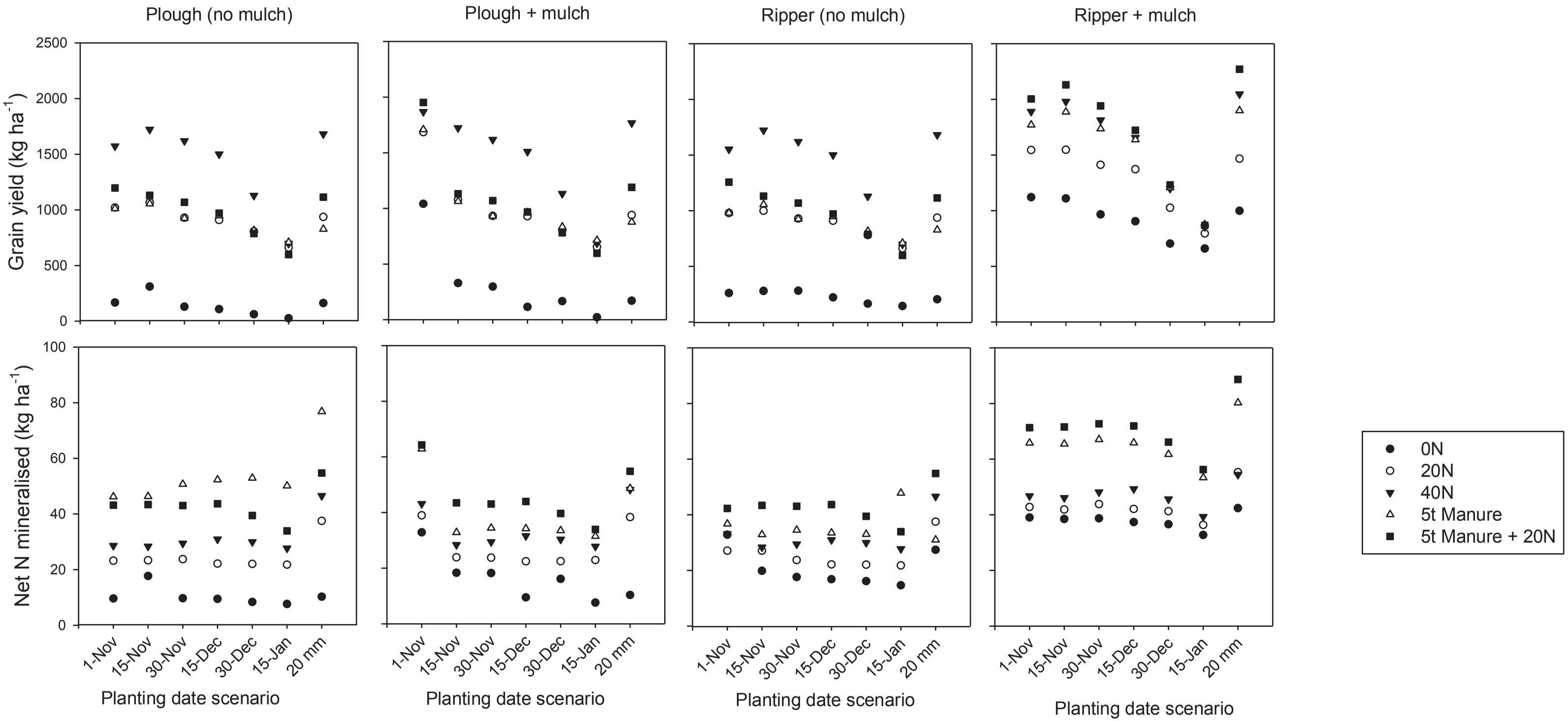


Figure 3.6: Impact of different planting strategies and fertility amendments on average maize grain yields (a – d) and net N mineralised in season (e – h) under plough only (a and e), plough + mulch (b and f), ripper only (c and g) and ripper + mulch (d and h) on a sandy soil in semi-arid Zimbabwe (simulated average for the period 1984 – 2015).

3.3.4. *Treatment effects on grain yield and production risks*

There was a strong positive and significant relationship between net N mineralised in season and maize grain yields ($r = 0.74$; $P < 0.05$). This corresponded with maize grain yield differences between N application rates, which varied in the order 40N > manure + 20N > manure only > 20N > 0N averaging 1485, 1202, 1095, 1026 and 397 kg ha^{-1} respectively (Figure 3.6). The maize grain yields were also significantly different between the different planting date strategies (Figure 3.6). The highest yielding scenario (planting on 15 November) had an average yield of 755 kg ha^{-1}, whereas very late planting (15 January) gave the lowest yield of 550 kg ha^{-1} over the 30-year period and across all fertility and tillage treatments. The grain yields followed the trend: planting after 20 mm rain > 15 Nov >1 Nov > 30 Nov > 15 Dec > 31 Dec > 15 January. Average yield loss per day from planting date 15 November through to 15 December averaged 4, 14, 23, 14 and 15 kg ha^{-1} for the five fertility treatments 0N, 20N, 40N, manure only and manure + 20N respectively. From 15 December to 15 January, the yield loss per day delay in planting averaged 14, 21, 26, 25 and 29 kg ha^{-1} for the five fertility treatments.

a. *Effects of a false season start*

In the 30-year period, there were seven seasons with false rainfall onsets where 20 mm was accumulated in 1-2 days, followed by a dry spell of more than 10 consecutive days within 30 days after sowing. Only the 2002/03 season was considered a drought season of these seven seasons. On average, the false start to the season had negative effects on grain yields depending on the fertility treatment, tillage and mulch application. Addition of fertility amendments made crops susceptible to yield reduction, which followed the trend manure + 20N > manure > 40N > 20N with yield losses averaging 218, 212, 198 and 97 kg ha^{-1} compared to the yields in seasons without a false start. There was no yield penalty with a false start under the 0N treatment regardless of tillage and mulch combinations although this treatment, in the event of a false season start, was associated with failure to meet the household yield threshold of 1080 kg ha^{-1}. With respect to tillage and mulch across the fertility treatments, the grain yield penalties with a false start followed the trend: ripper + mulch > plough + mulch > ripper (no mulch) averaging 256, 190 and 182 kg ha^{-1} respectively. In general, the false season starts were associated with soil water stress during the emergence stage although this stress was low (>0.8) and experienced for no longer than five days. This soil water stress did not exhibit any specific trend with tillage, mulch application or soil fertility amendment.

b. *Effects of early-season mineralisation*

The yield benefits when planting coincided with early-season mineralisation were significant under the following planting date scenarios: 1 Nov, 15 Nov, 30 Nov and planting after 20 mm averaging 430, 132, 4 and 152 kg ha^{-1} respectively (Table 3.3). The yield benefits differed significantly between tillage and mulch applications. Overall, the yield benefits were highest with the ripper + mulch in combination with early planting and in these cases, the yields exceeded the required household grain yield threshold of 1080 kg ha^{-1}.

c. *Risk of crop failure and not attaining maize self-sufficiency*

The simulation results suggested that there was a higher risk of complete crop failure when no fertiliser was applied (0N) regardless of planting date scenario, tillage and mulch application relative to the other fertility amendments (Figure 3.7). The risk of crop failure under 0N further increased with later planting dates, whereas early planting and planting with the first effective rains could limit the probability of crop failure to 40 %. The risk of crop failure was lowest under ripper + mulch ranging from across the different planting date scenarios and between fertility treatments with the risk of complete crop failure in the range 0 to 30 % depending on planting date and fertility treatment.

Table 3.3: Yield benefits when planting coincides with a mineral N flush under different tillage, mulch and fertility amendments for selected planting date scenarios. Figures in brackets denote standard deviation

Tillage	Planting date scenario	Mean yield (kg ha^{-1}) when planting coincided with N flush	Mean yield (kg ha^{-1}) when planting missed the N flush	Mean yield benefit (kg ha^{-1})				
				0 N	20N	40N	Manure	Manure+20N
Plough (no mulch)	01-Nov	1718 (193)	1472 (395)	534	220	288	259	-69
	15-Nov	1113 (546)	1042 (657)	276	161	36	147	-265
	30-Nov	963 (494)	1096 (388)	-335	-14	-17	-345	48
	20-mm	1068 (563)	924 (521)	-128	45	189	588	26
Plough + mulch	01-Nov	1814 (996)	1428 (1196)	485	493	151	391	410
	15-Nov	1145 (915)	1121 (987)	-363	102	186	249	-56
	30-Nov	1028 (816)	1009 (965)	-218	181	14	101	14
	20-mm	1084 (905)	993 (753)	-136	188	376	314	206
Ripper (no mulch)	01-Nov	1834 (959)	1377 (1164)	613	622	299	279	464
	15-Nov	1146 (919)	1079 (968)	-334	153	243	270	3
	30-Nov	1055 (832)	950 (966)	-54	118	119	240	103
	20-mm	1248 (872)	1147 (812)	-74	37	114	-188	212
Ripper + mulch	01-Nov	1952 (997)	1321 (1062)	672	842	605	785	251
	15-Nov	1919 (1133)	1419 (1219)	396	712	441	445	505
	30-Nov	1672 (1142)	1637 (1100)	334	131	-137	127	-280
	20-mm	1885 (1270)	1459 (1148)	699	567	-259	778	344
				P value				SED
Tillage				0.006*				212.5
Mulch				0.013*				107.2
Fertility amendment				0.328				174.4
Planting date				0.012*				148.7

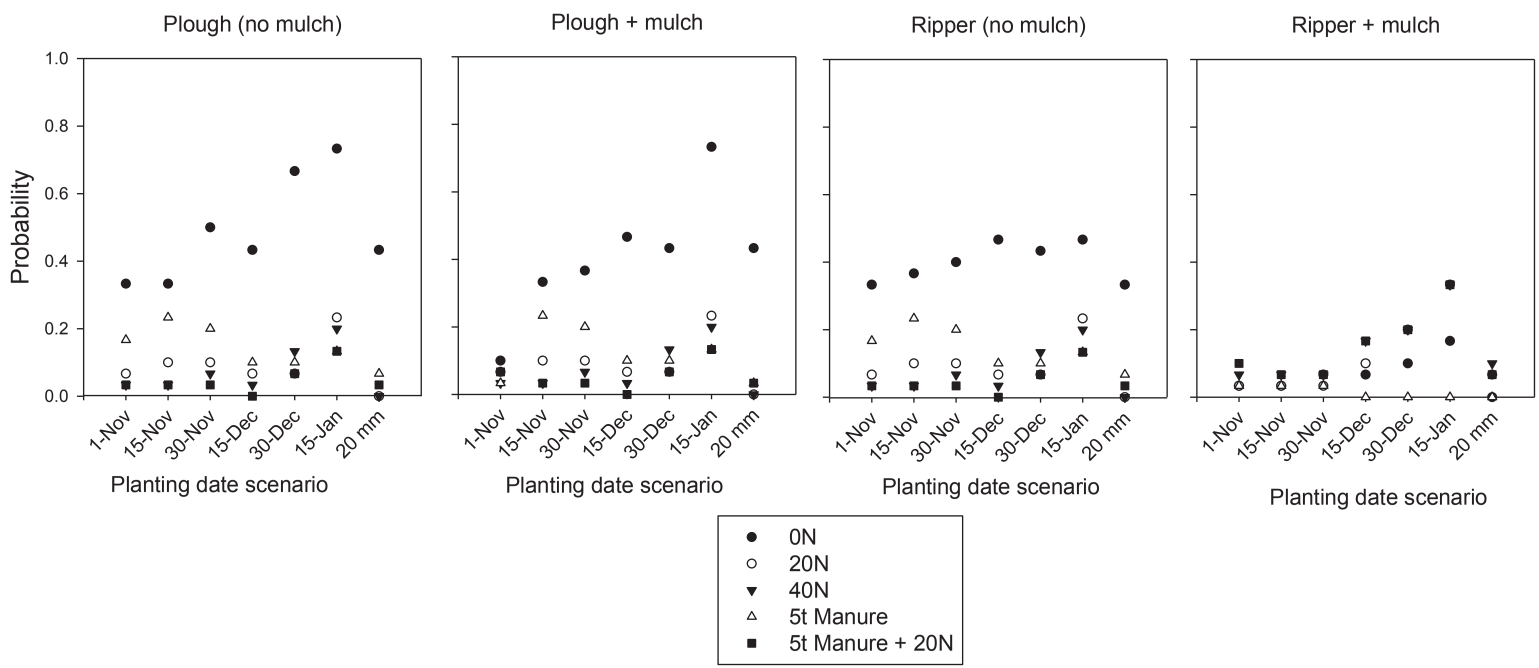


Figure 3.7: Probability of complete crop failure under different planting date strategies, tillage treatments and fertility amendments on a sandy soil in semi-arid Zimbabwe over a 30-year period (1984 – 2015)

The risk of not meeting the household maize grain yield threshold of 1080 kg ha^{-1} increased with later planting dates (Figure 3.8). Planting with the first effective rains had the highest probability of meeting and exceeding the threshold yield although this probability was highly variable (23–83 % where fertility amendments were incorporated and 0–40 % under the 0N fertility treatment). In comparison the latest planting date, 15 Jan, had a probability to meet the same yield of 0–30 %. The 0N treatment had 0–7 % chance of meeting the household maize grain requirement under the plough (no mulch) and ripper (no mulch) tillage whilst under the plough + mulch and ripper + mulch the probability was in the range 10–43 %. Under the plough (no mulch), plough + mulch and ripper (no mulch), the 40N treatment gave the highest probabilities of exceeding 1080 kg ha^{-1} with probabilities in the range 23–77 %. Under ripper + mulch, the manure + 20N gave the highest probabilities of having yields ≥1080 kg ha^{-1} in the range 27–83 %. Overall, the combination of early planting, ripper + mulch and N fertility amendment led to good yields and a low risk of complete crop failure and not meeting self-sufficiency.

3.4. Discussion

3.4.1. Performance of the model

The APSIM model reasonably predicted grain and stover yields, N mineralised and N uptake. The simulated stover and grain yield performance (RMSE/average yield) was in the range of 25–35 % which is in the same magnitude reported elsewhere for semi-arid SSA (Akponikpè et al., 2010). However, the model seemed to overestimate maize grain and stover yields under the plough + mulch treatment (Figure 3.1c and f) in the dry season of 2014/15. Similarly, Mupangwa et al. (2011b) observed an over prediction of grain and stover yields especially at low mulch levels < 2 t ha^{-1} in drought seasons, which they attributed to the model

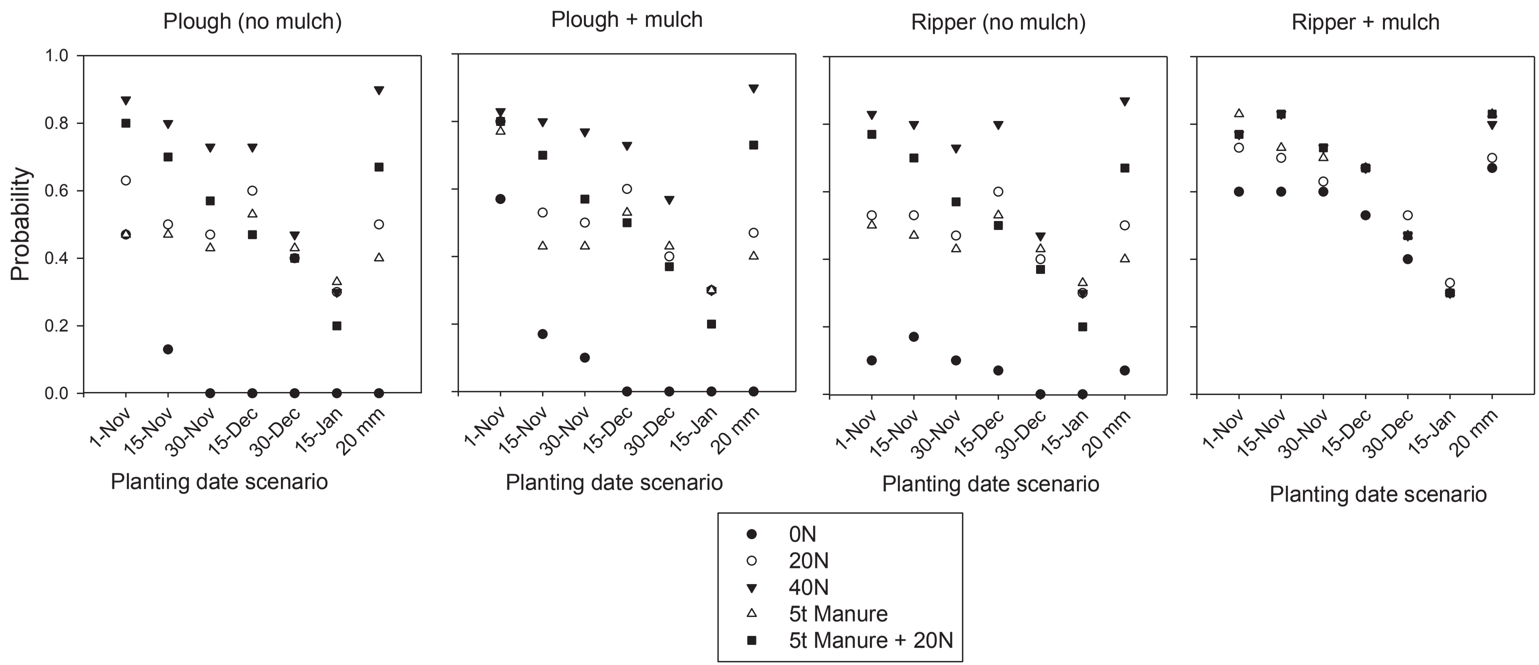


Figure 3.8: Probability of meeting and exceeding the annual household maize grain self-sufficiency yield of 1080 kg ha^{-1} under different planting date strategies, tillage treatments and fertility amendments on a sandy soil in semi-arid Zimbabwe over a 30-year period (1984 – 2015)

underpredicting immobilisation of the applied N at the low mulch rates. In the model, mineralisation/immobilisation of N is determined as the balance between the release of N during decomposition and N immobilisation during microbial synthesis and humification (Probert et al., 1998). In our case, no immobilisation was observed from the simulated daily N dynamics for the 2014/15 season (results not shown). The model indicated that there was an adequate supply of mineral N to satisfy the microbial demand therefore favouring net mineralisation leading to simulated yields that were larger than the observed.

The model predicted in-season net N mineralisation reasonably well (Figure 3.3). In the simulation experiment in our study, the model predicted N mineralisation with the first rains, which we equated to the "Birch effect". At present however, there is no mechanism in APSIM by which the user can specify this "Birch effect". This would need further investigations involving field measurements of N dynamics at the start of the rainy season. Better understanding of the process would enable farmers to optimise available N resources to improve N use efficiency as mineralisation of the soil organic matter releases a significant amount of N even in unamended soils (Snapp et al., 1998).

3.4.2. Tillage and mulch application options effects on maize yields

The ripper tillage in conjunction with mulch application yielded significantly more compared with plough tillage over the 30-year simulation period and across all planting date scenarios and fertility treatments. We attributed the higher maize yields to differences in availability of soil moisture due to higher infiltration as observed in this (Figure 3.4) and other studies (Thierfelder and Wall, 2009; Nyamadzawo et al., 2012). The model settings mimic reality where furrows created by ripping were reported to create more surface depressions compared with ploughing resulting in superior rainwater capture and therefore better infiltration (Mupangwa et al., 2016b). The model was also set to incorporate only 20% of the surface residues under the ripper tillage, meaning the positive effect with mulch application may not be due to incorporated organic matter but a result of the increased infiltration and reduced runoff we observed with the simulation study. Conservation tillage methods such as ripping have been reported to result in high pore volumes consequently increasing the infiltration capacity of a soil (Nyamangara et al., 2014a) thus reduced water stress. Mulch application has also been reported to reduce runoff and therefore lead to increased infiltration (Nyamadzawo et al., 2012). This may also explain why there was least risk of crop failure (0-30%) under ripper + mulch across the different planting date scenarios and across fertility treatments. The use of animal drawn tillage implements such as the ripper tine also reduces the labour and draught power requirement at land preparation compared with ploughing therefore offer a better chance of timely planting. Both the increase in infiltration and the early planting made possible thanks to the reduced labour requirements for the ripper tillage have been shown in our simulation study to lead to increased maize yields.

3.4.3. Risk management by early planting

Early planting has been reported to positively influence crop yields in other studies in the region (Nyagumbo et al., 2017). We attributed the increased maize yields associated with the early planting date to an extended growing period and therefore high in-season rainfall and net N mineralisation. Further yield benefits were obtained when early planting coincided with N mineralisation with the first rains of the season. A similar observation was made in some field experiments that quantified the amount of N released during the N flush (Salinas-Garcia et al., 1997; Riley, 1998). In our simulation experiment, the amount of N released by the flush was highly variable across seasons and fertility amendment. Franzluebbers et al. (1995) reported that the amount of N released is highly dependent on the quality and quantity of organic inputs among other factors which may explain the highly variable amount of N observed in our study.

Early planting can lead to increased yields but is very risky due to the high probability of the occurrence of false starts. False season starts have been reported in several studies to be a high risk to crop production in SSA (Raes et al., 2004; Kniveton et al., 2009; Lone and Warsi, 2009; Mupangwa et al., 2011a). In our study the false season starts occurred, approximately, in one out of four seasons. Other studies have reported high frequencies of false season starts in of 40–50% of seasons in semi-arid southern Africa (Benoit, 1977; Raes et al., 2004). In our study, although the false season starts resulted in low yields, they did not always result in complete crop failure as we hypothesised. The false season starts only led to some water stress in the early crop stages (emergence and juvenile) and not in the most critical stage when kernel weight and number is determined which is between two weeks before and 2–3 weeks after silking (NeSmith and Ritchie, 1992; Singh and Singh, 1995). When longer durations of water stress occur, they cause near total crop failure (NeSmith and Ritchie, 1992), but in our simulation such long periods of water stress were not linked to the false season starts.

Smallholder farmers use staggered opportunistic plantings to spread the risk associated with false season starts and dry spells in semi-arid southern Africa (Milgroom and Giller, 2013; Moyo et al., 2012). With this strategy, however, farmers tend not to invest in improved seed and manure/fertiliser application (Vanlauwe et al., 2014b; Njoroge et al., 2017), thus limiting the opportunity to maximize yields when planting coincides with the optimum planting window. Seasonal, weekly or fortnightly weather forecasts are therefore important in aiding farmers to make tactical within-season decisions on when to plant, weed and apply fertiliser (Moyo et al., 2012).

Our study only considered a few of the possible management options that could lead to attainment of household maize self-sufficiency in semi-arid southern Africa. Other studies have identified drivers of the whole aspect of food availability in the region that also include household incomes, labour availability, livestock production, market access and land availability (e.g. Homann-Kee Tui et al. (2015); Komarek et al. (2015); Frelat et al. (2016)). However, crop production remains the major source of energy containing foods and contributes up to 60% of food availability (Frelat et al., 2016) and therefore it remains important to improve management options that potentially increase yields and therefore food self-sufficiency. Our study showed that the strategic application of different agronomic management practices such as early planting in combination with reduced tillage, mulch and N containing fertility amendments is critical to reduce risk of crop failure and improve crop yields in the smallholder cropping systems of semi-arid areas of southern Africa.

3.5. Conclusions

We conclude that early planting in combination with reduced tillage, mulch application and N fertiliser application allows an 'average' farm household to at least meet their household grain requirement from a hectare of land as well as reduce the risk of complete crop failure. The yield benefits from planting early resulted from capturing the N released from the "Birch effect", total in-season mineral N and rainfall. However, when there is a false start to the season, farmers risk attaining low maize yields and not achieving food self-sufficiency. It is important that smallholder farmers be equipped and guided by reliable seasonal weather forecasts to enable them to plan their land preparation and planting operations to ensure they reap the benefits of timely planting. Practices such as reduced tillage that ease the labour and draught power burdens at the start of the season can be employed to allow farmers to plant early. This, in combination with other agronomic practices such as the application of fertility amendments and mulch may increase crop water use efficiency. As such, smallholder farmers can manage and mitigate risk and achieve maize self-sufficiency in the event of dry spells and low rainfall associated with rainfed cropping in semi-arid areas.

Acknowledgements

We thank the Netherlands Organization for International Cooperation in Higher Education (NUFFIC) for funding this work. We also thank the farmers Mr. and Mrs. A. Moyo in Matobo District who hosted the field trial, the resident agricultural extension officer Ms. S. Ncube who assisted in data collection and Dr. Jairos Rurinda for valuable contributions to an earlier version of this work.

CHAPTER 4

Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid southern Africa?

This chapter is published as:

Masvaya, E.N., Nyamangara, J., Descheemaeker, K., Giller, K.E., 2017. Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid southern Africa? Field Crop Res 209, 73-87.

Abstract

Intercropping cereals with legumes can potentially enhance productivity and soil fertility. There is limited experimental evidence on the mechanisms underlying benefits or risks in intercropping systems and belowground interactions in intercrops remain largely unstudied. Such understanding can inform strategies towards maximising returns to investments, particularly in poor fertility soils on smallholder farms in semi-arid areas of sub-Saharan Africa. Additive intercropping experiments were established covering several seasons (2010/11–2014/15) and different conditions (on-station and on-farm) to determine effects on soil chemical variables, root dynamics and yield of intercrops. Maize was planted with the first effective rains and received either no fertiliser or 40 kg N ha^{-1}. Cowpea was planted on the same date as maize or three weeks after planting maize in intercrops or sole stands and received no fertiliser. End-of-season available N was highest ($P< 0.05$) under the late planted intercrop with 40 kg N ha^{-1} treatment in 2013/14. Addition of 40 kg N ha^{-1} significantly increased maize grain yield by 500–1100 kg ha^{-1} in the 2013/14 season. There was generally greater productivity and over-yielding in the intercrops compared with the sole crops; most intercrops had a land equivalent ratio>1. The trials showed that intercropping, however, resulted in compromised cowpea yields especially under the relay intercrop compared with the sole cowpea stands whilst maize yield was either not affected or improved. We attributed this to the lack of below-ground niche differentiation in root distribution between maize and cowpea. Maize–cowpea intercropping with low doses of N fertiliser resulted in over-yielding compared with monocropping. Intercropping proved to be a robust option across seasons and soil types, confirming that it is a promising option for resource-poor smallholders.

Key words: Below-ground complementarity; Interspecific facilitation; Land-use efficiency; Niche differentiation; Root distribution; Root length density

4.1. Introduction

Agricultural production in sub-Saharan Africa (SSA) is under increasing pressure to meet food and nutrition security needs of the growing population whilst contending with the challenges of climate change and variability, degraded and infertile soils (Hobbs, 2007; Ngwira et al., 2012). Smallholder farmers in SSA often grow cereal crops such as maize (*Zea mays* L.) in continuous monoculture for food security even when there is limited profitability (Baudron et al., 2012a). Raising agricultural production requires a shift towards more sustainable cropping systems to help reverse soil degradation, reduce labour investments and improve production.

Cultivation of legumes in smallholder farming systems either as components of rotations or intercrops has the potential to increase nitrogen (N) availability in the soil through biological N_2-fixation (BNF) (Giller, 2001). The inclusion of grain legumes in crop production is also beneficial for diversified diets and income generation (Ngwira et al., 2012; Rusinamhodzi et al., 2012). However, relatively small areas are allocated to legume production, restricting crop rotation (Mapfumo and Giller, 2001; Nhemachena et al., 2003) resulting in small benefits from the legumes (Ncube, 2007). Intercropping cereals with legumes is one practice that has potential to enhance productivity and soil fertility simultaneously (Jeranyama et al., 2000; Rusinamhodzi et al., 2012).

Intercropping systems involve growing two or more crop species or genotypes together and coexisting for a time (Brooker et al., 2014). Intercropping can increase aggregate yields per unit input, insure against crop failure particularly in dry regions and enhance the efficiency of land-use by complete and complementary utilisation of nutrients, water and solar radiation (Li et al., 2014). Intercropping helps to pre-empt resources being used by weeds and can suppress weed growth (Brooker et al., 2014). Cereal-legume intercrops result in increased N availability for the cereal because competition for soil N from legumes is weak, and the non-legumes obtain additional N from biological N fixation by the legumes (Giller, 2001; Rusinamhodzi et al., 2006; Brooker et al., 2014).

Although intercropping may be beneficial, challenges may arise from strong interspecific competition for resources such as nutrients, water and light between the crops in time and space (Li et al., 2014). Ideal intercrops have complementary resource use and niche differentiation in space and time in order to optimise resource-use efficiency and crop yield simultaneously (Li et al., 2014). Studies in SSA on maize–cowpea intercrops resulted in poor cowpea yields attributed to shading by the maize especially when cowpea was planted at the same time as the maize (Jeranyama et al., 2000). When rainfall is plentiful shading out of the maize by the companion cowpea may occur (Shumba et al., 1990). The competition between crops can be managed by rearranging plant populations through substitutive or additive designs to maintain productivity of the main crop (Vandermeer, 1992). Competition between crops can also be managed by staggering the planting dates of the companion crops in relay intercropping. Relay intercrops are likely to increase labour demands (Rusinamhodzi et al., 2012; Brooker et al., 2014) but may provide the first crop with a higher chance for successful establishment and reduce the risk of total crop failure when rainfall is erratic within the season. However, there is limited experimental evidence on the mechanisms that lead to benefits or risks in intercropping systems (Li et al., 2014). In particular, the below-ground processes in intercropping systems remain largely unstudied in semi-arid areas in SSA although some work has been done in arid China (Mao et al., 2012). It is important to understand intercropping systems better to determine strategies that give the best returns to investments in poor fertility soils on smallholder farms in semi-arid areas in SSA.

In this study, we hypothesised that in risky rainfall environments and on different soil types (i) maize-cowpea intercropping results in over-yielding and therefore robust crop production; (ii) over-yielding in intercropping systems results from below-ground root distribution complementarity and (iii) relay intercropping results in temporal niche differentiation leading to improved land use efficiency compared with monocropping. The specific objectives of our study were: to determine the effects of intercropping on yields across seasons and in different contexts (on-station and on-farm under two management types – researcher and farmer managed), to assess the effect of intercropping on selected chemical soil variables and to understand the root dynamics of intercrop systems that contribute to observed effects on crop yield. Our study sites in semi-arid Zimbabwe are representative of larger areas in southern Africa that are characterised by poor soil fertility, low and unreliable rainfall and smallholder farming systems with many socio-economic constraints.

4.2. Materials and methods

4.2.1. Study area

The study was conducted in Matobo district, Matabeleland South Province located in south western Zimbabwe (Figure 4.1). The region is characterised by semi-arid climatic conditions and lies in agro-ecological region IV, which receives 450-650 mm per annum rainfall in a single season between October and April. The region is subject to frequent seasonal droughts and extended dry spells during the rainy season and the probability of receiving annual rainfall above 500 mm is only 45-65 % (Vincent and Thomas, 1961). The district has an annual mean temperature of 18.4 °C (Musiyiwa et al., 2015). Agro-ecological region IV is dominated by a semi-extensive farming system where crop production is strongly integrated with livestock production with the latter kept supporting crop production through the provision of draught power and manure, serve as a capital asset and diversify household income. Most smallholder farmers in semi-arid areas in Zimbabwe prefer to grow maize over sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* L.). Maize accounts for more than half of the total cropped area (Twomlow et al., 2006). Minor crops include cowpea (*Vigna unguiculata*

(L) Walp.), groundnut (*Arachis hypogaea* L.) and Bambara nut (*Vigna subterranea* (L.) Verdc.) (Ncube et al., 2009b). The dominant soils are sandy soils (Eutric Arenosols) derived from granite with pockets of clay soils (Chromic-Leptic Cambisols). In the smallholder areas of Zimbabwe, the arable fields are individually owned following allocation by the headmen. The fields are communally grazed during the dry season with the exception of securely fenced fields.

4.2.2. Research trials

Additive maize-cowpea intercrop trials were conducted both on-station at Matopos Research Station's Westacre Creek farm (2010/11–2012/13) and on-farm in Nqindi ward (2012/13–2014/15), both in Matobo district. On-farm, two sets of trials were set up, one farmer managed and the other researcher managed for two and three seasons respectively. The on-station trial was conducted on a clay soil (Chromic-Leptic Cambisols) while the on-farm trial was established on sandy soil (Eutric Arenosols) (IUSS Working Group, 2014). Both soil types are moderately deep to deep and well-drained. The on-station trial was researcher managed.

a. On-station researcher managed trial

An additive maize-cowpea trial was set up on-station for three seasons from 2010/11–2012/13. Maize was planted in planting basins and cowpea planted in furrows between the maize rows. Fertiliser was applied to all maize plots in this trial at 40 kg N ha^{-1}. Details of plant spacing and fertiliser application are given in Section 2.2.4. The trial was set up as a randomised complete block design with four replicates. The treatments were: (a) sole maize; (b) maize – cowpea intercrop with cowpea planted the same date as maize; (c) maize – cowpea intercrop with cowpea planted 3 weeks after planting (3WAP) maize; (d) sole cowpea planted on the same date as maize and (e) sole cowpea planted 3 WAP maize. Each plot measured 10 m × 8 m and yield determinations were made from net plots of size 4.5 m × 5 m. Rainfall events were recorded daily and measured with a rainfall gauge in the experimental field.

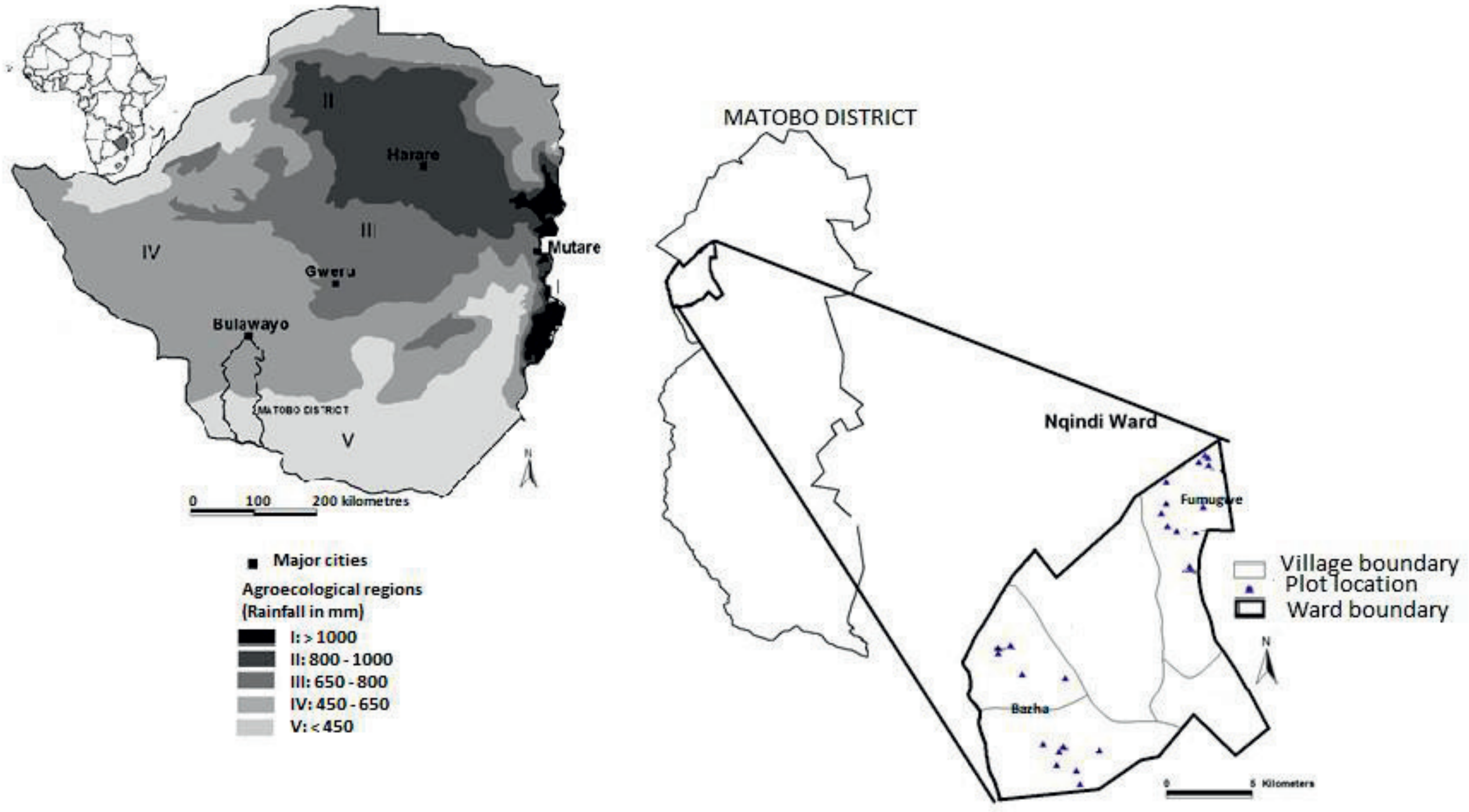


Figure 4.1: Location of on-farm trials in Nqindi ward, Matobo District, Zimbabwe

b. On-farm researcher managed trial

An additive maize-cowpea intercrop trial (mother-trial) was established on a farmer's field in 2012/13 and ran for three seasons up to 2014/15. Plots measured 7.2 m × 6 m with each block measuring 7.2 m × 53 m with 1 m pathways between plots. Rip lines were made using an animal-drawn ripper at 0.9 m row spacing for the sole maize and 0.45 m for the intercrop and sole cowpea treatments. The fertiliser treatments 0 and 40 kg N ha^{-1} (0N and 40N) were used to simulate typical conditions in semi-arid areas of Zimbabwe where farmers do not apply fertilisers and small doses of N fertiliser through "microdosing" are promoted (Mupangwa et al., 2012; Nyamangara et al., 2014b). The trial was set up as a randomised complete block design with three replicates. Treatments were: (a) sole cowpea planted on the same date as maize; (b) sole cowpea 3WAP; (c) sole maize (0 kg N ha^{-1}); (d) sole maize (40 kg N ha^{-1}); (e) maize-cowpea intercrop (0 kg N ha^{-1}) with cowpea planted on the same date as maize; (f) maize-cowpea 3WAP intercrop (0 kg N ha^{-1}); (g) maize-cowpea intercrop (40 kg N ha^{-1}) with cowpea planted on the same date as maize and (h) maize-cowpea 3WAP intercrop (40 kg N ha^{-1}). Yield was determined from net plots measuring 3.6 m × 4 m.

c. Farmer managed trials

A farmer research group comprising 24 farmers from two villages from Nqindi ward (Bazha and Fumugwe) was established in the 2013/14 season for participatory testing of intercropping for two seasons (Figure 4.1). The villages were representative of the villages in the ward which have small to medium distances to the main tarred road which leads to the nearest city, Bulawayo or growth point (Maphisa). The research group farmers were selected with the assistance of the local extension agent, based on similar soil texture (sandy soils), the availability of draught power (for land preparation) and reliable labour for trial management. On each farm, five adjacent plots measuring 20 m × 10 m each were established and the same treatments applied as used in the researcher-managed on-farm trials. In each of the two villages, each farmer chose between the two cowpea planting dates such that in total, 12 farmers hosted the same date intercrop trial and the other 12, the 3WAP trial. A single replicate was planted on each farm and treatments were maintained on the same field for two seasons from 2013/14–2014/15. The treatments were as follows: (a) sole maize (0 kg N ha^{-1}); (b) sole maize (40 kg N ha^{-1}); (c) additive maize-cowpea intercrop (0 kg N ha^{-1}) with either cowpea planted on the same date as maize or 3WAP; (d) additive maize-cowpea intercrop (40 kg N ha^{-1}) with either cowpea planted on the same date as maize or 3WAP; (e) sole cowpea either planted on the same date as maize or 3WAP. Crop yields were determined from net plots measuring 9 m × 6 m. Farmers measured daily rainfall using provided rain gauges and kept record books of the dates and operations carried out in the trial plots.

d. General trial management

In the 40 kg N ha^{-1} treatment, a basal application of compound D fertiliser (14 kg N ha^{-1}, 12 kg P ha^{-1} and 12 kg K ha^{-1}) was applied in hand-hoe made planting basins (on-station) or planting furrows made by an animal drawn ripper (on-farm). The remainder of the N requirement for the 40 kg N ha^{-1} treatment was applied as a top dressing of 75 kg ammonium nitrate (AN, 34.5% N) ha^{-1} at the 5 – 6 leaf stage and or when there was enough soil moisture. The 0 kg N ha^{-1} treatment received a basal application of single super phosphate (12 kg P ha^{-1}) and muriate of potash (12 kg K ha^{-1}) fertilisers. The basins or rip lines were planted to a short duration maize variety SC403. In the basins, maize was planted at a spacing of 0.9 m × 0.6 m with two plants per station whilst under the ripper tillage, maize was planted at 0.9 m × 0.3 m with one plant per station.

Cowpea was planted in hand-hoe or ripper tine furrows made between the maize rows. Cowpea in sole stands was planted at 0.45 m x 0.30 m whilst in the intercrop it was planted at 0.9 m × 0.15 m. No fertiliser was applied to the cowpea in any of the experiments. The cowpea variety CBC 2 used is an erect, short duration variety, which takes 85 days to reach maturity. The variety has narrow leaves and is not very susceptible to aphid (*Aphis craccivora*) attack because of the relatively smaller leaf area. The target population for maize was 37 000 plants ha^{-1} whilst that of cowpea was 74 000 plants ha^{-1}. The plots were kept weed free by an initial application of glyphosate [N-(phosphono-methyl) glycine herbicide soon after planting and subsequent hand hoe weeding. Pests and diseases were controlled as needed. Maize stalk borer (*Busseola fusca*) was controlled using thionex (Endosulfan) and aphids were controlled using dimethoate (2-dimethoxyphosphinothioylsulfanyl-N-methylacetamide). Fungal rust (*Uromyces appendiculatus*) in cowpea was controlled by spraying copper oxychloride (85% WP).

4.2.3. Soil and plant sampling

Soil samples in Nqindi from the researcher managed and farmer managed trials were collected up to 1 m depth (depth intervals of 0.1 m) at the time of trial establishment. Fresh samples were split into two, with one subsample used to determine available N and the other sample air-dried, ground and passed through a 2-mm sieve. The fresh soil samples for available N determination were refrigerated immediately after collection from the field and stored for a maximum of four days before N extraction. The dry soil samples were analysed for pH, texture, total N, total and available P and organic C using standard methods (Anderson and Ingram, 1993; Okalebo et al., 2002). Soil pH was determined in 1:5 soil suspension using 0.01M $CaCl_2$. Soil texture was determined using the hydrometer method. Soil organic C was determined using dichromate oxidation (with external heat applied) method (the modified Walkley-Black method). Total N and P were determined colorimetrically after Kjeldahl digestion (H_2O_2/HCl) of the soil and available P after extraction with $NaHCO_3$ (pH 8.5). N was extracted from the refrigerated fresh soil samples by shaking the fresh sample in 0.5 M K_2SO_4, within four days of sampling, and the NH_4^+-N and NO_3^--N content was determined colorimetrically (Anderson and Ingram, 1993). Bulk density, calculated as mass of oven dry soil core divided by volume, was determined (Table 4.1) using undisturbed cores of 5 cm internal diameter and height. In subsequent seasons, soil samples for complete chemical analyses were collected at the end of the season, within two weeks of harvesting, in the on-farm researcher managed trial. Ten sub-samples were collected randomly from each plot from 0 – 30 cm depth and mixed to produce a composite sample for analysis. The soil properties from the on-station site at Westacre Creek farm are reported by Mupangwa et al. (2013) and are presented in Table 4.1. No additional soil analysis was done at this site.

Table 4.1: Selected soil chemical and physical properties (a) on-station at Westacre Creek, Matopos Research Station* and (b) on-farm in Nqindi ward, Matobo district

a. On-station

Depth (cm)	pH (0.01M $CaCl_2$)	Available N (kg ha^{-1})	Olsen P (mg kg^{-1})	Organic C (g kg^{-1})	Particle size analysis		
					% Sand	% Silt	% Clay
0 – 6	7.5	15.8	5.1	4.6	38	20	41
6 – 16	7.6	3.1	8.5	8.0	39	23	38
16 – 40	7.7	ND	4.5	3.7	36	17	47
40 – 60	7.8	ND	3.4	4.8	31	17	52

b. On-farm

Depth (cm)	Bulk density (kg m^{-3})	pH (0.01M $CaCl_2$)	Available N (kg ha^{-1})	Olsen P (mg kg^{-1})	Organic C (g kg^{-1})	Particle size analysis		
						% Sand	% Silt	% Clay
0 – 10	1430	5.4	7.7	18.1	2.6	90	8	2
10 – 20	1424	4.5	6.4	5.5	2.5	82	8	10
20 – 30	1421	4.6	6.5	2.6	2.3	84	6	10
30 – 40	1552	4.3	6.7	1.3	1.7	80	6	14
40 – 50	1558	4.4	6.8	1.0	2.0	80	8	12
50 – 60	1614	4.7	7.6	ND	1.4	76	8	16
60 – 70	1422	4.5	6.4	ND	2.1	80	0	20
70 – 80	1612	4.6	7.4	ND	1.6	80	0	20
80 – 90	1666	4.6	7.6	ND	1.1	90	2	8
90 – 100	1673	4.7	7.8	ND	2.1	88	8	4

*Adapted from Mupangwa et al. (2013)

At the maize silking and cowpea flowering stages, the spatial root distribution was studied in the researcher managed trial in Nqindi by destructive sampling with soil monoliths excavated from each plot at 0.2 m depth intervals up to 1 m in the 2012/13 season. The five monoliths were excavated from the space between the plants, from the middle of the inter- and intra-row spaces with each monolith measuring 0.45 m x 0.15 m x 0.2 m up to 1 m depth in each plot. In the 2013/14 season, to reduce soil disturbance, soil cores were excavated from 0.2 m depth intervals up to 1 m using a soil corer 8 cm in diameter (Böhm, 1979). In each plot, six cores per sampling depth were collected. The maize silking and cowpea flowering dates were chosen to capture the moment when roots would be fully extended in the profile. Root distribution studies for cowpea were only taken for the first cowpea planting date because the late planted cowpea established poorly in both seasons. The soil samples were soaked in water for at least an hour and then samples were stirred vigorously and poured through a 2-mm sieve. The sieves were suspended in a large water bucket and shaken continuously by hand until the roots were washed free of soil. The roots of the maize and cowpea were distinguished by their different colours and texture. The maize roots were white with a smooth surface whilst the cowpea roots were brownish. The modified Newman-line intercept method was used to determine the root length from the soil monolith and soil core samples by counting the number of intersections of roots with a 1-cm mesh grid (Tennant, 1975).

At harvest maize grain and stover yields were determined from net plots and grain and stover samples were subsampled for moisture correction. Stover samples were oven dried at 65 ºC for two days then reweighed to determine stover dry weight. Grain moisture was determined using a grain moisture meter and yields were adjusted to 12% moisture content. Land equivalent ratios (LER) were calculated to evaluate the advantage of the intercropping to production as follows:

$$LER = \sum \left(\frac{Yi_i}{Ym_i} \right)$$

Where Yi_i is the yield of each crop in the intercrop and Ym_i the yield of each crop in the sole crop.

4.2.4. Data analysis

Grain and stover yields, root length densities (RLD) and LER values were first tested for normality using the Shapiro-Wilk W test and found to be normally distributed (Shapiro and Wilk, 1965). The crop yields, RLD and LER values were then subjected to analysis of variance following a generalised linear model (GLM) procedure using Genstat version 14 (VSN, 2011) to test the individual and interaction effects of intercropping treatment, cowpea planting date and fertiliser application. In the case of the farmer managed on-farm trials, the farmer's field was used as a random variable. Treatment means were separated using LSD at 5 % level of significance.

4.3. Results

4.3.1. Rainfall distribution

The total rainfall on-station during the 2011/12 and 2012/13 seasons (345 and 314 mm respectively) and on-farm in the 2012/13 and 2014/15 seasons (354 and 190 mm respectively) was below the long-term average (590 mm per annum) for the Matobo district and also below the lower limit (450 mm per annum) for the agro-ecological region. These seasons were characterised by several extended dry spells (Figure 4.2), which negatively affected crop performance. The total rainfall of 591 mm on-station in the 2010/11 season and 594 mm on-farm in the 2013/14 season were within the expected range for the region (450 – 600 mm). The 2013/14 season was characterised by high intensity storms, but the rains stopped prematurely in mid-March.

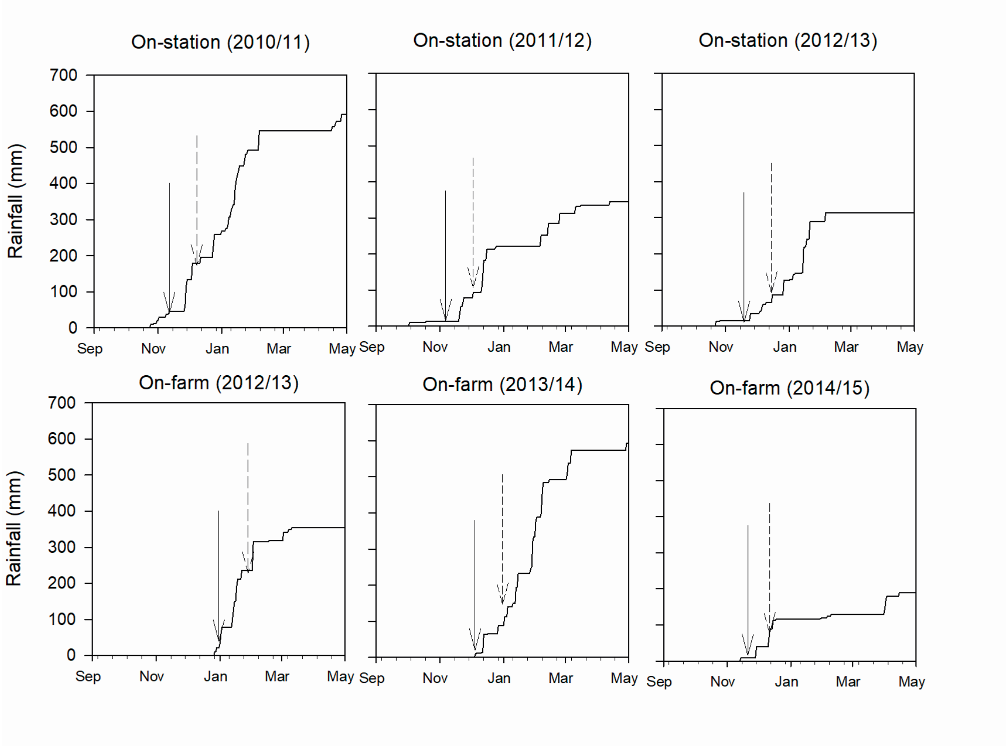


Figure 4.2: Cumulative rainfall at Westacre Creek Farm (on-station) from the 2010/11 – 2012/13 seasons and the researcher-managed on-farm study site in Nqindi ward, Matobo district, Zimbabwe from the 2012/13-2014/15 seasons. The solid and dashed arrows show the planting date for maize and for cowpea planted 3 weeks after maize respectively

4.3.2. Effect of intercropping on selected soil chemical properties of a sandy soil on-farm

In the on-farm researcher managed trial the end-of-season available N was significantly different ($P < 0.05$) between intercropping and fertiliser treatments only after the 2013/14 season (Table 4.2), with highest available N in the 3WAP intercrop + 40N treatment. The effect of intercropping and fertiliser treatments on available N was gone in the 2014/15 season. In the sole maize + 0N, available N decreased by 72% of initial N after three seasons. There were no significant differences in the other measured soil chemical properties (pH, Olsen P, organic C)

Table 4.2: Soil analysis (0-30 cm depth) after the 2012/13-2014/15 seasons in the on-farm researcher managed trial in Nqindi ward, Matobo

(a) 2012/13				
Treatment	pH (0.01M $CaCl_2$)	Available N (kg ha^{-1})	Olsen P (mg kg^{-1})	Organic C (g kg^{-1})
Sole maize (0N)	4.9	11.7	18.0	2.4
Sole maize (40N)	5.2	6.1	4.4	3.0
Sole cowpea (same date)	5.0	11.7	5.2	4.2
Sole cowpea (3WAP)	4.9	11.7	3.3	3.3
Intercrop (0N same date)	4.8	6.5	11.3	2.9
Intercrop (40N same date)	5.0	8.2	13.7	2.9
Intercrop (0N 3WAP)	4.8	8.2	14.2	2.7
Intercrop (40N 3WAP)	4.9	7.4	7.8	2.8
P	NS	NS	NS	NS
SED	0.25	6.50	6.30	0.50

(b) 2013/14				
Treatment	pH (0.01M $CaCl_2$)	Available N (kg ha^{-1})	Olsen P (mg kg^{-1})	Organic C (g kg^{-1})
Sole maize (0N)	4.9	5.2	1.3	3.0
Sole maize (40N)	4.9	20.4	3.3	4.2
Sole cowpea (same date)	5.1	26.0	2.8	4.0
Sole cowpea (3WAP)	4.8	21.7	13.4	3.6
Intercrop (0N same date)	4.9	23.4	4.7	3.4
Intercrop (40N same date)	4.9	25.6	5.5	4.2
Intercrop (0N 3WAP)	4.8	23.0	5.7	5.4
Intercrop (40N 3WAP)	4.8	33.8	3.6	4.5
P	NS	0.04	NS	NS
SED	0.10	6.63	4.26	0.67

(c) 2014/15				
Treatment	pH (0.01M $CaCl_2$)	Available N (kg ha^{-1})	Olsen P (mg kg^{-1})	Organic C (g kg^{-1})
Sole maize (0N)	4.4	3.5	0.0	1.1
Sole maize (40N)	4.0	10.0	0.7	3.0
Sole cowpea (same date)	4.5	25.6	ND	2.5
Sole cowpea (3WAP)	4.3	5.2	0.3	2.9
Intercrop (0N same date)	4.4	7.8	0.2	3.7
Intercrop (40N same date)	4.3	6.1	ND	2.3
Intercrop (0N 3WAP)	4.4	5.6	ND	2.5
Intercrop (40N 3WAP)	4.1	6.5	ND	3.3
P	NS	NS	NS	NS
SED	0.25	12.10	0.63	0.50

resulting from intercropping, time of intercropping and fertiliser application and their interactions in all three seasons. Except for the same date intercrop + 0N, intercropping and fertiliser application resulted in a consistent but not significant increase in the soil organic C content by 16 – 69% from the initial organic C content in the researcher managed on-farm trial (Table 4.1b).

4.3.3. Effect of intercropping on root length densities on a sandy soil on-farm

The root lengths of maize were significantly different ($P < 0.05$) across depths, between sole and intercropped maize and between fertiliser rates in both the 2012/13 and 2013/14 seasons (Figure 4.3). In 2012/2013, the RLD of maize was larger in the sole maize + 40N treatment than in the intercrop at most soil depths. In the same season, the maize roots for sole maize, regardless of fertiliser treatment, were mainly confined in the 0.2–0.4 m soil layer, whilst in the intercropped plots, maize roots were largely confined in the 0–0.2 m layer. In the wet season, 2013/14, the maize root length in both the sole and intercropped treatments was densest in the 0–0.2 m layer. Maize RLD was generally larger than that of cowpea in the intercrops in both seasons.

For cowpea, the sole crop roots were densest ($P < 0.05$) in the 0.2–0.6 m zone whilst in the intercrop the roots were densest in the 0–0.2 m zone in the 2012/13 season. The RLD for sole cowpea was greater than that of intercropped cowpea at most of the depths in the 2012/13 season. In the 2013/14 season, the RLD did not significantly differ between the intercropped and sole cowpea across the soil profile. Nevertheless, in this wetter season, the cowpea roots for the sole crop were confined to the 0–0.2 m zone whilst in the intercrop the roots were evenly distributed in the top 0.6 m.

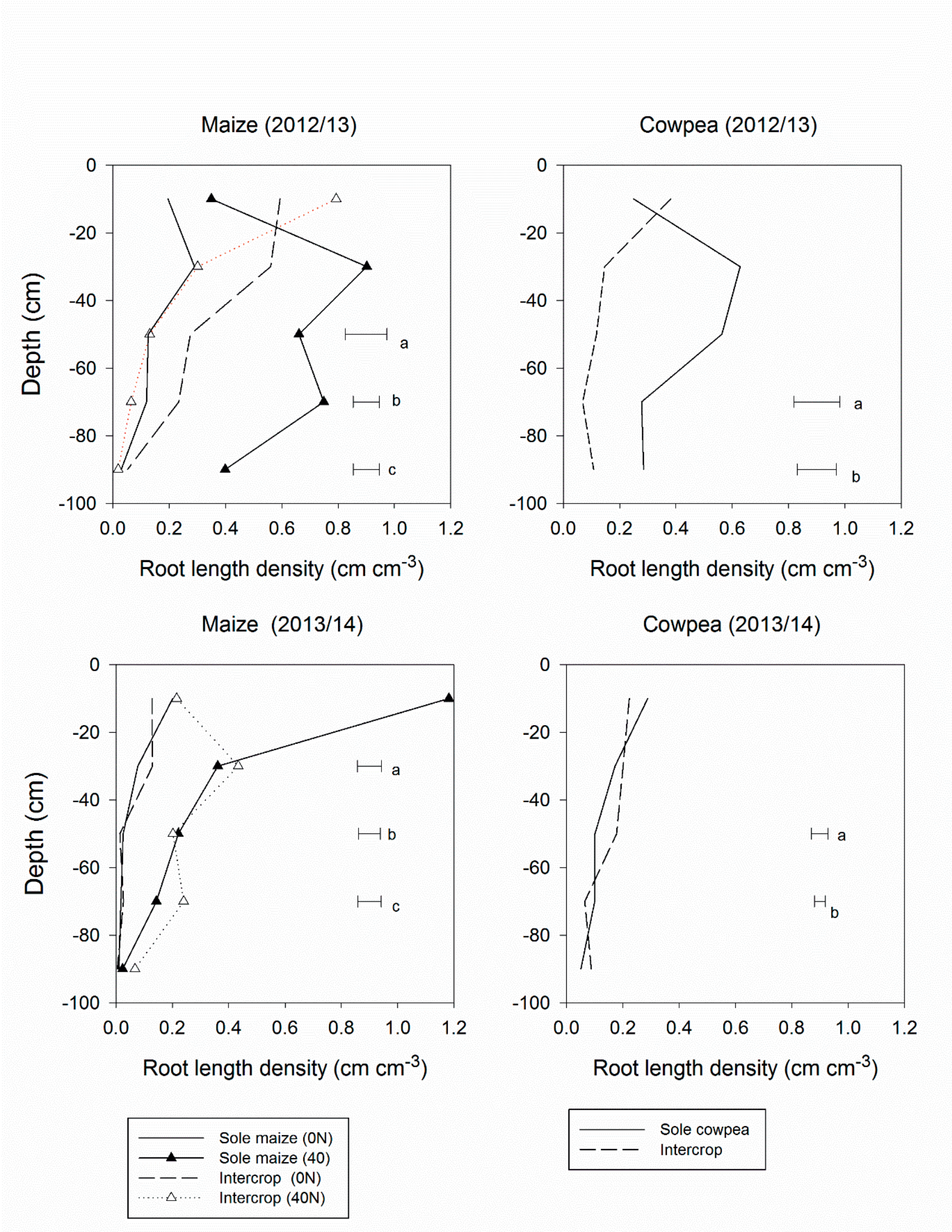


Figure 4.3: Root length densities of maize and cowpea (planted at the same date as maize) in the 2013/14 season from the researcher managed on-farm trial. Error bars represent standard error of the difference of the means of factors: (a) depth, (b) intercropping and (c) N fertiliser rate

4.3.4. *Effect of agronomic management on grain and stover yield*

a. *Researcher managed on-station trial*

On-station, in the 2010/11 and 2012/13 seasons, intercropping and time of planting cowpea had significant effects ($P < 0.05$) on both cowpea and maize yields (Figure 4.4). The same date intercrop reduced cowpea grain yields by between 20 and 63% and the relay intercrop by 62–68% when compared with sole cowpea stands in the two seasons. In the 2010/11 season, maize yields were significantly larger in the sole maize when compared with the same date maize-cowpea intercrop. In subsequent seasons, the maize grain yields were low < 500 kg ha^{-1} but followed the same trend as in the 2010/11 season although the differences in yield between the sole and same date intercrop were not significant.

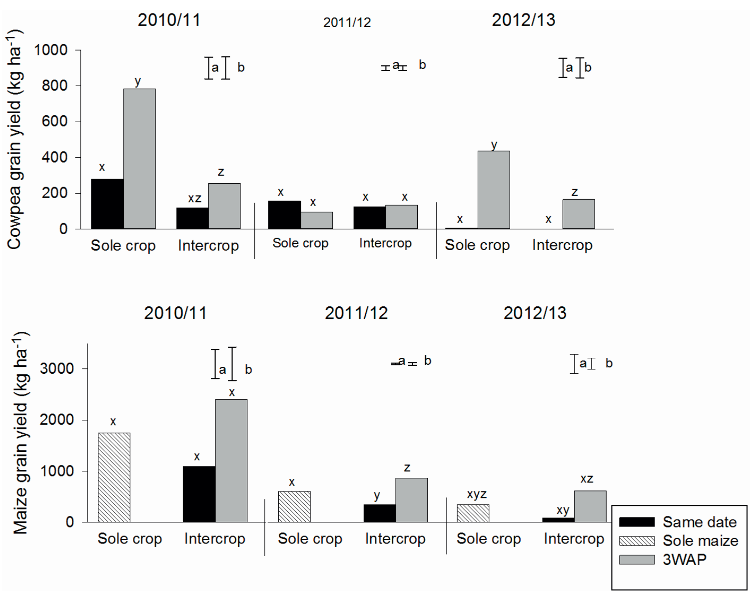


Figure 4.4: Cowpea and maize grain yields by time of intercropping and intercrop type in a researcher managed on-station trial at Westacre, Matopos Research Station. Error bars represent standard errors of the difference of the means of factors: (a) intercropping and (b) intercropping time. Means with the same letter are not different at $P < 0.05$ for the interaction of intercropping and intercropping time

Planting cowpeas three weeks after maize led to higher cowpea grain yields by 50–150% in 2010/11 and 2012/13 compared with cowpea in the same date intercrop. When cowpea was incorporated three weeks after maize, the maize yield (1500–2300 kg ha^{-1}) was higher when compared with the sole crop (1000–1800 kg ha^{-1}) implying that the late planted cowpea had a positive effect on maize growth.

b. *Researcher managed on-farm trial*

There was no maize and cowpea grain and very poor stover yields in the 2012/13 and 2014/15 seasons as a result of the low and poor rainfall distribution (Figure 4.5). In the 2013/14 season, the same date intercrop + 0 N resulted in low maize grain yields. Application of 40 kg N ha^{-1} significantly increased maize grain yields ($P < 0.05$) with yields in the range 1250–1280 kg ha^{-1} compared with the 0N treatment with yields of 135–460 kg ha^{-1} regardless of intercropping. The 40N treatment also resulted in significantly larger maize stover yields in all three seasons compared to no fertiliser input (Figure 4.5). Time of incorporating cowpea into an intercrop had significant effects on maize grain under the 0N fertility treatment and on stover yields under the 0N fertility treatment in the 2013/14 season and under the 40N treatment in the 2012/13 and 2013/14 seasons. For grain yields, the same date intercrop decreased maize yields by 163 kg ha^{-1} (55%) whilst the relay intercrop increased grain yields by 170 kg ha^{-1} (57%) compared with the sole maize crop. Relay intercropping generally decreased maize stover yields with the 40N treatment in 2012/13 and 2013/14 by between 40–380 kg ha^{-1} compared with both the sole crop and the same date intercrop. Under the 0N treatment in 2013/14, however, the relay intercrop increased stover yields by compared with the sole crop and the same date intercrop.

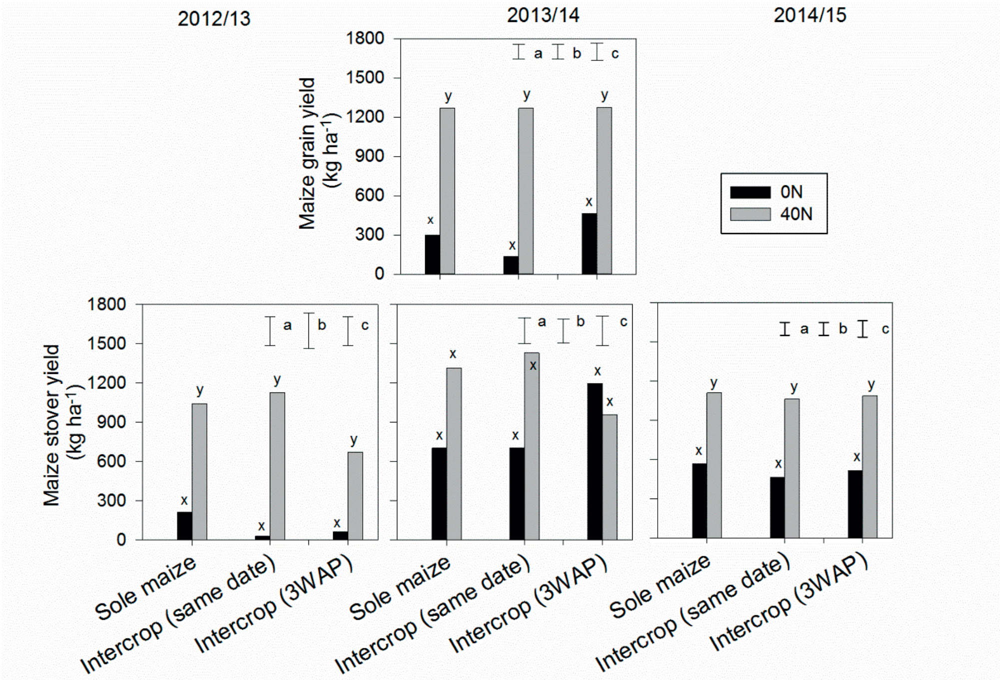


Figure 4.5: Effect of intercropping, time of sowing of cowpea and fertiliser application on maize grain and stover yields in on-farm researcher managed trials in Nqindi ward, Matobo district. Error bars represent standard errors of the difference of the means of yields for factors: (a) intercropping (b) N fertiliser and (c) intercropping time. Means with the same letter are not different at $P < 0.05$ for the interaction of intercropping, N fertiliser rate and intercropping time

Cowpea grain (2013/14) and stover yields (2013/14 and 2014/15 seasons) were affected significantly by time of planting ($P < 0.05$) (Figure 4.6). Generally, the later the cowpea was planted the poorer the yields regardless of whether the cowpea was planted as a sole crop or intercropped with maize. In the 2013/14 season, cowpea grain yield for the early planted crop ranged from 400–700 kg ha^{-1}. There were no cowpea yields recorded for the second cowpea planting date (3WAP) following poor establishment of the crop as the planting coincided with a 10 day long dry spell in the 2013/14 season. In the 2014/15 season, planting cowpea late reduced the stover yield by an average of 77% compared with planting cowpea with the first effective rains. Intercropping significantly reduced cowpea grain and stover yields in the 2013/14 season by 5–35% when compared with the sole cowpea stands although the average root length densities between the two crop stands were similar. There were no significant treatment effects on the cowpea yields resulting from the addition of fertiliser to maize although both grain and stover yields were higher when fertiliser was applied in the 2013/14 season.

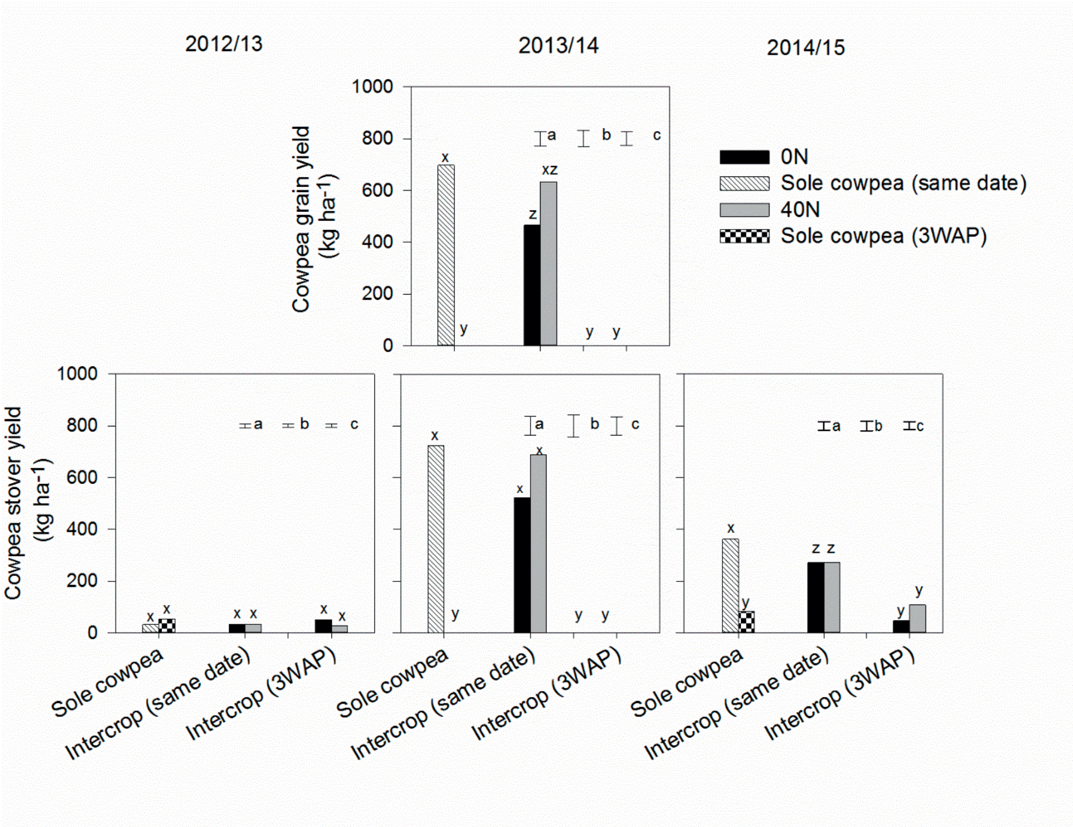


Figure 4.6: Effect of intercropping and date of planting on cowpea grain and biomass yields in an on-farm researcher managed trial in Nqindi ward, Matobo district. Errors bars represent standard error of the difference of the means of factors: (a) intercropping (b) N fertiliser and (c) intercropping time. Means with the same letter are not different at $P < 0.05$ for the interaction of intercropping, N fertiliser rate and intercropping time

c. Farmer managed on-farm trial

There were no significant maize yield penalties resulting from intercropping or time of incorporating cowpea into an intercrop. Addition of 40 kg N ha^{-1} significantly increased grain yield ($P < 0.05$) by 500–1100 kg ha^{-1} and stover yields by 1500–1700 kg ha^{-1} whether maize was planted as a sole crop or in an intercrop in the 2013/14 season (Table 4.3). The highest maize grain yields were obtained when cowpea was relayed by three weeks with the application of 40 kg N ha^{-1}.

Intercropping and time of intercropping significantly affected cowpea grain yields in the farmer managed trials (Table 4.4). Planting cowpea in sole stands gave the highest grain and stover yields in both the 2013/14 and 2014/15 seasons. Planting cowpea with the first rains together with maize (the same date intercrop) also resulted in higher cowpea grain and stover yields in both seasons compared with the later planting. Similar to the researcher-managed trial, the late planted cowpea was negatively affected by dry spells.

3.4.5. Effect of agronomic management on land equivalent ratios

The total yield was generally higher in the intercrops than the sole crops of either maize or cowpea. As such, most intercrop treatments both on-station and on-farm had LER > 1 pointing to the greater land-use efficiency of the maize-cowpea intercrop system compared to sole cropping (Figure 4.7; Annex B). The intercropping treatments both on-station and on-farm generally resulted in over yielding especially under the 40N treatments (Figures 4.7 and 4.8). However, the poorer the season in terms of rainfall distribution and amount, the smaller the LERs. There was considerable variability in monoculture maize and cowpea yield as well as in LER values between farms (Figure 4.8). The on-station relay intercrop (3WAP) performed significantly better with LER ranging from 1.8–2.5 compared with the same planting date intercrop with LER 0.5–2.4 in all three seasons. The smallest LER was obtained in the drought season of 2012/13. On-farm the LER trends were variable in both the farmer and researcher managed trials and a significant interaction effect was found between time of intercropping and fertiliser application in the researcher managed trial in the 2013/14 season. The same date intercrop was favourable if N fertiliser was applied whilst the relay crop was a better alternative under the treatment without fertiliser.

Table 4.3: Effect of intercropping, time of incorporation of cowpea into intercrops (same date – cowpea planted on the same date as maize; 3WAP – cowpea planted 3 weeks after planting maize) and N fertiliser application on maize (a) grain and (b) stover yield in farmer-managed intercrop trials in Matobo district in the 2013/14 and 2014/15 seasons

a. Maize grain yield (kg ha^{-1})

N treatment	2013/14 Sole maize	2013/14 Intercrop maize Same date	2013/14 Intercrop maize 3WAP	2014/15 Sole maize	2014/15 Intercrop maize Same date	2014/15 Intercrop maize 3WAP
0N	354 (12) §	363 (8)	334 (9)	0 (12)	0 (12)	0 (12)
40N	1202 (14)	933 (7)	1402 (10)	183 (12)	158 (12)	209 (12)

	2013/14 *P*	2013/14 SED	2014/15 *P*	2014/15 SED
Intercropping	NS	154.7	NS	34.6
N treatment	<0.001	153.3	0.001	34.6
Intercropping time	NS	216.6	NS	42.3
Intercropping*N treatment interaction	NS	274.6	NS	48.9
N treatment *intercropping time interaction	NS	274.6	NS	59.9

b. Maize stover yield (kg ha^{-1})

N treatment	2013/14 Sole maize	2013/14 Intercrop maize Same date	2013/14 Intercrop maize 3WAP	2014/15 Sole maize	2014/15 Intercrop maize Same date	2014/15 Intercrop maize 3WAP
0N	756 (12)	769 (8)	746 (9)	569 (12)	466 (12)	518 (12)
40N	2340 (14)	2367 (7)	2392 (10)	1110 (12)	1064 (12)	1087 (12)

	2013/14 *P*	2013/14 SED	2014/15 *P*	2014/15 SED
Intercropping	NS	284.7	NS	101.2
N treatment	<0.001	282.2	<0.001	101.2
Intercropping time	NS	353.9	NS	124.0
Intercropping*N treatment interaction	NS	505.4	NS	143.1
N treatment *intercropping time interaction	NS	505.4	NS	143.1

§Number in parenthesis represents the number of observations in that treatment (*n*)

Table 4.4: Effect of intercropping and time of planting cowpea on cowpea grain and stover yield (same date – cowpea planted on the same date as maize; 3WAP – cowpea planted 3 weeks after planting maize) in farmer managed intercrop trials in Matobo district (2013/14 and 2014/15 seasons)

a. Cowpea grain yields (kg ha^{-1})						
	2013/14			2014/15		
		Intercrop			Intercrop	
	Sole	0N	40N	Sole	0N	40N
Same date	1040.9	697.8	754.3	122.5	46.7	71.7
3WAP	573.0	427.1	418.4	0	0	0
		P	SED		*P*	SED
Intercropping		0.009	96.1		0.03	14.1
Intercropping time		<0.001	99.7		<0.001	13.3
Interaction		NS	140.4		0.03	19.9

b. Cowpea stover yields (kg ha^{-1})						
	2013/14			2014/15		
		Intercrop			Intercrop	
	Sole	0N	40N	Sole	0N	40N
Same date	1146	722.0	811.0	362.1	225.7	226.6
3WAP	637.0	452.0	509.0	83.8	28.3	89.3
		P	SED		*P*	SED
Intercropping		NS	214.1		0.015	31.8
Intercropping time		0.047	218.0		<0.001	30.0
Interaction		NS	3061		0.088	44.8

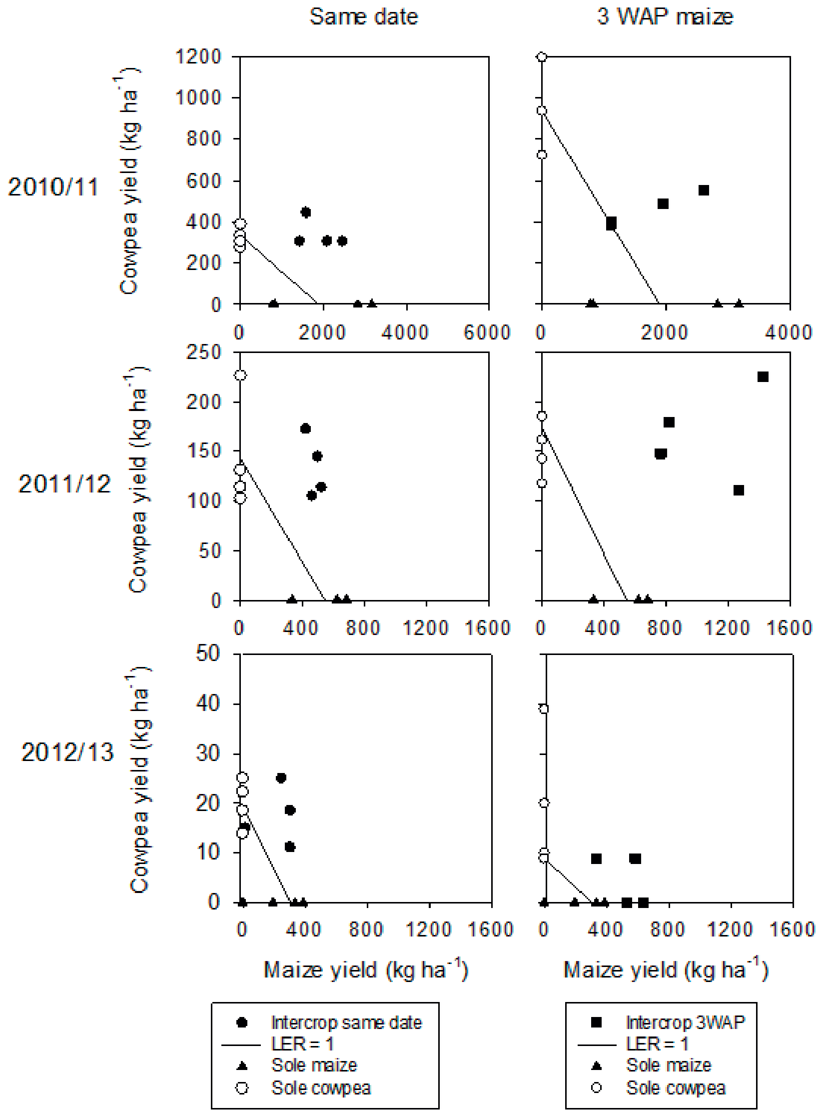


Figure 4.7: Maize and cowpea yield in the 2010/11, 2011/12 and 2012/13 seasons at Westacre Creek, Matopos Research Station. All points falling above the lines connecting the two monocrops (mean LER = 1) represent yield combinations that resulted in overyielding and all points below represent combinations for intercrops that were inferior to the monocrop alternatives. (Note: The axes scales are different for each season)

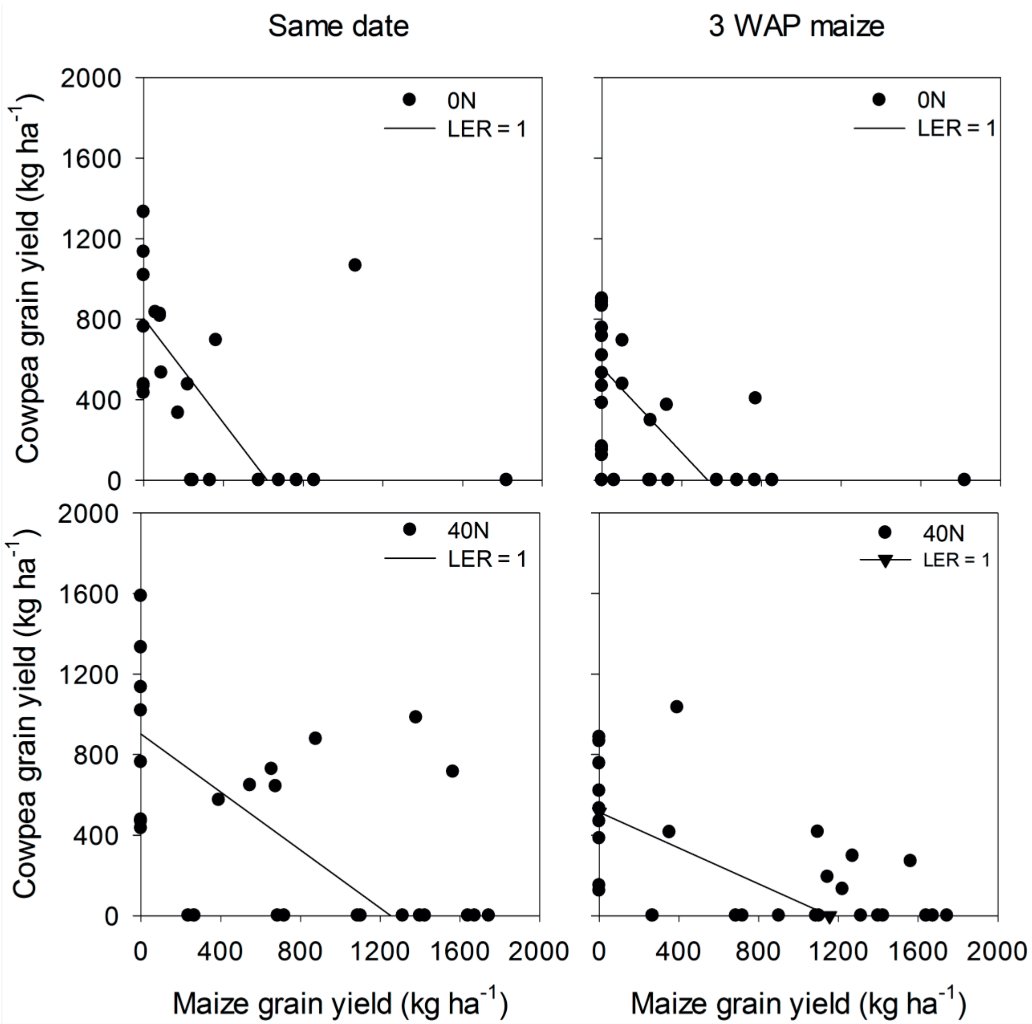


Figure 4.8: Maize and cowpea yield sets from intercropped treatments (evaluation of yield advantage in intercropping systems) in farmer managed intercrop trials in the 2013/14 season. Each dot represents each yield set observation. The straight line connecting the two monocrops represents the average LER = 1 for the study sites for each trial set (the average was obtained by averaging the monocrops). All points falling above the LER = 1 represent yield combinations that resulted in overyielding and all points below represent combinations for intercrops that were inferior to the monocrop alternatives

4.4. Discussion

4.4.1. Maize – cowpea intercrops and over-yielding

Improved crop and soil productivity can be realised with intercropping in conjunction with low rates of N fertiliser. In general, intercropping maize and cowpea resulted in over-yielding with LER values above 1 although crop yields were highly variable depending on the rainfall distribution in the different seasons. Enhanced productivity of intercrops has been recorded elsewhere in Zimbabwe and in the region (Jeranyama et al., 2000; Ngwira et al., 2012; Rusinamhodzi et al., 2012; Thierfelder et al., 2012). Maize yields were generally not compromised as a result of adding cowpea either planted together with the maize or as a relay crop. This was true both on the heavy textured clay soil and the light textured sandy soil, regardless of the season. However, in the first season in the on-station trial the maize yield was reduced by planting maize and cowpea on the same date whilst in the researcher managed on-farm trial, in 2013/14, the treatment without fertiliser maize yields were also reduced by intercropping. Cowpea yield penalties due to intercropping were more common and occurred in all experiments and seasons.

The total biomass (maize + cowpea stover) in intercrops was higher than in sole maize or cowpea stands. This increased biomass production is seen as a benefit of intercropping in the mixed crop-livestock systems, which are characterised by competing uses of crop residues mainly for livestock feed and for maintaining soil organic matter (Baudron et al., 2012b; Ngwira et al., 2012; Thierfelder et al., 2012). Maize-cowpea intercropping results in greater vegetative cover compared with the sole crop stands and therefore a reduction in soil evaporation and increased water use efficiency (Mao et al., 2012). Where LER > 1, water may have been used more effectively as more water was used by the crop through transpiration than lost due to evaporation or weeds. As such, there with higher output (kg grain/biomass) in intercrop systems per unit of rainfall compared with the monocrops.

In addition, intercrops with N_2-fixing legumes may reduce the C:N ratio of the resulting mulch mixture. The decomposition of this mulch will release nitrogen, as opposed to the decomposition of high C:N materials such as maize stalks, which require that soil microbes use the available N for their own metabolic needs resulting in temporary N immobilisation (Giller et al., 2011; Grahmann et al., 2013). This may explain our finding of increased available N in the sole cowpea and intercrop plots. Legume-fixed N may be less susceptible to loss from the soil system when compared with chemical fertiliser, thus improving the ability of the soil to supply N (Crews and Peoples, 2004). The increased production of high-quality biomass plays a vital role for crop-livestock farmers by improving the quantity and quality of animal feed in the dry season while maintaining grain yield from the same piece of land. Even in case of poor grain yields, the production of large amounts of high-quality feed in the intercrops may allow to maintain animal production and farmers will be able to sell excess animals or livestock products to purchase cereal grain (Belel et al., 2014).

Maize yields responded to N fertiliser application more than to intercropping meaning that although planting legumes may improve soil N (Jeranyama et al., 2000), in the short term N fertiliser is required on the degraded sandy soils. This finding is similar to that of a study on similar sandy soils in humid Zimbabwe (Dunjana et al., 2014). Indeed, intercropping non-legumes with N fixing legumes alone cannot replace the role of N fertiliser in these cropping systems if the priority is increased yields. Under semi-arid conditions in Zimbabwe, maize generally requires approximately 50 kg N ha^{-1} (Piha, 1993). Rusinamhodzi et al. (2006) measured 68–138 kg N ha^{-1} fixed through BNF yet little was transferred to the companion crop in an intercrop and the majority of the fixed N is used by the legume itself (van Kessel and Hartley, 2000). Although not significant, cowpea performed better with larger grain and stover yields in intercrops where 40N was applied. The application of a small quantity of N enhances vegetative growth and root activity in the legume, leading to the observed higher yields (Burris, 1959). Rusinamhodzi et al. (2012) also observed a significant response of cowpea yields to applied N and P fertiliser, which they attributed to well-timed staggered planting which saw the maturity of cowpea coinciding with adequate moisture conditions. The latter was, however, not the case in our study.

4.4.2. Does below-ground root complementarity explain over-yielding in intercrops?

Component crops in an intercrop may have different use of resources resulting in complementarity (Tsubo et al., 2005). In our study, however, we found only marginal below-ground complementarity in the maize-cowpea intercrop on the poor sandy soil as the roots of both crops were densest in the same depth zones in both the drier and the wetter season. As such, there was a lack of niche differentiation in terms of root growth with high competition for nutrients and water as a result. This also means that below-ground root complementary cannot serve as an explanation for the over-yielding observed in the maize – cowpea intercrops. Zhang et al. (2014) suggested that additional processes such as mycorrhizal colonisation and or above-ground complementarity or competition should be taken into account to understand complementarity which is not only defined by crop rooting patterns but also nutrient and water requirements and thus uptake. Maize had a higher RLD in the intercrop compared with the monocrop when grown without fertiliser in 2012/13. The maize RLD in the intercrop was generally larger compared with the cowpea. This may explain the asymmetric interspecific facilitation in the intercrops illustrated by the negative effect on the cowpea grain yields compared to no (on the sandy soil) or a positive (on the clay soil) effect on maize grain and stover yields. However, the actual mechanism of the facilitation in the intercrop was unknown in the present study. According to Hayes et al. (1999) under conditions of P deficiency, as was the case in our study, acid phosphates secretion from roots is increased. It is possible that cowpea roots could secrete acid phosphates facilitating P nutrition in maize therefore increased RLD and generally increased growth. Rates of transfer of fixed N from legumes to companion cereal crops are considered to be small (van Kessel and Hartley, 2000; Giller, 2001) and is unlikely to be important in this case. Further research on possible mechanisms for interspecific facilitation in intercrops is needed.

4.4.3. Relay intercropping and its effects on land use efficiency

The relay intercrop studied here resulted in a temporal niche differentiation with maize having a head start in development compared to the late planted cowpea. This resulted in cowpea grain and stover yield penalties as the plantings coincided with dry spells on the sandy soils on-farm. In the 2013/14 season, both the sole and intercrop 3WAP cowpea crop completely failed to establish. The dry spells resulted in soil crusting, which impeded crop emergence and resulted in poor cowpea stands. The relay intercrop, however, resulted in benefits in maize grain yield on-station on the clay soil (Figure 4.4; Annex B) and no effect on the maize on-farm on the sandy soil (Figure 4.5; Annex B). This is because by the time cowpea is introduced into the intercrop, the maize root system would have been well developed. The clay soils on-station have a high water holding capacity (Mupangwa et al., 2012) such that growth of the late planted cowpea in this soil is possible even in drier seasons like 2012/13. On-farm, the sandy soil, typical of two-thirds of Zimbabwean soils, has a poor water holding capacity (Mapfumo and Giller, 2001; Moyo, 2001), which may explain the poor yields associated with the late planted cowpea on sandy soils. In addition to the differences in soil type, planting basins used on-station tend to hold more water than rip lines especially at the beginning of the season. Mupangwa et al. (2015) showed that planting basins start off with marginally higher soil water contents compared with other tillage methods like ripping or single conventional ploughing although this changed as the season progressed both on a clay and sandy soil.

4.4.4. Maize-cowpea intercropping in the context of smallholder farmers in semi-arid areas

With LERs generally above one, maize-legume intercropping increases household food security and leads to dietary diversification. However, the benefits of intercropping were dependent on the rainfall pattern in the different seasons and trials. For example, in the on-station trial in the first season and the researcher-managed on-farm trial in the second season without fertiliser, maize yields were reduced when both crops were planted together at the same time. This risk may discourage smallholder farmers to invest and change their production system from monocropping of maize to intercropping. This is because of the importance of maize, which guarantees food security at household level and can always be marketed in case of excess production (Baudron et al., 2012a; Thierfelder et al., 2012).

Our study focused on two fixed planting times for cowpea, whereas farmers in reality observe the rainfall patterns before making the decision on whether or not to plant (Musiyiwa et al., 2015). This helps to avoid the challenges we encountered in our study of cowpea planting times coinciding with dry spells and resulting very small cowpea yields or complete cowpea failure especially on-farm on the sandy soil. Whether farmers adopt intercropping is dependent on several factors which include soil fertility status, climate, land and livestock holding, labour availability and farmers' goals and attitudes (Zingore et al., 2007; Giller et al., 2011). Resource poor farmers may not be able or willing to invest seed, fertiliser/manure and labour in a second crop if there is a possibility of the crop failing. Although farmers appreciated the concept and potential benefits of intercropping, the relay intercrop was not viewed as a practical option. The associated risk of poor cowpea yields, and the additional labour required when planting the second crop were mentioned as disincentives. Production of legumes in smallholder farming systems remains a challenge also because of farmers lacking access to markets to purchase improved legume seed and sell their produce (Mazvimavi and Twomlow, 2009).

Although cowpea grows well in most smallholder areas and even on granitic sandy soils, it is very susceptible to pests, especially aphids, which can significantly affect the overall performance of the crop. In our study, we controlled pest attacks on the cowpea with pesticides which, however, are not readily available locally and beyond the reach of resource poor farmers.

Soils in the study area were nutrient poor (Table 4.1) and intercropping may reduce the quantity of fertiliser N required by the cereal in the short term. This is appealing for resource poor farmers who cannot afford large fertiliser quantities. In our study the addition of small amounts of N fertiliser, typical of smallholder farmers, in conjunction with intercropping led to positive responses in yields. However, once N is made available, the resulting vigorous plant growth may exacerbate other nutrient deficiencies. In our study, NPK or PK fertiliser was added to the maize but not to the cowpea which is typical of smallholder farmers who apply little or no fertility amendments to legume crops (Ronner et al., 2016). With the intensification of the cropping system as with intercropping, nutrient requirements for the legume need to be addressed especially as soils in the study area are nutrient poor (Table 4.1). As such manure, if available, is a key nutrient resource on smallholder farms as it provides both macro- and micronutrients (Zingore et al., 2008).

While our study presents the technical performance of intercropping at plot level, farmers in semi-arid Zimbabwe with farm sizes of 3.5 – 5 ha with different crop and livestock enterprises look beyond the plot for household food security (Ncube et al., 2009b). Interactions between the different parts of the farm and the trade-offs between different economic or production objectives, especially with the mixed farming practice in semi-arid Zimbabwe, may cause the production efficiency of a farm to be different from what may be inferred at lower scales such as the plot.

4.5. Conclusions

Maize-cowpea intercropping has the potential to improve land-use efficiency through over-yielding compared with maize monocropping regardless of time of intercropping, season quality and soil type in smallholder systems where the use of external inputs such as fertiliser is restricted. The intercropping trials resulted in compromised cowpea yields especially under the relay intercrop compared with the sole cowpea stands whilst those of maize were either not affected or improved. We attributed the poor cowpea yields in the intercrops to the lack of below-ground niche differentiation in root distribution between maize and cowpea. As such, over-yielding in the intercrops could not be attributed to below-ground root complementary in root patterns. Maize had a high root length density meaning it explored more soil volume and therefore more resources required for crop growth and as such performed better than the cowpea. As trends were consistent over different seasons, the maize – cowpea intercrop with small doses of N fertiliser is a robust system for food and livestock feed production. Nevertheless, for intercropping to be attractive to smallholder farmers, current constraints with respect to reliable access to input and output markets and credit schemes would have to be removed.

Acknowledgement

We thank the Netherlands Organization for International Cooperation in Higher Education (NUFFIC) for funding.

CHAPTER 5

Maize-cowpea intercropping leads to improved productivity and food self-sufficiency in semi-arid southern Africa: A modelling perspective

This chapter will be submitted as:

Masvaya, E.N., Nyamangara, J., Giller, K.E., Descheemaeker, K., 2019. Maize-cowpea intercropping leads to improved productivity and food self-sufficiency in semi-arid southern Africa: A modelling perspective.

Abstract

Smallholder farmers in Zimbabwe must cope with small farm sizes, low soil fertility and production risks associated with rainfed agriculture. Integration of legumes into maize-based cropping systems is advocated as a means to increase on-farm productivity in smallholder farming systems. We hypothesized that maize-cowpea intercrops are a low-risk option, leading to household food self-sufficiency in semi-arid southern Africa. A calibrated APSIM model was used to investigate the performance of maize-cowpea intercropping scenarios across 30 growing seasons (1985–2015) in five sites (Masvingo, Matobo–sand, Matobo–clay, Nkayi and Umzingwane) in two agroecological zones of Zimbabwe. The following scenarios were simulated: planting date (cowpea planted 0–4 weeks after planting maize), fertiliser rate (0, 40, 80 kg N ha^{-1} for maize and 0 and 40 kg N ha^{-1} for cowpea) and plant population (37 000, 74 000 and 144 000 plants ha^{-1} for cowpea whilst maize was maintained at 37 000 plants ha^{-1}). Intercropping reduced mean maize yields by 3–25% in comparison with the sole maize across all the sites, with the largest decrease in maize yields associated with planting maize and cowpea on the same date. For cowpea, however, a week's delay in planting resulted in a reduction in the average cowpea yields of between 21–65 % compared to planting at the same time with maize across all sites. The application of fertiliser led to an increase in grain yields for maize by between 23–34 kg grain kg^{-1} N applied on the sandy soils whilst on the clay, the increase was between 12–17 kg grain kg^{-1} N applied regardless of intercropping. However, the increase in fertiliser application to maize led to decreased cowpea yields in the intercrops compared with the sole cowpea crops by 19-60 % on the sand and 13% on the clay. The cowpea plant population variations influenced the cowpea yields with no pronounced effect on maize yields at all five sites. The increase in cowpea yield when the high cowpea population was compared with the low population was in the range 14–95%. At all sites, most maize-cowpea intercropping scenarios had a high probability of meeting household energy and protein requirements. Planting maize and cowpea at populations of 37 000 and 74 000 plants ha^{-1} respectively on the same date and with 40 kg N ha^{-1} was the best intercropping scenario that maximised the probability of meeting household energy and protein requirements in the range 83–97 % and 83–100 % respectively across all sites on sandy soils. On the clay, the relay intercropping scenarios where N fertiliser was applied, and cowpea was planted 2–4 weeks after maize met household nutrition needs in all 30-seasons. If farmers were to attain household energy and protein self-sufficiency, maize-cowpea intercropping would be better than growing sole crops as it is a more efficient system to achieving food security. Sole crops would require more land to support household nutrition needs which is not practical for resource constrained smallholder farmers in this region.

Key words: APSIM; Crop simulation modelling; Food self-sufficiency; Semi-Arid; Smallholder farming

5.1. Introduction

In Southern Africa, the crop yields and incomes from smallholder farms are generally low and variable. Food insecurity is a major problem in the area. (Tittonell and Giller, 2013; Arslan et al., 2015). These challenges are particularly acute in arid and semi-arid climates where current climate variability and associated water stress are combined with depleted soil fertility and low-external input cropping that result in the low crop yields. Global climate models indicate that Southern Africa will be severely affected by climate change. Rainfall patterns are expected to change, with growing seasons starting later and shortened; also, a moderate decline of the total amount of rainfall is expected by 2050 (Brown et al., 2012; Davis and Hirji, 2014). The decrease in yield will be dependent on climate and management scenarios, but it is likely that poverty and food insecurity will be rampant in rural areas (Arslan et al., 2015). Because of the economic dependence on rainfed agriculture, a lack of access to insurance and credit, and labour constraints, among other factors, the majority of smallholder farmers in sub-Saharan Africa (SSA) are vulnerable to the effects of climate variability and change (IPCC, 2014; Descheemaeker et al., 2016a).

Cereal-legume intercrops have the potential to improve the overall productivity and soil fertility in smallholder farming systems (Ngwira et al., 2012; Rusinamhodzi et al., 2012; Thierfelder et al., 2012; Masvaya et al., 2017a). Intercropping, the planting of two or more crops either simultaneously or in relay, allows for an intensification of the cropping system. Land use efficiency is enhanced by it, due to a complementary utilisation of nutrients, water and solar radiation, and the risk of complete crop failure reduced (Rusinamhodzi et al., 2012; Li et al., 2014). Therefore, intercrops provide better production stability than monocrops. Despite the benefits, the adoption of legume technologies is hampered by farmers' lack of information on management options, resulting in their poor implementation (Chimonyo et al., 2016), by high seed costs, and by poor market infrastructure (Mazvimavi and Twomlow, 2009). Smallholders grow legumes on very small pieces of land or in haphazard intercrops; as such the potential benefit of soil fertility improvements from biological N-fixation are thus not realised (Ncube et al., 2007b).

Intercropping has been proposed as a climate-smart agriculture (CSA) option in its own right (Arslan et al., 2015) or as a co-intervention in conservation agriculture (CA) systems (Thierfelder et al., 2017). Climate-smart agriculture encompasses interventions defined by their ability to deliver on three fundamental dimensions: a) adaptation to the effects of climate change, thereby building resilience into the system; b) provision of mitigation benefits in terms of greenhouse gas emission reduction and building carbon stocks (both above and below ground) and c) improved productivity and food security (Campbell et al., 2014; Lipper et al., 2014). Smallholder farmers are however more concerned with being able to feed their families which make the dimensions of adaptation and improved productivity more important to them than the mitigation aspect (Descheemaeker et al., 2016a).

By field experimentation, researchers have tried to determine best-fit management options for intercropping systems (e.g. Kermah et al., 2017; Masvaya et al., 2017). Yet, due to the site-specificity and short duration of the experimental studies, their results are limited to the agro-ecologies, seasons and soil types where the testing took place. Gaps still exist in our knowledge concerning the suitability of intercropping to a wider set of environments and seasons, and on management practices that could make the cropping system climate-smart in the smallholder context. Crop models based on biophysical processes and their interactions are designed to capture system feedback and help us to better understand and predict the system's behaviour. Simulation of intercropping interactions can complement field trials by predicting crop response across a broader range of contexts than can be covered by experimental studies alone

(Whitbread et al., 2010). Modelling can also assist in exploring different management options. In intercropping systems, options include the timing of incorporating a legume crop in an intercrop, different fertiliser application rates and plant populations. Information on their effects is needed for developing suitable cropping recommendations.

The Agriculture Production Systems sIMulator (APSIM) model has been used to simulate an array of cropping systems across all continents. It can simulate the response of a range of crops to different climates and soils under different management options, by virtue of rigorous testing (Keating et al., 2003). In this study, it was hypothesised that maize-cowpea intercrops are a low-risk option, leading to household food self-sufficiency in semi-arid Southern Africa. The objectives of this study were to (i) evaluate the performance of APSIM in simulating crop yields from maize-cowpea intercrops; (ii) assess the effects of the timing of the incorporation of cowpea in an intercrop, N fertiliser application rates, and cowpea plant populations on maize and cowpea yields and total soil N; and (iii) determine whether maize-cowpea intercropping is capable of consistently meeting the energy and protein needs of average farming households.

5.2. Materials and methods

5.2.1. Study sites

Field experiments were conducted in four districts of southern Zimbabwe, namely: Masvingo, Matobo, Nkayi and Umzingwane (Table 5.1). Zimbabwe is divided into five agro-ecological regions mainly on the basis of the amount, distribution and reliability of rainfall (Vincent et al., 1960). The districts mentioned lie in agro-ecological zones (AER) III and IV. In AER III, annual rainfall is in the range of 600–800 mm; it is not reliable, and mid-season droughts may occur. The farming system is dominated by maize (*Zea mays* L.) production with some livestock rearing. The latter allows tillage and soil fertility improvement through manure. Rainfall is lower and even less reliable in AER IV (450–650 mm per annum). In this region

Table 5.1: General characteristics of the study sites

Site	District and site location	Average temperature (ºC)	Agro-ecological Zone	Annual average precipitation (mm)	Soil type
Masvingo	Masvingo 20°3'S, 30°52'E	19.4 °C	III*	648	Arenosol
Matopos Research Institute (Matobo-clay)	Matobo 20°23'S, 28°33'E	18.4 °C	IV**	580	Cambisol
Matobo (Matobo-sand)	Matobo 20°39'S, 28°15'E	18.4 °C	IV	580	Arenosol
Nkayi	Nkayi 19°0'S, 28°54'E	20.1 °C	IV	650	Arenosol
Umzingwane	Umzingwane 20°21'S, 28°57'E	19.4 °C	IV	581	Arenosol

*Agro-ecological zone III receives annual rainfall in the range of 600 – 800 mm; the rainfall is not reliable and mid-season droughts may occur.

livestock are dominant, and the growing of drought-tolerant crops such as sorghum (*Sorghum bicolor*, (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R. Br.) is recommended. Groundnut (*Arachis hypogaea* L.) and sugar bean (*Phaseolus vulgaris* L.) are the major legumes in the sub-humid areas, whereas cowpea (*Vigna unguiculata*, (L.) Walp.) is predominant in the semi-arid areas (Nyamangara et al., 2013). The rainfall season in Zimbabwe is unimodal, with distinct wet (November–March) and dry (April– October) seasons. Sole cropping is predominant, although legumes such as cowpea and bambara nut (*Vigna subterranea* (L.) Verdc) and other crops such as pumpkins (*Cucurbita maxima* L.) and melons

(*Citrullus lanatus* (Thunb)) are often sparsely intercropped with the main cereal crops (Ncube et al., 2007b).

5.2.2. Descriptions of field experiments used for model testing

Additive maize-cowpea intercrop trials were conducted on-station for three seasons at Matopos Research Institute's Westacre Creek farm (2010/11 – 2012/13) and on-farm for two seasons in Matobo district (2012/13 – 2014/15) and Nkayi (2008/09 – 2009/10) and for one season in Masvingo and Umzingwane (2008/09). The on-station trial was conducted on a clay soil (Chromic-Leptic Cambisols). The soils in Masvingo, Umzingwane and Matobo districts were sandy soils derived from granite (Eutric Arenosols) (IUSS Working Group, 2014); in Nkayi, however, the soils were Aeolian Kalahari sands. All three soil types are moderately deep to deep and well-drained. Rainfall events were measured with a rainfall gauge and recorded daily at all locations for the duration of the experiments. The daily rainfall data was used in the model testing.

a. On-farm researcher-established and farmer-managed trials

Each trial in Masvingo, Nkayi and Umzingwane districts comprised three adjacent plots measuring 20 m × 10 m with the following treatments: (a) sole maize (40 kg N ha^{-1}); (b) additive maize-cowpea intercrop (40 kg N ha^{-1}), with cowpea planted four weeks after planting maize (4WAP); and (c) sole cowpea planted 4WAP (0 kg N ha^{-1}). These were replicated on three farms in each district. Crop yields were determined from net plots measuring 8 m × 6 m.

b. On-farm researcher-managed trial

In Matobo district, an additive maize-cowpea intercrop trial was established on one farmer's field, set up as a randomised complete block design with three replicates. Treatments were: (a) sole cowpea planted on the same date as maize (0 kg N ha^{-1}); (b) sole cowpea 3WAP (0 kg N ha^{-1}); (c) sole maize (0 kg N ha^{-1}); (d) sole maize (40 kg N ha^{-1}); (e) maize-cowpea intercrop

(0 kg N ha^{-1}) with cowpea planted on the same date as the maize; (f) maize-cowpea 3WAP intercrop (0 kg N ha^{-1}); (g) maize-cowpea intercrop (40 kg N ha^{-1}) with cowpea planted on the same date as the maize; and (h) maize-cowpea 3WAP intercrop (40 kg N ha^{-1}). The details of this experiment are provided in Masvaya et al. (2017a).

c. On-station trial

In the on-station additive maize-cowpea trial, maize was planted in planting basins and the cowpea was planted in furrows between the maize rows. Fertiliser was applied to all maize plots in this trial at 40 kg N ha^{-1}. The trial was set up as a randomised complete block design with four replicates and plots measuring 15 m × 8 m. The treatments were: (a) sole maize; (b) maize – cowpea intercrop with cowpea planted the same date as maize; (c) maize-cowpea intercrop with cowpea planted 3WAP maize; (d) sole cowpea planted on the same date as the maize; and (e) sole cowpea planted 3 WAP maize. Yield measurements were made from net plots measuring 6 m × 4.5 m. Details of this trial are provided in Masvaya et al. (2017a).

5.2.3. Model description

The APSIM crop-simulation model was created to respond to the need for improved planning and forecasts for crop production under different climate, soil and management conditions (Keating et al., 2003). The APSIM model can simulate resource use in intercrop systems and allows for any number of biological modules to compete daily via allocation rules specified within an 'arbitrator' module, called Canopy, that is linked to the APSIM engine along with the competing crop modules.

a. APSIM – Canopy

The Canopy module within APSIM enables the model to simulate resource competition between different crop species (with a maximum of ten crops) grown in an intercrop. The module is useful when the simulated cropping system involves competition for solar radiation, nutrients and water between crop species. The Canopy module determines the amount of solar radiation intercepted by each component of the intercrop on the basis of the leaf area index (LAI), the extinction coefficient and the height of each crop. The total radiation intercepted in a layer is divided amongst the canopies occupying the layer (Keating et al., 2003). Various canopy layers are defined, starting with the top of the tallest canopy – that of the dominant species in the system. The fraction of light transmitted through the top layer can be calculated on the basis of the LAI (Knörzer et al., 2011). 47% of the leaf area is assumed to be located in the top 10% of height, 27% in the next 10%, 15% in the next 10%, and so on for each species (Keating et al., 2003). Water and nitrogen uptake by the intercrops is regulated by an arbitrary daily rotation, which gives each competing species the opportunity to capture soil resources on a particular day, followed by a day of no uptake, leaving resources available for the competitor.

5.2.4. Model inputs

a. Climate and soil data

Long-term daily maximum and minimum temperatures and radiation and rainfall data were obtained from the national weather stations close to the study sites. These data covered a 30-year period (from 1980 to 2010 in Nkayi and from 1985 to 2015 at all other sites). In addition, weather data were recorded on-site in the periods the trials were conducted. Gaps in the rainfall and temperature data were filled in using data from www.tutiempo.net, whilst radiation data was obtained from the NCEP climate forecasting system reanalysis (Saha et al., 2014). The soil parameters for the different sites were obtained from literature; chemical and texture parameters were obtained from soil analyses (Table 5.2). Prior to crop establishment, soil samples were collected in each site and analysed for soil organic carbon (SOC), soil total nitrogen and phosphorus, soil texture, and pH ($CaCl_2$), following procedures described by Okalebo et al. (2002).

Table 5.2: Properties of the soil series available in APSIM's soil module which best describe soil water properties

Site (reference)	Depth (cm)	Bulk density (kg/m3)	AirDry (mm/mm)	LL (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	Maize LL (mm/mm)	CowpeaLL (mm/mm)	O.C (%)	pH	NH_4-N (kg ha^{-1})	NO_3-N (kg ha^{-1})
Masvingo (Shamudzarira and Robertson, 2002)	0-10	1.44	0.04	0.06	0.17	0.30	0.06	0.11	0.57	6.0	1.40	6.62
	10-20	1.50	0.04	0.06	0.18	0.30	0.06	0.14	0.37	6.0	1.65	4.26
	20-41	1.48	0.05	0.07	0.19	0.32	0.07	0.16	0.21	6.0	1.89	0.96
	41-68	1.50	0.05	0.07	0.19	0.33	0.07	0.17	0.11	6.2	1.91	0.55
	68-94	1.53	0.06	0.08	0.20	0.34	0.08	0.19	0.07	6.5	1.98	0.11
	94-120	1.57	0.06	0.08	0.21	0.35	0.08	0.2	0.05	6.5	2.10	0.11
Nkayi (Masikati, 2006)	0-15	1.43	0.03	0.04	0.14	0.44	0.04	0.04	0.66	5.7	0.42	0.51
	15-30	1.42	0.07	0.07	0.15	0.45	0.07	0.07	0.42	5.7	0.62	0.84
	30-45	1.42	0.09	0.13	0.20	0.45	0.13	0.13	0.35	5.8	0.62	1.18
	45-60	1.55	0.09	0.13	0.20	0.40	0.13	0.13	0.25	5.8	0.67	0.55
	60-75	1.55	0.09	0.18	0.22	0.40	0.18	0.18	0.14	5.9	0.68	0.37
	75-100	1.61	0.09	0.22	0.24	0.38	0.22	0.22	0.11	6.0	1.17	0.32
Mzingwane (generic soil from APSIM)	0-10	1.40	0.030	0.040	0.140	0.40	0.17	0.17	1.00	6.5	0.84	13.65
	10-30	1.40	0.070	0.070	0.150	0.41	0.18	0.18	0.62	6.5	1.26	4.41
	30-60	1.40	0.090	0.130	0.200	0.42	0.19	0.19	0.49	6.5	1.26	4.41
	60-90	1.40	0.090	0.130	0.200	0.43	0.22	0.22	0.45	6.5	1.34	3.57
	90-120	1.40	0.090	0.180	0.220	0.44	0.25	0.25	0.43	6.5	2.33	5.95
Matobo (Masikati, 2006)	0-15	1.43	0.03	0.04	0.14	0.44	0.04	0.04	0.66	6.0	0.32	3.39
	15-30	1.42	0.07	0.07	0.15	0.45	0.07	0.07	0.42	6.0	0.32	2.52
	30-45	1.42	0.09	0.13	0.20	0.45	0.13	0.13	0.35	6.0	0.32	1.68
	45-60	1.55	0.09	0.13	0.20	0.40	0.13	0.13	0.25	6.2	0.28	0.91
	60-75	1.55	0.09	0.18	0.22	0.40	0.18	0.18	0.14	6.5	0.28	0.55
	75-100	1.61	0.09	0.22	0.24	0.38	0.22	0.22	0.11	6.7	0.48	0.95
Westacre (Mupangwa, 2010)	0-10	1.51	0.02	0.03	0.15	0.30	0.03	0.03	1.00	4.9	0.60	3.16
	10-20	1.51	0.02	0.03	0.15	0.30	0.03	0.03	0.90	4.9	0.10	2.85
	20-30	1.51	0.02	0.03	0.15	0.36	0.03	0.03	0.70	4.9	0.10	1.86
	30-40	1.75	0.02	0.03	0.15	0.25	0.03	0.03	0.60	4.9	0.10	0.93
	40-50	1.60	0.04	0.05	0.16	0.30	0.05	0.05	0.50	4.9	0.10	0.72
	50-90	1.60	0.05	0.06	0.17	0.30	0.06	0.06	0.40	5.8	0.10	4.47

b. *Model performance indicators*

In this study, APSIM version 7.10 (available at www.apsim.info) was used to simulate the intercrop system. The yields per crop, treatment and site were used to test the model by comparing model outputs with observed data from the field experiment. Model performance was evaluated with root mean square error (RMSE) and relative root mean square error (RRMSE) providing indicators of the fit between the model predictions and the field-observed values. In this study, we considered relative root mean RRMSE ≤ 15% as "good" agreement; 15–30% as "moderate" agreement; and ≥ 30% as "poor" agreement (Yang et al., 2014). Model efficiency (EF, a perfect fit between predictions and observations gives EF = 1) was also calculated to interpret the predictive ability of the model. The index of agreement, *d* (0–1), was calculated and is both a relative and bounded measure, which provides a single index of model performance that encompasses bias and variability. The model simulates well when *d* approaches 1 (Moriasi et al., 2007).

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{0.5} \quad (1)$$

$$RRMSE = 100 \times \frac{\left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{0.5}}{O_m} \quad (2)$$

$$EF = \frac{\left[\sum_{i=1}^{n}(O_i - O_m)^2 - \sum_{i=1}^{n}(P_i - O_i)^2\right]}{\sum_{i=1}^{n}(P_i - O_i)^2} \quad (3)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P'_i| + |O'_i|)^2} \quad (4)$$

Here, P_i is simulated values; O_i is measured values; O_m is mean of measured values, and *n* is the number of the observations. $P' = P_i - O_m$ and $O' = O_i - O_m$

5.2.5. Scenario analyses

Three scenarios, differentiated by management options, were developed in order to determine whether maize-cowpea intercropping results in household food self-sufficiency. Although not exhaustive, these scenarios offered a good starting point for assessing the performance of an intercropping system under various management strategies. The maize variety SC401 and the cowpea variety Banjo were selected in the model as sufficiently representative of the varieties planted at the study sites. The model was reset every 1st July to initial water, N, surface OM and phosphorus values, to remove year-to-year effects.

For each study site, the following scenarios were simulated:

i. Planting dates: In the simulations, maize was planted with the first rains and the cowpea in staggered plantings from 0 – 4 weeks after the maize. Maize and cowpea were planted at populations of 37 000 and 74 000 plants ha^{-1} respectively, as in the field trials. Fertiliser was applied to the maize at 40 kg N ha^{-1} as follows: 14 kg N ha^{-1} was applied at planting and then top dressed with 26 kg N ha^{-1} 42 days after planting. The cowpea did not receive any fertiliser.

ii. N fertiliser application: The fertiliser application for maize was simulated with no added N (0 N), 40 kg N ha^{-1} (40N) and the recommended 80 kg N ha^{-1} (80N). For the cowpea, fertiliser application was simulated at 0 and 40 kg N ha^{-1}. Maize and cowpea were planted on the same date at populations of 37 000 and 74 000 plants ha^{-1} respectively. To both the maize and cowpea, fertiliser was applied at planting at 14 kg N ha^{-1} (14N); the remainder was applied 42 days after planting either crop.

iii. Plant populations: The maize plant population was fixed at 37 000 plants ha^{-1} whilst the cowpea plant populations varied from the recommended population of 148 000 ha^{-1} (high – H) to 74 000 (medium – M) and 37 000 plants ha^{-1} (low – L). Maize and cowpea were planted on the same date. Each of the plant population scenarios was run for two maize fertiliser rates, namely 0 and 40 kg N ha^{-1}. The cowpea received no fertiliser.

Currently, APSIM does not have a function with which the intercrop spatial arrangement can be specified. The model only allows for the manipulation of the plant populations and planting dates through the APSIM manager.

For each scenario, we simulated grain yields, cumulative total N uptake and crop water uptake (from the whole profile) for each crop. The outputs for grain yields were analysed descriptively, using means and standard deviations for three of the five study sites. Masvingo, Matobo-clay and Matobo-sand were chosen for this analysis as they represent contrasting sites in terms of agro-ecology (AER III versus AER IV) and soil type. The daily energy and protein requirement of a male adult equivalent is 2500 kcal and 63 g respectively (FAO, 2004; WHO, 2007). The energy and protein content per 100 g of maize is 358 kcal and 9.2 g respectively (FAO, 1995), while that of cowpea per 100 g of grain is 80 kcal and 24 g respectively (USDA, 2018). We determined the energy and protein production for each cropping scenario based on the grain yields, the grain energy and protein content of both crops, taking into account the average family and farm sizes for each AER (Table 3). Family and farm sizes were obtained from other studies that collected this data in the study areas (Musiyiwa, 2014; Homann-Kee Tui et al., 2015; Kunzekweguta, 2016). For the purposes of this study, it was assumed that each household dedicated the entire farm cropland to the tested cropping system scenario.

5.3. Results

5.3.1. Model evaluation

Simulated maize and cowpea grain yields generally approximated the observed yields from the field trials across the different growing seasons (Figure 5.1). The model captured the direction and relative magnitude of the maize yield responses to N fertiliser application and cowpea incorporation at all sites. The model simulations for grain yields were satisfactory with a RMSE of 540 and 222 kg ha^{-1}; RRMSE of 29% and 18%; EF of 0.5 and 0.71 and *d* of 0.60 and 0.89 for maize and cowpea respectively when intercrops and monocrops were taken together.

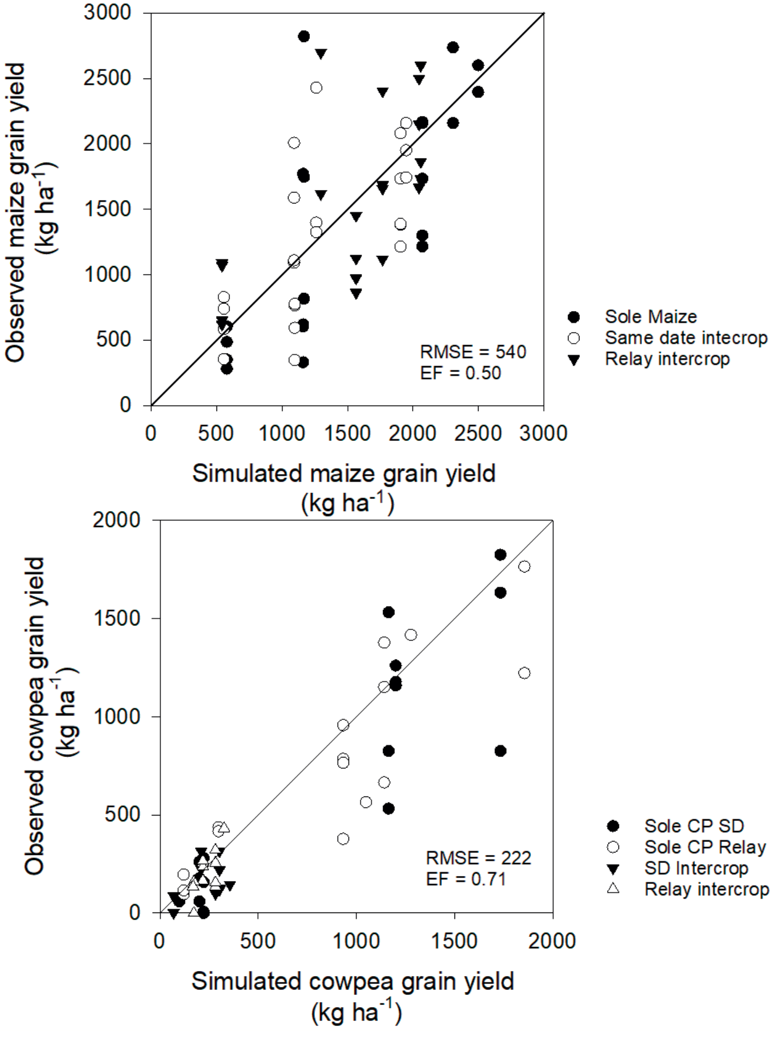


Figure 5.1: Observed and predicted maize and cowpea grain yields across all locations

5.3.2. Scenario analyses

a. Planting dates: time to incorporate cowpea

Intercropping maize and cowpea resulted in a mean yield reduction for maize ranging from 3% to 25% compared with sole maize, regardless of time the cowpea was integrated in the intercrop (Figure 5.2). The same-date intercrop resulted in the highest mean yield reduction by 14% to 25% across all sites. The more the cowpea planting was delayed in the relay intercrops, the higher was the maize yield in comparison with the same-date intercrop. At all sites, incorporating cowpea into the intercrop reduced the N and water uptake of maize in the intercrop compared with the sole maize. N uptake by sole maize exceeded the intercropped maize scenarios by 8–28% on the clay and 10–32% on sands, averaged over the 30-seasons. Water uptake followed the same trend; it was higher in the sole maize crop across all sites by 9–27%.

For intercropped cowpea, yields followed a reverse trend to the maize yields (Figure 5.2), with the same-date intercrop always yielding best. The longer the delay in planting cowpea in the intercrop, the lower the resultant cowpea yields. Just a week delay in planting resulted at all sites in a reduction of the average cowpea yield of between 21–65% compared to planting at the same time with maize. Cowpea planted on the same date as maize had a higher N and water uptake than cowpea planted at later dates into the intercrop. The difference in N uptake between the same date planted cowpea and the later planting dates increased at all sites with the later the planting date from between 4–13% with 1–2-week delay in planting to 32–40% with a 3–4-week delay.

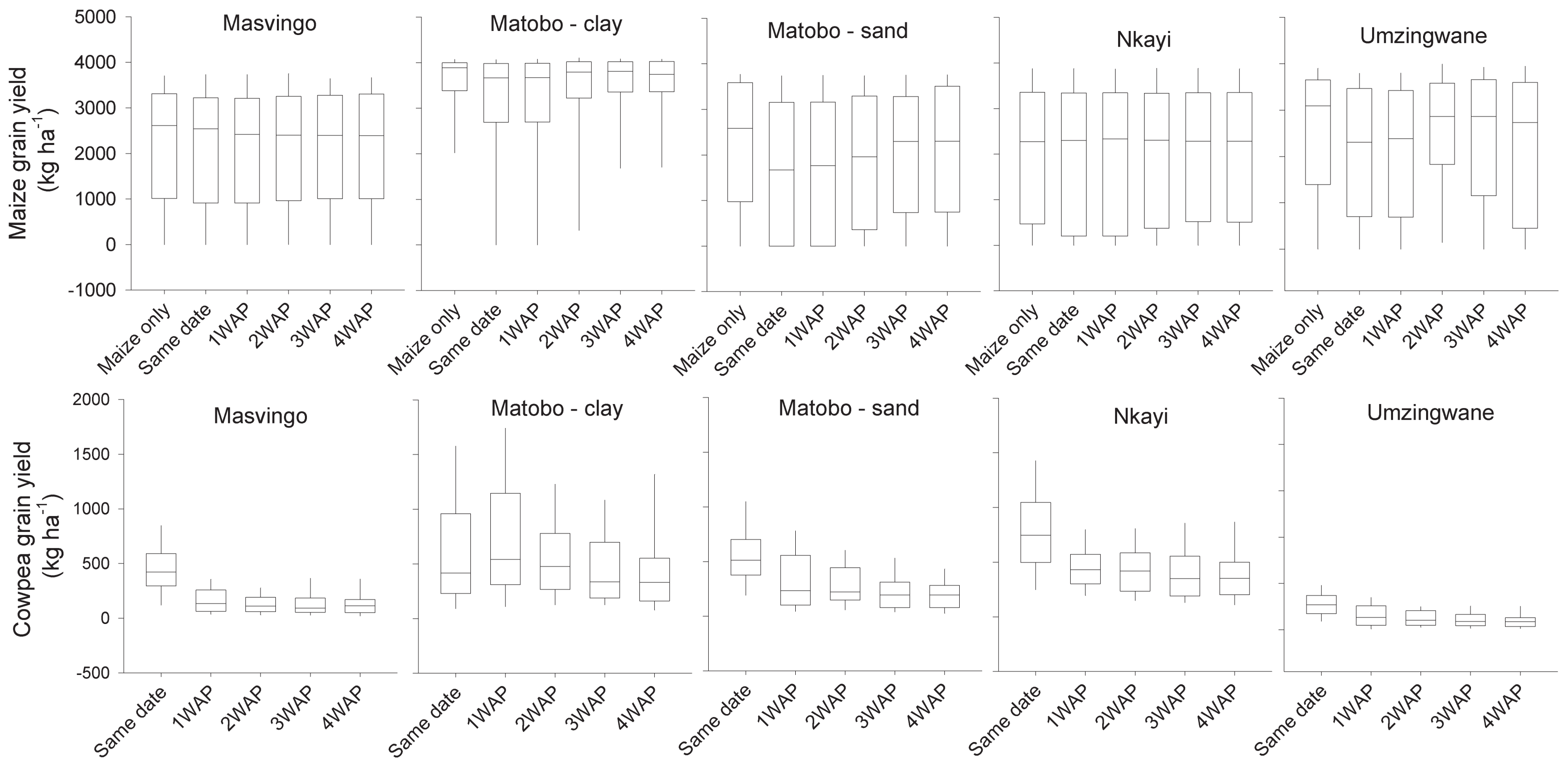


Figure 5.2: Simulated yield response of maize–cowpea intercrop to different cowpea planting date scenarios at five sites in semi-arid Zimbabwe (Masvingo, Matobo-Clay, Matobo – Sand, Nkayi and Umzingwane) over a 30-year period (1985-2015). The plant populations for maize and

b. *Fertiliser application*

Maize grain yields increased when more N fertiliser was applied to the intercrops (Figure 5.3). Maize yields on the sandy soils in Masvingo, Matobo, Nkayi and Umzingwane were more responsive to fertiliser application than those on the clay. The application of fertiliser led to an increase in grain yields, both in intercrops and sole crops, by between 23–34 kg grain kg^{-1} N applied on the sandy soils, whilst on the clay the increase was between 12–17 kg grain kg^{-1} N applied.

Generally, the application of fertiliser to maize did not result in yield benefits for the cowpea in the intercrops. Instead, the increase in fertiliser application to maize led to decreased cowpea yields compared with the sole cowpea crop (0N) by 60% on the sand, by 13% on the clay in Matobo, and by 19–22% in Masvingo and Nkayi. In Umzingwane, however, the model predicted a general increase in the cowpea yield with the 40N fertiliser application to maize. Application of N fertiliser to sole cowpea (with 40N treatment) increased yields, although this increase was highly variable across sites, ranging between 7–372%. Cowpea was highly responsive to the fertiliser addition on the clay in Matobo, in Masvingo and Nkayi. In the intercrop, the effect of N fertiliser application to both maize and cowpea (40N maize + 40N cowpea treatment) resulted in variable responses in cowpea yields across all sites (Figure 5.3). The mean cowpea yield with this scenario was low, in the range of 100–284 kg ha^{-1}.

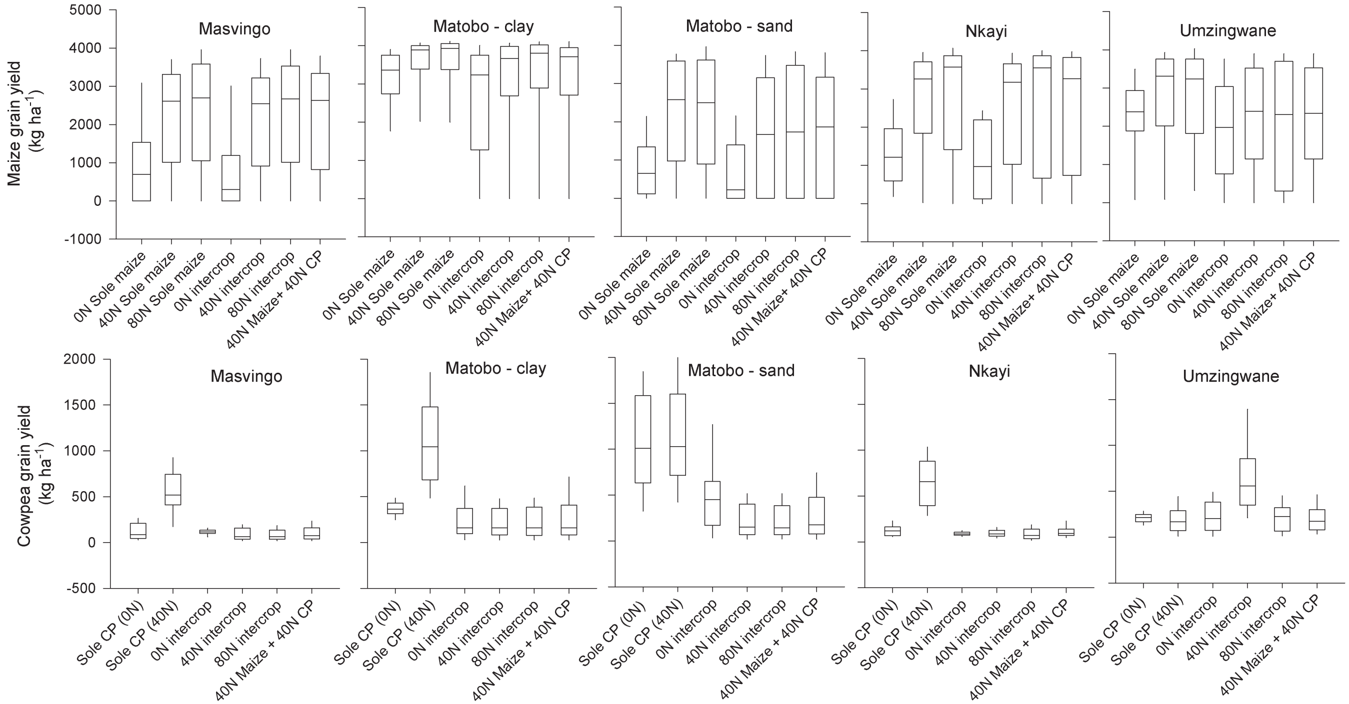


Figure 5.3: Simulated mean yield response of maize–cowpea intercrops across five sites in semi-arid southern Zimbabwe in response to N fertiliser application. Maize and cowpea were planted on the same date at plant populations of 37 000 and 74 000 plants ha^{-1} respectively. (For the intercrops labelled 0N, 40N and 80N, fertiliser was applied only to the maize)

c. Plant populations

Manipulating the cowpea plant population had no pronounced effect on the maize yield (Figure 5.4). The population variations, however, influenced the cowpea yields at all five sites. Except with the 0N treatment, cowpea yields generally increased with an increase in cowpea plant population in the intercrops. The increase in yield, when the high population was compared with the low population, was in the range of 14–95% for the sole crop and the 40N intercrop. Under the 0N treatment, except in Masvingo, the low cowpea population generally resulted in higher cowpea yields in comparison with the high population in the intercrop treatment in the range of 27–44%. With the addition of fertiliser to the maize, the increasing cowpea population resulted in increased cowpea yields.

d. Effect of treatments on energy and protein self-sufficiency

At all sites, most maize-cowpea intercropping scenarios had a high probability of meeting household energy and protein requirements if the specific treatment was applied to the entire farm size (Table 5.3; Annex C figures 1–3). Planting maize and cowpea at populations of 37 000 and 74 000 plants ha^{-1} respectively on the same date and with 40 kg N ha^{-1} applied to the maize maximised the probability of meeting household energy and protein requirements; the probabilities were in the range of 83–90% and 80–83% respectively on sandy soils. On the clay (Matobo – Clay), the relay intercropping scenarios where cowpea was planted 2 to 4 weeks after the maize were better suited. With relay intercropping on the clay, household energy needs were met in 28–29 out of 30 seasons whilst protein needs were met in all 30 seasons. On average, the yields in this scenario exceeded energy and protein requirements, delivering 300 and 600% of the required amount respectively. The poorest-performing intercropping scenario was intercropping with the medium cowpea population and 0N fertiliser (0N M) on sandy soils, which had a probability of meeting the household energy requirement of 40–47%.

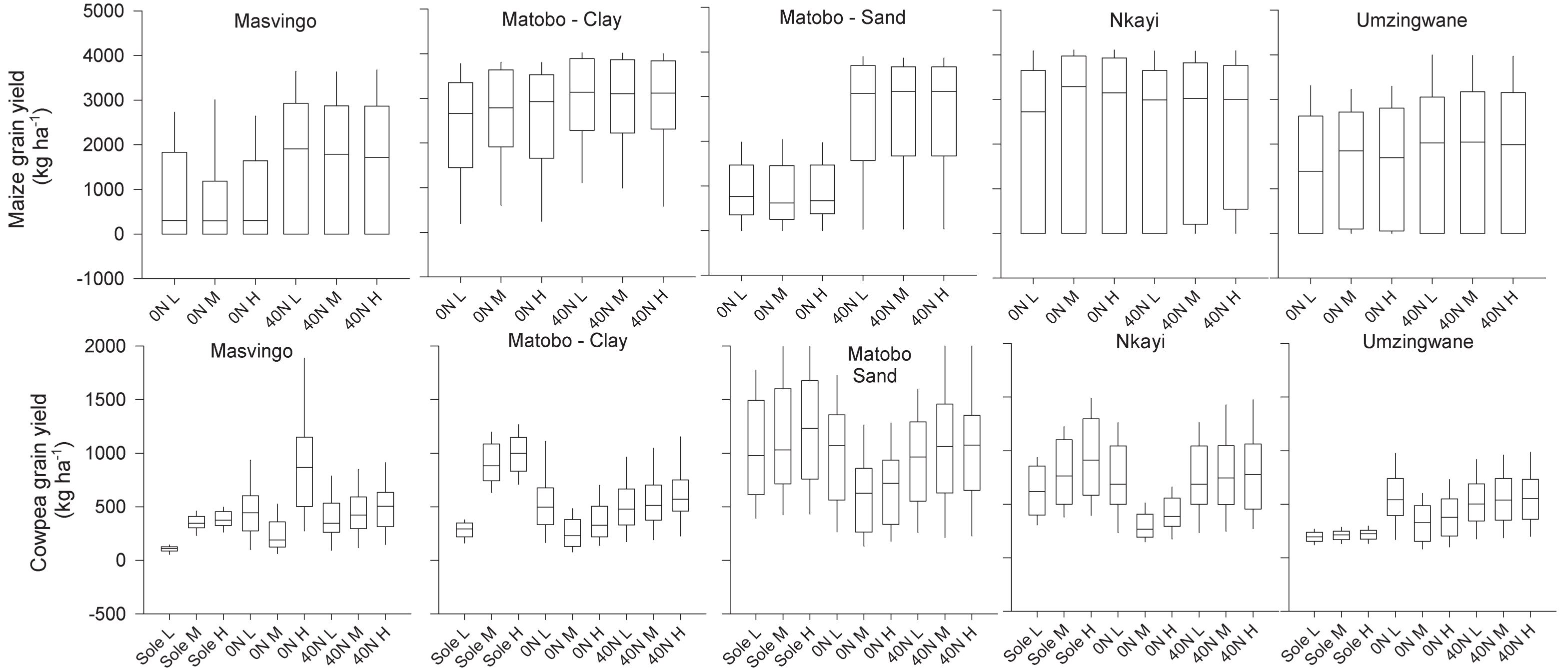


Figure 5.4: Simulated mean yield response of maize–cowpea intercrops across five sites in semi-arid southern Zimbabwe in response to different cowpea plant populations: Low (L) = 37 000 plants ha^{-1}, Medium (M) = 74 000 plants ha^{-1} and High (H) = 148 000 plants ha^{-1}. Maize population was simulated at 37 000 plants ha^{-1}.

Table 5.3: Average household energy and protein production based on household and landholdings at the study locations. The figures in brackets denote the probability of meeting the household energy and protein requirements over the 30-year model simulation period.

	AER III	**AER IV**
Average family size (male adult equivalent)	4.1	5.0
Average farm size (ha)	1.6	2.0
Energy requirement (Mcal ha^{-1} yr^{-1})	2339	2282
Protein requirement (kg ha^{-1} yr^{-1})	59	58

		Masvingo		Matobo-clay		Matobo-sand	
	Scenario	Energy (Mcal)	Protein (kg)	Energy (Mcal)	Protein (kg)	Energy (Mcal)	Protein (kg)
Planting date	Sole maize (40N)	7734 (0.83)	199 (0.83)	12762 (1.00)	328 (1.00)	7978 (0.77)	205 (0.80)
	Intercrop (same date + 40N)	7757 (0.83)	300 (0.83)	11371 (0.93)	433 (1.00)	9995 (0.90)	508 (0.80)
	2WAP	7637 (0.83)	229 (0.83)	12094 (0.93)	443 (1.00)	7050 (0.73)	244 (0.83)
	4WAP	7786 (0.83)	230 (0.83)	12460 (0.97)	426 (1.00)	7558 (0.80)	240 (0.83)
Fertiliser	Sole maize (0N)	3206 (0.57)	82 (0.57)	11039 (1.00)	284 (1.00)	3113 (0.53)	80 (0.53)
	Sole maize (80N)	8169 (0.83)	209 (0.83)	12952 (1.00)	333 (1.00)	8180 (0.80)	210 (0.80)
	Intercrop (0N)	3954 (0.47)	101 (0.47)	9453 (0.87)	300 (1.00)	3085 (0.40)	194 (0.87)
	Intercrop (80N)	8048 (0.83)	226 (0.83)	11331 (0.87)	340 (0.97)	6622 (0.63)	216 (0.83)
	Intercrop (40N Maize and 40N Cowpea)	7560 (0.80)	217 (0.83)	11134 (0.87)	340 (1.00)	6276 (0.63)	224 (0.83)
	Sole cowpea (0N)	100 (0.00)	30 (0.17)	295 (0.00)	89 (0.97)	919 (0.09)	275 (0.97)
Population	Intercrop (0N) L	3487 (0.57)	193 (0.97)	8958 (0.90)	349 (0.93)	4087 (0.70)	344(0.90)
	Intercrop (0N) M	3056 (0.47)	132 (0.47)	9567 (0.87)	305 (1.00)	3692 (0.40)	244 (0.87)
	Intercrop (0N) H	3711 (0.60)	298 (0.97)	9288 (0.90)	318 (0.93)	3819 (0.67)	244 (0.90)
	Intercrop (40N) L	6406 (0.70)	255 (0.90)	10908 (0.93)	394 (0.93)	9803 (0.83)	475 (0.93)
	Intercrop (40N) H	6483 (0.73)	278 (0.90)	10873 (0.90)	419 (0.97)	10060 (0.87)	513 (0.90)

NB: The energy and protein content per 100 g of maize is 358 kcal and 9.2 g respectively (FAO, 1995); that of cowpea per 100 g of grain is 80 kcal and 24 g respectively (USDA, 2018).

The sole cowpea scenarios (0N), however, had the highest probability of not meeting energy needs (0–9%). The scenario, however, had a high probability (97%) of meeting protein needs in sites in AER IV. Calculated on the basis of yields averaged over 30 seasons, the sole cowpea would require between 3.5–30 ha of land to meet both energy and protein requirements.

5.4. Discussion

5.4.1. Model evaluation

The APSIM maize model has been validated and used in many contexts globally (Holzworth et al., 2014). In this study, the APSIM model was used to determine how intercrops of maize and cowpea responded to different management strategies and whether the technology was a low-risk option for attaining household energy and protein self-sufficiency in semi-arid Zimbabwe. APSIM was able to simulate competitive dynamics in maize-cowpea intercrops fairly well, as the simulated and measured yields matched closely. This has also been observed in other studies on maize-legume intercrops (Keating and Carberry, 1993; Smith et al., 2016) and on sorghum-cowpea intercrops (Chimonyo et al., 2016). The model showed that crop yields responded to fertiliser application and the cowpea planting time, thereby providing information that can be useful for developing successful crop management strategies. The outcomes of model testing resulted in a high *d*-index and reasonably good RMSE and EF-values across all treatments and locations, indicating that the efficiency and robustness of the model was adequate, and that the model could be applied effectively in the environments under study.

5.4.2. Intercropping management scenarios

The model predicted that mean maize yields would be negatively affected by intercropping when compared to the sole crops, whilst cowpea yields would be severely affected (Figures 5.2 – 5.4). This implies that maize is a stronger competitor for resources than cowpea in the intercrops, in all the management scenarios tested in this study. This can be explained by dividing the canopies into canopy layers, as APSIM does. The cowpea in the understorey scarcely gets any light, because the incoming light is reduced by the taller first layer of the maize (Knörzer et al., 2011). The negative impact on maize yields in the intercrop compared with sole maize can be explained by the lower nutrient and water uptake of the maize in the intercrops. The model alternates the daily water and N uptake between the crops in the intercrop, with the available soil water and N in the profile being shared between the two crops, whilst in sole crops these resources are available to just one crop (Keating et al., 2003). Although crops simultaneously take up water and nutrients in reality, some field studies concur with the findings of our simulation study, reporting lower water and N uptake by individual crops in an intercrop compared with their sole crops (Wahua, 1983; Gou et al., 2018). Wahua (1983) found that the N uptake of intercropped maize was reduced by 19% compared to sole maize. Other studies have reported on the total uptake in intercrops, and not that of the individual crops; they indicate higher total water and nutrient uptake in arid environments (e.g. Ghanbari et al. (2010). In this study, the maize-cowpea intercropping exploited more stored water than the sole maize crop; however, the intercrop's beneficial effects (reduced evaporation and crop transpiration) appeared to greatly compensate for the interception and uptake losses near the cowpea canopy.

The ideal planting date leads to good yields and low temporal variation (Kucharik, 2008). In our simulation experiments, the maize yield was hardly affected by the timing of the planting of cowpea into the intercrop at all sites (Figure 5.2). However, the later the cowpea is planted into the intercrop, the lower the cowpea yields were. When the cowpea was introduced when the maize crop had already developed a canopy, it suffered from the shading effect. Awal et al. (2006) made a similar observation in trials with maize-peanut intercrops; they established that the shading by maize increased the ratio of diffuse to direct radiation inside the intercrop canopy. However APSIM, like most other common crop-simulation models, does not distinguish between direct and diffuse radiation (Keating and Carberry, 1993). In our simulation, the late-planted cowpea also gave poorer yields because it was taking up less N and water. The simulation results suggested that the best scenario at all sites in terms of average yields for both crops was the same-date intercrop with 40N fertiliser.

The simulation results suggested that both maize and cowpea responded better to fertiliser application in the sole stands than in the intercrops (Figure 5.3). In the intercrops, the maize yields responded positively whilst cowpea yields were depressed. This implies that the application of fertiliser facilitates maize growth such that the maize crop outcompetes the companion cowpea crop. The modelling study conducted by Smith (2014) also found that when N fertiliser was added to the intercrop system, maize became dominant whilst cowpea yields were suppressed. Chimonyo et al. (2016) attributed the positive response to fertiliser application of sorghum in a sorghum-cowpea intercrop to improvements in water use efficiency. Field studies on the effects of fertiliser application on maize-cowpea intercrop systems, and the competitive dynamics involved, have produced varied results. Maize and cowpea yields can both be suppressed in fertilised intercrop systems (Ofori and Stern, 1987); cowpea has been observed to outcompete maize in seasons with low rainfall (Shumba et al., 1990). Evidence of maize benefitting from fertilised intercropping has also been reported (Rusinamhodzi et al., 2012; Masvaya et al., 2017a).

Increasing the plant population of cowpea did not have a pronounced effect on maize yields, whereas the cowpea yields were improved. This may have been because being below the maize canopy, cowpea did not compete with maize for radiation. The increased cowpea yields can be explained by the larger extinction coefficient of the cowpea canopy, accounting for an increase in the amount of solar radiation received by the crop in the understorey (Keating and Carberry, 1993; Knörzer et al., 2011). Cowpea yields in intercrops could also be improved by changing row orientations and arrangements so as to reduce competition for resources. However, APSIM currently does not include the option to define row orientation (Knörzer et al., 2011).

5.4.3. *Effect of treatments on energy and protein self-sufficiency*

Our study showed the that the chances of meeting household energy and protein needs were consistently greater in fertilised intercropping systems than with sole crops of either maize or cowpea. It also showed, however, that maize-cowpea intercropping turned out to be a very risky option, in terms of the chances of meeting household nutrition needs, in semi-arid Zimbabwe. This conclusion is supported by findings in a study on the same system in Malawi (Smith, 2014). Other studies in SSA have suggested that intercropping maize with legumes result in meeting household energy and protein requirements, but also that intercrops are less stable than monocrops (Ollenburger and Snapp, 2014; Smith et al., 2016; Snapp et al., 2018). A cropping system is considered favourably stable when it is consistently high-yielding across sites, regardless of season quality. In our study, all intercropping scenarios had a high probability (>60%) of exceeding household energy and protein requirements at all sites. Sole cropping of cowpea required more land to meet household needs and is not entirely feasible given the small landholdings in the study area. Thus, intercropping is more efficient in producing food on the available land. While our study assumed that all crop land would be allocated to the maize-cowpea intercropping, in reality smallholder farmers engage in different cropping and livestock-raising activities and look beyond the field level for household food security. At the farm level, whether household nutrition needs are met depends on how the farmer allocates the available resources, such as land and labour, as well as on the availability of alternative sources of nutrition, such as edible insects (Frelat et al., 2016; Manditsera et al., 2019).

The main concern of smallholder farmers is to feed their families with their own production. Therefore, increasing the productivity and the adaptability of cropping systems is important in the face of climate change. The intercrop (40N) M scenario consistently resulted in households meeting their energy and protein needs, regardless of the site and soil type, unlike the sole-crop scenarios, which indicates that this option may meet the criteria of a climate-smart management strategy. However, as the mitigation aspect was not considered in this study, we cannot conclude that maize-cowpea intercropping is climate-smart. Only recently has work been done to evaluate how intercrops reduce greenhouse gas emissions directly (Ricord, 2018). This study established that intercropping systems are effectively reducing N_2O emissions on a loamy soil in Argentina and that they have the potential to sustainably reduce the emission of one the most potent greenhouse gases. However, this study concluded that to assess intercrop systems in terms of C storage and CO_2 reduction, long-term studies are needed (more than 10 years).

5.6. Conclusions

APSIM proved to be an effective tool for assessing the performance of maize-cowpea intercropping under different management scenarios in two agro-ecological zones in semi-arid Zimbabwe. Maize is a stronger competitor for resources than cowpea; therefore, it was not affected by changes in the cowpea planting date and population density. At the sites considered in this study, the maize in the intercrop system positively responded to increases in N fertiliser application whilst cowpea was most responsive to increases in the cowpea plant populations. Planting maize and cowpea on the same date with 40 kg N ha^{-1} applied to the maize crop, was the option that had the highest probability of meeting household energy and protein needs; this, therefore, can be considered the best management strategy. Our model showed that maize-cowpea intercropping is a more efficient system than growing the same crops sole, and that it is more likely to ensure household energy and protein self-sufficiency.

CHAPTER 6

GENERAL DISCUSSION

6.1. Introduction

In this study, I explored the crop-production potential of two systems that have been proposed in risky semi-arid environments as climate-smart technologies that allow sustainable intensification: conservation agriculture (CA) and maize-legume intercropping. These technologies are claimed to have the potential to sustainably increase agricultural productivity and incomes while ensuring the possibility to adapt to climate change and to reduce and/or remove greenhouse gas emissions (Arslan et al., 2015). Sustainable intensification (SI) aims at increasing food production from existing cropland in ways that have a low environmental impact, do not undermine the capacity to continue producing food in the future, and at the same time increase contributions to natural capital (Pretty et al., 2011; Campbell et al., 2014).

I tested the claims made for these technologies, by quantifying the crop productivity and soil N dynamics in semi-arid southern Zimbabwe, using field and modelling approaches, and taking into account the effect of various management practices. In this discussion, I first bring together the main findings from the preceding chapters and highlight the lessons learnt (section 6.1). Next, I explore the feasibility of the application of CA and intercropping for the diversity of farmers in this region (section 6.2). I then point to the relevance of these findings for current debates on CSA and SI (sections 6.3 – 6.4). I conclude with a reflection on the limitations of this thesis and suggestions for further research.

6.2. General findings

The findings of this study generally apply to smallholder farming in semi-arid southern Zimbabwe. Chapters 2 and 3 explored the potential of CA to increase the productivity and efficiency of a maize-based smallholder systems in risky environments characterised by nutrient-poor sand soils and poor rainfall. In Chapter 2, it was established that plough tillage positively affected mineralisation, N uptake and crop yields more than ripper tillage. However, when combined with mulch application, the ripper tillage did not reduce mineralisation; ripper + mulch resulted in yields comparable to those obtained under plough tillage without mulch. Nitrogen-containing fertiliser and manure application had the effect of improving maize yields on these soils, regardless of the tillage method used and whether or not mulch was applied. In Chapter 3, a risk assessment was conducted of different management options in terms of planting dates, tillage, mulch and fertility amendments over a longer period (30 years) under the current climate. This study showed that ripper tillage, in combination with mulch application, gave significantly higher maize yields compared with the plough tillage across all planting date scenarios and fertility treatments. Early planting, irrespective of the tillage method employed, proved the better planting date option; it fostered household grain self-sufficiency and reduced the risk of complete crop failure except in the event of false season starts. The yield benefits resulted from capturing the N mineralised by virtue of the "Birch effect" and the in-season rainfall. The early planting dates also involved a risk: false season starts which could result in crop yield losses.

In Chapters 4 and 5 I evaluated the potential of maize-cowpea intercropping systems in the semi-arid areas. I found that maize-cowpea intercropping could improve land-use efficiency where the use of external inputs such as fertiliser is restricted. Regardless of the time of intercropping, the season quality and the soil type, the yields were higher than in maize monocrop systems (Chapter 4). Although the trials showed intercropping was productive, it resulted in severely compromised cowpea yields compared with the sole cowpea stands, whilst the maize yields were either not affected or improved by intercropping. Maize outcompeted cowpea in the intercrop; this was attributed to a lack of below-ground complementarity between the roots of the different species (Chapter 4) and to shading of the cowpea by the maize canopy (Chapter 5). In Chapter 5, the maize-cowpea intercrop was proposed as a risk-averse cropping option that allowed households to be energy and protein self-sufficient over a long-term period of 30 years in semi-arid southern Zimbabwe. The maize in the intercrop system responded positively to increases in N fertiliser application, whilst cowpea was most responsive to increases in cowpea plant populations. The study showed that maize-cowpea intercropping is a better and more effective way to attain household energy and protein self-sufficiency than growing sole crops. Sole crops would require more land and labour to support household nutrition needs.

Throughout the study, I was confronted with a large variability in terms of weather conditions and crop yields. The latter made it apparent that there was a heterogeneity among farmers which it is important to recognise when making recommendations on the cropping systems.

6.3. The feasibility of the application of conservation agriculture and intercropping in semi-arid Southern Africa

6.3.1. Characteristics of smallholder farmers in semi-arid Zimbabwe

Smallholder farmers in semi-arid southern Zimbabwe constitute a heterogeneous group. They combine farm and off-farm activities to achieve food security and to sustain or improve their livelihoods (Ncube et al., 2009b; Homann-Kee Tui et al., 2015). As a rule, smallholder farmers in the region have access to both privately-managed fields, on which they grow their crops, and to communally-managed grazing lands. The arable fields are also communally grazed during the dry season, unless they are securely fenced off. Most smallholder farmers in semi-arid areas in Zimbabwe prefer to grow maize, which takes up more than half of the total cropped area (Twomlow et al., 2006). Minor crops include cowpea (*Vigna unguiculata* (L) Walp.), groundnut (*Arachis hypogaea* L.), and Bambara nut (*Vigna subterranea* (L.) Verdc.) (Ncube et al., 2009b). The dominant soils are sandy soils (Eutric Arenosols) derived from granite, with pockets of clay soils (Chromic-Leptic Cambisols). Over 40% of households in semi-arid Zimbabwe own draught animals (ZimVac, 2012).

Farm households are diverse in terms of resource endowments as well. The impacts of climate change on agriculture and on the livelihoods of these farmers will also be heterogeneous, as vulnerability to climate change varies between crops and regions and with farmers' socio-economic conditions. Depending on the biophysical and socio-economic context, it will be easier for some farmers to adopt new cropping technologies than for others. A study in semi-arid Zimbabwe distinguished between three groups of farmers: better, medium and poorly resourced (Ncube et al., 2009b). Better-resourced farmers own large implements such as the plough and a Scotch cart (ox-drawn cart). Some medium-resourced farmers own some large implements as well, unlike the poorly-resourced farmers. Better-resourced farmers own more livestock and are also able to buy fertiliser, which they apply in good seasons. Even though the better-resourced farmers seem to be assured of draught power every season, they are also vulnerable to reductions in livestock herd sizes due to drought and outbreaks of animal diseases (Homann-Kee Tui et al., 2015). Medium-resourced and poorly-resourced farmers have limited means for replenishing soil fertility. As the sandy soils get exhausted, and leave no nutrients to mine, these two groups continuously experience very poor yields.

Household sizes vary from 6–9 persons, with 2–5 people contributing to active labour on-farm; the size of the landholdings varies from 1–5 ha (Mupangwa, 2010; Musiyiwa, 2014; Homann-Kee Tui et al., 2015; Kunzekweguta, 2016). Considering the limited available household labour, cropping systems that intensify production on the available land would be more appropriate in this region. In other regions such as northern Zimbabwe, extensification has been viewed as an option on the relatively fertile soils (Baudron et al., 2012b).

6.3.2. Conservation agriculture in semi-arid Zimbabwe

Continuous conventional tillage with limited cereal-legume crop associations and without any (organic or inorganic) soil fertility amendment application has contributed substantially toward declining crop and soil productivity in Southern Africa (Thierfelder et al., 2012; Mupangwa et al., 2016a). Conservation agriculture (CA), a farming systems approach that aims at improving soil and crop productivity, has the potential to increase and stabilise the yields of major cereal and legume crops and to improve the profitability of smallholder cropping systems under different agro-ecological conditions (Ngwira et al., 2012; Thierfelder et al., 2013). I found that the combination of two CA principles – minimum soil disturbance and maintenance of a permanent soil cover (mulch) – did not reduce soil mineral N availability for crop uptake and resulted in yields comparable with those obtained with plough tillage treatment. The ripper tillage reduces the effects of labour bottlenecks at the beginning of the cropping season, which are common in smallholder systems in SSA (Sims and Kienzle, 2016). In Zimbabwe, the poorly-resourced farmers with limited access to draught power are encouraged to prepare their fields in the dry season using hand hoes (digging pits for fertiliser/manure and seed placement). The spreading of the labour requirement for land preparation allows for early planting (Twomlow et al., 2008).

Farmers, however, participate in other activities, on- or off-farm, and may be unable to commit labour to dry season land preparation. Also, the digging of pits with hand hoes has been shunned in some communities, as the practice is labour-intensive and backbreaking. Some farmers use the term *Dhiga ufe* – meaning ‘dig and die’ for CA. The high labour demand, entailed by manual land preparation and weed control (Rusinamhodzi, 2015), has reduced the appeal of CA for smallholder farmers whose livelihoods are not entirely dependent on crop production. The willingness to adopt of CA is limited by other factors as well. Farmers use crop residues as livestock feed in the dry months; therefore, not much is left over to be applied as mulch. They often lack access to appropriate machinery to ease land preparation and resent the increased need for weed control (Giller et al., 2009; Mavunganidze et al., 2014; Valbuena et al., 2015). Our results (Chapter 3) showed that early planting in combination with ripper tillage and mulch application was the best strategy for achieving food self-sufficiency in semi-arid southern Zimbabwe. Reduced tillage methods employing animal power, such as the use of the ripper (see Chapters 2 and 3), can increase the productivity per unit area by improving the timeliness of farm operations, including planting (Sims and Kienzle, 2016). The use of the ripper curbs the amount of time spent on land preparation, and the labour demand associated with it; but it also necessitates the use of herbicides to manage weeds. Hence, mechanising at least the tillage operation may allow farmers to plant early in the season, allowing the crops to capture N released with the first rains. Other studies (Traore et al., 2015) have shown early planting to be an essential entry point for yield stabilisation for medium- and poorly-resourced small farmers, and therefore as a useful adaptation strategy in the face of climate change. Although ripping may be favourable, poorly-resourced farmers in Zimbabwe who seldom own land preparation equipment such as a plough (Zingore et al., 2007; Ncube et al., 2009b), may not be able to afford rippers; and without a plough to mount them on, the cheaper ripper tine attachments available on the market are of no use to them. Only a few equipment manufacturers have been producing rippers and ripper tine attachments, and some manufacturers require pre-financing for production. Strengthening the market linkages between smallholder farmers and agro-dealers may help to further the uptake of technologies such as ripping and bring smallholder farmers a step closer to achieving the yield benefits indicated in this thesis.

6.3.3. Intercropping as an option in semi-arid Zimbabwe

While maize is one of the least profitable and most input-intensive crops, farmers in semi-arid Zimbabwe do not want to risk producing too little maize to feed their families (Baudron et al., 2012a). Therefore, it is important to look for ways to diversify cropping that do not reduce the land area allocated to the production of maize. In this study, maize-cowpea intercropping did not compromise (Chapter 4). Either the maize yields were improved (on clay soils), or they were similar to sole maize yields (on sandy soils). The study also showed that maize yield can be compromised by intercropping from slight to significant yield reductions (Chapter 5). However, the cowpea yields were severely compromised by intercropping in both the trials and the modelling scenarios (Chapter 4 and 5). This was attributed to the lack of below-ground niche differentiation between maize and cowpea roots (Chapter 4) and to the shading of the cowpea by maize (Chapter 5). Maize outcompeted cowpea in the intercrop regardless of the cowpea planting date, fertiliser application rate and cowpea plant populations (Chapter 5).

Studying the rooting pattern provided insights into inter-species competition of intercropped species. Maize was the stronger competitor for nutrients, as shown by higher N and water uptake (Chapter 5); this may have been due to a lack of below-ground complementarity between the two crops (Chapter 4). Alternative legume options that are hardy and have a different rooting pattern can possibly reduce below-ground competition and achieve higher yields for the legume. In the region, pigeon pea (*Cajanus cajan* (L.) Millsp.) has been used successfully in intercrops with maize on relatively heavy and fertile soils; there were substantial yield benefits for both crops.

This thesis showed that landholdings which are relatively small can be used more efficiently if intercropping is employed, as it leads to overyielding as shown by the Land Equivalent Ratios (LER). The LERs were greater than 1 (Figures 4.7 and 4.8), regardless of the season quality. This means that intercropping is more efficient than sole crops in ensuring household food self-sufficiency, owing to the complementary and productive use of the available growth resources. Hence, intercropping clearly has the potential to help address the constraints of food security and income faced by resource-poor smallholder farmers (a claim also made by Rusinamhodzi et al., 2012 and Smith et al., 2016).

Intercropping increases the labour demands significantly compared with the conventional maize sole cropping systems, as has been reported in other studies in Southern Africa, e.g. Ngwira et al., 2012 and Rusinamhodzi et al., 2012. With the increased production attained by cereal-legume intercropping, however, there are higher returns per unit of labour invested. Thus, the system offers economic and other benefits to smallholder farmers (Ngwira et al., 2012; Rusinamhodzi et al., 2012; Kermah et al., 2017).

Crop rotation has always proved to be a challenge in smallholder systems (Ncube et al., 2007b). Farmers tend to focus on growing the main cereal crops, allocating larger areas to them than to the legumes. In this situation, if any rotations do take place, they will not be very efficient. Cereal-legume intercropping not only has the advantage of growing two crops on the same piece of land; the cereal crop may gain from biological N_2-fixation (BNF) by the legume in the current and preceding seasons. When fertiliser access is limited, or farmers have no ability to buy N input, BNF by the legume is the major source of nitrogen in the cereal-legume intercropping system (Naudin et al., 2010; Fujita et al., 1992).

6.4. Climate-smart technologies

6.4.1. Seasonal variability

All the trials were conducted under rain-fed conditions; therefore, water limitations affected yields. The high yields of maize and cowpea in a season of good rainfall (chapters 2 and 4) suggest that water was probably a significant yield-reducing factor in the trials. Erratic distribution of rainfall resulted in highly variable crop yields, N-recovery efficiency and agronomic N efficiency (Chapter 2). This makes it challenging to come up with adequate planting date, manure, fertiliser and tillage recommendations (Chapter 3). maize and cowpea grain and stover yields were affected by the amount and seasonal distribution of rainfall. Two thirds of the seasons in which the field experiments were conducted (Chapters 2 and 4) were classified as droughts. The low amount of rainfall affected the crop yields negatively. Low rainfall and uneven rainfall distribution, characteristic of semi-arid areas of Southern Africa, are clearly major challenges for crop production (Nyamangara et al., 2014). Thierfelder et al. (2013) reported that CA systems have a great potential for mitigating the effects of seasonal dry spells, as the high infiltration rates in CA would lead to greater soil moisture availability for crops. This was, however, not the case in our experiment (with a mulch cover of 0 and 2–4 t ha^{-1} in the first and third seasons respectively) conducted during seasons with long dry spells midway through the season lasting for more than 21 days. Although cowpea is a drought-resistant crop, the long dry spells negatively impacted the crop's growth in the intercropping field experiments.

The field trials alone, conducted during only three seasons, did not allow us to conclude whether or not the cropping systems studied deserve to be classified as climate-smart options. The modelling approaches, applied consecutively, gave much more insight into the cropping systems' ability to ensure household food self-sufficiency in the long term. They allowed a more reliable answer to the question whether or not the cropping systems studied can be classified as climate-smart.

6.4.2. Are CA and maize-cowpea intercropping climate-smart options for semi-arid Zimbabwe?

Climate-smart agriculture (CSA) interventions are defined by their ability to deliver on three fundamental dimensions: a) adaptation to the effects of climate change, thereby building resilience into the system; b) provision of mitigation benefits in terms of greenhouse gas (GHG) emission reduction and building carbon (C) stocks (both above and below ground) and c) improved reliability, sustainability, productivity and profitability of agricultural production systems (Campbell et al., 2014; Lipper et al., 2014). It is important to assess the performance of CSA technologies, as climate change will strongly affect rainfed agriculture. Smallholder farmers, whether better or poorly resourced, will have to cope with highly variable, short and unpredictable rainfall. This will make it harder for them to improve crop productivity and welfare.

The cropping systems studied in this thesis, CA and intercropping, have been put forward as CSA technologies (Khatri-Chhetri et al., 2017; Thierfelder et al., 2017; Mullins et al., 2018). In Chapter 3, the CA option (ripper and mulch) consistently had the highest yields throughout the simulation period of 30-years, regardless of season type (Figure 3.4). This means that the technology partly meets the requirements of a CSA intervention; that is, it can adapt to rainfall variability and improves crop productivity in relation to conventional tillage. A lot of studies in the region have demonstrated that CA has the potential to improve the productivity by increasing crop yields (e.g. Nyamangara et al., 2013; Ndlovu et al., 2014; Nyamangara et al. 2014a; 2014b; Mupangwa et al., 2016). Nyamangara et al. (2013; 2014a; 2014b) reported that consistent yield benefits were realised with CA when applied in combination with mineral fertiliser. Other studies have also demonstrated the capacity of CA systems to adapt to climate variability. They have been reported to increase crop water efficiency by increasing infiltration and thus soil water. By tiding crops over dry spells or drought seasons they lead to greater yield stability (e.g. Thierfelder and Wall, 2009; Nyamadzawo et al., 2012; Mupangwa et al., 2016).

There is however, a dearth of information on the mitigation aspect of CA systems in the region of my study. There is conflicting evidence on the ability of CA farming systems to mitigate the negative effects of climate change (by sequestering C, reducing GHG emissions, etc.). Studies by for example Soler et al. (2011); Dossou-Yovo et al. (2016) have shown that by employing different combinations of CA principles and fertiliser application regimes in semi-arid West Africa, it was possible to reduce GHG emissions from the soil and to sequester carbon. Closer to the study region, effects of CA on C sequestration have been variable. For example, Nyamadzawo et al. (2012); Thierfelder et al. (2013) recorded significantly greater soil organic carbon (SOC) under CA compared with conventional agriculture in studies in Zimbabwe and Zambia. However, Cheesman et al. (2016) and Nyamangara et al. (2013) have observed little change in SOC in southern Africa. The researchers attributed this to low biomass production, the limited amount of crop residues retained and, in addition, a lack of application of the three principles of CA by most farmers.

In the study region, the soils are predominantly sandy soils which have very little capacity to store C (Zingore et al., 2005; Powlson et al., 2011). A study by Chivenge et al. (2007) observed no changes in SOC, nine years after conversion from conventional tillage to reduced tillage systems in a sandy soil, except when crop residues were returned to the soil as mulch. Thierfelder et al. (2017) state that benefits in C sequestration and GHG-emission reduction with CA are likely to occur in the medium to long term; but this is largely dependent on the agro-ecology, duration of consistent CA practice, the biomass input, and the cropping system type. In the light of these findings and considering the characteristics of the smallholder farmers and the farming systems (section 6.2) in the study region, achieving the mitigatory component of CSA with CA seems ambitious.

In Chapters 4 and 5, we showed that there was increased productivity in the maize-cowpea intercrop system. Thierfelder et al. (2017) contend that intercropping is a possible co-intervention that can help deliver the mitigation benefits of CA as well. Intercropping was shown to consistently lead to overyielding, and to be able to meet and exceed household energy and protein requirements. The mitigation aspect of the intercropping system was not investigated in the course of this study; therefore, I could not conclude that maize-cowpea intercropping is climate-smart. There have been very few studies aiming to assess the effectiveness of intercropping as a mitigatory intervention that can help combat climate change. Existing research across the globe provides conflicting evidence. For example, maize-soybean intercropping reduced soil N_2O emissions relative to monocultured maize on a silty loam soil in northern China (Huang et al., 2017), whilst in another study in southwestern Europe, the presence of legume cover crops during the intercrop period led to increased N_2O losses (Guardia et al., 2016). Cong et al. (2015) reported that the total root biomass in intercrops was on average greater than the average root biomass in sole crops, providing a possible explanation for the observed divergence in soil C sequestration between sole crop and intercrop systems. Legumes included in intercrops produce their own N from the atmosphere via symbiotic N_2 fixation or mineralisation of legume litter (Carlsson and Huss-Danell, 2014). This reduces the required amount of inorganic fertiliser and mitigates GHG emissions, as less N from the fertiliser will be lost to the atmosphere as N_2O.

Despite the various benefits claimed for CSA technologies, the current rate of adoption by farmers is limited (Khatri-Chhetri et al., 2017). There are many factors that influence the extent of adoption of CSA technologies, such as the socio-economic characteristics of farmers, the bio-physical characteristics of particular locations, and the attributes of the different technologies (Campbell et al., 2016). My results suggest that the benefits are not spectacular. This may account in part for the low adoption rate. Scaling out CSA in diverse agro-ecological zones is a challenge; it requires the identification, prioritisation and promotion of available CSA technologies, taking account of local climate risks and the demand for technology. My study contributed to exploring the effects of different CSA technologies that are already practised by smallholder farmers in semi-arid Southern Africa. Both CA and intercropping, to some extent, achieve the goals of CSA technologies, although the evidence concerning the mitigation aspect is inconclusive. Considering the definition of CSA, it remains elusive whether a technology can only be considered climate-smart if it delivers on all three dimensions. In my view, technologies should be considered climate-smart if they make significant strides towards achieving the goals associated with any of the three CSA pillars.

6.5. Towards sustainable intensification in semi-arid Southern Africa

In this section I go into the question whether farmers in the region can achieve sustainable intensification by intensifying and diversifying with CA and intercropping. Sustainable intensification (SI) is broadly defined as the investment of inputs and capital to increase crop productivity in the long term while protecting the underlying resource base (Pretty et al., 2011). Sustainably intensified farming systems are hypothesised to contribute to feeding a growing population. A second hypothesis is that CA and intercropping can contribute to SI. Sustainable intensification, however, is an evolving concept and subject to debate; it needs to be further defined and elaborated for greater clarity. Smith et al. (2017) identified five SI domains with specific indicators and metrics suited to smallholder farming systems, namely: productivity, environmental sustainability, social sustainability, economic sustainability, and human well-being.

In my study, I found that CA and intercropping increased productivity in both the short and long term by increasing crop yields. Crop yields are the most common indicator of SI, and the one that is most likely to convince smallholder farmers of the value of SI-technologies. As mentioned in preceding sections, both CA practices and maize-cowpea intercropping resulted in higher yields. In my findings the LER were consistently higher than 1. Intercropping and CA cropping systems also led to higher fertiliser input efficiency. In Chapter 2, the N recovery was high with CA practices. Measured on the basis of these three indicators: yield, LER (with intercropping) and input efficiency, CA and intercropping clearly improve productivity.

The application of small amounts of N fertiliser, as in my study, is typical of smallholder farmers. In conjunction with intercropping it led to increased productivity (Chapter 4). However, once small amounts of N are made available, the resulting vigorous plant growth may exacerbate other nutrient deficiencies, thereby impacting negatively on the environment. In our study, NPK or PK fertiliser was added to the maize but not to the cowpea; this also is typical of smallholder farmers, who apply little or no fertility amendments to legume crops (Ronner et al., 2016). With the intensification of the cropping system through intercropping or CA practices, the nutrient requirements of the legume need to be addressed for the soils to positively benefit from the legume. Integrated soil fertility-management options that promote the judicious use of mineral and organic fertilisers can result in better crop and soil productivity (Vanlauwe et al., 2010). However, fertiliser use by smallholder farmers remains sketchy, which is partly explained by their poor availability in rural markets.

CA and maize-cowpea intercropping systems have the potential to improve soil fertility (Chapters 2 and 4) and thus to contribute to environmental sustainability. Soils in semi-arid Southern Africa are inherently infertile, low in organic matter content and water-holding capacity and are prone to degradation (Ncube et al., 2007a; Hove et al., 2008; Mupangwa et al., 2012). Intensive tillage and the exportation of crop biomass, which prevent the build-up of soil organic matter and impairs soil physical properties, are unsustainable practices that lead to erosion and poor soil fertility. These are major causes of yield gaps in African smallholder agriculture (Tittonell and Giller, 2013).

In Chapters 3 and 5, CA and intercropping were shown to lead to food self-sufficiency in smallholder households of semi-arid Zimbabwe, thus contributing to human well-being. The grain production was simulated to meet household energy and protein needs, and thereby to ensure nutrition security in these risky environments. However, both CA and intercropping require substantial labour. Resource and labour constraints have hampered the adoption of these technologies. As the migration of able-bodied man and women to urban centres within and outside the country continues, the situation may remain the same in the foreseeable future (Giller et al., 2013).

In my investigation I did not focus on indicators relating to the social and economic sustainability dimension of SI. Nonetheless, the increase in yields is likely to increase the farmers' income through excess grain sales. Other studies in the region have reported that CA leads to economic sustainability, with farmers realising higher gross margins and increased labour productivity (Mazvimavi and Twomlow, 2009; Ngwira et al., 2012). Maize-legume intercropping was shown to be more profitable than maize monocropping (Ngwira et al., 2012; Rusinamhodzi et al., 2012; Kermah et al., 2017). On the basis of the findings of this study, the hypothesis that CA and intercropping are means to achieve SI holds.

6.6. Limitations of the study, concluding remarks and suggestions for future research

As I carried out my work in semi-arid Zimbabwe, I expected to be able to make recommendations on how farmers could improve their cropping practices and improve their ability to meet household nutrition needs. However, as I came to acknowledge the diversity of farmers within communities, I realised that no single approach could produce the same results for all farms. Recommendations would also have to take into account the seasonal variability, which complicated things further.

It is necessary to quantify the impacts of the future climate on crop production and provide best-bet adaptation strategies that can help ensure food security in the region. At the same time, farmers should be consulted on their preferences for adaptation options that would make them resilient to climate change. Farmer engagement will allow for research to focus on farmer priorities in different locations, characterised by specific climatic risks.

After having analysed the effect of seasonal variability on crop yields and food self-sufficiency, it became clear that it would be important to furnish farmers with detailed seasonal climate forecasts that allow them to make decisions on when or whether to plan different farm operations. It remains a challenge to provide farmers with adequate weather information and to train them to understand it to an extent that allows them to make the appropriate management decisions.

My work focused at the field scale, yet it is the decisions farmers, in their diversity, make at the household level that determine whether or not a household will be food self-sufficient. Crop production plays a very important role in ensuring food availability at the household level, but factors affecting food availability at the regional level need to be considered as well.

My conclusions can be summed up thus: sustainable intensification of crop production and the use of climate-smart technologies in semi-arid southern Zimbabwe can help smallholder farmers achieve food self-sufficiency in the changing climate. This study contributes, both by the methods employed and the results obtained, to the body of knowledge on cropping system options. On the basis of this knowledge, extension services in the region can fine-tune their advice to farmers, with a view to improving crop productivity.

REFERENCES

Akponikpè, P.I., Gérard, B., Michels, K., Bielders, C., 2010. Use of the APSIM model in long term simulation to support decision making regarding nitrogen management for pearl millet in the Sahel. Eur J Agron 32, 144-154.

Anderson, J.M., Ingram, J., 1993. Tropical Soil Biology and Fertility: A Handbook of Method. CAB International.

Angás, P., Lampurlanés, J., Cantero-Martínez, C., 2006. Tillage and N fertilization: effects on N dynamics and barley yield under semiarid Mediterranean conditions. Soil Tillage Res 87, 59-71.

Arslan, A., McCarthy, N., Lipper, L., Asfaw, S., Cattaneo, A., 2014. Adoption and intensity of adoption of conservation farming practices in Zambia. Agric Ecosyst Environ. 187, 72-86.

Arslan, A., McCarthy, N., Lipper, L., Asfaw, S., Cattaneo, A., Kokwe, M., 2015. Climate Smart Agriculture? Assessing the Adaptation Implications in Zambia. J Agr Econ 66, 753-780.

Awal, M., Koshi, H., Ikeda, T., 2006. Radiation interception and use by maize/peanut intercrop canopy. Agric For Meteorol 139, 74-83.

Bartholomew, W., Kirkham, D., 1960. Mathematical description and interpretations of culture-induced soil nitrogen changes. Transactions 7th Int. Congr. Soil Sci. 2, 471-477.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agr Syst 94, 13-25.

Baudron, F., Andersson, J.A., Corbeels, M., Giller, K.E., 2012a. Failing to yield? Ploughs, conservation agriculture and the problem of agricultural intensification: an example from the Zambezi Valley, Zimbabwe. J Dev Stud 48, 393-412.

Baudron, F., Tittonell, P., Corbeels, M., Letourmy, P., Giller, K.E., 2012b. Comparative performance of conservation agriculture and current smallholder farming practices in semi-arid Zimbabwe. Field Crop Res 132, 117-128.

Belel, M.D., Halim, R., Rafii, M., Saud, H., 2014. Intercropping of corn with some selected legumes for improved forage production: A review. J Agr Sci 6, 48.

Benbi, D.K., Richter, J., 2002. A critical review of some approaches to modelling nitrogen mineralization. Biol Fert Soils 35, 168-183.

Benoit, P., 1977. The start of the growing season in Northern Nigeria. Agric Meteorol 18, 91-99.

Bhatasara, S., 2015. Rethinking climate change research in Zimbabwe. J Environ Stud Sci, 1-14.

Birch, H., 1960. Nitrification in soils after different periods of dryness. Plant Soil 12, 81-96.

Bognonkpe, J.-P., Becker, M., 2009. Native soil N mineralization in major rice based cropping systems. J Anim Plant Sci 4, 384-398.

Böhm, W., 1979. Methods of studying root systems. Springer-Verlag, Berlin.

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen—total. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of soil analysis. Part 2. Chemical and microbiological properties. Am Soc Agron, Madison, WI, pp. 595-624.

Brooker, R.W., Bennett, A.E., Cong, W.F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P., Jones, H.G., Karley, A.J., 2014. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytol 206, 107-117.

Brouder, S.M., Gomez-Macpherson, H., 2014. The impact of conservation agriculture on smallholder agricultural yields: A scoping review of the evidence. Agric Ecosyst Environ 187, 11-32.

Brown, D., Chanakira, R.R., Chatiza, K., Dhliwayo, M., Dodman, D., Masiiwa, M., Muchadenyika, D., Mugabe, P., Zvigadza, S., 2012. Climate change impacts, vulnerability and adaptation in Zimbabwe. International Institute for Environment and Development London, UK.

Burris, R., 1959. Nitrogen nutrition. Annu Rev Plant Biol 10, 301-328.

Cabrera, M., 1993. Modeling the flush of nitrogen mineralization caused by drying and rewetting soils. Soil Sci Soc Am J 57, 63-66.

Cabrera, M., Kissel, D., 1988. Evaluation of a method to predict nitrogen mineralized from soil organic matter under field conditions. Soil Sci Soc Am J 52, 1027-1031.

Campbell, B.M., Thornton, P., Zougmoré, R., Van Asten, P., Lipper, L., 2014. Sustainable intensification: What is its role in climate smart agriculture? Curr Opin Environ Sustain. 8, 39-43.

Campbell, B.M., Vermeulen, S.J., Aggarwal, P.K., Corner-Dolloff, C., Girvetz, E., Loboguerrero, A.M., Ramirez-Villegas, J., Rosenstock, T., Sebastian, L., Thornton, P.K., 2016. Reducing risks to food security from climate change. Global Food Security 11, 34-43.

Carlsson, G., Huss-Danell, K., 2014. Does nitrogen transfer between plants confound 15 N-based quantifications of N 2 fixation? Plant Soil 374, 345-358.

Chamberlin, J., Jayne, T.S., Headey, D., 2014. Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. Food Policy 48, 51-65.

Cheesman, S., Thierfelder, C., Eash, N.S., Kassie, G.T., Frossard, E., 2016. Soil carbon stocks in conservation agriculture systems of Southern Africa. Soil Tillage Res 156, 99-109.

Chianu, J., Chianu, J., Mairura, F., 2012. Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. Agron Sustain Dev 32, 545-566.

Chikowo, R., 2011. Climatic Risk Analysis in Conservation Agriculture in Varied Biophysical and Socio–economic Settings of Southern Africa. FAO Regional Emergency Office for Southern Africa (REOSA), Johannesburg, 2011.

Chikowo, R., Mapfumo, P., Nyamugafata, P., Giller, K.E., 2004. Maize productivity and mineral N dynamics following different soil fertility management practices on a depleted sandy soil in Zimbabwe. Agric Ecosyst Environ 102, 119-131.

Chikowo, R., Mapfumo, P., Nyamugafata, P., Nyamadzawo, G., Giller, K.E., 2003. Nitrate-N dynamics following improved fallows and maize root development in a Zimbabwean sandy clay loam. Agroforest Syst 59, 187-195.

Chikowo, R., Zingore, S., Nyamangara, J., Bekunda, M., Messina, J., Snapp, S., 2015. Approaches to Reinforce Crop Productivity Under Rain-fed Conditions in Sub-humid Environments in Sub-Saharan Africa. In: Lal, R., Singh, B.R., Mwaseba, D.L., Kraybill, D., Hansen, D.O., Eik, L.O. (Eds.), Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa. Springer International Publishing, pp. 235-253.

Chimonyo, V., Modi, A., Mabhaudhi, T., 2016. Assessment of sorghum–cowpea intercrop system under waterlimited conditions using a decision support tool. Water SA 42, 316-327.

Chimonyo, V.G.P., Modi, A.T., Mabhaudhi, T., 2015. Perspective on crop modelling in the management of intercropping systems. Arch Agron Soil Sci 61, 1511-1529.

Chivenge, P., Murwira, H., Giller, K., Mapfumo, P., Six, J., 2007. Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. Soil Tillage Res 94, 328-337.

Cong, W.F., Hoffland, E., Li, L., Six, J., Sun, J.H., Bao, X.G., Zhang, F.S., Van Der Werf, W., 2015. Intercropping enhances soil carbon and nitrogen. Global Change Biol 21, 1715-1726.

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., Twomlow, S., 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? Agr Ecosyst Environ 126, 24-35.

Crews, T., Peoples, M., 2004. Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. Agr Ecosyst Environ 102, 279-297.

Davis, R., Hirji, R., 2014. Climate change and water resources planning, development and management in Zimbabwe. An Issues Paper. World Bank.

Descheemaeker, K., Oosting, S.J., Tui, S.H.-K., Masikati, P., Falconnier, G.N., Giller, K.E., 2016a. Climate change adaptation and mitigation in smallholder crop–livestock systems in sub-Saharan Africa: a call for integrated impact assessments. Reg Environ Change 16, 2331-2343.

Descheemaeker, K., Ronner, E., Ollenburger, M., Franke, L., Klapwijk, L., Falconnier, G., Wichern, J., Giller, K., 2016b. Which options fit best? Operationalizing the socio-ecological niche concept. Exp Agr.

Dossou-Yovo, E.R., Brüggemann, N., Ampofo, E., Igue, A.M., Jesse, N., Huat, J., Agbossou, E.K., 2016. Combining no-tillage, rice straw mulch and nitrogen fertilizer application to increase the soil carbon balance of upland rice field in northern Benin. Soil Tillage Res 163, 152-159.

Droppelmann, K.J., Snapp, S.S., Waddington, S.R., 2017. Sustainable intensification options for smallholder maize-based farming systems in sub-Saharan Africa. Food Security 9, 133-150.

Dunjana, N., Nyamugafata, P., Nyamangara, J., Mango, N., 2014. Cattle manure and inorganic nitrogen fertilizer application effects on soil hydraulic properties and maize yield of two soils of Murewa district, Zimbabwe. Soil Use Manage 30, 579-587.

Erenstein, O., Sayre, K., Wall, P., Hellin, J., Dixon, J., 2012. Conservation Agriculture in maize- and wheat-based systems in the (sub)tropics: lessons from adaptation initiatives in South Asia, Mexico, and Southern Africa. J. Sustain. Agric. 32, 261-275.

Falconnier, G.N., Descheemaeker, K., Mourik, T.A.V., Giller, K.E., 2016. Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali. Field Crop Res 187, 113-126.

FAO, 1995. Sorghum and millets in human nutrition. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/docrep/t0818e/T0818E0b.htm. Accessed 27 April 2018.

FAO, 2004. Human energy requirements. Report of a Joint FAO/WHO/UNU Expert Consultation, Rome, 17-24 October 2001.

FAO, 2011. Save and grow: A policymaker's guide to the sustainable intensification of smallholder crop production. Food and Agriculture Organization of the United Nations.

Franzluebbers, A., Hons, F., Zuberer, D., 1995. Tillage and crop effects on seasonal soil carbon and nitrogen dynamics. Soil Sci Soc Am J 59, 1618-1624.

Frelat, R., Lopez-Ridaura, S., Giller, K.E., Herrero, M., Douxchamps, S., Djurfeldt, A.A., Erenstein, O., Henderson, B., Kassie, M., Paul, B.K., 2016. Drivers of household food availability in sub-Saharan Africa based on big data from small farms. Proc. Natl. Acad. Sci. U.S.A. 113, 458-463.

Gaydon, D., Probert, M., Buresh, R., Meinke, H., Suriadi, A., Dobermann, A., Bouman, B., Timsina, J., 2012. Rice in cropping systems—Modelling transitions between flooded and non-flooded soil environments. Eur J Agron 39, 9-24.

Ghanbari, A., Dahmardeh, M., Siahsar, B.A., Ramroudi, M., 2010. Effect of maize (Zea mays L.)-cowpea (Vigna unguiculata L.) intercropping on light distribution, soil temperature and soil moisture in arid environment. J Food Agric Environ 8, 102-108.

Giller, K.E., 2001. Nitrogen fixation in tropical cropping systems. Cabi, Wallingford, UK.

Giller, K.E., Andersson, J.A., Corbeels, M., Kirkegaard, J., Mortensen, D., Erenstein, O., Vanlauwe, B., 2015. Beyond conservation agriculture. Front Plant Sci 6.

Giller, K.E., Baudron, F., Matema, S., Milgroom, J., Murungweni, C., Guerbois, C., Twine, W., 2013. Population and livelihoods on the edge. In: Andersson, J.A., de Garine-Wichatitsky, M., Cumming, D.H.M., Dzingirai, V., Giller, K.E. (Eds.), Transfrontier conservation areas: People living on the edge. Routledge, London, pp. 62-88.

Giller, K.E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W.D., Mafongoya, P.L., 1997. Building soil nitrogen capital in Africa. Replenishing soil fertility in Africa, 151-192.

Giller, K.E., Corbeels, M., Nyamangara, J., Triomphe, B., Affholder, F., Scopel, E., Tittonell, P., 2011. A research agenda to explore the role of conservation agriculture in African smallholder farming systems. Field Crop Res 124, 468-472.

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crop Res 114, 23-34.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812-818.

Gou, F., Van Ittersum, M.K., Couëdel, A., Zhang, Y., Wang, Y., Van Der Putten, P.E., Zhang, L., Van Der Werf, W., 2018. Intercropping with wheat lowers nutrient uptake and biomass accumulation of maize, but increases photosynthetic rate of the ear leaf. AoB Plants 10, ply010.

Gou, F., van Ittersum, M.K., Wang, G., van der Putten, P.E.L., van der Werf, W., 2016. Yield and yield components of wheat and maize in wheat–maize intercropping in the Netherlands. Eur J Agron 76, 17-27.

Gowing, J., Palmer, M., 2008. Sustainable agricultural development in sub-Saharan Africa: the case for a paradigm shift in land husbandry. Soil Use Manage 24, 92-99.

Grahmann, K., Verhulst, N., Buerkert, A., Ortiz-Monasterio, I., Govaerts, B., 2013. Nitrogen use efficiency and optimization of nitrogen fertilization in conservation agriculture. CAB Reviews 8, 1-19.

Guardia, G., Abalos, D., García-Marco, S., Quemada, M., Alonso-Ayuso, M., Cárdenas, L.M., Dixon, E.R., Vallejo, A., 2016. Effect of cover crops on greenhouse gas emissions in an irrigated field under integrated soil fertility management. Biogeosciences 13, 5245-5257.

Hartemink, A.E., Huting, J., 2008. Land cover, extent, and properties of Arenosols in Southern Africa. Arid Land Res Manag 22, 134-147.

Hayes, J.E., Richardson, A.E., Simpson, R.J., 1999. Phytase and acid phosphatase activities in extracts from roots of temperate pasture grass and legume seedlings. Funct Plant Biol 26, 801-809.

Hobbs, P.R., 2007. Conservation agriculture: what is it and why is it important for future sustainable food production? J Agr Sci - Cambridge 145, 127.

Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos Trans R Soc Lond B Biol Sci 363, 543-555.

Holzworth, D.P., Huth, N.I., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., 2014. APSIM–evolution towards a new generation of agricultural systems simulation. Environ Modell Softw 62, 327-350.

Homann-Kee Tui, S., Valbuena, D., Masikati, P., Descheemaeker, K., Nyamangara, J., Claessens, L., Erenstein, O., van Rooyen, A., Nkomboni, D., 2015. Economic trade-offs of biomass use in crop-livestock systems: Exploring more sustainable options in semi-arid Zimbabwe. Agr Syst 134, 48-60.

Hove, L., Mashingaidze, N., Twomlow, S., Nyathi, P., Moyo, M., Mupangwa, W., Masvaya, E., 2008. Micro Doses, Mega Benefits Promoting Fertilizer Use in Semi-Arid Zimbabwe. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

Huang, J., Sui, P., Gao, W., Chen, Y., 2017. Effect of Maize-Soybean Intercropping on Soil Nitrous Oxide Emissions in Silt Loam Soil of the North China Plain. Pedosphere.

IPCC, 2014. Climate Change 2014–Impacts, Adaptation and Vulnerability: Regional Aspects. Cambridge University Press.

IUSS Working Group, W.R.B., 2014. World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports 106. Food and Agriculture Organistion of the United Nations, Rome.

Jeranyama, P., Hesterman, O.B., Waddington, S.R., Harwood, R.R., 2000. Relay-intercropping of sunnhemp and cowpea into a smallholder maize system in Zimbabwe. Agron J 92, 239-244.

Keating, B.A., Carberry, P.S., 1993. Resource capture and use in intercropping: solar radiation. Field Crop Res 34, 273-301.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N., Meinke, H., Hochman, Z., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur J Agron 18, 267-288.

Kermah, M., Franke, A.C., Adjei-Nsiah, S., Ahiabor, B.D.K., Abaidoo, R.C., Giller, K.E., 2017. Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of northern Ghana. Field Crop Res 213, 38-50.

Khanna, P.K., Raison, R.J., 2013. In situ core methods for estimating soil mineral-N fluxes: Re-evaluation based on 25 years of application and experience. Soil Biol Biochem 64, 203-210.

Khatri-Chhetri, A., Aggarwal, P.K., Joshi, P.K., Vyas, S., 2017. Farmers' prioritization of climate-smart agriculture (CSA) technologies. Agr Syst 151, 184-191.

Kihara, J., Bationo, A., Mugendi, D.N., Martius, C., Vlek, P.L.G., 2011. Conservation tillage, local organic resources and nitrogen fertilizer combinations affect maize productivity, soil structure and nutrient balances in semi-arid Kenya. Nutr Cycl Agroecosys 90, 213-225.

Kniveton, D.R., Layberry, R., Williams, C.J.R., Peck, M., 2009. Trends in the start of the wet season over Africa. Int J Climatol 29, 1216-1225.

Knörzer, H., Lawes, R., Robertson, M., Graeff-Hönninger, S., Claupein, W., 2011. Evaluation and performance of the APSIM crop growth model for German winter wheat, maize and fieldpea varieties in monocropping and intercropping systems. JAST-B 1, 698-717.

Komarek, A.M., Li, L., Bellotti, W.D., 2015. Whole-farm economic and risk effects of conservation agriculture in a crop-livestock system in western China. Agr Syst 137, 220-226.

Kucharik, C.J., 2008. Contribution of Planting Date Trends to Increased Maize Yields in the Central United States Agron J 100, 328-336.

Kunzekweguta, M.O.N., 2016. Drivers of smallholder adoption and the intensity of conservation agriculture in the Masvingo District of Zimbabwe. Lincoln University.

Lal, R., 1995. Tillage and Mulching Effects on Maize Yield for Seventeen Consecutive Seasons on a Tropical Alfisol. J Sustain Agr 5, 79-93.

Lal, R., 2007. Constraints to adopting no-till farming in developing countries. Soil and Tillage Research 94, 1-3.

Li, L., Tilman, D., Lambers, H., Zhang, F.S., 2014. Plant diversity and overyielding: insights from belowground facilitation of intercropping in agriculture. New Phytol 203, 63-69.

Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., 2014. Climate-smart agriculture for food security. Nat Clim Change 4, 1068-1072.

Lone, A.A., Warsi, M.Z.K., 2009. Response of maize (Zea mays L.) to excess soil moisture (ESM) tolerance at different stages of life cycle. Bot Res Int 2, 211-217.

Manditsera, F.A., Luning, P.A., Fogliano, V., Lakemond, C.M., 2019. The contribution of wild harvested edible insects (Eulepida mashona and Henicus whellani) to nutrition security in Zimbabwe. J. Food Compos. Anal. 75, 17-25.

Manzoni, S., Jackson, R.B., Trofymow, J.A., Porporato, A., 2008. The global stoichiometry of litter nitrogen mineralization. Science 321, 684-686.

Mao, L., Zhang, L., Li, W., van der Werf, W., Sun, J., Spiertz, H., Li, L., 2012. Yield advantage and water saving in maize/pea intercrop. Field Crop Res 138, 11-20.

Mapfumo, P., Giller, K., 2001. Soil fertility management strategies and practices by smallholder farmers in semi-arid areas of Zimbabwe. ICRISAT Patancheru, India.

Masikati, P., 2006. Tillage and manure interactions under dryland cropping in semi-arid Zimbabwe. Department of Soil Science and Agricultural Engineering, University of Zimbabwe, Harare, Zimbabwe. MPhil Thesis.

Masvaya, E.N., Nyamangara, J., Descheemaeker, K., Giller, K.E., 2017a. Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid southern Africa? Field Crop Res 209, 73-87.

Masvaya, E.N., Nyamangara, J., Descheemaeker, K., Giller, K.E., 2017b. Tillage, mulch and fertiliser impacts on soil nitrogen availability and maize production in semi-arid Zimbabwe. Soil Tillage Res 168, 125-132.

Matthews, R., Stephens, W., Hess, T., Middleton, T., Graves, A., 2002. Applications of crop/soil simulation models in tropical agricultural systems. Adv Agron 76, 31-124.

Mavhura, E., Manatsa, D., Mushore, T., 2015. Adaptation to drought in arid and semi-arid environments: Case of the Zambezi Valley, Zimbabwe. Jàmbá 7, 1-7.

Mavunganidze, Z., Madakadze, I.C., Nyamangara, J., Mafongoya, P., 2014. The impact of tillage system and herbicides on weed density, diversity and yield of cotton (Gossipium hirsutum L.) and maize (Zea mays L.) under the smallholder sector. Crop Prot 58, 25-32.

Mazvimavi, K., Twomlow, S., 2009. Socioeconomic and institutional factors influencing adoption of conservation farming by vulnerable households in Zimbabwe. Agr Syst 101, 20-29.

Mengel, K., Kirkby, E.A., Kosegarten, H., Appel, T., 2001. Principles of Plant Nutrition. Springer Netherlands.

Milgroom, J., Giller, K., 2013. Courting the rain: rethinking seasonality and adaptation to recurrent drought in semi-arid southern Africa. Agr Syst 118, 91-104.

Mohanty, M., Reddy, K.S., Probert, M., Dalal, R.C., Rao, A.S., Menzies, N., 2011. Modelling N mineralization from green manure and farmyard manure from a laboratory incubation study. Ecol Model 222, 719-726.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. T ASABE 50, 885-900.

Morris, M.L., 2007. Fertilizer use in African agriculture: Lessons learned and good practice guidelines. World Bank Publications.

Moyo, M., 2001. Representative soil profiles of ICRISAT research sites. Chemistry and Soil Research Institute. Soils Report.

Moyo, M., Mvumi, B.M., Kunzekweguta, M., Mazvimavi, K., Craufurd, P., Dorward, P., 2012. Farmer perceptions on climate change and variability in semi-arid Zimbabwe in relation to climatology evidence. Afr Crop Sci J 20, 317-335.

Mtambanengwe, F., Mapfumo, P., 2005. Organic Matter Management as an Underlying Cause for Soil Fertility Gradients on Smallholder Farms in Zimbabwe. Nutr Cycl Agroecosys 73, 227-243.

Mullins, J., Zivin, J.G., Cattaneo, A., Paolantonio, A., Cavatassi, R., 2018. The Adoption of Climate Smart Agriculture: The Role of Information and Insurance Under Climate Change. Climate Smart Agriculture. Springer, pp. 353-383.

Mupangwa, W., 2010. Water and nitrogen management for risk mitigation in smallholder cropping systems. PhD thesis, University of the Free State, South Africa.

Mupangwa, W., Mutenje, M., Thierfelder, C., Nyagumbo, I., 2016a. Are conservation agriculture (CA) systems productive and profitable options for smallholder farmers in different agro-ecoregions of Zimbabwe? Renew Agr Food Syst 32, 87-103.

Mupangwa, W., Twomlow, S., Walker, S., 2012. Reduced tillage, mulching and rotational effects on maize (Zea mays L.), cowpea (Vigna unguiculata (Walp) L.) and sorghum (Sorghum bicolor L.(Moench)) yields under semi-arid conditions. Field Crop Res 132, 139-148.

Mupangwa, W., Twomlow, S., Walker, S., 2013. Cumulative effects of reduced tillage and mulching on soil properties under semi-arid conditions. J Arid Environ 91, 45-52.

Mupangwa, W., Twomlow, S., Walker, S., 2015. Reduced tillage and nitrogen effects on soil water dynamics and maize (Zea mays L.) yield under semi-arid conditions. Int J Agr Sustain, 1-18.

Mupangwa, W., Twomlow, S., Walker, S., 2016b. Reduced tillage and nitrogen effects on soil water dynamics and maize (Zea mays L.) yield under semi-arid conditions. Int J Agr Sustain 14, 13-30.

Mupangwa, W., Twomlow, S., Walker, S., Hove, L., 2007. Effect of minimum tillage and mulching on maize (Zea mays L.) yield and water content of clayey and sandy soils. Phys Chem Earth, Parts A/B/C 32, 1127-1134.

Mupangwa, W., Walker, S., Twomlow, S., 2011a. Start, end and dry spells of the growing season in semi-arid southern Zimbabwe. J Arid Environ 75, 1097-1104.

Mupangwa, W.T., Dimes, J., Walker, S., Twomlow, S., 2011b. Measuring and simulating maize (Zea mays L.) yield responses to reduced tillage and mulching under semi-arid conditions. Agric Sci 2, 167-174.

Murwira, H.K., Kirchmann, H., 1993. Nitrogen dynamics and maize growth in a Zimbabwean sandy soil under manure fertilisation. Commun Soil Sci Plan 24, 2343-2359.

Musiyiwa, K., 2014. Climate change in rural Zimbabwe: an assessment of the influences of gender in smallholding and its contribution towards adaptation to climate change in rural Zimbabwe. PhD thesis, Manchester Metropolitan University.

Musiyiwa, K., Leal Filho, W., Nyamangara, J., Harris, D., 2015. An Assessment of Gender Sensitive Adaptation Options to Climate Change in Smallholder Areas of Zimbabwe, Using Climate Analogue Analysis. In: Leal Filho, W., Esilaba, A.O., Rao, K.P.C., G, S. (Eds.), Adapting African agriculture to climate change transforming rural livelihoods. Springer, Berlin, pp. 109-117.

Ncube, B., 2007. Understanding cropping systems in the semi-arid environments of Zimbabwe: options for soil fertility management. Wageningen University, The Netherlands.

Ncube, B., Dimes, J., Twomlow, S., Mupangwa, W., Giller, K., 2007a. Raising the productivity of smallholder farms under semi-arid conditions by use of small doses of manure and nitrogen: a case of participatory research. Nutr Cycl Agroecosys 77, 53-67.

Ncube, B., Dimes, J.P., van Wijk, M.T., Twomlow, S.J., Giller, K.E., 2009a. Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in south-western Zimbabwe: Unravelling the effects of water and nitrogen using a simulation model. Field Crop Res 110, 173-184.

Ncube, B., Twomlow, S., Dimes, J., Van Wijk, M., Giller, K., 2009b. Resource flows, crops and soil fertility management in smallholder farming systems in semi-arid Zimbabwe. Soil Use Manage 25, 78-90.

Ncube, B., Twomlow, S.J., Van Wijk, M.T., Dimes, J.P., Giller, K.E., 2007b. Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in southwestern Zimbabwe. Plant Soil 299, 1-15.

Ndlovu, P.V., Mazvimavi, K., An, H., Murendo, C., 2014. Productivity and efficiency analysis of maize under conservation agriculture in Zimbabwe. Agric Syst 124.

NeSmith, D., Ritchie, J., 1992. Maize (Zea mays L.) response to a severe soil water-deficit during grain-filling. Field Crop Res 29, 23-35.

Ngoma, H., Mason, N.M., Sitko, N.J., 2015. Does minimum tillage with planting basins or ripping raise maize yields? Meso-panel data evidence from Zambia. Agr Ecosyst Environ 212, 21-29.

Ngwira, A.R., Aune, J.B., Mkwinda, S., 2012. On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. Field Crop Res 132, 149-157.

Nhemachena, C., Murwira, H.K., Mutiro, K., Chivenge, P., 2003. A socio-economic analysis of legume production motives and productivity variations among smallholder farmers of Shurugwi communal area, Zimbabwe. Grain Legumes and Green Manures for Soil Fertility in Southern Africa: Taking Stock of Progress: Proceedings of a Conference Held 8-11 October 2002 at the Leopard Rock Hotel, Vumba, Zimbabwe. CIMMYT, p. 223.

Njoroge, S., Schut, A.G.T., Giller, K.E., Zingore, S., 2017. Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms. Field Crop Res 214, 321-330.

Nyagumbo, I., 2008. A review of experiences and developments towards conservation agriculture and related systems in Zimbabwe. In: Goddard, T., Zoebisch, M.A., Gan, Y.T., Ellis, W., Watson, A., Sombatpanit, S. (Ed.), No-till Farming Systems. World Association of Soil and Water Conservation, Bangkok, Thailand, pp. 345–372.

Nyagumbo, I., Mkuhlani, S., Mupangwa, W., Rodriguez, D., 2017. Planting date and yield benefits from conservation agriculture practices across Southern Africa. Agr Syst 150, 21-33.

Nyakudya, I.W., Stroosnijder, L., 2015. Conservation tillage of rainfed maize in semi-arid Zimbabwe: A review. Soil Tillage Res 145, 184-197.

Nyamadzawo, G., Nyamugafata, P., Wuta, M., Nyamangara, J., Chikowo, R., 2012. Infiltration and runoff losses under fallowing and conservation agriculture practices on contrasting soils, Zimbabwe. Water SA 38, 233-240.

Nyamangara, J., Marondedze, A., Masvaya, E., Mawodza, T., Nyawasha, R., Nyengerai, K., Tirivavi, R., Nyamugafata, P., Wuta, M., 2014a. Influence of basin-based conservation agriculture on selected soil quality parameters under smallholder farming in Zimbabwe. Soil Use Manage 30, 550-559.

Nyamangara, J., Masvaya, E.N., Tirivavi, R., Nyengerai, K., 2013. Effect of hand-hoe based conservation agriculture on soil fertility and maize yield in selected smallholder areas in Zimbabwe. Soil Tillage Res 126, 19-25.

Nyamangara, J., Mudhara, M., Giller, K., 2005. Effectiveness of cattle manure and nitrogen fertilizer application on the agronomic and economic performance of maize. S Afr J Plant Soil 22, 59-63.

Nyamangara, J., Nyengerai, K., Masvaya, E., Tirivavi, R., Mashingaidze, N., Mupangwa, W., Dimes, J., Hove, L., Twomlow, S., 2014b. Effect of conservation agriculture on maize yield in the semi-arid areas of Zimbabwe. Exp Agr 50, 159-177.

Nyamangara, J., Piha, M., Giller, K., 2004. Effect of combined cattle manure and mineral nitrogen on maize N uptake and grain yield. Afr Crop Sci J 11, 389-300.

Ofori, F., Stern, W.R., 1987. Cereal–Legume Intercropping Systems. In: Brady, N.C. (Ed.), Advances in Agronomy. Academic Press, pp. 41-90.

Okalebo, J., Gathua, K., Woomer, P., 2002. Laboratory methods of plant and soil analysis: a working manual. TSBF-UNESCO, Nairobi.

Ollenburger, M., Snapp, S., 2014. Model applications for sustainable intensification of maize-based smallholder cropping in a changing world. In: Ahuja, L.R., Ma, L., Lascano, R.J. (Eds.), Practical Applications of Agricultural System Models to Optimize the Use of Limited Water. ASA, CSSA, SSSA, 5585 Guilford Rd., Madison, WI 53711-5801, USA, pp. 375-398.

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G., Giller, K.E., 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric Ecosyst Environ 83, 27-42.

Pedzisa, T., Rugube, L., Winter-Nelson, A., Baylis, K., Mazvimavi, K., 2015. Abandonment of Conservation Agriculture by Smallholder Farmers in Zimbabwe. J Sustain Dev 8, p69.

Peigné, J., Ball, B., Roger-Estrade, J., David, C., 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manage 23, 129-144.

Piha, M., 1993. Optimizing fertilizer use and practical rainfall capture in a semi-arid environment with variable rainfall. Exp Agr 29, 405-415.

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517, 365-368.

Powlson, D.S., Whitmore, A.P., Goulding, K.W.T., 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. Eur J Soil Sci 62, 42-55.

Pretty, J., Toulmin, C., Williams, S., 2011. Sustainable intensification in African agriculture. Int J Agr Sustain 9, 5-24.

Probert, M., Dimes, J., Keating, B., Dalal, R., Strong, W., 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agr Syst 56, 1-28.

Probert, M.E., Delve, R., Kimani, S., Dimes, J.P., 2005. Modelling nitrogen mineralization from manures: representing quality aspects by varying C: N ratio of sub-pools. Soil Biol Biochem 37, 279-287.

Qin, W., Hu, C., Oenema, O., 2015. Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis. Scientific reports 5.

Raes, D., Sithole, A., Makarau, A., Milford, J., 2004. Evaluation of first planting dates recommended by criteria currently used in Zimbabwe. Agric For Meteorol 125, 177-185.

Raison, R.J., Connell, M.J., Khanna, P.K., 1987. Methodology for studying fluxes of soil mineral-N in situ. Soil Biol Biochem 19, 521-530.

Rasouli, S., Whalen, J.K., Madramootoo, C.A., 2014. Review: Reducing residual soil nitrogen losses from agroecosystems for surface water protection in Quebec and Ontario, Canada: Best management practices, policies and perspectives. Can J Soil Sci 94, 109-127.

Ricord, M., 2018. Evaluating intercropping systems as a sustainable agroecosystem alternative to reduce greenhouse gas emissions. University of Waterloo.

Riley, H., 1998. Soil mineral-N and N-fertilizer requirements of spring cereals in two long-term tillage trials on loam soil in southeast Norway. Soil Tillage Res 48, 265-274.

Ronner, E., Franke, A., Vanlauwe, B., Dianda, M., Edeh, E., Ukem, B., Bala, A., van Heerwaarden, J., Giller, K., 2016. Understanding variability in soybean yield and response to P-fertilizer and rhizobium inoculants on farmers' fields in northern Nigeria. Field Crop Res 186, 133-145.

Rurinda, J., 2014. Vulnerability and adaptation to climate variability and change in smallholder farming systems in Zimbabwe. Wageningen University, Wageningen, p. 168.

Rurinda, J., Mapfumo, P., van Wijk, M., Mtambanengwe, F., Rufino, M., Chikowo, R., Giller, K., 2013a. Managing soil fertility to adapt to rainfall variability in smallholder cropping systems in Zimbabwe. Field Crop Res.

Rurinda, J., Mapfumo, P., van Wijk, M.T., Mtambanengwe, F., Rufino, M.C., Chikowo, R., Giller, K.E., 2013b. Managing soil fertility to adapt to rainfall variability in smallholder cropping systems in Zimbabwe. Field Crop Res 154, 211-225.

Rurinda, J., Wijk, M.T., Mapfumo, P., Descheemaeker, K., Supit, I., Giller, K.E., 2015. Climate change and maize yield in southern Africa: what can farm management do? Global Change Biol 21, 4588-4601.

Rusinamhodzi, L., 2015. Tinkering on the periphery: Labour burden not crop productivity increased under no-till planting basins on smallholder farms in Murehwa district, Zimbabwe. Field Crop Res 170, 66-75.

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 Crop Res 136, 12-22.

Rusinamhodzi, L., Corbeels, M., van Wijk, M.T., Rufino, M.C., Nyamangara, J., Giller, K.E., 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agron Sustain Dev 31, 657-673.

Rusinamhodzi, L., Murwira, H., Nyamangara, J., 2006. Cotton–cowpea intercropping and its N2 fixation capacity improves yield of a subsequent maize crop under Zimbabwean rain-fed conditions. Plant Soil 287, 327-336.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y., Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M.P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., Becker, E., 2014. The NCEP Climate Forecast System Version 2. J. Clim. 27, 2185-2208.

Sakala, W.D., Cadisch, G., Giller, K.E., 2000. Interactions between residues of maize and pigeonpea and mineral N fertilizers during decomposition and N mineralization. Soil Biol Biochem 32, 679-688.

Salinas-Garcia, J., Hons, F., Matocha, J., Zuberer, D., 1997. Soil carbon and nitrogen dynamics as affected by long-term tillage and nitrogen fertilization. Biol Fert Soils 25, 182-188.

Sanchez, P.A., 2002. Soil fertility and hunger in Africa. Science 295, 2019-2020.

Sanginga, N., 2003. Role of biological nitrogen fixation in legume based cropping systems; a case study of West Africa farming systems. Plant Soil 252, 25-39.

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M., Reinhardt, J., 2017. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. Reg Environ Change 17, 1585-1600.

Shamudzarira, Z., Robertson, M., 2002. Simulating response of maize to nitrogen fertilizer in semi-arid Zimbabwe. Exp Agr 38, 79-96.

Shapiro, S.S., Wilk, M.B., 1965. An analysis of variance test for normality (complete samples). Biometrika, 591-611.

Shumba, E., Dhliwayo, H., Mukoko, O., 1990. The potential of maize-cowpea intercropping in low rainfall areas of Zimbabwe. Zimbabwe J Agr Res 28, 33-38.

Shumba, E., Waddington, S., Rukuni, M., 1992. Use of tine-tillage, with atrazine weed control, to permit earlier planting of maize by smallholder farmers in Zimbabwe. Exp Agr 28, 443-443.

Sims, B., Kienzle, J., 2016. Making mechanization accessible to smallholder farmers in sub-Saharan Africa. Environments 3, 11.

Singh, B., Singh, D., 1995. Agronomic and physiological responses of sorghum, maize and pearl millet to irrigation. Field Crop Res 42, 57-67.

Sithole, N.J., Magwaza, L.S., Mafongoya, P.L., 2016. Conservation agriculture and its impact on soil quality and maize yield: A South African perspective. Soil Tillage Res 162, 55-67.

Smith, A., Snapp, S., Chikowo, R., Thorne, P., Bekunda, M., Glover, J., 2017. Measuring sustainable intensification in smallholder agroecosystems: A review. Global Food Security 12, 127-138.

Smith, A., Snapp, S., Dimes, J., Gwenambira, C., Chikowo, R., 2016. Doubled-up legume rotations improve soil fertility and maintain productivity under variable conditions in maize-based cropping systems in Malawi. Agr Syst 145, 139-149.

Smith, A.A., 2014. Effects of Maize Cowpea Intercropping on Yield Stability and Production Risk in Central Malawi: A Modeling Study. Michigan State University. Crop and Soil Sciences.

Snapp, S., Mafongoya, P., Waddington, S., 1998. Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa. Agric Ecosyst Environ 71, 185-200.

Snapp, S.S., Grabowski, P., Chikowo, R., Smith, A., Anders, E., Sirrine, D., Chimonyo, V., Bekunda, M., 2018. Maize yield and profitability tradeoffs with social, human and environmental performance: Is sustainable intensification feasible? Agr Syst 162, 77-88.

Soler, C.M.T., Bado, V.B., Traore, K., Bostick, W.M., Jones, J.W., Hoogenboom, G., 2011. Soil organic carbon dynamics and crop yield for different crop rotations in a degraded ferruginous tropical soil in a semi-arid region: a simulation approach. J Agric Sci 149, 579-593.

Spear, A.J., 1968. Tillage problems of peasant agriculture in Rhodesia. Supplement to Modern Farming. Salisbury, pp. 57–59.

Spear, D., Haimbili, E., Baudoin, M.-A., Hegga, S., Zaroug, M., Okeyo, A., Angula, M., 2018. Vulnerability and adaptation to climate change in semi-arid areas in Southern Africa. Collaborative Adaptation Research Initiative in Africa and Asia c/o IDRC, Ottawa, Canada.

Stanford, G., Smith, S., 1972. Nitrogen mineralization potentials of soils. Soil Sci Soc Am J 36, 465-472.

Stern, R., Rijks, D., Dale, I., Knock, J., 2006. Instat Climatic Guide. Statistical Service Center, Reading.

Stevenson, J.R., Serraj, R., Cassman, K.G., 2014. Evaluating conservation agriculture for small-scale farmers in Sub-Saharan Africa and South Asia. Agriculture, Ecosystems & Environment 187, 1-10.

Tadross, M., Suarez, P., Lotsch, A., Hachigonta, S., Mdoka, M., Unganai, L., Lucio, F., Kamdonyo, D., Muchinda, M., 2007. Changes in growing-season rainfall characteristics and downscaled scenarios of change over southern Africa: implications for growing maize. IPCC regional Expert Meeting on Regional Impacts, Adaptation, Vulnerability, and Mitigation, Nadi, Fiji, pp. 193-204.

Tennant, D., 1975. A test of a modified line intersect method of estimating root length. J Ecol, 995-1001.

Thierfelder, C., Cheesman, S., Rusinamhodzi, L., 2012. A comparative analysis of conservation agriculture systems: Benefits and challenges of rotations and intercropping in Zimbabwe. Field Crop Res 137, 237-250.

Thierfelder, C., Chivenge, P., Mupangwa, W., Rosenstock, T.S., Lamanna, C., Eyre, J.X., 2017. How climate-smart is conservation agriculture (CA)? - its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa. Food Security 9, 537-560.

Thierfelder, C., Mwila, M., Rusinamhodzi, L., 2013. Conservation agriculture in eastern and southern provinces of Zambia: Long-term effects on soil quality and maize productivity. Soil Tillage Res 126, 246-258.

Thierfelder, C., Wall, P.C., 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil Tillage Res 105, 217-227.

Tittonell, P., Giller, K.E., 2013. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. Field Crop Res 143, 76-90.

Traore, B., Descheemaeker, K., van Wijk, M.T., Corbeels, M., Supit, I., Giller, K.E., 2017. Modelling cereal crops to assess future climate risk for family food self-sufficiency in southern Mali. Field Crop Res 201, 133-145.

Traore, B., van Wijk, M.T., Descheemaeker, K., Corbeels, M., Rufino, M.C., Giller, K.E., 2015. Climate variability and change in Southern Mali: Leraning from farmer perceptions and on-farm trials. Exp Agr 51, 615-634.

Tsubo, M., Walker, S., Ogindo, H., 2005. A simulation model of cereal–legume intercropping systems for semi-arid regions: II. Model application. Field Crop Res 93, 23-33.

Twomlow, S., Urolov, J., Jenrich, M., Oldrieve, B., 2008. Lessons from the field–Zimbabwe's conservation agriculture task force. Journal of SAT Agricultural Research 6, 1-11.

USDA-SCS, 1986. Urban hydrology for small watersheds. Technical release 55, 2-6.

USDA, 2018. National Nutrient Database Basic Report 16062: Cowpeas, common (blackeyes, crowder, southern), mature seeds, raw. https://ndb.nal.usda.gov/ndb/foods/show/4801?manu=&fgcd=&ds= Accessed: 14 November 2018.

Valbuena, D., Tui, S.H.-K., Erenstein, O., Teufel, N., Duncan, A., Abdoulaye, T., Swain, B., Mekonnen, K., Germaine, I., Gérard, B., 2015. Identifying determinants, pressures and trade-offs of crop residue use in mixed smallholder farms in Sub-Saharan Africa and South Asia. Agr Syst 134, 107-118.

van Ittersum, M.K., van Bussel, L.G., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., de Groot, H., Wiebe, K., Mason-D'Croz, D., 2016. Can sub-Saharan Africa feed itself? Proc Natl Acad Sci U.S.A. 113, 14964-14969.

van Kessel, C., Hartley, C., 2000. Agricultural management of grain legumes: has it led to an increase in nitrogen fixation? Field Crop Res 65, 165-181.

Vandermeer, J.H., 1992. The ecology of intercropping. Cambridge University Press.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K., 2010. Integrated soil fertility management operational definition and consequences for implementation and dissemination. Outlook Agr 39, 17-24.

Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C., Nziguheba, G., Schut, M., Van Asten, P., 2014a. Sustainable intensification and the African smallholder farmer. Curr Opin Environ Sustain 8, 15-22.

Vanlauwe, B., Wendt, J., Giller, K., Corbeels, M., Gerard, B., Nolte, C., 2014b. A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity. Field Crop Res 155, 10-13.

Verachtert, E., Govaerts, B., Lichter, K., Sayre, K., Ceballos-Ramirez, J., Luna-Guido, M., Deckers, J., Dendooven, L., 2009. Short term changes in dynamics of C and N in soil when crops are cultivated on permanent raised beds. Plant Soil 320, 281-293.

Verhulst, N., Francois, I., Grahmann, K., Cox, R., Govaerts, B., Verhulst, N., Francois, I., Grahmann, K., Cox, R., Govaerts, B., 2014. Nitrogen use efficiency and optimization of nitrogen fertilization in conservation agriculture. CIMMYT, Mexico DF.

Vincent, V., Thomas, R., Staples, R., 1960. An agricultural survey of Southern Rhodesia. Part 1. Agro-ecological survey. Government Printers, Salisbury.

VSN, 2011. GenStat for Windows. 14th ed. VSN International Hemel Hempstead,UK.

Wahua, T., 1983. Nutrient uptake by intercropped maize and cowpeas and a concept of nutrient supplementation index (NSI). Exp Agr 19, 263-275.

Whitbread, A.M., Robertson, M.J., Carberry, P.S., Dimes, J.P., 2010. How farming systems simulation can aid the development of more sustainable smallholder farming systems in southern Africa. Eur J Agron 32, 51-58.

WHO, 2007. Protein and amino acid requirements in human nutrition: report of a joint WHO/FAO/UNU expert consultation. World Health Organization, Geneva, Switzerland.

WRB, 2006. Working Group (2006) World reference base for soil resources. A framework for international classification, correlation and communication, 2nd edn (World Soil Resources Reports 103). Food and Agriculture Organization of the United Nations, Rome.

Yang, J.M., Yang, J.Y., Liu, S., Hoogenboom, G., 2014. An evaluation of the statistical methods for testing the performance of crop models with observed data. Agr Syst 127, 81-89.

Zhang, C., Postma, J.A., York, L.M., Lynch, J.P., 2014. Root foraging elicits niche complementarity-dependent yield advantage in the ancient ‘three sisters’(maize/bean/squash) polyculture. Ann Bot-London 114, 1719–1733.

ZIMSTAT, 2012. Census 2012: Provincial Report (Matabeleland South) Zimbabwe Population Census 2012. Central Statistical Office, Harare.

ZimVac, 2012. Rural Livelihoods Assessment. Zimbabwe Vulnerability Assessment Committee SIRDC, Food and Nutrition Council (FNC), Harare.

Zingore, S., Delve, R.J., Nyamangara, J., Giller, K.E., 2008. Multiple benefits of manure: the key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. Nutr Cycl Agroecosys 80, 267-282.

Zingore, S., Manyame, C., Nyamugafata, P., Giller, K., 2005. Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. Eur J Soil Sci 56, 727-736.

Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agr Ecosyst Environ 119, 112-126.

ANNEX A: Average net N mineralised in-season (Chapter 3)

ANNEX A: Average net N mineralised in-season across tillage, mulch application, planting date scenarios and fertility amendment.

Tillage	Planting date scenario	Net N mineralised in season (kg ha^{-1}) 0 N	20N	40N	Manure	Manure+20N
Plough (no mulch)	01-Nov	9.6 (0.0 – 26.5)	23.2 (0.0 – 41.7)	28.6 (0.0 – 50.4)	46.2 (0.0 – 56.3)	43.2 (0.0 – 62.6)
	15-Nov	17.7 (0.0 – 46.5)	23.3 (0.0 – 40.0)	28.4 ((-1.6) – 49.6)	46.3 (0.0 – 76.8)	43.4 (0.0 – 67.5)
	30-Nov	9.7 (0.0 – 30.0)	23.7 (0.0 – 42.3)	29.5 ((-4.1) – 51.3)	50.7 (0.0 – 63.9)	43.0 (0.0 – 70.3)
	15-Dec	9.5 (6.0 – 12.5)	22.1 (0.5 – 39.0)	31.0 (0.9 – 68.0)	52.3 (7.5 – 60.9)	43.7 (12.4 – 68.8)
	31-Dec	8.4 (4.5 – 12.5)	22.0 (6.8 – 44.6)	30.0 (5.9 – 56.6)	52.9 (8.2 – 64.2)	39.5 (11.9 – 63.7)
	15-Jan	7.6 (3.3 – 11.1)	21.8 (5.7 – 43.4)	27.7 (4.9 – 50.9)	50.1 (7.2 – 59.4)	33.9 (11.6 – 49.3)
	20-mm	10.4 (0.0 – 30.0)	38.3 (9.2 – 59.9)	48.3 (8.2 – 75.4)	48.7 (11.3 – 92.0)	54.8 (11.9 – 84.5)
Plough + mulch	01-Nov	32.9 (0.0 – 52.5)	39.0 (0.0 – 52.5)	43.1 (0.0 – 74.9)	62.9 (0.0 – 103.4)	64.3 (0.0 – 108.1)
	15-Nov	18.3 (0.0 – 27.7)	23.9 (0.0 – 27.6)	28.4 ((-1.4) – 76.0)	32.8 (0.0 – 56.8)	43.5 (0.0 – 67.5)
	30-Nov	18.2 (0.0 – 26.0)	23.7 (0.0 – 26.0)	29.5 ((-4.4) – 51.3)	34.4 (0.0 – 63.9)	43.1 (0.0 – 70.6)
	15-Dec	9.5 (6.0 – 24.8)	22.5 (6.0 – 23.6)	31.6 (2.5 – 68.0)	34.2 (7.9 – 61.7)	44.0 (9.4 – 69.0)
	31-Dec	16.1 (4.0 – 28.9)	22.5 (4.6 – 28.9)	30.4 (3.7 – 56.7)	33.5 (6.0 – 64.3)	39.7 (9.6 – 63.8)
	15-Jan	7.6 (0.0 – 30.0)	22.9 (3.2 – 28.0)	27.8 (1.8 – 51.0)	31.5 (3.8 – 60.1)	33.9 (11.6 – 49.9)
	20-mm	10.4 (4.9 – 50.0)	38.3 (4.9 – 53.6)	48.3 (13.3 – 87.0)	48.7 (14.0 – 78.0)	54.8 (18.9 – 84.0)
Ripper (no mulch)	01-Nov	32.8 (0.0 – 52.5)	27.1 (0.0 – 57.7)	33.1 (0.0 – 53.8)	36.7 (0.0 – 57.7)	42.3 (0.0 – 60.4)
	15-Nov	19.8 (0.0 – 46.1)	27.1 (0.0 – 56.9)	28.4 ((-1.6) – 49.6)	32.9 (0.0 – 56.9)	43.4 (0.0 – 67.5)
	30-Nov	17.6 (0.0 – 44.6)	23.7 (0.0 – 63.9)	29.4 ((4.1) – 51.3)	34.5 (0.0 – 63.9)	43.1 (0.0 – 70.6)
	15-Dec	16.8 (7.6 – 23.6)	22.1 (7.7 – 61.1)	31.0 (0.9 – 68.0)	33.5 (7.7 – 61.1)	43.7 (12.4 – 68.8)
	31-Dec	16.1 (6.9 – 28.7)	22.0 (8.2 – 64.1)	30.0 (5.9 – 56.6)	33.0 (8.2 – 64.1)	39.5 (11.9 – 63.7)
	15-Jan	14.7 (5.0 – 25.7)	21.8 (11.7 – 76.9)	27.7 (4.9 – 50.9)	47.8 (11.3 – 76.6)	33.9 (11.7 – 49.3)
	20-mm	27.4 (8.9 – 44.6)	37.5 (7.2 – 94.0)	46.6 (8.2 – 75.3)	31.0 (7.2 – 59.4)	54.9 (11.9 – 84.9)
Ripper + mulch	01-Nov	39.0 (0.0 – 57.8)	42.8 (0.0 – 66.1)	46.8 (0.0 – 74.7)	65.8 (0.0 – 100.6)	71.3 (0.0 – 109.3)
	15-Nov	38.5 (0.0 – 86.6)	41.9 (0.0 – 68.3)	46.1 (0.0 – 74.3)	65.4 (0.0 – 105.6)	71.6 (0.0 – 113.6)
	30-Nov	38.7 (0.0 – 61.0)	43.8 (0.0 – 72.7)	48.2 (0.0 – 82.3)	67.0 (0.0 – 114.2)	72.7 (0.0 – 123.8)
	15-Dec	37.4 (17.8 – 59.9)	42.1 (14.5 – 72.5)	49.3 (12.0 – 92.6)	65.9 (27.3 – 115.6)	71.9 (30.2 – 122.8)
	31-Dec	36.6 (12.8 – 60.1)	41.3 (10.8 – 74.3)	45.7 (10.4 – 78.6)	61.7 (21.0 – 100.8)	66.1 (23.5 – 103.7)
	15-Jan	32.7 (10.8 – 56.2)	36.3 (8.4 – 63.2)	39.3 (8.4 – 64.6)	53.3 (16.3 – 83.6)	56.2 (20.5 – 86.8)
	20-mm	42.4 (24.8 – 60.7)	55.3 (22.9 – 83.6)	54.4 (19.0 – 90.0)	80.3 (40.2 – 119.7)	88.7 (43.6 – 135.0)
		P value	SED			
Planting date		0.001*	0.8			
Tillage		0.001*	0.4			
Mulch		0.001*	0.4			
Fertility amendment		0.001*	0.7			
Interaction		0.003*	3.5			

*Figures in parentheses denote the range of net N mineralised over 30 seasons

ANNEX B: Land equivalence ratios of maize-cowpea intercrop (Chapter 4)

ANNEX B: Land equivalence ratios of maize-cowpea intercrop in relation to intercrop type and time of cowpea incorporation into the intercrop (same date – cowpea planted on the same date as maize; 3WAP – cowpea planted 3 weeks after planting maize) (a) at Westacre Creek, Matopos Research Station (2010/11 – 2012/13 seasons), (b) in the research managed on-farm trial (2012/3 – 2014/15 seasons) and (c) in the farmer managed trials in Matobo district in the 2013/14 and 2014/15 seasons

a. Researcher managed on-station trial

Time of intercropping	Land Equivalent Ratio 2010/11	2011/12	2012/13
Same date	2.42	1.51	0.53
3WAP	2.33	2.36	1.84
	P	SED	
Intercropping time	0.023	0.27	
Season	0.009	0.33	
Interaction	NS	0.47	

b. Researcher-managed on-farm trial

N treatment	Time of intercropping	Land Equivalent Ratio 2012/13[a]	2013/14		2014/15[b]
0N	Same date	-	0.90		-
	3WAP	-	1.59		-
40N	Same date	-	1.90		-
	3WAP	-	1.00		-
			P	SED	
N treatment		-	0.02	0.37	-
Intercropping time		-	0.01	0.21	-
Interaction		-	NS	0.43	-

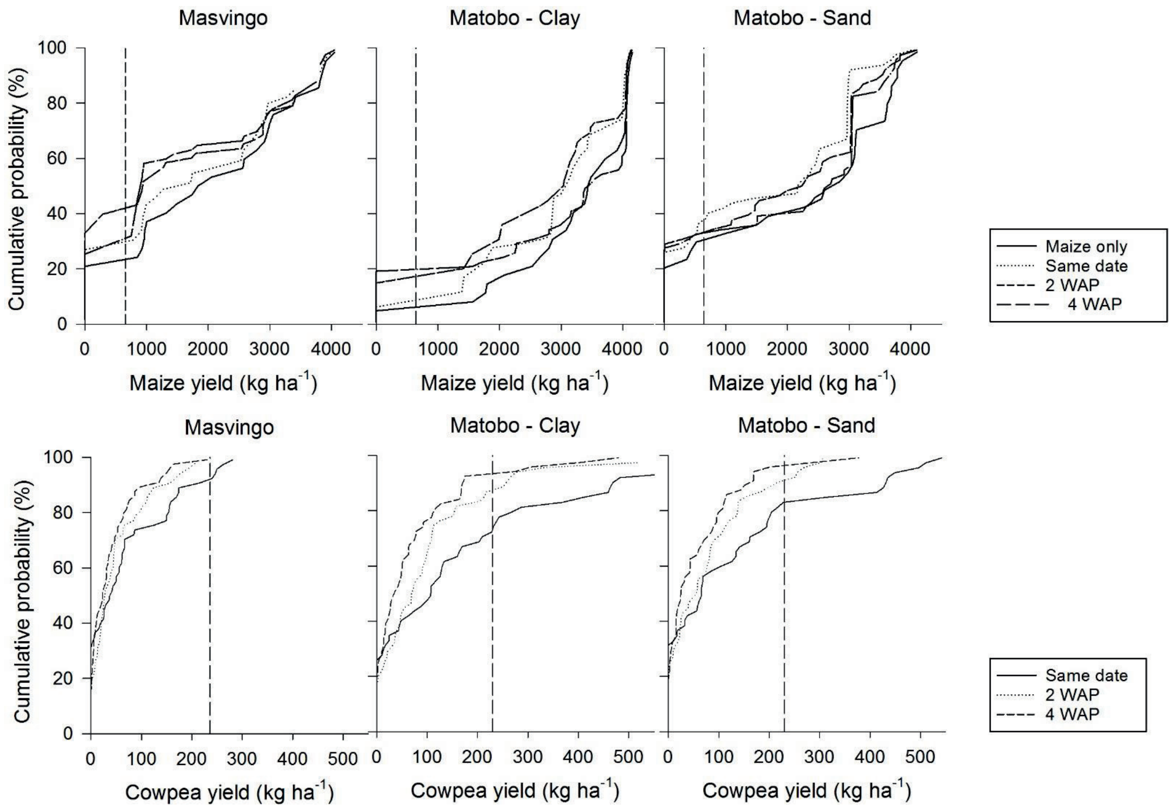
c. Farmer managed trials

N treatment	Time of intercropping	Land Equivalent Ratio 2013/14		2014/15[d]	
0N	Same date	1.63		-	
	3WAP	1.31		-	
40N	Same date	1.61		1.50	
	3WAP	1.89		-	
		P	SED	*P*	SED
N treatment		NS	0.29	-	-
Intercropping time		NS	0.29	-	-
Interaction		NS	0.41	-	-

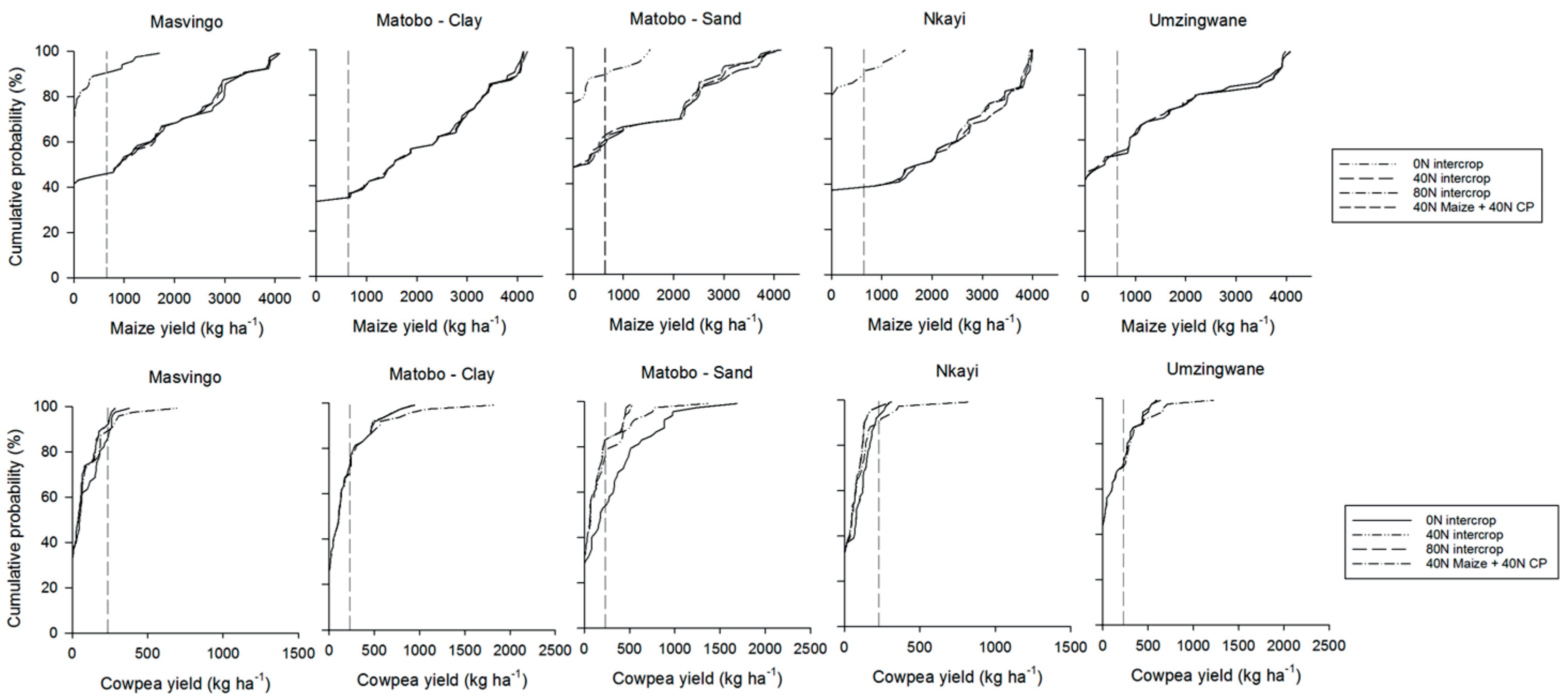
[a] In the 2012/13 and 2014/15 seasons, both maize and cowpea did not yield any grain in the researcher managed trial, LER was not calculated

[b] In the 2014/15 season, there were no maize grain yields under the 0N treatment and cowpea grain yields 3 WAP, LER was not calculated.

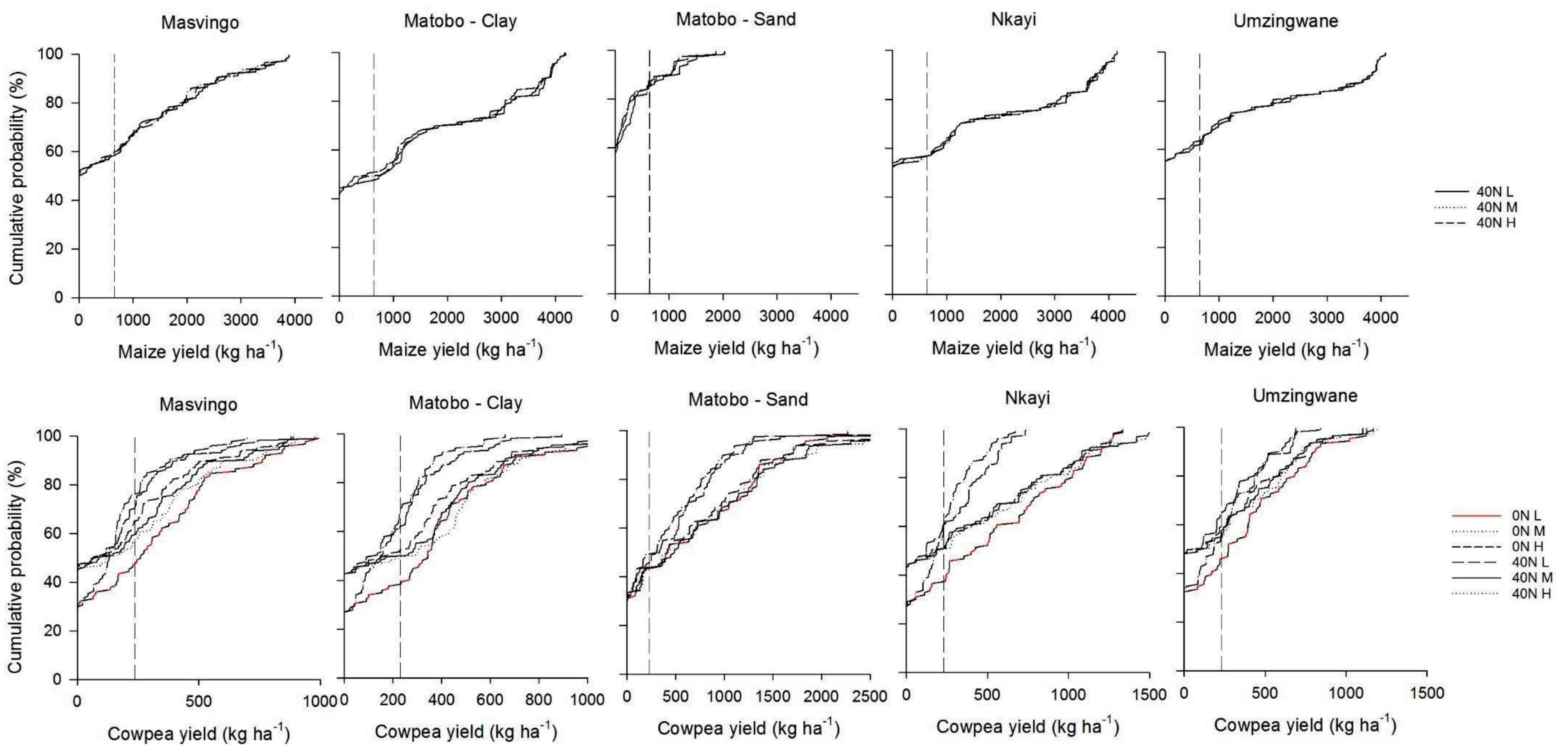
ANNEX C: Cumulative probability curves for simulated maize and cowpea grain yields (Chapter 5)



Annex C1: Cumulative probability curves for simulated maize and cowpea grain yield responses to different cowpea planting date scenarios at three sites in semi-arid Zimbabwe. The vertical dashed lines indicate the maize and cowpea threshold needs to meet household energy and protein requirements respectively.



Annex C2: Cumulative probability curves for simulated maize and cowpea grain yields in response to N fertiliser application at five sites in semi-arid Zimbabwe. The vertical dashed lines indicate the maize and cowpea threshold needs to meet household energy and protein requirements respectively.



Annex C3: Cumulative probability curves for simulated maize and cowpea grain yields at five sites in semi-arid Zimbabwe in response to different cowpea plant populations: Low (L) = 37 000 plants ha-1, Medium (M) = 74 000 plants ha-1 and High (H) = 148 000 plants ha^{-1}. Maize population was simulated at 37 000 plants ha^{-1}. The vertical dashed lines indicate the maize and cowpea threshold needs to meet household energy and protein requirements respectively.

SUMMARY

Smallholder agriculture in sub-Saharan Africa (SSA) is largely rainfed, which makes rural household susceptible to the increasingly variable climate. Agricultural production is already risky, due to low and unpredictable rainfall, high temperatures, high climatic variability, low soil fertility, land degradation, attacks of pests and diseases, and weed infestation, among other factors. The anticipated negative effects of climate change will make rainfed agriculture even riskier. Nonetheless, to feed the growing population in the future, drastic yet sustainable measures must be applied on existing cropland. To this end, two approaches have been proposed in recent times, climate-smart agriculture (CSA) and sustainable intensification (SI).

Climate-smart agriculture (CSA) may be defined as an approach for transforming and reorienting agricultural development under the new realities of climate change. CSA interventions are defined by three fundamental dimensions: a) adaptation to the effects of climate change; b) provision of mitigation benefits in terms of greenhouse gas emission reduction and building carbon (C) stocks and c) improved reliability, sustainability, productivity and profitability of agricultural production systems. Sustainable intensification (SI) is a process or system where agricultural yields are increased without adverse impact in the other sustainability domains (environment, social, economic) and without the conversion of additional non-agricultural land. Conservation agriculture (CA) and legume technologies such as intercropping have been put forward as promising options to achieve both CSA and SI. CA has been promoted vigorously in SSA. It is claimed to stabilise crop yields and increase drought resilience, and to cushion smallholder farmers against the adverse effects of soil fertility decline. Incorporation of legumes into cereal-based cropping systems is an inexpensive means to achieve crop diversification whilst rebuilding soil fertility. In intercropping systems

two or more crop species or genotypes are grown together and coexist for a time. However, a lack of strategical planning is responsible for very low yields of the component crops.

In this study, field experiments and crop modelling were employed to provide an ex ante understanding of the impact of CA and intercropping systems, both in the short and long term, in semi-arid southern Zimbabwe. The potential of CA and intercropping was determined by quantifying crop productivity and soil N dynamics. Through this, the study aimed at a better understanding of the potential and feasibility of SI and CSA approaches to contribute to farmers' livelihoods.

We first sought to determine, through on-farm experimentation, if and how CA practices, such as reduced tillage and mulching in combination with fertility amendments such as manure and fertiliser, and their interactions improve soil mineral N release, plant N uptake and ultimately maize yields (Chapter 2). A field experiment was set up in the Matobo district for three consecutive seasons. The effects of two tillage systems in combination with two mulch-management levels and five fertility amendment regimes on crop yields and N dynamics were evaluated. Individually, the CA principles of minimum soil disturbance (ripping) and maintenance of a permanent soil cover (mulch) resulted in reduced soil mineral N available for crop uptake and ultimately in low yields from a poor-fertility soil. However, where the principles were applied together and in combination with fertiliser and/or manure application, the ripper tillage and mulch application did not reduce mineralisation and resulted in yields comparable to those obtained under plough tillage without mulch. While nutrient inputs were key to ensure production in the infertile, sandy soils predominant in the semi-arid regions of Southern Africa, the N recovery by maize and the agronomic N efficiency were highly variable over the three seasons. This variability and uncertainty complicate farmers' decision-making.

To explore tillage and soil fertility amendment strategies over a longer time period and diverse weather conditions, Agricultural Production Systems sIMulator (APSIM) model was fed with current climate data (1984/85–2014/15) for Matobo district (Chapter 3). The model was used also to assess seasonal N mineralisation, crop yield, and the likelihood of experiencing complete crop failure and of achieving maize grain yields that ensured food self-sufficiency for an average farm household. The ripper tillage in conjunction with mulch application yielded significantly more compared with plough tillage, which was attributed to better soil moisture conditions due to higher infiltration. Early planting in combination with reduced tillage, mulch application and N fertiliser application allowed an average farm household to at least meet their household grain requirement from a hectare of land; it also reduced the risk of complete crop failure. The advantage of early planting was attributed to N mineralisation with the first rains of the season. Early planting can lead to increased yields, but it is very risky, because of the frequent occurrence of false starts, in which case yields decline.

Maize-cowpea intercropping experiments covering several seasons and conditions showed that intercrops performed better in terms of productivity than the sole crops; most intercrops had a land equivalent ratio exceeding 1. Maize yields responded to N fertiliser application more than to intercropping, which indicates that although planting legumes may improve soil N in the short term, N fertiliser is still required on the degraded sandy soils. Intercropping severely compromised cowpea yields, compared with sole cowpea stands. With maize, the effect of intercropping ranged from increased to significant reductions in yields dependent on the intercropping scenario. We found only marginal below-ground complementarity in the maize-cowpea intercrop on the poor sandy soil. The roots of both crops were densest in the same depth zones both in a dry and in a wet season. The lack of niche differentiation in terms of root growth resulted in high competition for nutrients and water. The maize root length density in the intercrop was generally higher compared with the cowpea, which would explain the negative effect on the cowpea grain yields. Maize-cowpea intercropping with low doses of N fertiliser proved to be a robust option across seasons and soil types, confirming that it is a promising option for resource-poor smallholders.

Smallholder farmers in Zimbabwe must cope with small farm sizes, low soil fertility and production risks associated with rainfed agriculture. We tested the hypothesis that maize-cowpea intercrops are a low-risk option, contributing to household food self-sufficiency in semi-arid Southern Africa (Chapter 5). We used the APSIM model evaluated for maize-cowpea intercropping, using long-term climate data for four districts and two soil types (sand and clay), to identify the best management intercropping practices – that is, those that consistently assured energy and protein self-sufficiency. Different scenarios of planting dates, fertiliser rates and plant population were tested. Intercropping had a small negative effect on the mean maize yields in comparison with the sole maize. Cowpea yield decreased proportionate to the delay in planting in the intercrop. Modelling showed that maize-cowpea intercropping allows farmers to attain household energy and protein self-sufficiency more easily than growing the same crops sole. Most maize-cowpea intercropping scenarios had a high probability of meeting household energy and protein requirements. Planting maize and cowpea at populations of 37 000 and 74 000 plants ha^{-1} respectively on the same date and with 40 kg N ha^{-1} applied to maize was the best intercropping scenario, maximising the probability of meeting household energy and protein requirements on sandy soils. On the clay soils, the relay intercropping scenarios, with cowpea planted 2 to 4 weeks after maize, met household nutrition needs.

In Chapter 6, the cropping technologies were framed in the context of smallholders in semi-arid southern Zimbabwe to enable a discussion on the feasibility of CA and maize-cowpea intercropping as SI and CSA approaches in the region. Although ripping may be favourable, poorly-resourced farmers in Zimbabwe who seldom own land-preparation equipment may not be able to afford rippers or be willing to purchase the cheaper ripper tine attachments when they do not own a plough. Manufacturers requiring pre-financing for production have been producing only few rippers and ripper tine attachments. Intercropping will also only be attractive for smallholder farmers if reliable access to input and output markets and credit schemes will be ensured. Strengthening the market linkages between smallholder farmers and agro-dealers may help to foster the uptake of technologies and bring farmers a step closer to achieving the yield benefits observed in this study. Smallholder farmers in semi-arid Zimbabwe may be open to diversifying cropping and to intercropping, if it does not reduce the land allocated to maize or require too much labour. CA and intercropping may offer options to intensify agricultural production while at the same time reducing the risk in the face of climate variability. Whether that makes CA and intercropping climate-smart depends on how strictly the CSA definition is interpreted. Smallholder farmers are more concerned with meeting household food needs than with mitigating greenhouse gas emissions. Moreover, in the area which the study focused on, most farms are on sandy soils which have little capacity to store soil organic carbon. This makes it virtually impossible to meet the mitigation criteria of CSA.

Both CA and intercropping require substantial labour. Labour constraints hamper the adoption of these technologies in smallholder areas of Zimbabwe. If the large-scale migration of able-bodied men and women to urban centres within and outside the country continues, the problem of labour constraints may remain the same for the foreseeable future. In order to persuade farmers to adopt CA and intercropping, so as to increase the resilience to climate change, it would be important to consult them on their preferences and involve them in the process of adapting the options to their context. Farmer engagement will allow for research to focus on farmer priorities in different locations characterised by specific climatic risks.

ACKNOWLEDGEMENTS

This PhD journey has been long and windy but the support of so many people made the journey easier. I acknowledge fully the mentorship and support from my supervisors. I would like to thank my promotor Prof. Ken Giller who afforded me the opportunity to study under him, from guiding me to source funding for my study, believing in me, wise counsel and the guidance through the study. I am extremely grateful to my supervisor Dr Katrien Descheemaeker for being there every step of the way. I thank her for her energy which encouraged me, dedication, passion for her work and constructive feedback. I would like to thank my co-promotor Prof. Justice Nyamangara for facilitating the start of my studies and the work in Zimbabwe. I thank him for affording many opportunities to grow in the science fraternity. I would like to thank Drs Vimbayi Chimonyo, Walter Mupangwa, Jairos Rurinda, Joseph Eyre, John Dimes and Patricia Masikati-Hlanguyo for their insightful tips on crop growth modelling.

My ICRISAT family has been the best, I thank them for the support throughout the years. I thank Irene Ncube, Oliver Katsaura, Rumbidzayi Gwanoya and Oswell Ncube for helping manage my grant, Dr Kizito Mazvimavi for the support during my studies and Dr Andre van Rooyen who agreed to let me go to school in the first place and for always having words of encouragement. I thank my next-door neighbour Dr Conrad Murendo for always checking in on me. A special thank you to my work brothers: Ronald Tirivavi, Machiweyi Kunzekweguta, Alec Magaisa, Robert Shamwarira and Simon Gwara. Thank you to Dorcas Mutsago, Murairo Madzvamuse, Getrude Mpofu and Jethro Ndlovu for the technical assistance in my study. Thank you to the drivers especially Alphias Khanye and the late Timothy Mpofu. I would like to thank my Matopos family, Givious and Faith Sisito for always managing to make me smile. To my "sister" Dr Pauline Chivenge who always encouraged me during this journey, I remain grateful – we made it! Thank you so much to Catherine Donono for being there for me, for the long afternoon walks and talks. Thank you too to Moleen Chiwona, Sibongile Tshili, Chenai

Madamombe-Makamure, Nester Mashingaidze and my fellow sisters on the PhD track: Dr Kumbirai Musiyiwa, Dr. Tarisayi Pedzisa Shiela Chikulo and Doreen Tivenga for always encouraging me.

I thank the PPS administration and finance staff past and present for all logistical arrangements: Linda Kaster, Charlotte Schilt, Karen Hendricks, Ria van Dijk and Alex-Jan de Leeuw. Thank you to my PPS friends and colleagues for those talks loaded with advice, lunches, dinners and walks: Leonard Rusinamhodzi, Bouba Traore, Benjamin Kibor, Guillaume Ezui, Edouard Rurangwa, Greta van den Brand, Esther Ronner, Marius Assogba, Lotte Klapwijk, Samuel Njoroge, Admire Katunga, Eva Huet and Hannington Bukomeko. I would especially like to thank Eva and Esther for agreeing to be my paranymphs! Thank you also to friends from the CSA Luuk van Dijk and Waga Mazengia.

I would like to thank my Zimbabwean family in Wageningen: Mutsvandiani Chikutuma, Praxedes Dube, Betty Masamba, Anna Alesho, Lesley Macheka, Merjury Shiri, Steven Matema, Innocent Nyakudya and the Maphosas. I thank my African choir family, the community of Titus Brandsma Parish and the Amazing Grace Parish for making me feel at home. A big thank you to Patience Muchada-Venus and Valentijn Venus for helping me settle in The Netherlands and providing me with a home away from home.

My study would not have been possible without the farmers who contributed enormously to the work. I would especially like to thank Mr. and Mrs. Agripper Moyo, Councillor Moyo and his wife who facilitated my work in Matobo district. I am also indebted to the government extension officers who facilitated the farmer group formations in Nkayi, Umzingwane, Masvingo and Matobo. I grateful to the Netherlands Organization for International Cooperation in Higher Education (NUFFIC) for funding my PhD studies.

Lastly, I want to thank my family for being my loudest cheerleaders. The Masvayas and Zinyembes, I am truly grateful. I thank my parents for sticking with me through it all and always believing in me, my amazing sister Chenai, brothers, aunt Flo, sister-in-law and niece Manaya. You have made all this worthwhile.

ABOUT THE AUTHOR

Esther Nyaradzo Masvaya was born on 2 February 1983 in Harare, Zimbabwe. She attended her high school at Monte Cassino Girls' High School in Macheke. She studied Agriculture at the University of Zimbabwe, Harare specialising in Soil Science and graduated with Honours in 2005. In the same year, she started a Masters in Soil and Environmental Management again at the University of Zimbabwe. Work on her Masters' thesis centred on exploring soil fertility gradients in rural Zimbabwe with funding from the Regional Universities Forum (RUFORUM) and Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT). She graduated in 2007.

In 2007, she was employed by the International Crops Research Institute of the Semi-Arid Tropics (ICRISAT) as a Scientific Officer (Agronomy). While at ICRISAT he was admitted as a PhD student in the Plant Production Systems Group of Wageningen University in 2012 and received funding from NUFFIC to pursue the PhD.

LIST OF PUBLICATIONS

Peer reviewed scientific publications

Masvaya, E.N., Nyamangara, J., Giller, K.E., and Descheemaeker, K. 2018. *Risk management options in maize cropping systems in semi-arid areas of Southern Africa*. Field Crops Research 11/2018; 228:110-121., doi:10.1016/j.fcr.2018.09.002

Masvaya, E.N., Nyamangara, J., Descheemaeker, K., and Giller, K.E. 2017. *Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid southern Africa?*. Field Crops Research 08/2017; 209:73-87., doi:10.1016/j.fcr.2017.04.016

Masvaya, E.N., Nyamangara, J., Descheemaeker, K., and Giller, K.E. 2017. *Tillage, mulch and fertiliser impacts on soil nitrogen availability and maize production in semi-arid Zimbabwe*. Soil and Tillage Research 05/2017; 168:125-132., doi:10.1016/j.still.2016.12.007

Mupangwa, W., Walker, S., Masvaya, E., Magombeyi, M., and Munguambe, P. 2016. *Rainfall risk and the potential of reduced tillage systems to conserve soil water in semi-arid cropping systems of southern Africa*. 03/2016; 1(1)., doi:10.3934/agrfood.2016.1.85

Nyamangara, J., Masvaya, E.N., Tirivavi, R.D., and Munodawafa, A. 2015. *Grain Yield Responses of Selected Crop Varieties at Two Pairs of Temperature Analogue Sites in Sub-humid and Semi-arid Areas of Zimbabwe*. Adapting African Agriculture to Climate Change, 01/2015: pages 85-95; ISBN: 978-3-319-12999-0, doi:10.1007/978-3-319-13000-2_7

Nyamangara, J., Marondedze, A., Masvaya, E.N., Mawodza, T., Nyawasha, R., Nyengerai, K., Tirivavi, R., Nyamugafata, P., and Wuta, M. 2014. *Influence of basin-based conservation agriculture on selected soil quality parameters under smallholder farming in Zimbabwe*. Soil Use and Management 10/2014; 30(4)., doi:10.1111/sum.12149

Nyamangara, J., Nyengerai, K., Masvaya, E.N., Tirivavi, R., Mashingaidze, N., Mupangwa, W., Dimes, J., and Hove, L. 2014. *Effect of conservation agriculture on maize yield in the semi-arid areas of Zimbabwe*. Experimental Agriculture 04/2013; 50(2)., doi:10.1017/S0014479713000562

Nyamangara, J., Masvaya, E.N., Tirivavi, R. and Nyengerai, K. 2013. *Effect of hand-hoe based conservation agriculture on soil fertility and maize yield in selected smallholder areas in Zimbabwe*. Soil and Tillage Research 01/2013; 126., doi:10.1016/j.still.2012.07.018

Nyamangara, J., Mashingaidze, N., Masvaya, E.N., Nyengerai, K., Kunzekweguta, M., Tirivavi, R., and Mazvimavi, K. 2013. *Weed growth and labor demand under hand-hoe based reduced tillage in smallholder farmers' fields in Zimbabwe*. Agriculture Ecosystems & Environment 01/2013; 187., doi:10.1016/j.agee.2013.10.005

Nyamangara, J., Makarimayi, E., Masvaya, E.N., Zingore, S., and Delve, R.J. 2011. *Effect of soil fertility management strategies and resource-endowment on spatial soil fertility gradients, plant nutrient uptake and maize growth at two smallholder areas, north-western Zimbabwe*. South African Journal of Plant and Soil 01/2011; 28(1):1-10., doi:10.1080/02571862.2011.10640006

Masvaya, E.N., Nyamangara, J., Nyawasha, R.W., Zingore, S., Delve, R.J., and Giller, K.E. 2010. *Effect of Farmer Resource Endowment and Management Strategies on Spatial Variability of Soil Fertility in Contrasting Agro-ecological Zones in Zimbabwe*. Nutrient Cycling in Agroecosystems 09/2010; 88:111-120., doi:10.1007/s10705-009-9262-y

Conference proceedings

Masvaya, E.N. Nyamangara, J., Giller, K.E., Katrien Descheemaeker. 2018. Dealing with Climate Risk for Maize Production on Infertile Soils in Semi-Arid Southern Africa. *XV European Society for Agronomy Congress.* Geneva, Switzerland.

Masvaya, E.N. and Mazvimavi, K. 2014. Conservation agriculture in Zimbabwe highlights – ICRISAT. *Regional Conservation Agriculture Symposium*. Bulawayo, Zimbabwe

Masvaya, E.N., Nyamangara, J., Tirivavi, R. and Hove, L. 2012. The potential of maize-cowpea intercrops to increase crop productivity under reduced tillage in the semi-arid areas of Zimbabwe. *International Conference on Integrated Soil Fertility Management in Africa: From Microbes to market.* Nairobi, Kenya.

Nyamangara, J., Nyengerai, K., Masvaya, E.N., Tirivavi, R., Mashingaidze, N., Mupangwa, W., Dimes, J., Hove, L. and Twomlow, S. 2011. Effect of conservation agriculture on maize yield in the semi-arid areas of Zimbabwe. *5th World Congress of Conservation Agriculture incorporating 3rd Farming Systems Design Conference*. Brisbane, Australia. www.wcca2011.org.

Nyamangara, J. and Masvaya, E.N. 2011. Soil fertility status under conservation agriculture in selected smallholder areas with contrasting agroecological conditions in Zimbabwe. *Regional Conservation Agriculture Symposium*. Johannesburg, South Africa.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the 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 (6 ECTS)

- Effect of soil disturbance on the potential mineralization of soil organic carbon and nitrogen

Writing of project proposal (4.5 ECTS)

- Exploring opportunities to improve resource use efficiencies using conservation agriculture practices in smallholder farms in semi-arid areas

Post-graduate courses (3.6 ECTS)

- Mixed linear models; PE&RC (2012)
- Farming systems and rural livelihoods: vulnerability and adaptation, WondoGenet, Ethiopia; PE&RC, WASS, WIAS (2013)

Laboratory training and working visits (1.8 ECTS)

- APSIM Training; CIMMYT, Zimbabwe (2015)

Invited review of (unpublished) journal manuscript (4 ECTS)

- Nutrient Cycling in Agroecosystems: response of maize and pigeon pea cropping systems to fertilizers in Tanzania (2017)
- Archives of Agronomy and Soil Science: silage maize quality in production systems with Italian ryegrass after liming (2017)
- Field Crops Research: testing pearl millet and cowpea intercropping systems under extreme climatic conditions (2017)
- Field Crops Research: the effects of plastic mulching and nitrogen application rate on maize yield and nitrogen translocation in Loess Plateau of China (2017)

Deficiency, refresh, brush-up courses (6 ECTS)

- Quantitative analysis of cropping and grassland systems; PPS (2012)

Competence strengthening / skills courses (1.5 ECTS)

- Scientific publishing; WGS (2012)
- Scientific writing; Midlands State University and ICRISAT (2014)
- Research ethics; WASS (2017)

PE&RC Annual meetings, seminars and the PE&RC weekend (0.9 ECTS)

- PE&RC weekend (2017)
- PE&RC Day (2017)

Discussion groups / local seminars / other scientific meetings (7.5 ECTS)

- Plant production systems and WACASA lunch meetings (2012-2017)

- Conservation agriculture regional working group (2013-2015)
- Soil science society of Zimbabwe meetings (2013-2018)
- ICRISAT workshops and seminars (2013-2018)

International symposia, workshops and conferences (6.6 ECTS)

- Integrated soil fertility management in Africa: from microbes to markets international conference (2012)
- Conservation agriculture regional working group workshop (2014)
- XV European society for agronomy congress: innovative cropping and farming systems for high quality food production systems (2018)

FINANCIAL SUPPORT

The research described in this thesis was financially supported by the Netherlands Organization for International Cooperation in Higher Education and Research (NUFFIC) through the Netherlands Fellowship Programme (NFP).

Financial support from Wageningen University for printing this thesis is gratefully acknowledged.